New Ru-Based Catalysts and Strategies for Kinetically Controlled Stereoselective Olefin Metathesis

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Abstract

- *Chapter 1. In Situ Methylene Capping: A Key Strategy in Catalytic Stereoretentive Olefin Metathesis*

A general approach for *in situ* methylene capping that significantly expands the scope of catalyst-controlled stereoselective olefin metathesis is presented. By incorporation of stereodefined 2-butene as the capping reagent, the catechothiolate Ru complex is enabled to catalyze olefin metathesis reactions of terminal alkenes. Substrates bearing a carboxylic acid, an aldehyde, an aryl substituent, an α substituent were thus converted to the desired products in 47–88% yield and 90:10–98:2 *Z:E* selectivity. The capping strategy was also applied in ring-closing metathesis reactions leading to 14- to 21-membered macrocyclic alkenes (96:4–98:2 *Z:E*). The utility of this method was highlighted through synthesis of a platelet aggregate inhibitor and two members of the prostaglandin family compounds by cross-metathesis reaction, as well as a strained 14-membered ring stapled peptide by macrocyclic ring-closing metathesis. Examples of the corresponding *E*-selective cross-processes are provided as well.

- *Chapter 2. Synthesis of Z- or E-Trisubstituted Allylic Alcohols and Ethers by Kinetically Controlled Catalytic Cross-Metathesis*

Kinetically controlled Ru-catalyzed cross-metathesis reactions that generate *Z*- or *E*-trisubstituted alkenes are discussed. Reactions were catalyzed by catechothiolate Ru complex to generate trisubstituted allylic alcohols and ethers in up to 81% yield and >98% stereoisomeric purity. The approach is applicable to synthesis of products containing an alcohol, an aldehyde, a carboxylic acid or an alkenyl substituent. Mechanistic models that account for the observed trends in efficiency and stereoselectivity will be provided.

- *Chapter 3. A New Ru-Based Catechothiolate Complex Bearing an Unsaturated NHC Ligand for Synthesis of Z-α,β-Unsaturated Carbonyl Compounds by Cross Metathesis*

Design and development of a new Ru catechothiolate complex that may be used to promote Z-selective cross-metathesis transformations that afford *Z-α,β*-unsaturated esters, acids, and amides (including Weinweb amides) are discussed. Comparison between Ru catechothiolate complexes with an unsaturated NHC and a saturated NHC ligand will be provided. Utility of the approach is demonstrated by an eight-step synthesis (15% overall yield) of an intermediate for synthesis of stagonolide E, and a five-step synthesis of a precursor to dihydrocompactin

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Acknowledgements

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Chapter One

In Situ Methylene Capping: A Key Strategy in Catalytic Stereoretentive Olefin Metathesis

1.1. Introduction

The development of methods for synthesis of C–C double bonds has received considerable attention in organic synthesis because of the prevalence of these motifs in various biologically active molecules[1] and vast number of building blocks that are key to chemical synthesis[2] (Scheme 1.1). Despite notable advances,[3] a significant limitation of existing methods is that *Z/E* mixtures are often generated, with the lower energy *E* alkenes as major isomers.[4] To access *Z* olefins stereoselectively,[5] several strategies may be used; these include Wittig-type transformations,[6] Still-Gennari processes,[7] partial hydrogenation of alkynes,[8] and catalytic cross-coupling reactions[9] (Scheme 1.2). However, Wittig-type and Still-Gennari approaches do not always generate high selectivity, and alkyne

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(1) (a) Kobayashi, J.; Wantanabe, D.; Kawasaki, N.; Tsuda, M. *J. Org. Chem*. **1997**, *62*, 9236–9239. (b) Kemp, M. S. *Phytochemistry*. **1978**, *5*, 1002. (c) Funk, C. D. *Science* **2001**, *294*, 1871–1875.

(2) Meek, S. J.; O'Brien, R. V.; Liaveria, J.; Schrock, R. R.; Hoveyda, A. H. *Nature* **2011**, *471*, 461–466.

(3) *Modern Carbonyl Olefination*; Takeda, T., Ed.; Wiley-VCH: Weinheim, Germany, 2003.

(4) (a) Julia, M.; Paris, J.-M. *Tetrahedron Lett.* **1973**, *14*, 4833–4836. (b) Staden, F.; Gravestock, D.; Ager, D. J.; *Chem. Soc. Rev*. **2002**, *31*, 195-200.

(5) Siau, W. Y.; Zhang, Y.; Zhao, Y. *Top. Curr. Chem.* **2012**, *327*, 33–58.

(6) (a) Bergelson, L. D.; Shemyakin, M. M. *Tetrahedron* **1963**, *19*, 149–159. (b) Maercker, A. *Org. React.* **1965**, *14*, 270–490. (c) Hoffmann, R. W. *Angew. Chem., Int. Ed*. **2001**, *40*, 1411–1416. (d) Robiette, R.; Richardson, J.; Aggarwal, V. K.; Jarvey, J. N. *J. Am. Chem. Soc*. **2006**, *128*, 2394–2409.

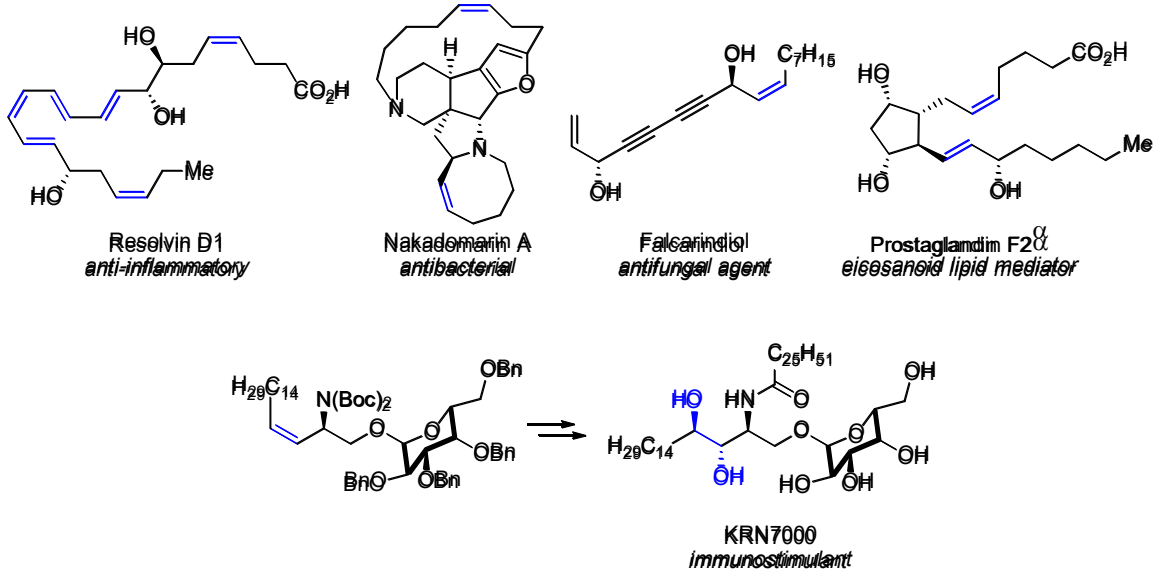
(7) (a) Still, W. C.; Gennari, C. *Tetrahedron Lett.* **1983**, *24*, 4405–4408. (b) Patois, C.; Savignac, P.; About-Jaudet, E.; Collignon, N. *Org. Synth*, **1998**, *9*, 88. (c) Ando, K. *J. Org. Chem*. **1997**, *62*, 1934–1939.

(8) (a) Lindlar, H.; Dubuis, R. *Org. Synth.* **1966**, *46*, 89. (b) Overman, E.; Brown, M. J.; McCann, S. F. *Org. Synth*. **1990**, *68*, 182.

(9) Hegedus, L. S.; Soderberg, B. C. G. *Transition Metals in the Synthesis of Complex Organic Molecules*, 3rd ed.; University Science Books: Sausalito, CA, 2009.

reductions can suffer from over-reduction, olefin isomerization and inferior reproducibility. Cross-coupling processes require a priori stereoselective synthesis of the requisite *Z* alkene substrate. Kinetically controlled catalytic olefin metathesis strategies for synthesis of Z alkenes would be a significant addition to this repertoire, as such processes would offer an entirely distinct bond disconnection (vs a Wittig-type or a cross-coupling reaction) as well as one that is more atom-economic.

Scheme 1.1. Natural Products Bearing Stereodefined Alkenes



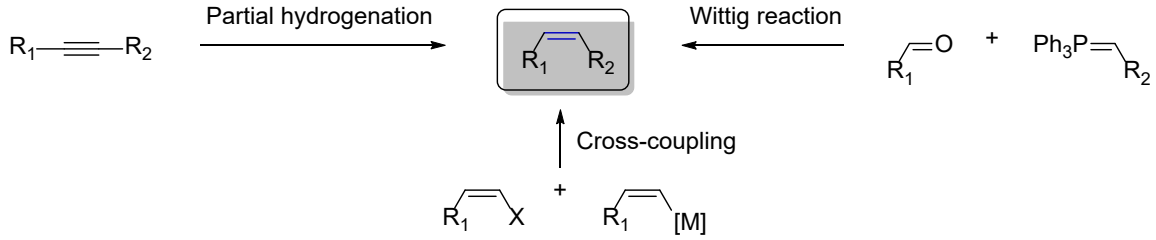
Olefin metathesis is a broadly applicable strategy for alkene synthesis, and Ru-based complexes have played a critical role in this emergence.[10,11] The advantageous characteristics of Ru-dichloro catalysts include robustness and compatibility to key

(10) (a) Hoveyda, A. H.; Zhugralin, A. R. *Nature* **2007**, *450*, 243–251. (b) Hoveyda, A. H. *J. Org. Chem.* **2014**, *79*, 4763–4792. (c) *Handbook of Metathesis*; Grubbs, R. H., Wenzel, A. G., O'Leary, D. J., Khosravi, E., Eds.; Wiley-VCH: Weinheim, Germany, 2014.

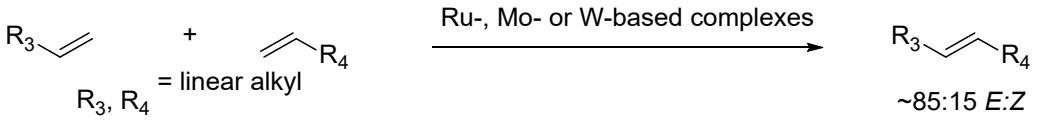
(11) (a) Nguyen, S. T.; Johnson, L. K.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1992**, *114*, 3974–3975. (b) Schwab, P.; France, M. B.; Ziller, J. W.; Grubbs, R. H. *Angew. Chem., Int. Ed.* **1995**, *34*, 2039–2041. (c) Scholl, M.; Ding, S.; Lee, C. W.; Grubbs, R. H. *Org. Lett.* **1999**, *6*, 953–956. (d) Kingsbury, J. S.; Harrity, J. P. A.; Bonitatebus, P. J.; Hoveyda, A. H. *J. Am. Chem. Soc.* **1999**, *121*, 791–799. (e) Garber, S. B.; Kingsbury, J. S.; Gray, B. L.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2000**, *122*, 8168–8179.

functional units such as aldehydes, ketones and carboxylic acids. Yet, a glaring shortcoming in the state-of-the-art is that olefin metathesis reactions catalyzed by Ru-dichloro complexes generally deliver stereoisomeric mixtures with *E* alkenes as the major component (Scheme 1.2). To address this issue, a number of research groups have focused on developing olefin metathesis catalysts and methods that may be used for preparation of alkenes in high stereoisomeric purity.

Scheme 1.2. Commonly Used Methods for Preparation of *Z* Olefins



Scheme 1.3. Catalytic Cross-Metathesis



1.2. *Z*-Selective Olefin Metathesis with Ru Catechothiolate Complexes

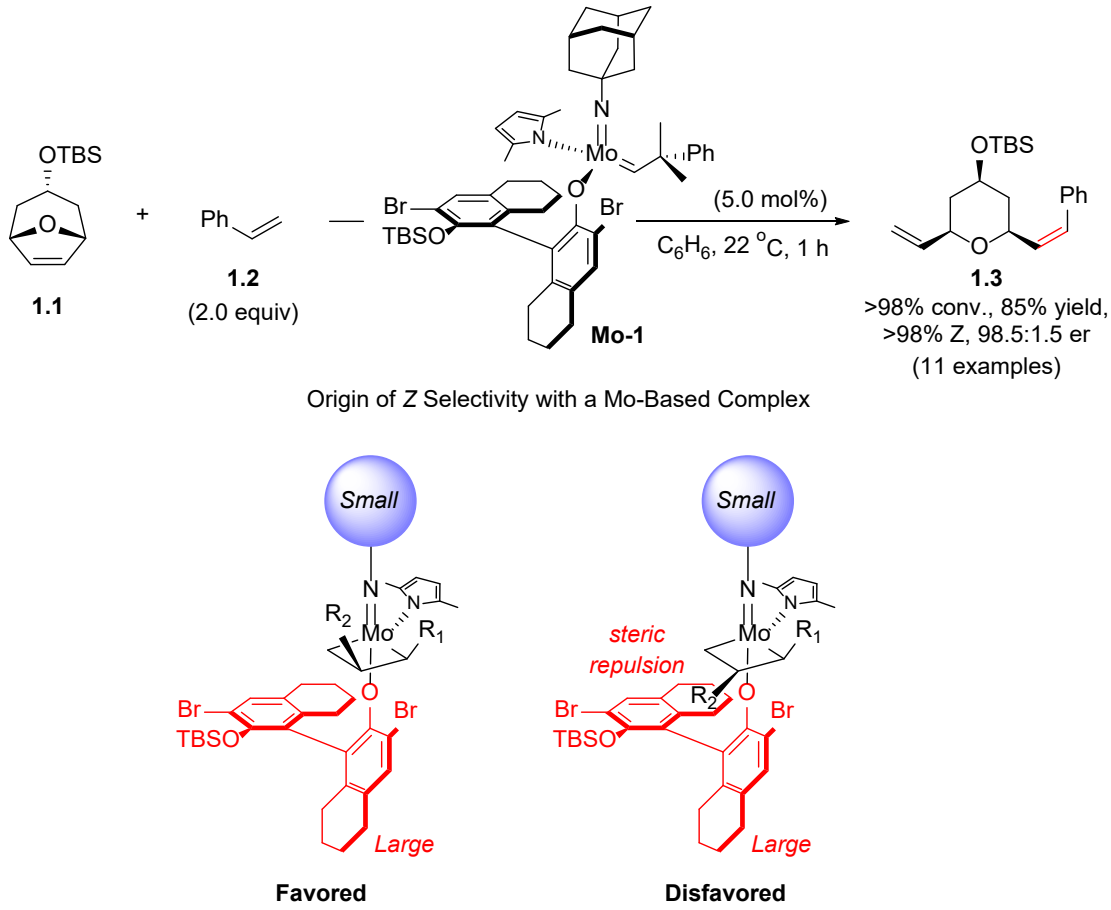
1.2.1. The Advent of *Z*-Selective Catalytic Olefin Metathesis

The first examples of kinetically controlled olefin metathesis were reported in 2009 by Hoveyda and Schrock[12] (Scheme 1.3): a high-oxidation-state stereogenic-at-Mo imido monoaryloxide pyrrolide (MAP) complex was shown to promote catalytic *Z*-selective ring-opening/cross-metathesis (ROCM) of oxabicyclic alkenes and styrenes. It was proposed that *Z* selectivity originates from size difference between imido and aryloxide ligands (Scheme 1.4); this allows for the metallocyclobutane substituents to orient towards smaller

(12) Ibrahem, I.; Yu, M.; Schrock, R. R.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2009**, *131*, 3844–3845.

imido moiety, resulting in kinetic preference for formation of the *Z* product isomer. This initial discovery subsequently led to the development of MAP-Mo-catalyzed *Z*-selective ring-opening metathesis polymerization (ROMP), [13] cross-metathesis (CM),[2] and macrocyclic ring-closing metathesis (MRCM).[14]

Scheme 1.4. The First Examples of Kinetically Controlled *Z*-Selective Catalytic Olefin Metathesis



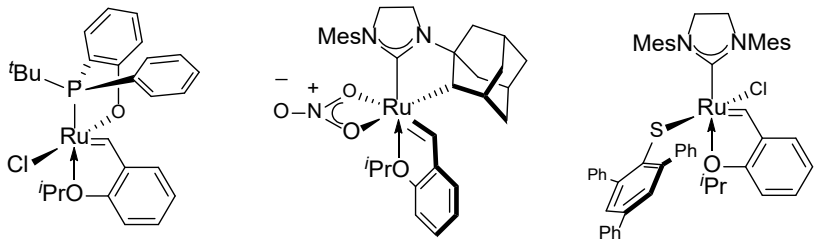
The 2009 Hoveyda/Schrock mechanistic model has inspired the development of Ru-based complexes that facilitate *Z*-selective metathesis reactions. Since 2010, several *Z*-selective Ru complexes have been disclosed (Scheme 1.5). These include complexes that

(13) Flook, M. M.; Jiang, A. J.; Schrock, R. R.; Muller, P.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2009**, *131*, 7962–7963.

(14) Yu, M.; Wang, C.; Kyle, A. F.; Jakubec, P.; Dixon, D. J.; Schrock, R. R.; Hoveyda, A. H. *Nature* **2011**, *479*, 88–93.

bear a bidentate phosphine,[15] a bidentate N-heterocyclic carbene (NHC),[16] or an arylthiolate ligand[17]. Nonetheless, these systems not only do not provide the same range of functional group compatibility as the Ru-dichloride catalysts, the reactions performed with these complexes were limited in scope, often affording products in low yield and/or *Z*:*E* ratio.

Scheme 1.5. Previously Reported *Z*-Selective Ru-Based Olefin Metathesis Complexes



Ru-2 **Ru-3** **Ru-4**

In 2010, Chen *et al.* reported that **Ru-2** and related analogues can be used to promote co-polymerization of norbornene with cyclooctene; however, *Z* selectivity did not exceed 50%.[15] In 2011, Grubbs and coworkers reported the discovery of a *Z*-selective Ru-based complex bearing an alkyl and an oxo anionic ligand (**Ru-3**).[16] Although **Ru-3** has

(15) Torker, S.; Muller, A.; Chen, P. *Angew. Chem., Int. Ed.* **2010**, *49*, 3762–3766.

(16) (a) Endo, K.; Grubbs, R. H. *J. Am. Chem. Soc.* **2011**, *133*, 8525–8527. (b) Keitz, B. K.; Endo, K.;Herbert, M. B.; Grubbs, R. H. *J. Am. Chem. Soc.* **2011**, *133*, 9686–9688. (c) Keitz, B. K.; Endo, K.; Patel, P. R.; Herbert, M. B.; Grubbs, R. H. *J. Am. Chem. Soc.* **2012**, *134*, 693–699. (d) Keitz, B. K.; Fedorov, A.; Grubbs, R. H. *J. Am. Chem. Soc.* **2012**, *134*, 2040–2043. (e) Marx, V. M.; Herbert, M. B.; Keitz, B. K.; Grubbs, R. H. *J. Am. Chem. Soc.* **2013**, *135*, 94–97. (f) Herbert, M. B.; Marx, V. M.; Pederson, R. L.; Grubbs, R. H. *Angew. Chem., Int. Ed.* **2013**, *52*, 310–314. (g) Rosebrugh, L. E.; Herbert, M. B.; Marx, V.M.; Keitz, B. K.; Grubbs, R. H. *J. Am. Chem. Soc.* **2013**, *135*, 1276–1279. (h) Cannon, J. S.; Grubbs, R. H. *Angew. Chem., Int. Ed.,* **2013**, *52*, 9001–9004. (i) Rosebrugh, L. E.; Marx, V. M.; Keitz, B. K.; Grubbs, R. H. *J. Am. Chem. Soc.* **2013**, *135*, 10032–10035. (j) Chong, W.; Carlson, J. S.; Bedke, D. K.; Vanderwal, C. D. *Angew. Chem., Int. Ed.* **2013**, *52*, 10052–10055. (k) Hartung, J.; Grubbs, R. H. *J. Am. Chem. Soc.* **2013**, *135*, 10183–10185. (l) Quigley, B. L.; Grubbs, R. H. *Chem. Sci.* **2014**, *5*, 501–506. (m) Hartung, J.; Grubbs, R. H. *Angew. Chem., Int. Ed.* **2014**, *53*, 3885–3888. (n) Mangold, S. L.; O'Leary, D. J.; Grubbs, R. H. *J. Am. Chem. Soc*. **2014**, 136, 12469–12478.

(17) (a) Occhipinti, G.; Hansen, F. R.; Tornroos, K. W.; Jensen, V. R. *J. Am. Chem. Soc.* **2013**, *135*, 3331–3334. (b) Occhipinti, G.; Koudriavtsev, V.; Tornroos, K. W.; Jensen, V. R. *Dalton Trans.* **2014**, *43*, 11106–11117.

been used in ROMP, ROCM, CM, and RCM, reactions are inefficient with an aryl olefin substrate, an α-branched alkene, or one that contains a polar functional groups (e.g., an alcohol, an aldehyde, or a carboxylic acid). Complex **Ru-4** has been used for homocoupling of terminal alkenes through olefin metathesis. However, and this is a common problem with many kinetically *Z*-selective processes, product stereoisomeric purity erodes rapidly as the reaction proceeds. This is likely because product re-entry into a catalytic cycle, leading to equilibration and formation of increasing amounts of the lower energy *E* isomer, which does not as readily coordinate with a catalyst designed to generate *Z* alkenes (often referred to as post-metathesis isomerization).[14]

1.2.2 Design of *Z*-Selective Ru-Based Catechothiolate Complexes

In a reaction catalyzed by a Ru-dichloro complex, the corresponding ruthenacylcobutane is preferentially formed *anti* to the NHC ligand (**mcb**$_{anti}$, Scheme 1.6). This is for several reasons: (1) To minimize dipole[18] and electron–electron repulsion, [19] the chloride ligands are favored to be *anti*. (2) To avoid steric repulsion that would exist between the NHC ligand and a *syn* metallacyclobutane. Thus, as was the case in the original Hoveyda/Schrock model, the metallacycle substituents are preferentially disposed anti, leading to formation of *E* alkene isomers.

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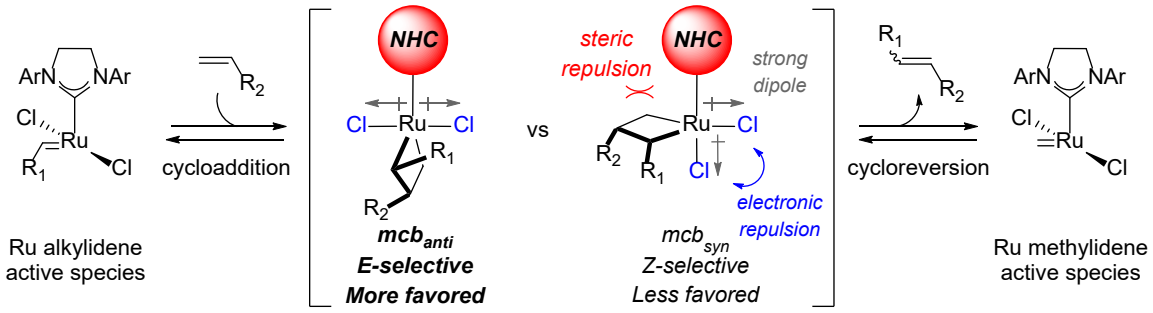
(18) (a) Benitez, D.; Goddard, W. A., III. *J. Am. Chem. Soc.* **2005**, *127*, 12218−12219. (b) Correa, A.; Cavallo, L. *J. Am. Chem. Soc.* **2006**, *128*, 13352−13353. (c) Khan, R. K. M.; Zhugralin, A. R.; Torker, S.; O'Brien, R. V.; Lombardi, P. J.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2012**, *134*, 12438−12441.

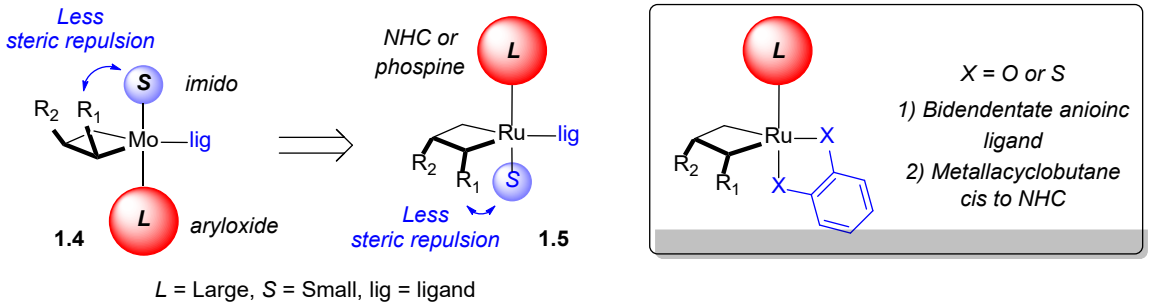
(19) (a) Ung, T.; Hejl, A.; Grubbs, R. H.; Schrodi, Y. *Organometallics* **2004**, *23*, 5399–5401. (b) Slugovc, C.; Perner, B.; Stelzer, F.; Mereiter, K. *Organometallics* **2004**, *23*, 3622–3626. (c) Barbasiewicz, M.; Szadkowska, A.; Bujok, R.; Grela, K. Straub, B. F.; Lemcoff, N. G. *Inorg. Chem.* **2009**, *48*, 10819–10825.

Scheme 1.6. Mechanistic Principles Leading to the Design of Ru Catechothiolate Complexes



Hoveyda et al. thus surmised that high *Z* selectivity for a Ru-based complex may be obtained if the metallacyclobutane ring is forced to reside within the equatorial plane (Scheme 1.7). This way, owing to the size difference between a larger NHC and a smaller anionic ligand, an all-*syn*-substituted metallacyclobutane (**1.5**, Scheme 1.7) should be generated preferentially, resulting in kinetic *Z* selectivity.

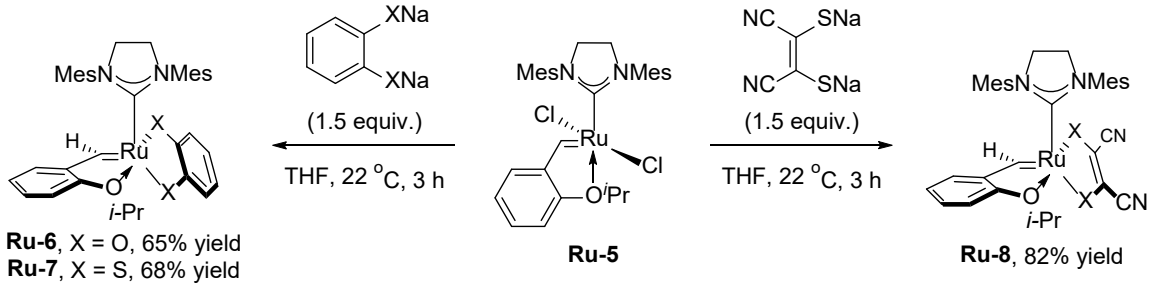
Scheme 1.7. Stereochemical Model for *Z* Selectivity for Ru-Based Catechothiolate Catalysts



It was thus envisioned that the metallacyclobutane ring could be forced to be within the equatorial plane by tethering the anionic ligands (box, Scheme 1.7), leading to the discovery of dithiolate systems. Complexes such as (**Ru-6-8**) were initially prepared from commercially available **Ru-5** and disodium salts of catechols and dithiols (Scheme 1.8).[20]

(20) Khan, R. K. M.; Torker, S.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2013**, *135*, 10258–10261.

Scheme 1.8. Preparation of Ru Catechothiolate Complexes



Ru-6, X = O, 65% yield
Ru-7, X = S, 68% yield

Ru-5

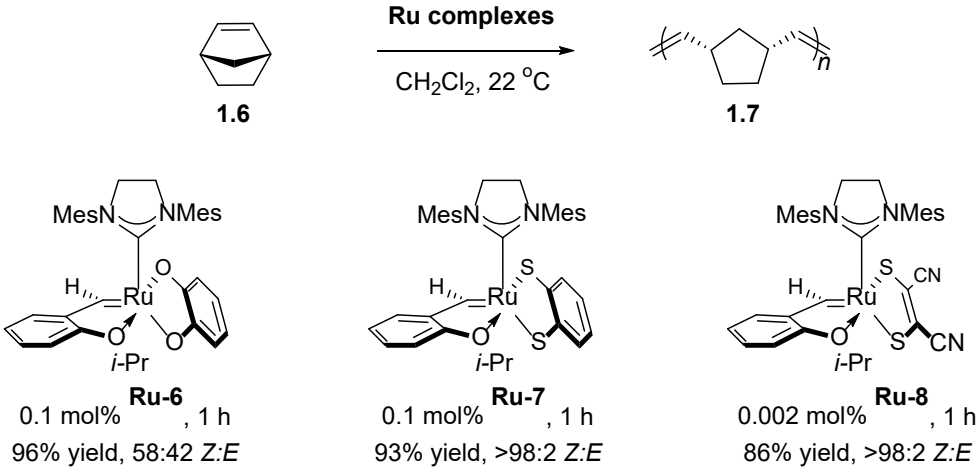
Ru-8, 82% yield

1.2.3 Ru Catechothiolate Complexes as Catalysts in Ring-Opening Metathesis Polymerization (ROMP) and Ring-Opening Cross-Metathesis (ROCM)

It was found that **Ru-7** and **Ru-8** afford high *Z* selectivity (>98:2 *Z:E*) and efficiency (up to 43,000 turnovers with **Ru-8**) for ROMP of nonbornene (Scheme 1.9). Whereas the reaction with **Ru-6** was similarly efficient, selectivity was minimal (58:42 *Z:E*).[17] The dithiolate complexes were found to be more robust (e.g., no ligand loss in the presence of an alcohol).[21] DFT studies[21] indicated that the turnover-limiting step for a reaction involving a Ru catechothiolate complex is probably the formation of the metallacyclobutane whereas olefin coordination is irreversible in a catalytic cycle that involves a catecholate catalyst. In the case that alkene association, the loosely bound alkene is too distal for steric effects to have an impact (namely, for the ruthenacycle substituents to prefer disposition towards the smaller apical ligand).

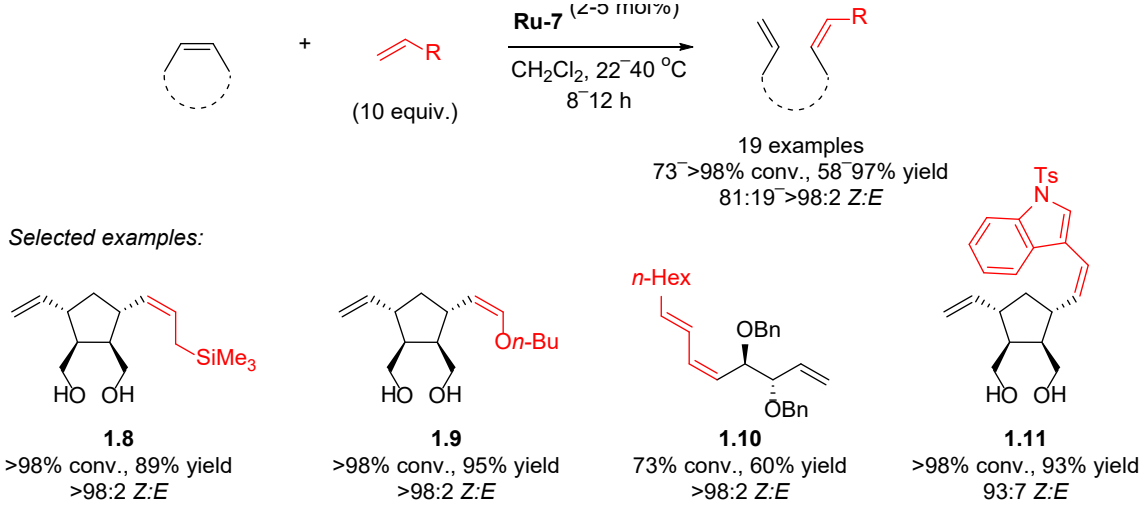
(21) For studies that shed light on the importance of *S*-based (vs *O*-based) bidentate ligands, see: Khan, R. K. M.; Torker, S.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2014**, *136*, 14337–14340.

Scheme 1.9. Catalytic ROMP with Ru Catechothiolate Complexes



Ru catechothiolate catalysts may be used to promote diastereoselective ROCM (Scheme 1.10).[22] Prior to these latter studies, Mo-based MAP complexes were used for *Z*-selective ROCM,[11,23] with only one report of a *Z*- and enantioselective ROCM method involving enol ethers as cross partners.[13k]

Scheme 1.10. *Z*-Selective ROCM with Ru Catechothiolate Complexes



(22) Koh, M. J.; Khan, R. K. M.; Torker, S.; Hoveyda, A. H. *Angew. Chem., Int. Ed.* **2014**, *53*, 1968–1972.

(23) (a) Yu, M.; Ibrahem, I.; Hasegawa, M.; Schrock, R. R.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2012**, *134*, 2788–2799.

The method is broadly applicable (Scheme 1.10). Importantly, the presence of an allylic hydroxy group was found to engender more efficient and stereoselective transformations (for **1.10**, benzyl ether groups point away from catechothiolate ligand and therefore do not impact efficiency). For example, ROCM with allylic alcohol **1.3** afforded the desired product in >98:2 *Z:E* ratio and >98:2 dr. In contrast, attempts at performing the same with allylic ether **1.14** led to <2% conversion. A plausible rationale is that the hydroxy group engages in hydrogen-bonding with the apical sulfide ligand (**1.17**), decreasing the severity of *trans* influence (between σ-donating NHC ligand and the sulfide; see **1.18**).[24,25,26] With an allylic methyl ether, not only is H-bonding precluded, it is likely that electron–electron repulsion involving the oxygen atom of the hydroxy group and the anionic sulfide renders the corresponding transition state even more energetically demanding. The allylic hydroxy unit not only alleviates *trans* influence, it is probably key to obtaining high dr owing to enhance structural organization within a transition state.

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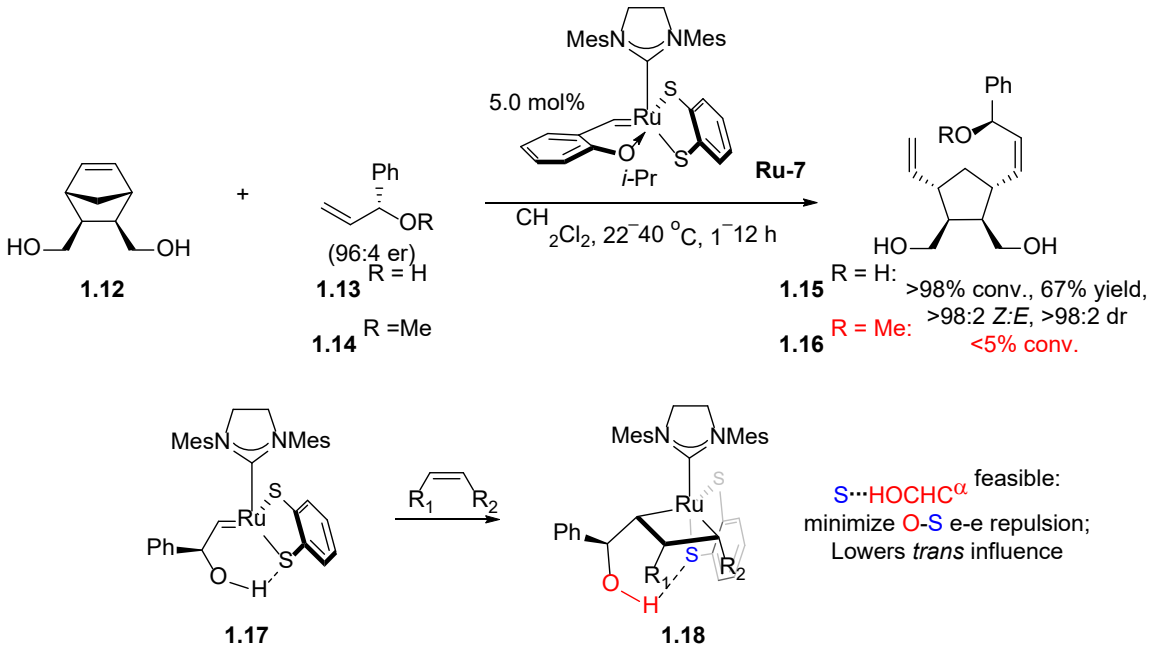
(24) For studies on H-bonding interactions with *S*-containing functional groups, see: (a) Wennmohs, F.; Staemmler, V; Schindler, M. *J. Chem. Phys.* **2003**, *119*, 3208–3218. (b) Tsogoeva, S. B.; Yalalov, D. A; Hateley, M. J.; Weckbecker, C.; Hutchmacher, K. *Eur. J. Org. Chem.* **2005**, 4995–5000. (c) Schreiner, E.; Nair, N. N.; Pollet, R.; Staemmler, V.; Marx, D.; *Proc. Natl. Acad. Sci.* **2007**, *104*, 20725–20730. (d) Zhou, P.; Tian, F.; Lv, F.; Shang, Z. *Proteins Struct. Funct. Bioinf.* **2008**, *76*, 151–163.

(25) For studies on H-bonding interactions in other Ru-based complexes, see: (a) Hoveyda, A. H.; Lombardi, P. J.; O'Brien, R. V.; Zhugralin, A. R. *J. Am. Chem. Soc.* **2009**, *131*, 8378–8379. For related studies, see: (b) Hoye, T. R.; Zhao, H. *Org. Lett.* **1999**, *1*, 1123–1125. (c) Fuwa, H.; Saito, A.; Sasaki, M. *Angew. Chem., Int. Ed.* **2010**, *49*, 3041–3044. (d) Lin, Y. A.; Chalker, J. M.; Davis, B. G. *J. Am. Chem. Soc.* **2010**, *132*, 16805–16811. (e) Donohoe, T. J.; Basutto, J. A.; Bower, J. F.; Rathi, A. *Org. Lett.* **2011**, *13*, 1036–1039.

(26) For the importance of minimizing trans influence in Ru-catalyzed olefin metathesis, see: Khan, R. K. M.; Zhugralin, A. R.; Torker, S.; O'Brien, R. V.; Lombardi, P. J.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2012**, *134*, 12438−12441.

Scheme 1.11. ROCM with an Enantiomerically Enriched Allylic Alcohol



1.2.4 Stereoselective *Z*-Allylic Alcohol Synthesis with Ru Catechothiolate Catalysts

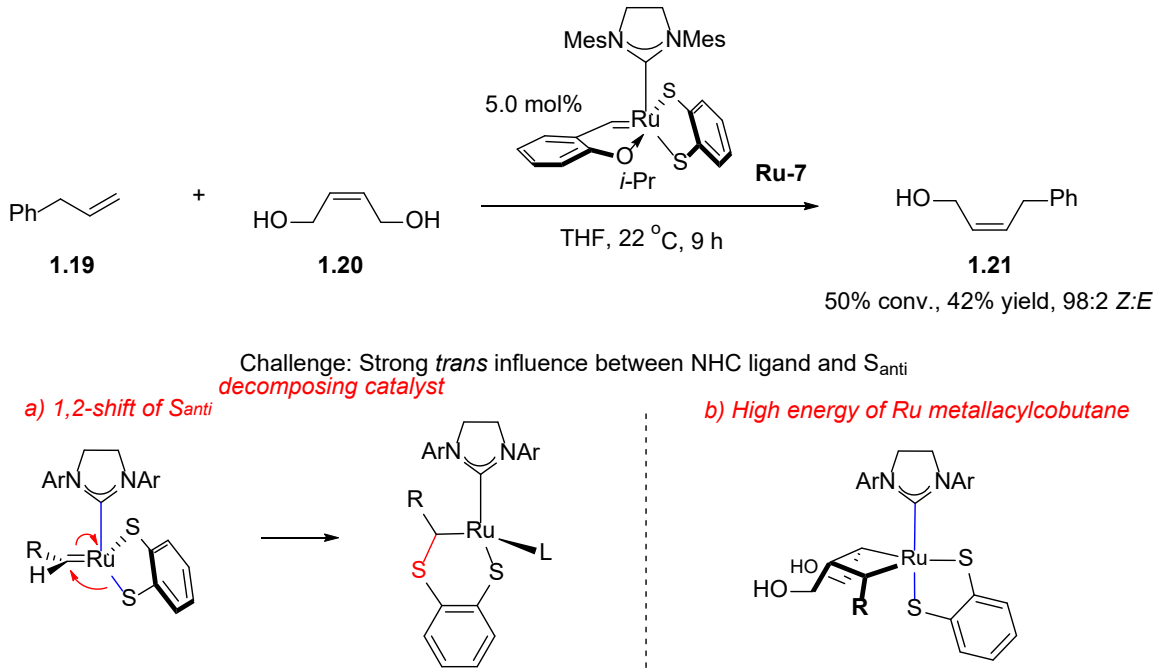
A longstanding limitation in olefin metathesis has been the lack of broadly applicable methods for preparation of *Z*-allylic alcohols, widely used fragments in chemical synthesis. In addition to challenges associated with kinetically controlled *Z*-selective olefin metathesis,[27] the allylic hydroxy group is susceptible to undesired redox isomerization under Ru catalysis due to possible involvement of Ru-H species.[28] The initial reaction between allyl benzene **1.19** and cis-2-butene-1,4-diol **1.20** with **Ru-7** as the catalyst (Scheme 1.12) afforded product **1.21** in 42% yield and >98:2 *Z:E* ratio. The unsatisfactory efficiency of this reaction is probably due to that the strong *trans* influence between a NHC ligand and an apical sulfide ligand will lead migration of sulfide to Ru

(27) For post-metathesis problems in Z selective metathesis reaction, see: see: (a) ref. 2. (b) ref. 14. (c) Ritter, T.; Hejl, A.; Wenzel, A. G.; Funk, T. W.; Grubbs, R. H. *Organometallics* **2006**, *25*, 5740–5745.

(28) Trost, B. M.; Kulawiec, R. J. *J. Am. Chem. Soc.* **1993**, *115*, 2027–2036.

alkylidene or methylidene to decompose active Ru species.[29] Therefore, the strong *trans* influence also increase energy barrier for formation of Ru metallacyclobutane and decrease reaction efficiency. To improve the reaction, another Ru-based catechothiolate complex (**Ru-9**) which introduces two chlorine atoms on original catechothiolate ligand was developed (Scheme 1.14).[30] The sulfide ligand with chloro-substituents possess less electron density so that *trans* influence between the NHC and apical sulfide ligand decrease. As a result, **Ru-9** is less prone to decompose and could promote the reaction by decreasing energy barrier for formation of Ru metallacyclobutane.

Scheme 1.12. CM for Synthesis of *Z*-Allylic Alcohols and the Associated Challenges



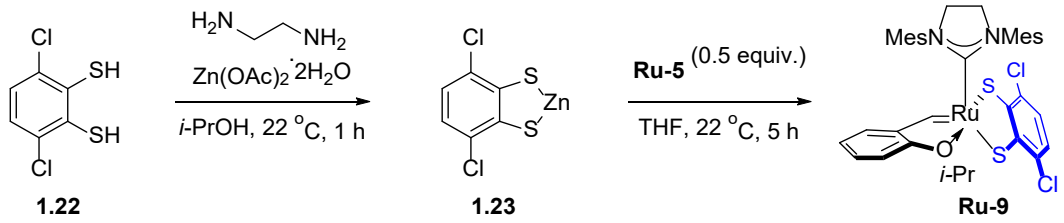
The Ru-based catechothiolate complex **Ru-9** could be prepared with a more efficient method (Scheme 1.13). The more practical synthesis starts with the reaction

(29) For an example of 1,2-thio group migration into carbenoids, see: Feng, X.; Shi, W.; Wang, J. *J. Org. Chem.* **2005**, *70*, 4191–4194.

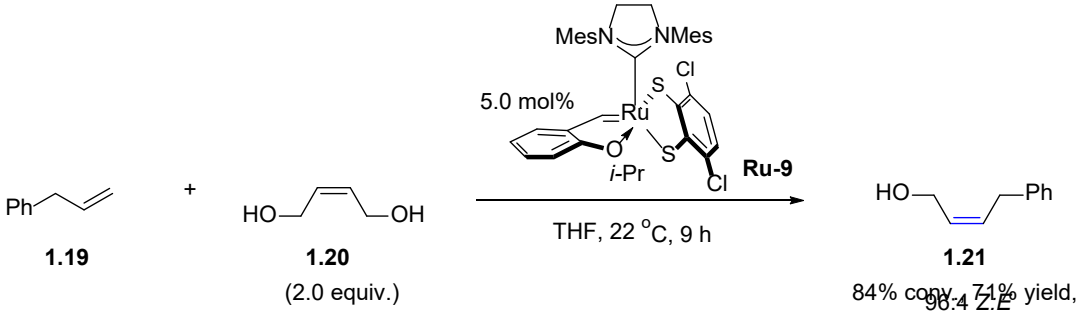
(30) Koh, M. J.; Khan, R. K. M.; Torker, S.; Yu, M.; Mikus, M. S.; Hoveyda, A. H. *Nature* **2015**, *517*, 181–186.

between 3,6-dichlorobenzene-1,2-dithiol **1.22** and hydrated zinc acetate under ambient conditions. The resulting air-stable Zn dithiolate **1.23** was substituted onto **Ru-5** to afford **Ru-9**, requiring only a simple filtration for purification. Under identical condition as before, complex **Ru-9** affords product **1.21** in higher yield (71% vs 40%) while retaining high *Z* selectivity (96:4 *Z:E*). It was also found that **Ru-9** is compatible with various functional groups, including aldehyde (**1.24**), acid (**1.25**), aryl alkene (**1.26**), and conjugated diene (**1.27**).

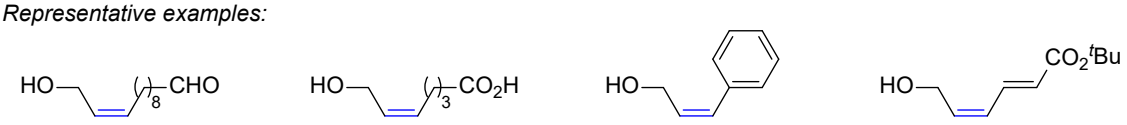
Scheme 1.13. Synthesis of Ru Catechothiolate Complexes



Scheme 1.14. CM for Accessing *Z*-Allylic Alcohols with Ru Catechothiolate Complexes



Representative examples:

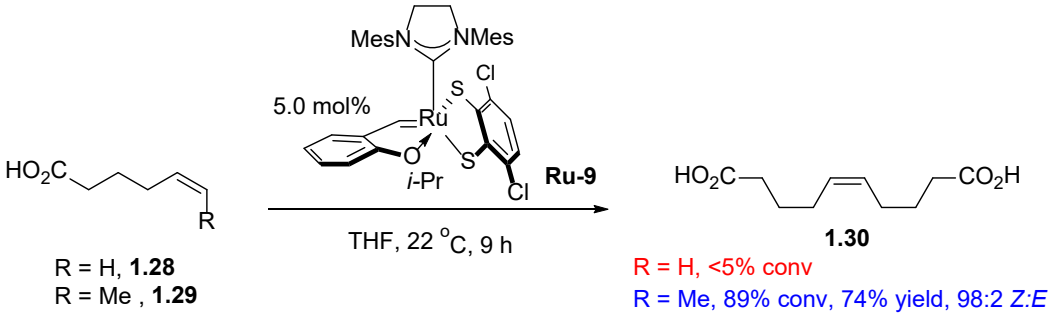


1.3 In Situ Methylene Capping for *Z*-Selective Cross-Metathesis with Ru-Based Catechothiolate Complexes

1.3.1 Challenges Associated with Reactions with Monosubstituted Alkenes

Although use of **Ru-9** can lead to efficient formation of various *Z*-allylic alcohols, transformations were severely inefficient when two monosubstituted alkenes were involved (Scheme 1.15). For example, there was <2% conversion of 5-hexenoic acid **1.28** to **1.30**. In sharp contrast, with *Z*-5-heptenoic acid **1.29** as the substrate, CM proceeded efficiently (89% conv, 74% yield) affording **1.30** with high stereoisomeric purity (98:2 *Z:E*).[31] We surmised that the reason for this difference is the involvement of different Ru species (Scheme 1.15). In the reactions of monosubstituted alkenes, the catalytic species is a highly sensitive Ru methylidene (see Scheme 1.12), whereas in the case of internal alkenes, a longer living Ru alkylidene is involved.

Scheme 1.15. Challenges Associated with Ru Catechothiolate Complexes[a]



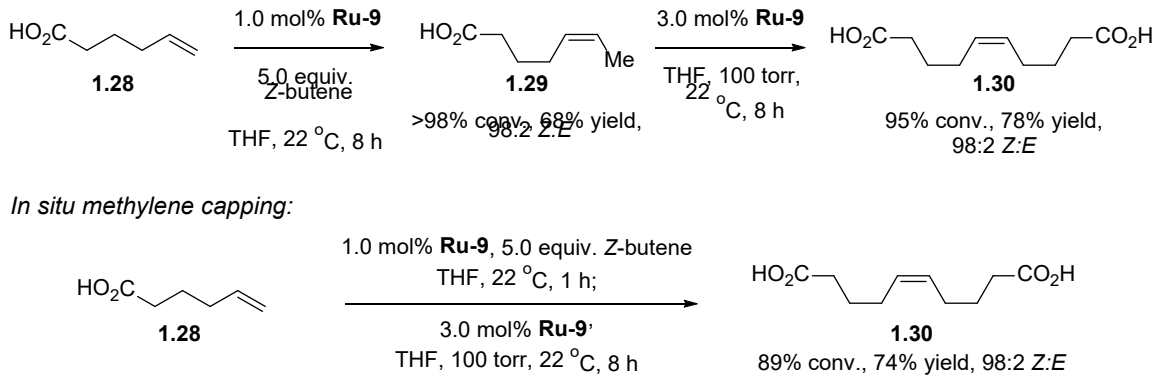
[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

(31) Xu, C.; Shen, X.; Hoveyda, A. H. *J. Am. Chem. Soc*. **2017**, *139*, 10919–10928.

1.3.2 In Situ Methylene Capping as a Solution

Considering the fact that monosubstituted alkenes are more readily available and cheaper than internal alkenes, we strove to improve the efficiency of Ru catechothiolate complexes in the presence of terminal alkenes. Rather than modifying the catalysts, we sought to modify the reagents. Since 5-hexenoic acid **1.28** affords same products as 5-heptenoic acid **1.29**, we chose to convert **1.28** to **1.29** first, before performing CM. We thus found that 5-heptenoic acid **1.29** can be generated from 5-hexenoic acid **1.28** rapidly and with high selectivity (98:2 *Z:E*) in the presence of **Ru-9** through CM with *Z*-butene (Scheme 1.16). With this exciting result in hand, we further investigated if the CM events (**1.28** ⟶ **1.29** and **1.29** ⟶ **1.30**) might be performed in a single vessel. We thus established that by treating 5-hexenoic acid **1.28** with 5.0 equivalents of *Z*-butene and 1.0 mol % **Ru-9**, followed by the addition of a second batch of **Ru-9** (3 mol %) and placing the mixture 100 torr of pressure, **1.30** could be obtained in 74% yield and with 98:2 *Z:E* selectivity. Because homocoupling of **1.29** generates *Z*-butene as the byproduct, the mixture was subjected to mild vacuum to drive the reaction to completion. Hence, olefin metathesis involving a Ru catechothiolate complex and monosubstituted alkenes was achieved through methylene capping strategy.

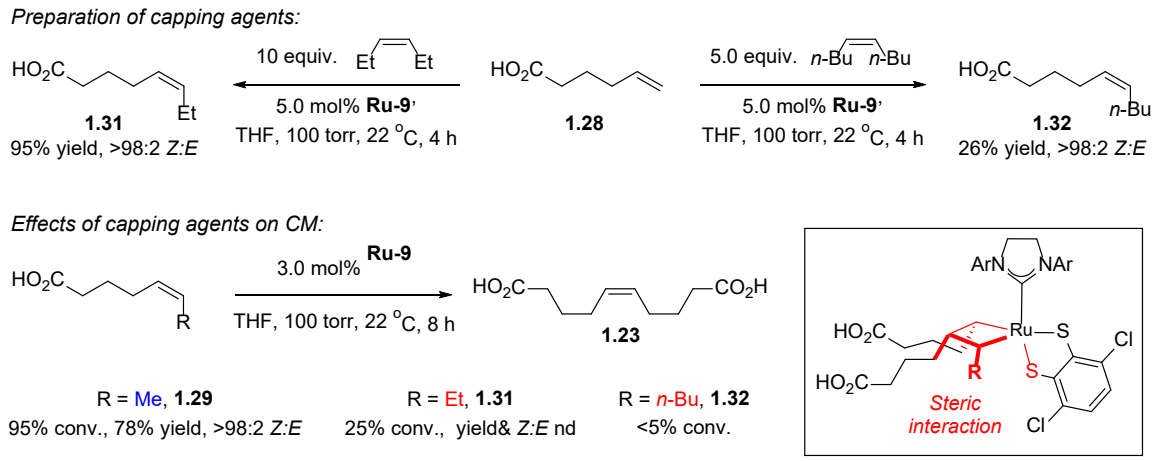
Scheme 1.16. Methylene Capping Strategy for CM of Monosubstituted Alkenes with a Ru Catechothiolate Complex[a]



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

The capping agent, *Z*-butene, is inexpensive and readily available and has an ideal boiling point (3.7 °C), which makes it easy to handle and also readily removable under vacuum. Other than *cis*-butene, other possible capping agents, such as *cis*-3-hexene and *Z*-5-decene, were investigated as well (Scheme 1.17). With *cis*-3-hexene, ethyl-substituted 5-hexenoic acid **1.31** was readily generated (>98% conv) with exclusive *Z* selectivity. On the other hand, homocoupling of **1.31** was inefficient (25% conv, under otherwise identical conditions). With *Z*-5-decene, **1.32** again was readily formed, but, as in the latter case, homocoupling was even less efficient (<5% conv). It was thus established that *Z*-butene is the optimal capping agent. While *Z*-butene is large enough to decrease decomposition of a Ru catechothiolate complex, it is sufficiently small to ensure efficient metallacyclobutane formation.

Scheme 1.17. Study of Different Capping Agent Candidates[a]



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

1.3.3 Methylene Capping in *Z*-Selective Cross-Metathesis

Next, we focused on investigating the applicability of the aforementioned capping method to CM reactions of various *Z*-1,2-disubstituted alkenes (Scheme 1.18). Typically, for optimal efficiency, the more readily available monosubstituted alkene was used in excess (3.0 equiv). The alkenes substrates were first treated with 20 equiv *Z*-butene and 1.0 mol% **Ru-9** to generate the corresponding methyl-substituted olefin (condition A). Then 4.0 mol % **Ru-9** was added and the mixture was allowed to stir under 100 torr vacuum for the necessary length of time for the process to reach completion. In the case of aryl olefins, complete capping proved difficult (typically, ~80% conv) and, as a result, the *β*-methyl derivative obtained by an alternative procedure was used (condition B). *β*-Methyl aryl olefins substrates were prepared in one step by catalytic cross-coupling reaction between an arylboronic acid pinacol ester and *Z*-1-bromopropene.[32]

(32) Miyaura, N.; Yamada, K.; Suzuki, A. *Tetrahedron Lett*. **1979**, *20*, 3437–3440.

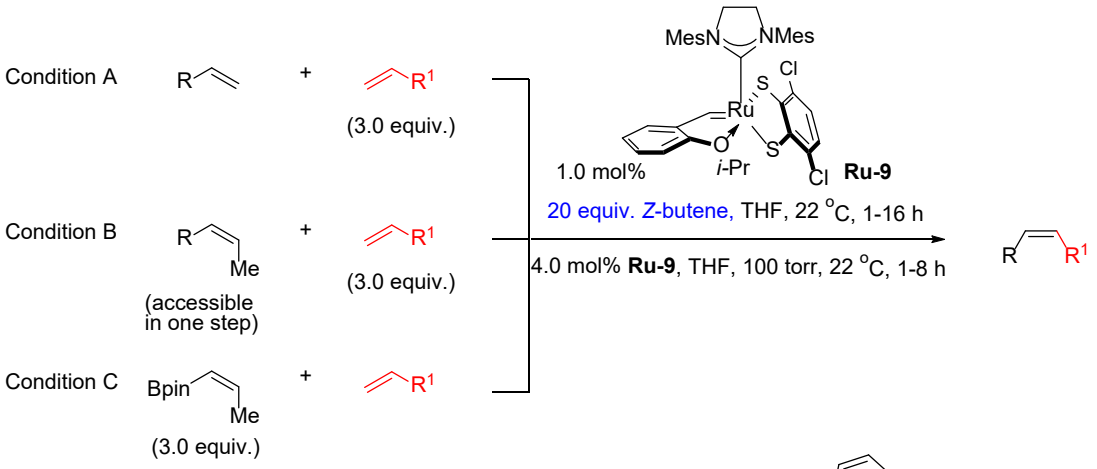
Methylene capping renders CM reactions performed in the presence of a Ru catechothiolate complex compatible with a broad range of polar functional groups. For example, olefins containing an alcohol (**1.33**, **1.36**), an aldehyde (**1.37**, **1.45**, **1.46**), a ketone (**1.40**), a phenol (**1.40**), or a carboxylic acid afforded products in 47–80% yield and 90:10 to >98:2 *Z:E* selectivity. Moreover, the approach may be used to generate a *Z*-alkenyl boronic pinacol ester (**1.46**), a key building block;[33] however, the *Z*-methyl-substituted alkenyl–Bpin substrate must be present in excess (condition C). *α*-Branched alkenes **1.41** and **1.42** were prepared with similar efficiency and stereoisomeric purity. Notably, this class of substrates did not require capping, probably because the hindered *α*-branched alkenes do not undergo facile homometathesis to generate a Ru-based methylidene. *Z,E*-Dienes **1.47–1.49** were obtained in 56–80% yield and 95:5–97:3 *Z:E* ratio. Carboxylic acid **1.47** can be synthesized by CM only with a Ru catechothiolate complex; other *Z*-selective catalysts, Ru-, Mo-, or W-based, rapidly decompose in the presence of an acid moiety. Attempts to generate 1,3-dienes **1.48** and **1.49** with alternative catalyst systems have been reported to be inefficient.[34]

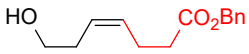
Amino acid-derived alkenes **1.50-1.52** were isolated in 47-88% yield and 91:9 to >98:2 *Z:E* selectivity. Although bidentate Ru–alkyl complex **Ru-3** has been utilized in CM reactions with amino acid-containing alkenes, reactions with substrates bearing a glycine or a methionine residue have been found to be severely inefficient.[13n]

Scheme 1.18. CM for Accessing *Z*-Alkenes with a Ru Catechothiolate Complex[a]

(33) Kiesewetter, E. T.; O'Brien, R.; Yu, E. C.; Meek, S. J. Schrock, R. R.; Hoveyda, A. H. *J. Am. Chem. Soc*. **2013**, *135*, 6026–6029.

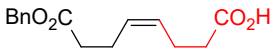
(34) Luo, S.-X.; Cannon, J. S.; Taylor, B. L. H.; Engle, K. M.; Houk, K. N.; Grubbs, R. H. *J. Am. Chem. Soc.* **2016**, *138*, 14309–14046.





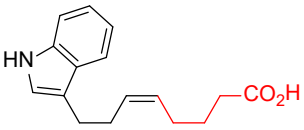
1.33

(Condition A)
95% conv., 56% yield, 95:5 *Z:E*



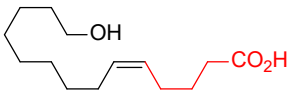
1.34

(Condition A)
88% conv., 74% yield, 97:3 *Z:E*



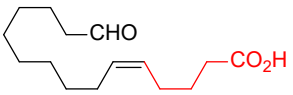
1.35

(Condition A)
88% conv., 58% yield, >98:2 *Z:E*



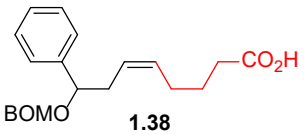
1.36

(Condition A)
78% conv., 58% yield, >98:2 *Z:E*



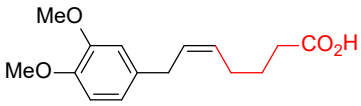
1.37

(Condition A)
74% conv., 66% yield, >98:2 *Z:E*



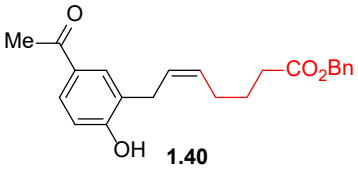
1.38

(Condition A)
79% conv., 64% yield, >98:2 *Z:E*



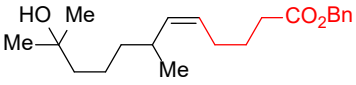
1.39

(Condition A)
88% conv., 64% yield, 98:2 *Z:E*



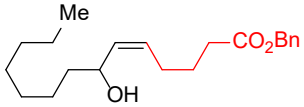
1.40

(Condition A)
92% conv., 48% yield, 96:4 *Z:E*



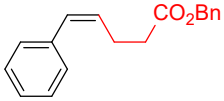
1.41

(Condition A)
64% conv., 58% yield, 98:2 *Z:E*



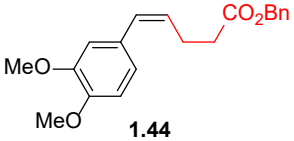
1.42

(Condition A)
63% conv., 47% yield, 90:10 *Z:E*



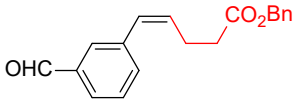
1.43

(Condition B)
66% conv., 48% yield, 96:4 *Z:E*



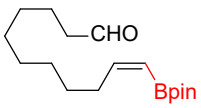
1.44

(Condition B)
56% conv., 50% yield, 92:8 *Z:E*



1.45

(Condition B)
88% conv., 64% yield, 96:4 *Z:E*



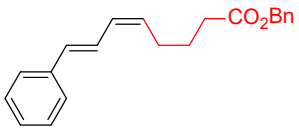
1.46

(Condition C)
98% conv., 54% yield, 95:5 *Z:E*

1.47

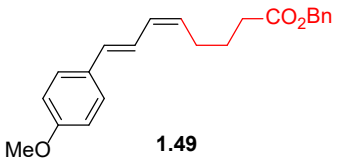
(Condition A)
77% conv., 59% yield, 95:5 *Z:E*

Scheme 1.18. CM for Accessing *Z*-Alkenes with a Ru Catechothiolate Complex (continued)[a]



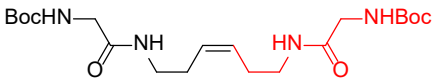
1.48

(Condition A)
95% conv., 80% yield, 97:3 *Z:E*



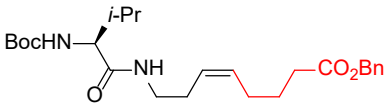
1.49

(Condition A)
90% conv., 56% yield, 97:3 *Z:E*



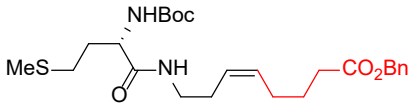
1.50

(Condition A)
95% conv., 88% yield, >98:2 *Z:E*



1.51

(Condition A)
95% conv., 47% yield, 91:9 *Z:E*



1.52

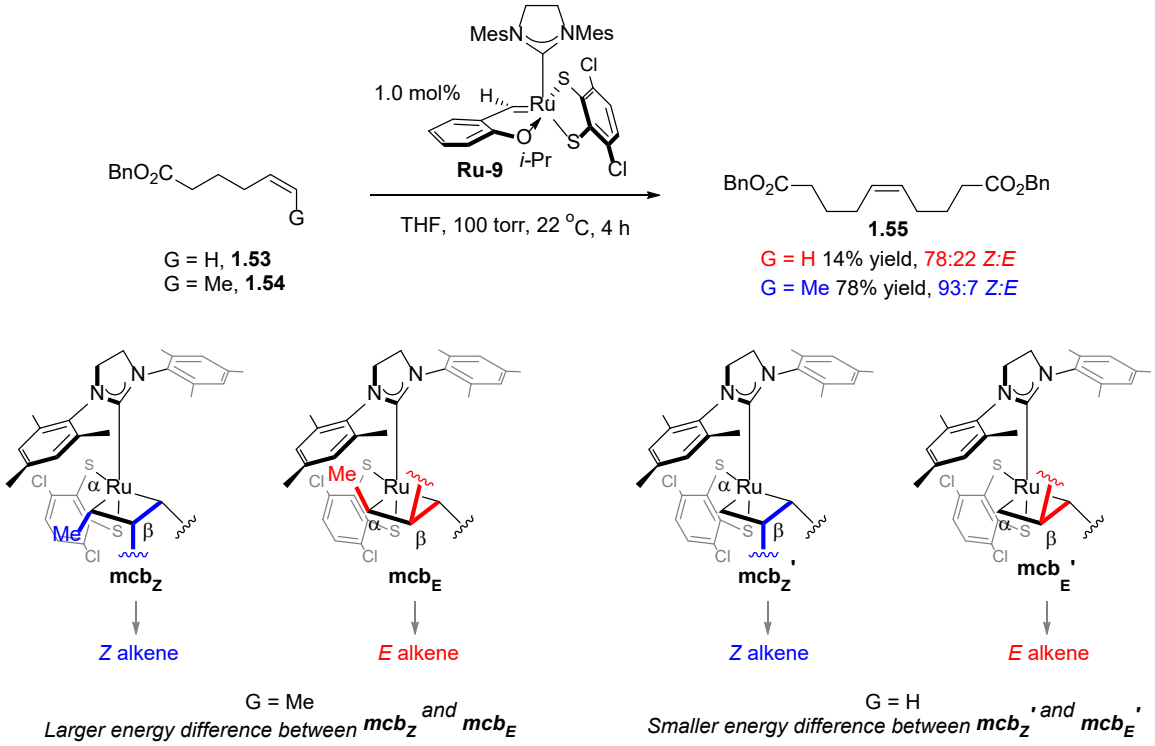
(Condition A)
73% conv., 51% yield, >98:2 *Z:E*

[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^1H or ^{13}C NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For **1.43-1.45**, *Z*-*β*-methylstyrene was used (condition B); *Z*-1-propenylboronic acid pinacol ester used to prepare **1.46**. For full details, see the Experimental Section.

1.3.4 Methylene Capping Can Improve Stereoselectivity

Methylene capping not only provides a way to increase efficiency, it can also improve stereoselectivity. For instance, in homometathesis of methyl-substituted benzyl 5-hexenoate **1.54**, product **1.55** was generated in 78% yield and 93:7 *Z:E* selectivity (Scheme 1.19). In contrast, with benzyl 5-hexenoate, **1.55** was obtained with 78:22 *Z:E* ratio (14% yield). This difference in stereoselectivity is likely because the additional substituent causes the energy difference between **mcbz** and **mcbE** to be higher (greater steric repulsion between the Me and NAr moieties in the latter). This distinction is absent in the case of monosubstituted alkene substrates.

Scheme 1.19. The Origin of Higher *Z* Selectivity with 1,2-Disubstituted Alkenes[a]

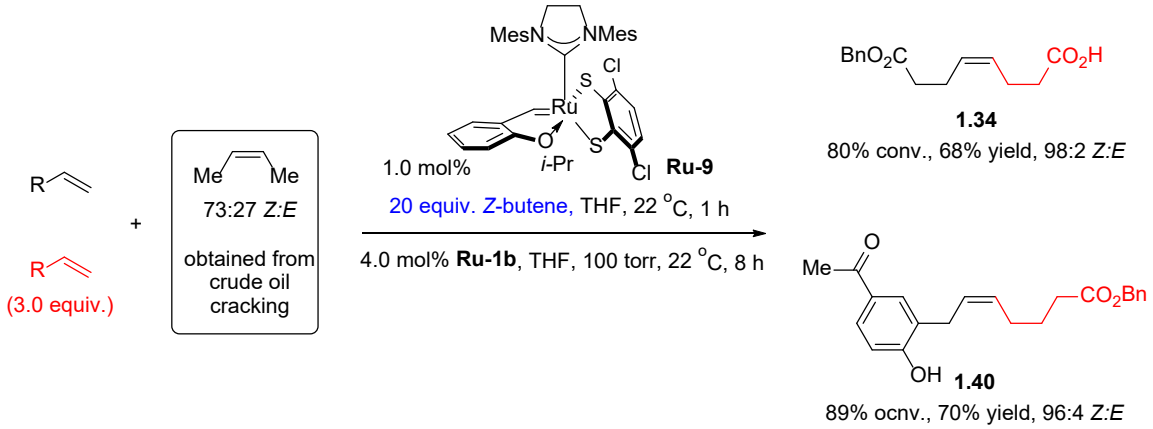


[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

1.3.5 Other 2-Butene Isomers as Capping Agents

A mixture of *Z*- and *E*-butene, a byproduct derived from crude cracking oil and less expensive than isomerically pure forms, may be used. For example, compounds **1.34** and **1.40** were synthesized in 68–70% yield and 96:4–98:2 *Z:E* selectivity through the use of a 73:27 mixture of *Z:E* 2-butene (Scheme 1.20). These are similar to the results observed when pure *Z*-butene was used, which means that reaction with *E*-butene is significantly slower, probably because of the aforementioned steric repulsion in the corresponding metallacyclobutane intermediate (see Scheme 1.19).

Scheme 1.20. Cross-Metathesis with a *Z/E*-Butene Mixtures as the Capping Agent[a]



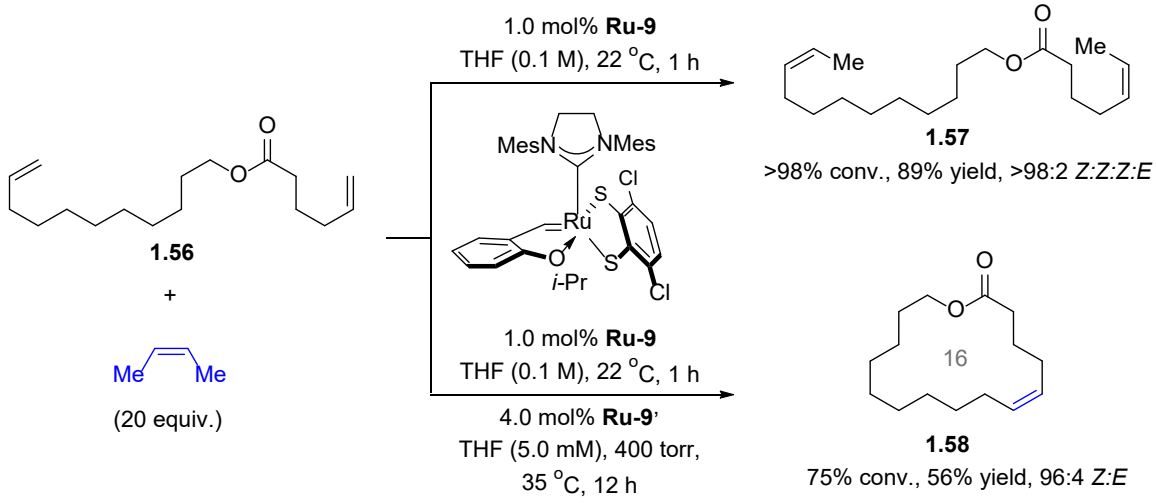
[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^1H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

1.4 Methylene Capping in *Z*-Selective Macrocyclic Ring-Closing Metathesis (MRCM)

1.4.1 Initial Studies

To begin, we subjected diene **1.56** with 20 equivalents of *Z*-butene, and 1.0 mol % catechothiolate complex **Ru-9** to obtain **1.57** in 89% yield as a single stereoisomer (Scheme 1.21). Next, 4.0 mol % **Ru-9** was added to the reaction and 400 torr vacuum was applied, resulting in the formation of MRCM product **1.58** in 56% yield and 96:4 *Z:E* selectivity. In the absence of methylene capping, **1.58** was obtained in just 11% yield and 59:41 *Z:E* ratio (Scheme 1.22). Since control experiments indicated no post-metathesis isomerization, the minimal stereoselectivity is probably derived from kinetics. As was noted above, there is a larger energy gap between ruthenacyclobutane that leads to a *Z*-alkene (**mcbz**") and an *E*-alkene (**mcb**$_{\mathbf{E}}$") in the case of a methyl-capped alkene substrate (e.g., **1.57**).

Scheme 1.21. In Situ Methylene Capping for Macrocyclic Ring-Closing Metathesis[a]

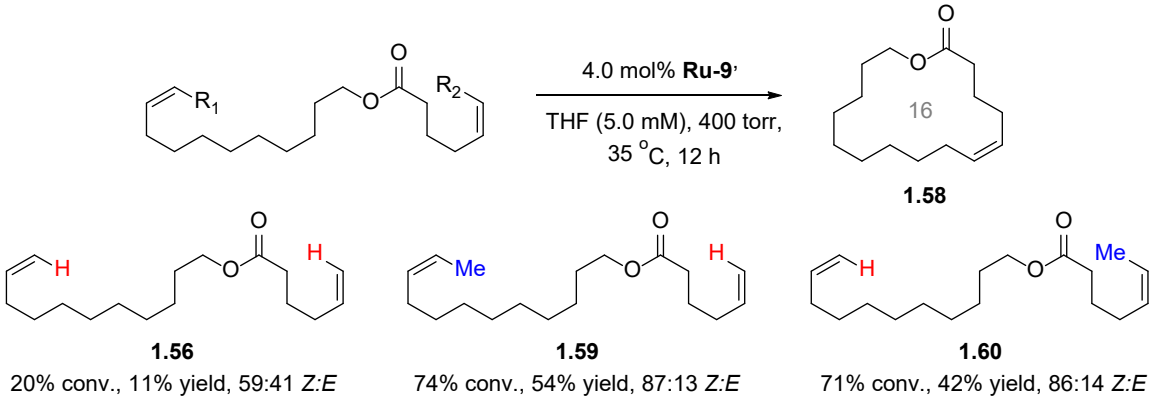


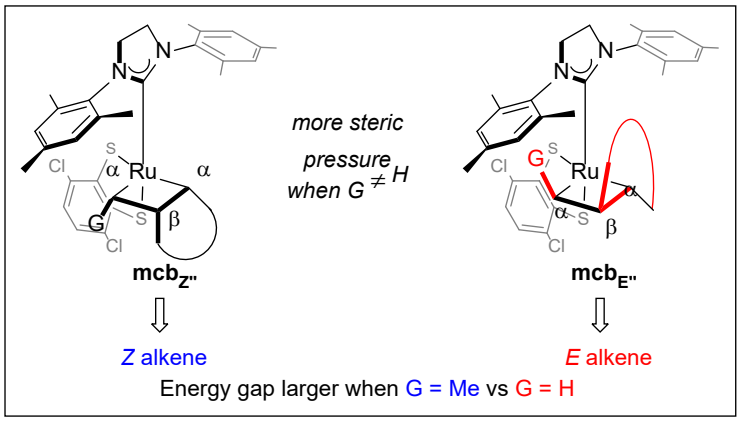
[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

When only one monosubstituted alkene was capped (**1.59** and **1.60**) the macrocyclic products were isolated in 54% and 42% yield with 87:13 and 86:14 *Z:E,* respectively, which is also less efficient and stereoselective than reactions with capped diene **1.57** as substrate. The lower selectivity might arise from competitive homocoupling through the reaction of a monosubsituted olefin, affording a stereoisomeric mixture of 1,2-disubstituted olefins. Such byproducts can be transformed to the macrocyclic alkene by a so-called "back-biting" mechanism,[35] but since a mixture of *E*- and *Z*-alkenes is involved, the final stereoselectivity would likely be lower.

35) Conrad, J. C.; Eelman, M. D.; Duarte Silva, J. A.; Monfette, S.; Parnas, H. H.; Snelgrove, J. L.; Fogg, D. E. *J. Am. Chem. Soc*. **2007**, *129*, 1024−1025.

Scheme 1.22. Doubly-Capped Dienes Undergo Ring-Closing Metathesis with Higher *Z* Selectivity[a]





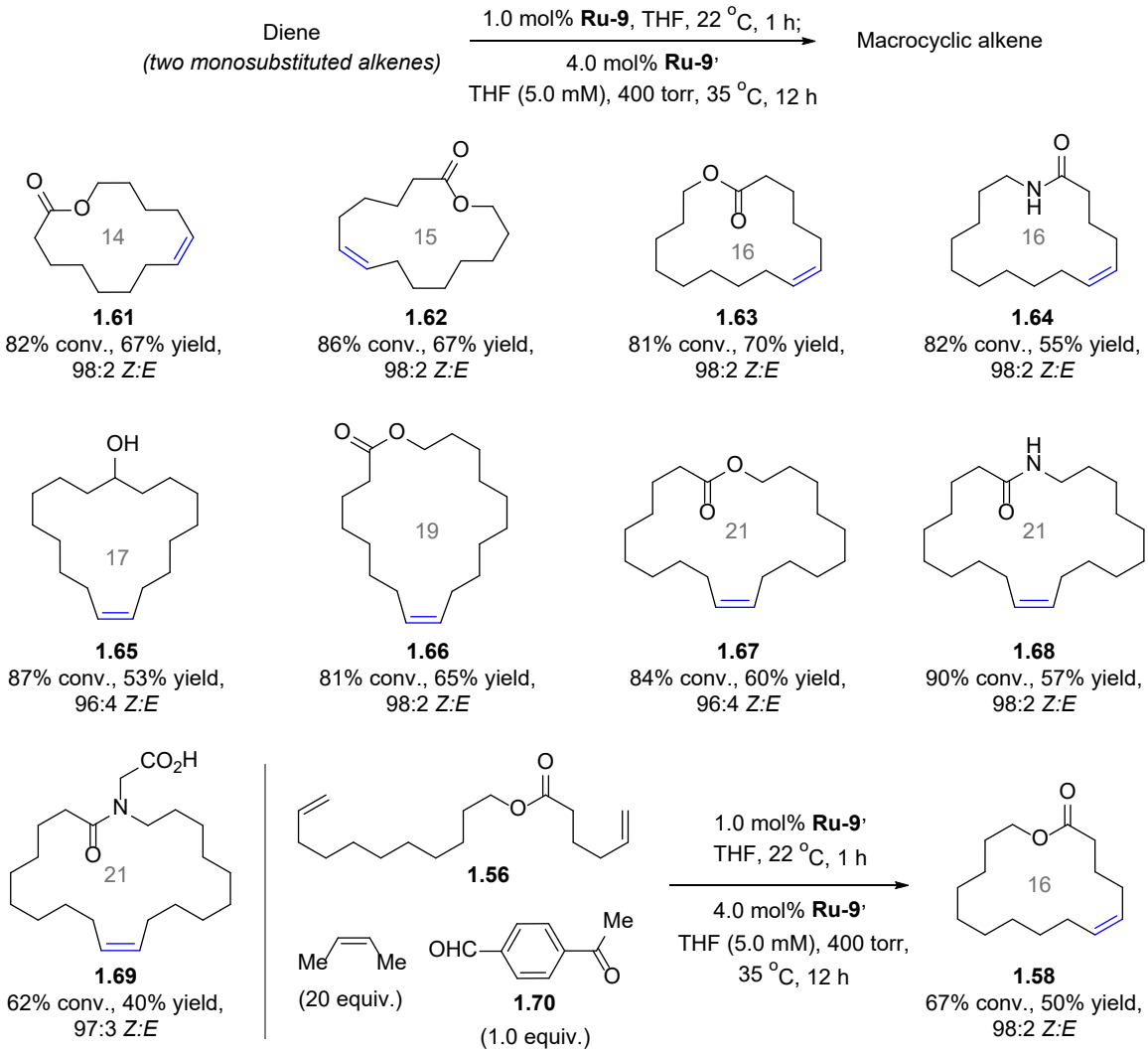
[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR or ^{13}C spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

1.4.2 Macrocyclic Ring-Closing Metathesis for Synthesis of Macrocyclic Rings Containing *Z* Alkenes

By applying the capping method, we synthesized several 14- to 21-membered rings in 53–70% yield with 96:4–98:2 *Z:E* selectivity (Scheme 1.23). The method is compatible with amides (**1.64**, **1.68**), alcohols (**1.65**), and acids (**1.72**). However, in the presence of a carboxylic acid, yields were reduced (40%). The presence of a ketone or an aldehyde moiety was tolerated as well. Addition of 1.0 equivalent of *p*-acetophenylaldehyde (**1.70**)

to a mixture containing diene **1.58** reduced efficiency but did not alter stereoisomeric purity to a significant degree (Scheme 1.23).

Scheme 1.23. Substrate Scope of Macrocyclic Ring-Closing Metathesis[a]



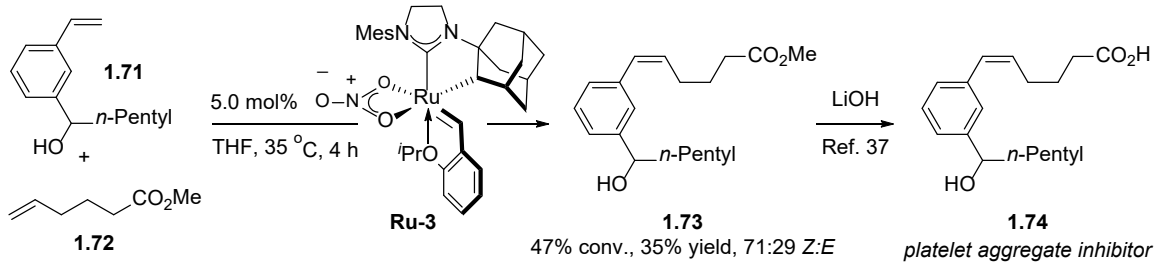
[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^1H or ^{13}C NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

1.5 Applications of in Situ Methylene Capping Method for Synthesis of Biologically Active Molecules

1.5.1 Preparation of a Platelet Aggregate Inhibitor

To demonstrate utility of the capping strategy, we first chose to synthesize a platelet aggregate inhibitor (Scheme 1.24), which was previously accomplished in eight steps with **Ru-3** was used to prepare the *Z*-alkene moiety in 35% yield and 79:21 *Z:E* ratio.[36]

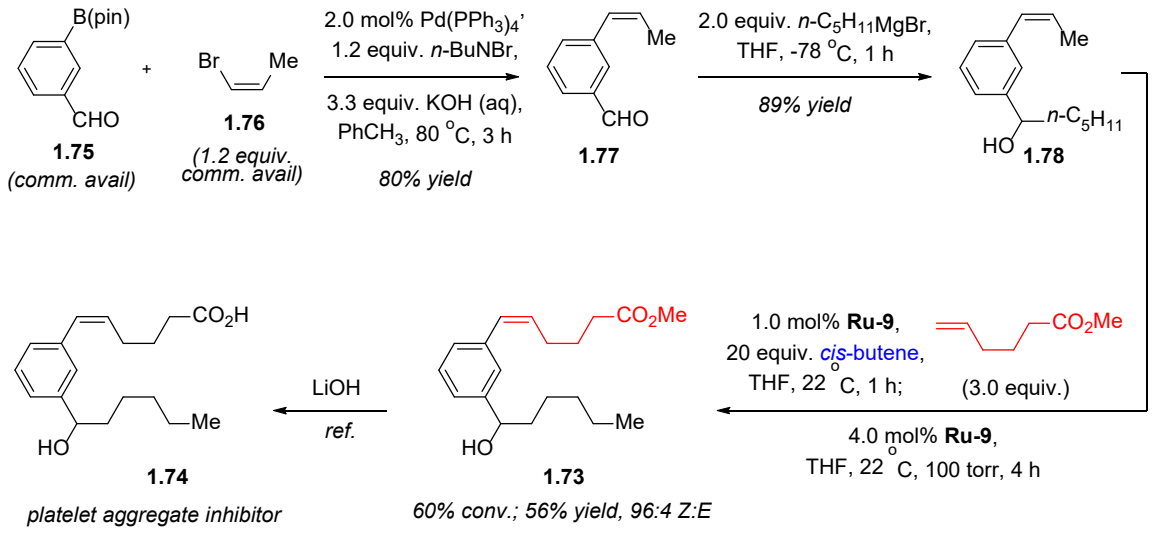
Scheme 1.24. Previous Synthesis of a Platelet Aggregate Inhibitor with **Ru-3**



Our route commenced with Suzuki-Miyaura cross-coupling of two commercially available starting materials (**1.75** and **1.76**, Scheme 1.25). The resulting *β*-methyl styrene **1.77** was converted to afford secondary alcohol **1.78**. This was followed by CM in the presence of **Ru-9** to generate **1.73** in 58% yield and 96:4 *Z:E* selectivity, which could be transformed to platelet aggregate inhibitor **1.74** through hydrolysis.[37] By applying the combination of methylene capping/cross-metathesis approach, the route leading to the target molecule was rendered significantly more concise (i.e., 4 vs 8 steps).

(36) Hachem, A.; Roussel, P.; Ménager, E.; Grée, D.; Le Floc'h, Y.; Grée, R.; Cerletti, C.; Rolland, Y.; Simonet, S.; Verbeuren, T. *Bioorg. Med. Chem. Lett*. **2002**, *12*, 2511−2514.

Scheme 1.25. Application to Synthesis of a Platelet Aggregate Inhibitor[a]



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

1.5.2 Synthesis of Prostaglandin E2 and F2α

Prostaglandin E2 and F2α are representative members of an important class of molecules that can impact many physiological disorders.[37] Several prostaglandins that contain *Z*-alkenes have been commercialized as "block-buster" drugs.[38] Due to presence of a carboxylic acid,[39] a pair of hydroxy groups, and a chelating carbonyl unit, synthesis of these molecules by the use of CM processes challenge the limits of the state-of-the-art.

Our synthesis route began with commercially available furfural, which was converted to **1.79** in four steps and 24% overall yield (Scheme 1.26). Next, compound **1.79** and 5-hexenoic acid **1.28** were capped separately and then subjected to 15 mol % **Ru-9**.

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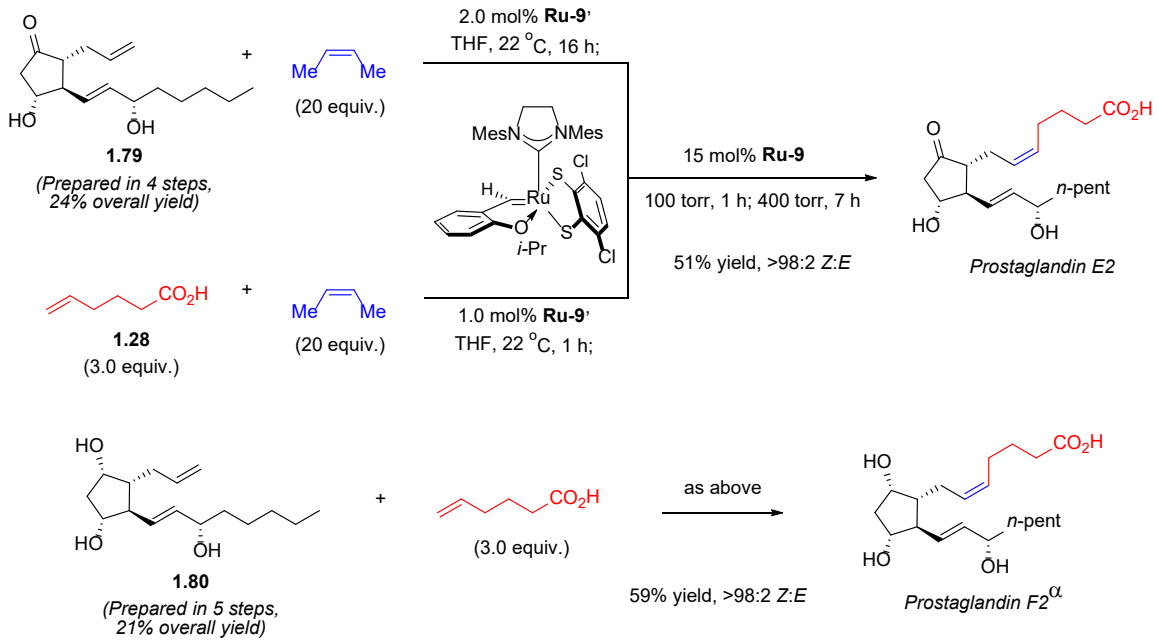
(37) Funk, C. D. *Science* **2001**, *294*, 1871−1875.

(38) Nair, S. K.; Henegar, K. E. In *Modern Drug Synthesis*; Li, J. J., Johnson, D. S., Eds.; Wiley: New Jersey, 2010; pp 329−338.

(39) For studies regarding the significance of of the carboxylic acid group to biological activity of this class of compounds, see: Ungrin, M. D.; Carrière, M.-C.; Denis, D.; Lamontagne, S.; Sawyer, N.; Stocco, R.; Tremblay, N.; Metters, K. M.; Abramovitz, M. *Mol. Pharmacol*. **2001**, *59*, 1446−1456.

Prostaglandin E2 was thus generated in 51% yield and with exclusive *Z* selectivity. In a similar manner, we converted **1.80**, which was obtained by reduction of **1.80**, to prostaglandin F2α in 59% yield and >98:2 *Z:E* selectivity. Due to the challenging nature of the above CM processes, higher catalyst loadings were required (2.0 mol % for capping and 15 mol % for CM). Even so, because there is no need for protection/deprotection sequences and because *Z* selectivities are high, we consider the above routes as an improvement in the state-of-the-art. It is worth noting that, by varying identity of acid-based cross partner, analogues of prostaglandin E and F2α may be generated from same core molecules (**1.79** and **1.80**).

Scheme 1.26. Application to Synthesis of Prostaglandin E2 and F2α[a]



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^1H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

1.5.3 Synthesis of a Stapled Peptide Bearing a *Z*-Olefin Linkage

Hydrocarbon-stapled peptides are α- helical ligands that have been used for gaining a greater understanding of protein–protein associations and are leading candidates for therapeutic regulation of intercellular interactions.[40] Reliable access to stapled peptides with stereochemically defined olefin linkages allows for detailed examination of conformational preferences and their connection to biological activity. *Z*-Selective MRCM of peptidic dienes is feasible with bidentate Ru–alkyl complexes (e.g., **Ru-3**) but extended hydrocarbon tethers are required[13n] to ensure Ru carbene is appropriately distal from any polar functionalities within amino acid side chains, which can cause catalyst inhibition. Thus, MRCM of diene **1.81** in the presence of **Ru-3** did not lead to the formation of any of the 14-membered ring peptide **1.82** (<5%, Scheme 1.26). In contrast, subjection of **1.81** to 2.0 mol % catechothiolate **Ru-9** and *Z*-butene (20 equiv; 22 °C, 12 h), followed by placing the mixture under mild vacuum and the addition of 10 mol % **Ru-9**, allowed us to isolate stapled peptide **1.82,** precursor to a potent δ and μ opioid receptor agonist,[39b] in 72% yield with >98:2 *Z:E* selectivity. We were able to perform the MRCM at higher concentration (250 vs <5 mM) and be using a paraffin pellet that contains **Ru-9**, thus elevating the practicality of the method.[41]

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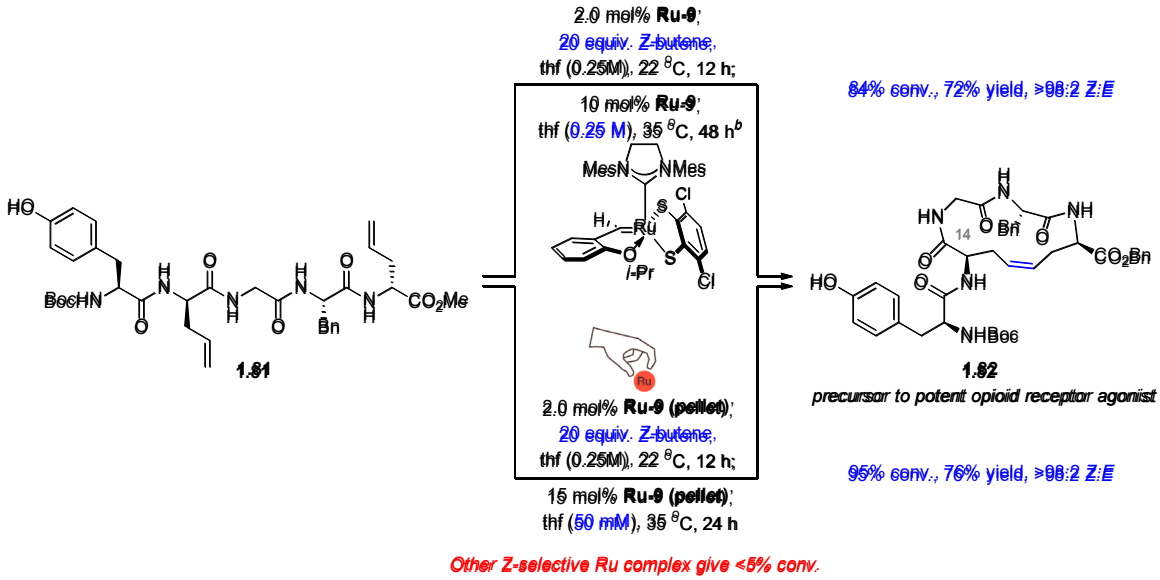
(40) (a) Bird, G. H.; Mazzola, E.; Opoku-Nsiah, K.; Lammert, M. A.; Godes, M.; Neuberg, D. S.; Walensky, L. D. *Nat. Chem. Biol.* **2016**, *12*, 845−852. (b) Mollica, A.; Guardiani, G.; Davis, P.; Ma, S.-W.; Porreca, F.; Lai, J.; Mannina, L.; Sobolev, A. P.; Hruby, V. J. *J. Med. Chem*. **2007**, *50*, 3138−3142.

(41) Ondi, L.; Nagy, G. M.; Czirok, J. B.; Bucsai, A.; Frater, G. E. *Org. Process Res. Dev*. **2016**, *20*, 1709−1716.

Scheme 1.27. The Application to Synthesis of a Stapled Peptide[a]



[a]Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). [b]Reactions were performed under N_2 atm. For full details, see the Experimental Section.

1.6 In Situ Methylene Capping Method for *E*-Selective Olefin Metathesis

1.6.1 Initial Investigations

Disubstituted *E*-selective olefin metathesis is another important set of reactions, offering pathways for direct synthesis of various bioactive compounds.[42] Although reactions with the commonly used Ru-dichloro complexes usually generate *E* alkenes as the major products, the level of selectivity is dependent on the relative size of the olefin substituents (i.e., thermodynamic control). For example, with alkyl-substituted alkenes, products are obtained in ~85:15 *E:Z* ratio, separation of which is often difficult.

(42) For representative biologically active molecule containing an *E* alkene, see: (a) Sano, S.; Kobayashi, Y.; Kondo, T.; Takebayashi, M.; Maruyama, S.; Fujita, T.; Nagao, Y. *Tetrahedron Lett*. **1995**, *36*, 2097–2100. (b) Couladouros, E. A.; Mihou, A. P. *Tetrahedron Lett*. **1999**, *40*, 4861–4862. (c) Duffield, J. J.; Pettit, G. R. *J. Nat. Prod*. **2001**, *64*, 472–479.

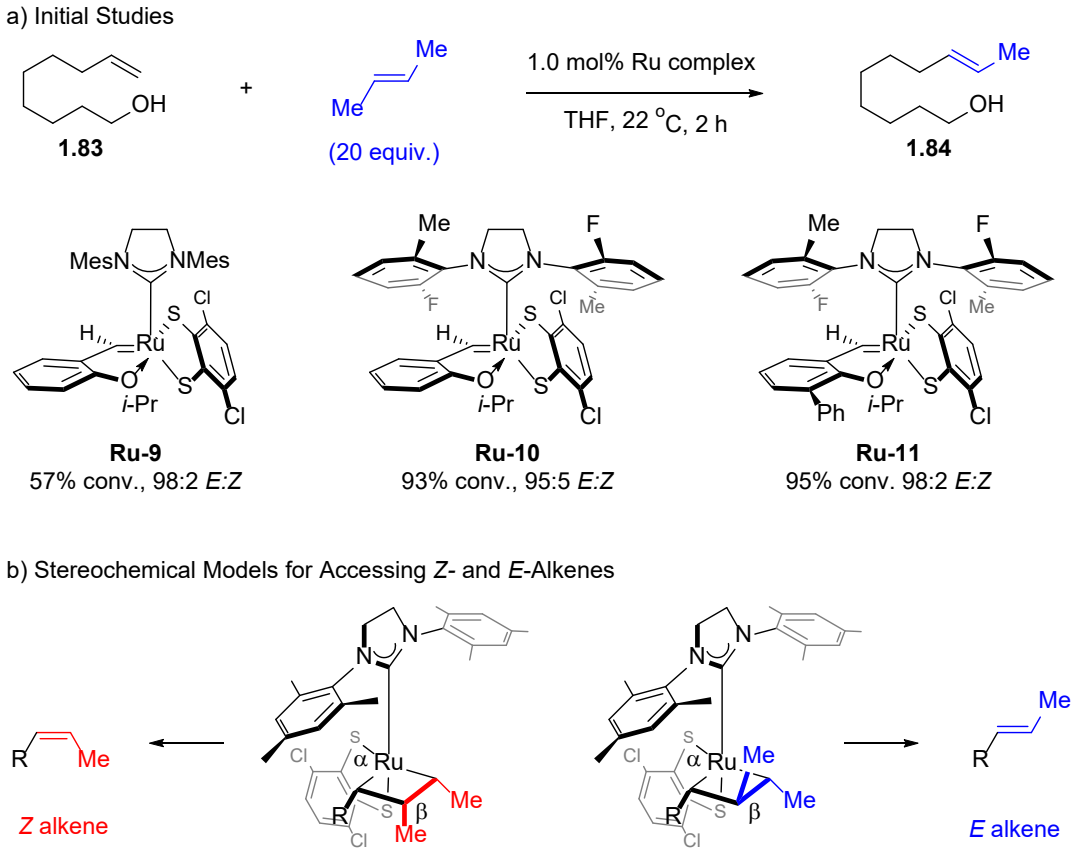
Efficient kinetically controlled *E*-selective CM reactions were first introduced by Hoveyda *et al*. through the use of Mo-based monoaryloxide pyrrolide (MAP) complexes to generate *trans* alkenyl halides.[43] The corresponding *E*-selective MRCM process were subsequently outlined by the same team.[44] Grubbs and co-workers have reported *E*-selective metathesis by employing a modified version of Hoveyda's Ru catechothiolate complex with a fast-initiating phenylidene group; transformations involved a monosubstituted and an *E*-disubstituted alkene.[45] The question for us was whether the capping strategy could be used for converting available monosubstituted alkenes to *E* olefin products in high yield and selectivity in a single vessel.

(43) For first examples of efficient kinetically controlled *E*-selective CM, see: Nguyen, T. T.; Koh, M. J.; Shen, X.; Romiti, F.; Schrock, R. R.; Hoveyda, A. H. *Science* **2016**, *352*, 569−575.

(44) For first examples of kinetically controlled *E*-selective MRCM, see: Shen, X.; Nguyen, T. T.; Koh, M. J.; Xu, D.; Speed, A. W. H.; Schrock, R. R.; Hoveyda, A. H. *Nature* **2017**, *541*, 380−386.

(45) Tonia, S. A.; Grubbs, R. H. *J. Am. Chem. Soc*. **2017**, *139*, 1532–1537.

Scheme 1.28. Probing the Effectiveness of Ru Catechothiolate Catalysts in *E*-Selective CM[a]



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). For full details, see the Experimental Section.

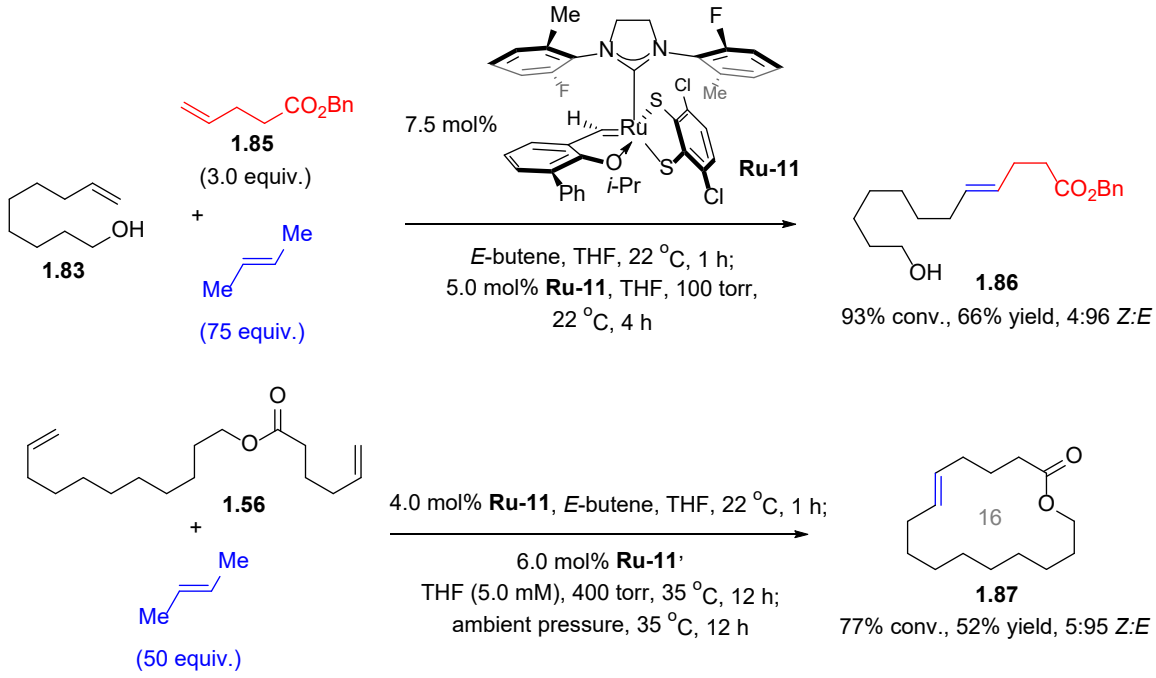
We first investigated the capping of monosubstituted alkene with *E*-butene (Scheme 1.28). For the reaction between **1.83** and *E*-butene in the presence of catechothiolate complex **Ru-9** there was 57% conversion to **1.84** with 98:2 *E:Z* ratio after two hours at room temperature. When **Ru-10**, which contains a smaller NHC ligand, was used, efficiency improved (93% conv, 95:5 *E:Z*). Similar efficiency was observed with **Ru-11**, which contains a faster-initiating ligand,[48] and there was a distinct improvement in the *E*:*Z* ratio (95% conv, 98:2 *E:Z*). The above efficiency and selectivity trend can be rationalized by the fact that in *E*-selective metathesis, the *β*-substituent of a

metallacyclobutane is oriented towards the NHC ligand, and, as a result, a less sizeable NHC ligand means a more facile transformation.

1.6.2 *E*-Selective Cross-Metathesis and Macrocyclic Ring-Closing Metathesis

Next, we explored the scope of catalytic methylene capping/*E*-selective CM and RCM (Scheme 1.29). The reaction of monosubstituted alkene **1.83** and **1.85** with 75 equivalents of *E*-butene afforded *E*-alkene **1.86** in 66% yield and 96:4 *E:Z* selectivity. Diene **1.56**, which was employed in *Z*-selective MRCM, was subjected to 50 equivalents of *E*-butene and 4.0 mol % **Ru-11**, followed by the addition of 6.0 mol % of the same complex under mild vacuum, resulting in the formation of *E*-macrocycle **1.87** in 52% yield and 95:5 *E:Z* selectivity. Hence, by altering the identity of the capping agent, either *Z*- or *E*-macrocyclic alkene (e.g. **1.58** or **1.87**) can be generated from same substrate. The large excess of *E*-butene and higher catalyst loading is owing to lower reactivity of *E*-alkenes.

Scheme 1.29. Application to *E*-Selective CM and MRCM[a]



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

1.7 Conclusions

The investigations described above demonstrate that the combination of methylene capping and the relatively high activity and unique ability of Ru catechothiolate catalysts (vs other Ru-based variants) to remain active in the presence of key function units, such as aldehydes, ketones, and carboxylic acids, can be used to expand the scope of kinetically *Z*- or *E*-selective olefin metathesis reactions. Applications of related strategies to the development of stereoselective metathesis reactions will be provided in the subsequent chapters of this thesis.

1.8 Experimental

1.8.1 General

Unless otherwise noted, transformations were performed with distilled and degassed solvents under an atmosphere of dry N_2, in oven- (135 °C) or flame-dried glassware with standard dry box or vacuum line techniques. ^{1}H NMR spectra were recorded on a Varian Unity INOVA 400 (400 MHz), 500 (500 MHz) or a 600 (600 MHz) spectrometer. Chemical shifts are reported in ppm from tetramethylsilane with the solvent resonance resulting from incomplete deuterium incorporation as the internal standard ($CDCl_3$: δ 7.26 ppm, DMSO-d_6: δ 2.50 ppm). Data are reported as follows: chemical shift, integration, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, br = broad, m = multiplet), and coupling constants (Hz). ^{13}C NMR spectra were recorded on a Varian Unity INOVA 400 (100 MHz), 500 (125MHz), or 600 (151 MHz) spectrometers with complete proton decoupling. Chemical shifts are reported in ppm from tetramethylsilane with the

solvent resonance as the internal standard ($CDCl_3$: δ 77.16 ppm). High-resolution mass spectrometry was performed on a Micromass LCT ESI-MS and JEOL Accu TOF Dart (positive mode) at the Boston College Mass Spectrometry Facility. Melting points were determined using a Thomas Hoover Uni-melt capillary melting point apparatus. Infrared (IR) spectra were recorded on a Bruker FTIR Alpha (ATR Mode) spectrometer, ν_{max} in cm^{-1}. Bands are characterized as broad (br), strong (s), medium (m), or weak (w). Values for *E*:*Z* ratios of products were determined by analysis of ^1H NMR or quantitative ^{13}C NMR (13 second delay time) spectra. Specific rotations were measured using a Rudolph Research Analytical Autopol IV Polarimeter. In the olefin metathesis reaction, 100 torr vacuum is applied for 1-8 h, which often results in complete solvent evaporation.

Solvents

Tetrahydrofuran (THF) was distilled from Na/benzophenone. CH_2Cl_2 were purified under a positive pressure of dry argon gas by a modified Innovative Technologies purification system. $CDCl_3$ and DMSO-d_6 were purchased from Cambridge Isotope Laboratories and stored over activated 4Å molecular sieves prior to use. CH_3CN was used as received. Hexamethylphosphoramide (HMPA) was distilled from CaH_2 and stored over activated 4Å molecular sieves prior to use. Purification procedures of products were carried out with reagent grade solvents (Fisher) under bench-top conditions.

Reagents

(*Z*)-2-Butene (Aldrich) was dissolved in dried THF and stored in the freezer at –50 °C; Weight percent (wt %) was calculated based on the ^1H NMR analysis of the mixture. (*Z*)-3-hexene (Alfa Aesar), (*Z*)-5-decene (Alfa Aesar), hex-5-enoic acid (Aldrich), 3-buten-1-ol (Oakwood), 9-decen-1-ol (Aldrich), dec-9-enal (Aldrich), 2,6-dimethyloct-7-en-2-ol (dihydromyrcenol, Aldrich), 4-allylphenol (Aldrich), 1-decen-3-ol (TCI), (*Z*)-prop-1-en-1-

ylbenzene (*cis*-β-methyl styrene, Aldrich), (*E*)-buta-1,3-dien-1-ylbenzene (Aldrich), dec-9-enoic acid (Aldrich), *N*-(3-dimethylaminopropyl)-*N*'-ethylcarbodiimide hydrochloride (EDC·HCl, Advanced ChemTech), 4-dimethylaminopyridine (DMAP, Advanced ChemTech), methyl 5-hexenoate (TCI), 3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzaldehyde (Combi-blocks), (*Z*)-1-bromoprop-1-ene (Aldrich), tetrakis(triphenylphosphine)palladium(0) ($Pd(PPh_4)_3$ (Strem)), *tetra*-*n*-butylammonium bromide (Aldrich), potassium hydroxide (Aldrich), (*Z*)-4,4,5,5-tetramethyl-2-(prop-1-en-1-yl)-1,3,2-dioxaborolane (Aldrich), 1-bromopentane (Aldrich), Mg turnings (Aldrich), $BrCH_2CH_2Br$ (Aldrich), L-selectride (Aldrich), hydrogen fluoride pyridine (Aldrich) were used as received.

Benzyl pent-4-enoate (from 4-pentenoic acid (Aldrich)) and benzyl hex-5-enoate (from 5-hexenoic acid (Aldrich)) were prepared in analogy to reported procedures.[46]. 3-(But-3-en-1-yl)-1H-indole (from indole (Aldrich)),[47] (*E*)-1-(buta-1,3-dien-1-yl)-4-methoxybenzene (from *trans*-*p*-methoxycinnamaldehyde (Aldrich))[48], (*Z*)-1,2-dimethoxy-3-(prop-1-en-1-yl)benzene (from (*Z*)-1-bromoprop-1-ene (Aldrich))[49], *tert*-butyl (2-(but-3-en-1-ylamino)-2-oxoethyl)carbamate (from but-3-en-1-amine (Aldrich)), and (*S*)-*tert*-butyl (1-(but-3-en-1-ylamino)-3-methyl-1-oxobutan-2-yl)carbamate (from but-3-en-1-amine (Aldrich)) and (*S*)-*tert*-butyl (1-(but-3-en-1-ylamino)-4-(methylthio)-1-oxobutan-2-yl)carbamate (from but-3-en-1-amine (Aldrich))[50] were prepared according to a reported procedures. Undec-

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10-en-1-yl hex-5-enoate (from hex-5-enoic acid (Aldrich) and undec-10-en-1-ol (Aldrich)), hex-5-en-1-yl non-8-enoate (from non-8-enoic acid (Aldrich) and hex-5-en-1-ol (Aldrich)), non-8-en-1-yl hept-6-enoate (from hept-6-enoic acid (Aldrich) and non-8-en-1-ol (Aldrich)), dec-9-en-1-yl hept-6-enoate (from hept-6-enoic acid (Aldrich) and dec-9-en-1-ol (Aldrich)), undec-10-en-1-yl non-8-enoate (from non-8-enoic acid (Aldrich) and undec-10-en-1-ol (Aldrich)), undec-10-en-1-yl undec-10-enoate (from undec-10-enoic acid (Aldrich) and undec-10-en-1-ol (Aldrich), *N*-(undec-10-en-1-yl)hex-5-enamide, *N*-(undec-10-en-1-yl)undec-10-enamide, [51] nonadeca-1,18-dien-10-ol, [52] 2-(*N*-(undec-10-en-1-yl)undec-10-enamido)acetic acid, [53] 4-((*tert*-butyldimethylsilyl)oxy)cyclopent-2-en-1-one[54], (*S*,*E*)-*tert*-butyl((1-iodooct-1-en-3- yl)oxy)dimethylsilane,[55] and (6*S*,9*R*,15*S*,18*R*)-methyl 9,18-diallyl-15-benzyl-6-(4-hydroxybenzyl)-2,2-dimethyl-4,7,10,13,16-pentaoxo-3-oxa-5,8,11,14,17-pentaazanonadecan-19-oate [56] were prepared according to reported procedures.

Organometallic complexes

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Complex **Ru-1a** (Aldrich) was used as received; **Ru-2a** was prepared according to a previously reported procedure.[57] **Ru-2b** was prepared according to previously reported procedure.[58]

1.8.2 Synthesis of capped alkenes by cross-metathesis

(*Z*)-Hept-5-enoic acid (1.29). In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 5-hexenoic acid (**1.28**, 14.5 mg, 0.127 mmol), *Z*-butene in THF (22 wt %, 647.0 mg, 2.54 mmol) and catechothiolate complex **Ru-9** (1.0 mg, 0.00127 mmol, 100 μL THF). The mixture was allowed to stir for 1 h at 22 °C, after which the reaction was quenched by the addition of undistilled (wet) diethyl ether. The volatiles were then removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.29** (15.4 mg, 0.121 mmol, 95% yield) in >98:2 *Z:E* ratio as colorless oil. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 5.57–5.45 (m, 1H), 5.43–5.30 (m, 1H), 2.38 (t, *J* = 7.1 Hz, 2H), 2.11 (q, *J* = 7.3 Hz, 2H), 1.71 (p, *J* = 7.4 Hz, 2H), 1.60 (d, *J* = 6.8 Hz, 3H); **HRMS[M+H]$^+$** Calcd for $C_7H_{13}O_2$: 129.0916, found: 129.0913. The characterization data are consistent with these previously reported.[59]

(*Z*)-Oct-5-enoic acid (1.31). In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 5-hexenoic acid (29.0 mg, 0.254 mmol), the *Z*-3-hexene (107.0 mg, 1.27 mmol) and **Ru-9** (4.9 mg, 0.00635 mmol, 100 μL THF). The mixture was allowed to stir for 1 h at 22 ºC, after which the reaction was quenched by wet (undistilled)

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diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.31** (29.8 mg, 0.211 mmol, 83% yield) in >98:2 *Z:E* ratio as colorless oil. **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.45–5.39 (m, 1H), 5.35–5.25 (m, 1H), 2.36 (t, *J*= 7.5 Hz, 2H), 2.10 (q, *J* = 7.4, 6.9 Hz, 2H), 2.03 (pd, *J* = 7.5, 1.5 Hz, 2H), 1.70 (p, *J* = 7.5 Hz, 2H), 0.95 (t, *J* = 7.5 Hz, 3H); **HRMS[M+H]$^+$** Calcd for $C_8H_{15}O_2$: 143.1072, found: 143.1068. The characterization data are consistent with these previously reported.[60]

(*Z*)-Dec-5-enoic acid (1.32). In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 5-hexenoic acid (14.5 mg, 0.127 mmol), the (*Z*)-5-decene (90.0 mg, 1.27 mmol) and **Ru-9** (2.4 mg, 0.00318 mmol, 100 μL THF). The mixture was allowed to stir for 1 h at 22 °C, after which the reaction was quenched by wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.32** (21.1 mg, 0.124 mmol, 98% yield) in >98:2 *Z:E* ratio as colorless oil. **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.46–5.38 (m, 1H), 5.36–5.29 (m, 1H), 2.36 (t, *J* = 7.5 Hz, 2H), 2.10 (q, *J* = 7.0 Hz, 2H), 2.02 (q, *J* = 6.8 Hz, 2H), 1.70 (p, *J* = 7.5 Hz, 2H), 1.35–1.28 (m, 4H), 0.92–0.87 (m, 3H); **HRMS[M+H]$^+$** Calcd for $C_{10}H_{19}O_2$: 171.1385, found: 171.1391. The characterization data are consistent with these previously reported.[61]

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1.8.3 Procedure for synthesis of alkene 1.30 by homometathesis of capped alkenes

(*Z*)-Dec-5-enedioic acid (2). In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with **1.29** (28.1 mg, 0.22 mmol) and a solution of **Ru-9** (3.4 mg, 0.0044 mmol, 200 μL THF). The system was placed under 100 torr of vacuum and was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.30** (16.3 mg, 0.16 mmol, 74% yield) in >98:2 *Z:E* as white solid. **M.p.**: 76−77 °C; **IR (neat):** 3021 (m), 2952 (m), 1703 (s), 1458 (m), 1410 (m), 1330 (m), 1244 (m), 1200 (m), 938 (m), 858 (m), 639 (s) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 11.19 (br, 2H), 5.42−5.36 (m, 2H), 2.36 (t, J = 7.3 Hz, 4H), 2.13−2.06 (m, 4H), 1.69 (p, J = 7.3 Hz, 4H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 180.3, 129.8, 33.5, 26.5, 24.6; **HRMS[M+H]$^+$** Calcd for $C_{10}H_{17}O_4$: 201.1127, Found: 201.1118.

1.8.4 Procedure for homocoupling with *Z*-butene as the methylene capping agent

In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the **1.29** (14.5 mg, 0.127 mmol), unpurified *Z*-butene in THF (22 wt%, 650 mg, 1.27 mmol), and a solution of **Ru-9** (1.0 mg, 0.00127 mmol, 200 μL THF), and then the vessel was sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr for 2 min). The flask containing the residue was charged with a solution of **Ru-9** (2.0 mg, 0.00254 mmol in 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by

the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.30** (17.8 mg, 0.089 mmol, 70% yield) in >98:2 *Z:E* as white solid.

1.8.5 Cross-metathesis with *Z*-butene as the methylene-capping agent

General procedure A: In a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with the alkene substrates (1:3 ratio), unpurified *Z*-butene in THF and a solution of the appropriate amount of **Ru-9** in THF. The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1–16 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of the appropriate amount of **Ru-9** in THF and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 1–8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. Silica gel chromatography was used to obtain pure products.

General procedure B (for the reactions with α-branched terminal alkenes, *Z*-β-methyl styrenes and *Z*-1-propenylboronic acid ester): In a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with the terminal alkene substrate, unpurified *Z*-2-butene in THF and a solution of the appropriate amount of **Ru-9** in THF. The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with th**e** other alkene (e.g. *cis*-β-methyl styrene**)** and a solution of the appropriate amount of **Ru-9** in THF and the system was placed under 100 torr of vacuum

generated from a diaphragm pump. The resulting solution was allowed to stir for 1□8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. Purification was performed by silica gel chromatography.

(*Z*)-Benzyl-7-hydroxyhept-4-enoate (1.33). Following the general procedure A, in a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with but-3-en-1-ol (7.2 mg, 0.10 mmol), benzyl pent-4-enoate (57.0 mg, 0.30 mmol) and *Z*-butene in THF (36 wt %, 312.0 mg, 2.01 mmol) and a solution of **Ru-9** (0.76 mg, 0.0010 mmol in 100 μL THF). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 16 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of **Ru-9** (3.00 mg, 0.0040 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (15% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford olefin product **1.33** (13.2 mg, 0.056 mmol, 56% yield) in 95:5 *Z:E* ratio as colorless oil. **IR (neat):** 3386 (br), 3012 (m), 2946 (m), 1731 (s), 1498 (m), 1418 (m), 1258 (m), 1151 (s), 1047 (s), 735 (s), 696 (s), 503 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.40–7.28 (m, 5H), 5.64–5.31 (m, 2H), 5.12 (s, 2H), 3.64 (t, *J* = 6.5 Hz, 2H), 2.47–2.40 (m, 4H), 2.34 (q, *J* = 6.3 Hz, 2H), 1.66 (br, 1H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 173.2, 136.1, 130.8, 128.7, 128.4, 128.4, 127.3, 66.4, 62.3, 34.2, 30.9, 22.9. **HRMS[M+H]$^+$** Calcd for $C_{14}H_{19}O_3$: 235.1334, Found: 235.1346.

(*Z*)-8-(Benzyloxy)-8-oxooct-4-enoic acid (1.34). Following the general procedure A, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with benzyl pent-4-enoate (25.4 mg, 0.127 mmol) and hex-5-enoic acid (38.1 mg, 0.38 mmol), unpurified *Z*-2-butene in THF (22 wt %, 650 mg, 2.54 mmol) and a solution of **Ru-9** (1.0 mg, 0.00127 mmol, 200 μL THF). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of **Ru-9** (3.9 mg, 0.00508 mmol in 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.34** (24.6 mg, 0.094 mmol, 74% yield) in >98:2 *Z*:*E* ratio as colorless oil. For the larger scale process, the above procedure was followed with benzyl pent-4-enoate (380.48 mg, 2.0 mmol) and hex-5-enoic acid (600.7 mg, 6.0 mmol), resulting in the formation of **1.34** (293.8 mg, 1.117 mmol, 56% yield) in 98:2 *Z*:*E* ratio as colorless oil. **IR (neat):** 3011 (br), 2954 (w), 1734 (s), 1708 (s), 1454 (w), 1382 (w), 1258 (m), 1213 (m), 1152 (m), 738 (m), 689 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 7.38−7.30 (m, 5H), 5.41−5.39 (m, 2H), 5.12 (s, 2H), 2.43−2.37 (m, 8H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 178.3, 173.1, 136.1, 129.3, 128.9, 128.7, 128.4, 128.4, 66.4, 34.3, 33.9, 22.9, 22.6; **HRMS[M+H]$^+$** Calcd for $C_{15}H_{19}O_4$: 263.1283, found: 263.1292.

(*Z*)-8-(1H-Indol-3-yl)oct-5-enoic acid (1.35). Following the general procedure A, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the

3-(but-3-en-1-yl)-1*H*-indole (21.7 mg, 0.127 mmol) and hex-5-enoic acid (43.5 mg, 0.381 mmol), unpurified *Z*-2-butene in THF (36 wt %, 396 mg, 2.54 mmol) and a solution of **Ru-9** (1.0 mg, 0.00127 mmol, 200 μL THF). The reaction vessel was then sealed. The mixture was allowed to stir at 22 ºC for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of **Ru-9** (3.9 mg, 0.00508 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.35** (19.0 mg, 0.074 mmol, 58% yield) in >98:2 *Z*:*E* ratio as colorless solid. **M.p.:** 65–67 °C; **IR (neat):** 3414 (m), 3055 (m), 3004 (m), 2927 (m), 2851 (m), 1701 (s), 1456 (m), 1419 (m), 1243 (m), 1090 (m), 1010 (m), 927 (w), 797 (m), 740 (s) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.90 (br, 1H), 7.63−7.59 (m, 1H), 7.34 (dt, *J* = 8.1, 0.9 Hz, 1H), 7.18 (ddd, *J* = 8.1, 7.0, 1.3 Hz, 1H), 7.11 (ddd, *J*= 8.1, 7.0, 1.1 Hz, 1H), 7.00 −6.97 (m, 1H), 5.60−5.48 (m, 1H), 5.42−5.31 (m, 1H), 2.82 (ddd, *J*= 7.6, 6.9, 0.9 Hz, 2H), 2.53−2.39 (m, 2H), 2.24 (t, *J* = 7.5 Hz, 2H), 2.12−1.98 (m, 2H), 1.68−1.55 (m, 2H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 179.9, 136.5, 130.9, 129.0, 127.7, 122.0, 121.4, 119.3, 119.0, 116.4, 111.2, 33.4, 28.0, 26.6, 25.4, 24.6; **HRMS[M+H]$^+$** Calcd for $C_{16}H_{20}O_2N$: 258.1494, found: 258.1502.

(*Z*)-14-Hydroxytetradec-5-enoic acid (1.36). Following the general procedure A, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the dec-9-en-1-ol (19.8 mg, 0.127 mmol) and hex-5-enoic acid (43.5 mg, 0.381 mmol),

unpurified *Z*-butene in THF (22 wt %, 650 mg, 2.54 mmol) and a solution of **Ru-9** (1.0 mg, 0.00127 mmol, 200 μL THF). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of **Ru-9** (3.9 mg, 0.00508 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.36** (16.8 mg, 0.074 mmol, 58% yield) in >98:2 *Z*:*E* ratio ratio as colorless oil. **IR (neat):** 3336 (br), 3006 (m), 2925 (s), 2854 (m), 1707 (s), 1457 (m), 1409 (m), 1260 (m), 1023 (m), 862 (m), 801 (m), 722 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 6.08 (br, 1H), 5.45−5.37 (m, 1H), 5.35−5.29 (m, 1H), 3.65 (t, *J* = 6.6 Hz, 2H), 2.35 (t, *J* = 7.4 Hz, 2H), 2.10 (q, *J* = 7.4 Hz, 2H), 2.01 (q, *J* = 6.8 Hz, 2H), 1.69 (m, 2H), 1.62−1.48 (m, 2H), 1.41−1.22 (m, 10H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 178.4, 131.4, 128.5, 63.2, 33.4, 32.7, 29.6, 29.4, 29.3, 29.1, 27.3, 26.6, 25.7, 24.8; **HRMS[M+H]$^+$** Calcd for $C_{14}H_{27}O_3$: 243.1960, found: 243.1970.

(*Z*)-14-Oxotetradec-5-enoic acid (1.37). Following the general procedure A, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the undec-10-enal (19.6 mg, 0.127 mmol) and hex-5-enoic acid (43.5 mg, 0.381 mmol), unpurified *Z*-butene in THF (22 wt %, 650 mg, 2.54 mmol) and a solution (200 μL) of **Ru-9** (1.0 mg, 0.00127 mmol, 200 μL THF). The vessel was sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask

containing the residue was then charged with a solution of **Ru-9** (3.9 mg, 0.00508 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.37** (20.1 mg, 0.084 mmol, 66% yield) in >98:2 *Z*:*E* ratio as colorless oil. **IR (neat):** 3006 (m), 2925 (m), 2853 (m), 1705 (s), 1458 (m), 1411 (m), 1239 (m), 1161 (m), 938 (m), 724 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 9.76 (t, *J* = 1.9 Hz, 1H), 5.45−5.37 (m, 1H), 5.36−5.28 (m, 1H), 2.42 (td, *J* = 7.3, 1.9 Hz, 2H), 2.36 (t, *J* = 7.5 Hz, 3H), 2.09 (q, *J* = 7.1 Hz, 2H), 2.00 (q, *J* = 6.9 Hz, 2H), 1.73−1.67 (m, 2H), 1.65−1.60 (m, 2H), 1.33−1.28 (m, 10H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 203.2, 178.6, 131.4, 128.4, 44.1, 33.3, 29.8, 29.4, 29.4, 29.3, 29.3, 27.3, 26.6, 24.8, 22.2; **HRMS[M+H]$^+$** Calcd for $C_{15}H_{27}O_5$: 255.1960, found: 255.1967.

(*Z*)-8-((Benzyloxy)methoxy)-8-phenyloct-5-enoic acid (1.38). Following the general procedure A, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the (1-((benzyloxy)methoxy)but-3-en-1-yl)benzene (34.0 mg, 0.127 mmol), hex-5-enoic acid (43.5 mg, 0.381 mmol), unpurified *Z*-2-butene in THF (22 wt %, 650 mg, 2.54 mmol) and a THF solution of **Ru-9** (1.0 mg, 0.00127 mmol, 200 μL THF). The reaction vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of **Ru-9** (3.9 mg, 0.00508 mmol, 200 μL THF) in and the system was placed under 100 torr of vacuum generated from a diaphragm pump.

The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.38** (28.7 mg, 0.081 mmol, 64% yield) in >98:2 *Z*:*E* ratio as colorless oil. **IR (neat):** 3086 (m), 3062 (m), 3029 (m), 2932 (m), 1706 (s), 1454 (m), 1410 (m), 1239 (m), 1100 (m), 1036 (s), 1025 (s), 735 (m), 699 (s) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 7.38−7.26 (m, 10H), 5.51−5.39 (m, 2H), 4.73 (d, *J* = 7.0 Hz, 1H), 4.70 (d, *J* = 11.6 Hz, 1H), 4.68 (dd, *J* = 7.5, 6.1 Hz, 1H), 4.64 (d, *J* = 7.0 Hz, 1H), 4.50 (d, *J* = 11.7 Hz, 1H), 2.60 (dt, *J* = 14.7, 7.3 Hz, 1H), 2.45 (dt, *J* = 13.8, 6.4 Hz, 1H), 2.28 (t, *J* = 7.5 Hz, 2H), 2.06−1.99 (m, 2H), 1.64-1.58 (m, 2H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 179.6, 141.8, 138.0, 130.9, 128.5, 128.5, 128.1, 128.1, 127.8, 127.1, 126.6, 92.5, 78.3, 69.8, 35.9, 33.4, 26.7, 24.5; **HRMS[M+NH_4]$^+$** Calcd for $C_{22}H_{30}O_4N$: 372.2175, found: 372.2171.

(*Z*)-7-(3,4-Dimethoxyphenyl)hept-5-enoic acid (1.39). Following the general procedure A, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the 4-allyl-1,2-dimethoxybenzene (17.8 mg, 0.10 mmol), hex-5-enoic acid (34.2 mg, 0.30 mmol), unpurified *Z*-butene in THF (17 wt %, 660 mg, 2.00 mmol) and a solution of **Ru-9** (0.76 mg, 0.0010 mmol in 200 μL THF). The vessel was sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of **Ru-9** (3.0 mg, 0.0040 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet

(undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.39** (17.1 mg, 0.064 mmol, 64% yield) in 98:2 *Z*:*E* ratio as colorless oil. **IR (neat):** 3008 (m), 2937 (s), 2837 (m), 1737 (m), 1706 (s), 1513 (s), 1464 (m), 1260 (s), 1234 (s), 1139 (s), 1029 (s), 756 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.80 (d, *J* = 7.9 Hz, 1H), 6.71 (d, *J* = 7.9 Hz, 1H), 6,70 (s, 1H), 5.65–5.56 (m, 1H), 5.53–5.42 (m, 1H), 3.86 (s, 3H), 3.85 (s, 3H), 3.34 (d, *J* = 7.3 Hz, 2H), 2.40 (t, *J* = 7.5 Hz, 2H), 2.22 (q, *J* = 7.1 Hz, 2H), 1.76 (p, *J* = 7.5 Hz, 2H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 179.3, 149.1, 147.4, 133.6, 129.8, 129.30, 120.2, 111.8, 111.5, 56.1, 56.0, 33.5, 33.2, 26.6, 24.7; **HRMS[M+H]$^+$** Calcd for $C_{15}H_{21}O_4$: 265.1434, Found: 265.1450.

(*Z*)-Benzyl-7-(5-acetyl-2-hydroxyphenyl)hept-5-enoate (1.40). Following the general procedure A, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the 1-(3-allyl-4-hydroxyphenyl)ethanone (16.4 mg, 0.10 mmol) and benzyl hex-5-enoate (61.2 mg, 0.30 mmol), unpurified *Z*-butene in THF (24 wt %, 466 mg, 2.00 mmol) and a solution of **Ru-9** (0.76 mg, 0.0010 mmol, 200 μL THF). The vessel was sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of **Ru-9** (3.0 mg, 0.0040 mmol in 200 μL THF, 4.0 mol %) in and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10%

ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.40** (22.2 mg, 0.063 mmol, 63% yield) in 97:3 *Z*:*E* ratio as yellow oil. **IR (neat):** 3275 (br), 3011 (m), 2951 (m), 1733 (s), 1652 (m), 1588 (s), 1421 (m), 1357 (m), 1276 (s), 1150 (m), 966 (m), 824 (m), 699 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.77–7.73 (m, 2H), 7.39–7.29 (m, 5H), 6.82 (d, *J* = 8.1 Hz, 1H), 5.90 (br, 1H), 5.67–5.48 (m, 2H), 5.13 (s, 2H), 3.39 (d, *J* = 4.9 Hz, 2H), 2.54 (s, 3H), 2.41 (t, *J* = 7.3 Hz, 2H), 2.26–2.20 (m, 2H), 1.79 (p, *J* = 7.3 Hz, 2H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 197.9, 174.0, 159.2, 136.0, 131.0, 130.9, 130.2, 129.0, 128.7, 128.4, 128.3, 127.9, 127.2, 115.5, 66.5, 33.8, 28.2, 26.7, 26.4, 24.8; **HRMS[M+H]$^+$** Calcd for $C_{22}H_{25}O_4$: 353.1747, Found: 353.1770.

Benzyl (*Z*)-11-hydroxy-7,11-dimethyldodec-5-enoate (1.41). Following the general procedure B, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the benzyl hex-5-enoate (77.7 mg, 0.381 mmol), unpurified *Z*-butene in THF (22 wt %, 650.0 mg, 2.54 mmol) and a solution of **Ru-9** (1.0 mg, 0.00127 mmol, 200 μL THF). The vessel was sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with dihydromyrcenol (19.8 mg, 0.13 mmol) and a solution of **Ru-9** (4.0 mg, 0.0052 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1~5% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.41** (23.8 mg, 0.075 mmol, 58% yield) in >98:2*Z*:*E* ratio as colorless oil. **IR (neat):** 3527 (br), 3034 (m), 2933 (m),

2867 (w), 1735 (s), 1455 (m), 1376 (m), 1309 (w), 1159 (s), 976 (w), 747 (m), 697 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.38−7.31(m, 5H), 5.29−5.24 (m, 1H), 5.17−5.11 (m, 3H), 2.39−2.36 (m, 3H), 2.09−2.05 (m, 2H), 1.82−1.65 (m, 2H), 1.43−1.33 (m, 2H), 1.33−1.18 (m, 10H), 0.91 (d, *J* = 6.7 Hz, 3H); **^{13}C NMR (125 MHz, $CDCl_3$):** δ 173.6, 137.5, 136.2, 128.7, 128.4, 128.3, 127.2, 71.1, 66.3, 44.2, 38.1, 33.9, 31.8, 29.4, 29.3, 27.0, 25.2, 22.4, 21.5; **HRMS[M+H-H_2O]$^+$** Calcd for $C_{21}H_{31}O_3$: 315.2324, found: 315.2309.

Benzyl (*Z*)-7-hydroxytetradec-5-enoate (1.42). In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the benzyl pent-4-enoate (77.7 mg, 0.381 mmol) unpurified *Z*-butene in THF solution (2.54 mmol) and a THF solution (200 μL) of **Ru-9** (1.0 mg, 0.00127 mmol). The vessel was sealed and the mixture was allowed to stir at 22 °C for 1 h. A separate oven-dried vial equipped with a magnetic stir bar was charged with dec-1-en-3-ol (19.8 mg, 0.127mmol) and unpurified *Z*-butene in THF (1.27 mmol) and a solution of **Ru-9** (1.5 mg, 0.00191 mmol, 200 μL THF). The vessel was sealed and the solution was allowed to stir at 22 °C for 1 h. The mixtures were then combined and the volatiles were removed *in vacuo* (100 torr for 2 mins). The flask containing the residue was charged with a solution of **Ru-9** (4.9 mg, 0.00635 mmol in 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.42** (19.7 mg, 0.060 mmol, 47% yield) in 90:10 *Z*:*E* ratio as colorless oil. **IR (neat):** 3430 (br), 3034 (w), 3006 (m), 2926 (s), 2854 (m), 1737 (s), 1456

(m), 1380 (m), 1311 (m), 1234 (m), 1214 (m), 1153 (m), 1045 (m), 1003 (m), 750 (m), 697 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 7.38−7.31 (m, 5H), 5.43−5.38 (m, 2H), 5.12 (s, 2H), 4.34 (q, *J* = 6.7 Hz, 1H), 2.38 (t, *J* = 7.3 Hz, 2H), 2.23−2.04 (m, 2H), 1.82−1.67 (m, 2H), 1.60−1.53 (m, 2H), 1.45−1.23 (m, 10H), 0.88 (t, *J* = 7.0 Hz, 3H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 173.6, 136.1, 134.1, 130.7, 128.7, 128.4, 128.4, 67.6, 66.4, 37.6, 33.7, 32.0, 29.7, 29.4, 27.0, 25.5, 24.9, 22.8, 14.3; **HRMS[M+H-H_2O]$^+$** Calcd for $C_{21}H_{31}O_2$: 315.2324, found: 315.2338.

(*Z*)-Benzyl 5-phenylpent-4-enoate (1.43). Following the general procedure B, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the benzyl pent-4-enoate (72.4 mg, 0.381 mmol), unpurified *Z*-2-butene in THF (22 wt %, 650 mg, 2.54 mmol) and a solution of **Ru-9** (1.0 mg, 0.00127 mmol, 200 μL THF). The vessel was then sealed. The mixture was allowed to stir at 22 ºC for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with (*Z*)-prop-1-en-1-ylbenzene (15.0 mg, 0.127 mmol, 200 μL THF) and a solution of **Ru-9** (3.9 mg, 0.00508 mmol) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.43** (16.4 mg, 0.061 mmol, 48% yield) in 96:4 *Z*:*E* ratio as colorless oil. **IR (neat):** 3063 (w), 3012 (w), 2954 (w), 2922 (w), 1734 (s), 1494 (m), 1447 (m), 1381 (m), 1352 (m), 1512 (s), 751 (m), 697 (s) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 7.41−7.20 (m, 10H), 6.48 (d, *J* = 11.6 Hz, 1H), 5.65 (dt, *J*= 11.6 Hz, 7.2 Hz,

1H), 5.12 (s, 2H), 2.83−2.63 (m, 2H), 2.51 (t, *J* = 7.5 Hz, 2H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 172.9, 137.3, 136.1, 130.4, 130.4, 128.9, 128.7, 128.4, 128.3, 128.3, 126.9, 66.4, 34.6, 24.2; **HRMS[M+H]$^+$** Calcd For $C_{18}H_{19}O_2$: 267.1385, found: 267.1380.

(*Z*)-Benzyl 5-(3,4-dimethoxyphenyl)pent-4-enoate (1.44). Following the general procedure B, in a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with benzyl pent-4-enoate (28.5 mg, 0.050 mmol), *Z*-butene in THF (24 wt %, 236 mg, 1.01 mmol) and a solution of catechothiolate complex **Ru-9** (0.38 mg, 0.0005 mmol, 100 μL THF). The reaction vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was charged with (*Z*)-1,2-dimethoxy-4-(prop-1-en-1-yl)benzene (8.9 mg, 0.05 mmol), followed by a solution of **Ru-9** (1.50 mg, 0.002 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 4 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (5% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.44** (8.2 mg, 0.025 mmol, 50% yield) in 92:8 *Z:E* ratio as colorless oil. **IR (neat):** 3007 (m), 2934 (m), 2836 (m), 1733 (s), 1602 (m), 1514 (s), 1456 (m), 1257 (s), 1238 (s), 1141 (s), 1027 (s), 750 (m), 656 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.37–7.28 (m, 5H), 6.87–6.79 (m, 3H), 6.40 (d, *J* = 11.6 Hz, 1H), 5.55 (dt, *J* = 11.6, 7.2 Hz, 1H), 5.12 (s, 2H), 3.88 (s, 3H), 3.85 (s, 3H), 2.70 (q, *J* = 7.5 Hz, 2H), 2.51 (t, *J* = 7.5 Hz, 2H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 172.9, 148.7, 148.1, 136.1, 130.3, 130.1,

129.1, 128.7, 128.4, 128.3, 121.4, 112.1, 111.1, 66.4, 56.1, 56.0, 34.6, 24.3; **HRMS[M+H]$^+$** Calcd for $C_{20}H_{23}O_4$: 327.1596, found: 327.1608.

(*Z*)-Methyl 6-(3-formylphenyl)hex-5-enoate (1.45). Following the general procedure B, in a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with methyl hex-5-enoate (19.2 mg, 0.15 mmol) and *Z*-butene in THF (17 wt %, 334 mg, 1.01 mmol) and a solution of **Ru-9** (0.38 mg, 0.00050 mmol, 100 μL THF). The vessel was sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with (*Z*)-3-(prop-1-en-1-yl)-benzaldehyde (7.3 mg, 0.050 mmol), followed by a solution of **Ru-9** (1.50 mg, 0.0020 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 4 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.45** (7.4 mg, 0.032 mmol, 64% yield) in 96:4 *Z:E* ratio as colorless oil. **IR (neat):** 3013 (m), 2950 (m), 2927 (m), 2852 (m), 2728 (m), 1734 (s), 1700 (s), 1598 (m), 1436 (m), 1376 (m), 1222 (m), 1155 (m), (m), 808 (m), 685 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 10.03 (s, 1H), 7.77–7.73 (m, 2H), 7.56–7.48 (m, 2H), 6.50 (d, *J* = 11.6 Hz, 1H), 5.74 (dt, *J* = 11.6, 7.4 Hz, 1H), 3.63 (s, 3H), 2.42–2.30 (m, 4H), 1.85–1.75 (m, 2H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 192.5, 173.9, 138.5, 136.6, 134.8, 133.4, 130.0, 129.0, 128.6, 128.0, 51.7, 33.6, 28.0, 25.1. **HRMS[M+H]$^+$** Calcd for $C_{14}H_{17}O_3$: 233.1178, found: 233.1189.

(*Z*)-11-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)undec-10-enal (1.46). Following the general procedure B, in a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with undec-10-enal (8.4 mg, 0.050 mmol), *Z*-butene in THF (36 wt %, 78.0 mg, 0.50 mmol) and a solution of **Ru-9** (0.38 mg, 0.00050 mmol, 100 μL THF). The vessel was then sealed, and the mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo*. The flask containing the residue was then charged with (*Z*)-4,4,5,5-tetramethyl-2-(prop-1-en-1-yl)-1,3,2-dioxaborolane (25.2 mg, 0.15 mmol), followed by a solution of **Ru-9** (1.50 mg, 0.0020 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 1 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (2% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.46** (7.9 mg, 0.027 mmol, 54% yield) in 95:5 *Z:E* ratio as colorless oil. **IR (neat):** 2979 (m), 2926 (s), 2855 (m), 1727 (s), 1628 (s), 1436 (m), 1320 (m), 1259 (s), 1145 (s), 968 (m), 760 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)** δ 9.76 (t, *J* = 1.9 Hz, 1H), 6.48–6.37 (m, 1H), 5.32 (d, *J* = 13.5 Hz, 1H), 2.48–2.34 (m, 4H), 1.66–1.58 (m, 2H), 1.44–1.20 (m, 22H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 203.1, 155.3, 82.9, 44.1, 32.3, 29.6, 29.5, 29.4, 29.3, 29.1, 25.0, 22.3; **HRMS[M+H]$^+$** Calcd for $C_{17}H_{32}BO_3$: 295.2445, found: 295.2446.

(5*Z*,7*E*)-12-Hydroxydodeca-5,7-dienoic acid (1.47). Following the general procedure A, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the (*E*)-octa-5,7-dien-1-ol (16.0 mg, 0.127 mmol) and 5-hexenoic acid (43.5 mg,

0.381 mmol), unpurified *Z*-butene in THF (24 wt %, 593 mg, 2.54 mmol) and a solution of **Ru-9** (1.0 mg, 0.00127 mmol, 200 μL THF). The vessel was sealed, and the mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of **Ru-9** (3.9 mg, 0.00508 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10~50% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.47** (16.1mg, 0.076 mmol, 59% yield) in 95:5 *Z*:*E* ratio as colorless oil. **IR (neat):** 3017 (m), 2926 (m), 2856 (m), 1707 (s), 1456 (m), 1437 (m), 1409 (m), 1246 (m), 1056 (m), 986 (m), 949 (m), 740 (w) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)**: δ 6.30 (dd, *J* = 15.1, 11.0 Hz, 1H), 6.01 (t, *J* = 10.9 Hz, 1H), 5.67 (dt, *J* = 14.7, 6.9 Hz, 1H), 5.35–5.23 (m, 1H), 3.67 (t, *J* = 6.7 Hz, 2H), 2.37 (t, *J* = 7.2 Hz, 2H), 2.25 (q, *J* = 7.4 Hz, 2H), 2.14 (q, *J* = 7.2 Hz, 2H), 1.73 (p, *J* = 7.2 Hz, 2H), 1.60 (dt, *J* = 14.8, 6.7 Hz, 2H), 1.49 (p, *J* = 7.1 Hz, 2H); **^{13}C NMR (125 MHz, $CDCl_3$)**: δ 180.0, 134.6, 130.1, 128.5, 126.0, 63.0, 32.8, 32.3, 31.9, 26.8, 25.2, 24.5; **HRMS[M+H]$^+$** Calcd For $C_{12}H_{21}O_3$: 213.1491, found: 213.1495.

Benzyl (5*Z*,7*E*)-8-phenylocta-5,7-dienoate (1.48). Following the general procedure A, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the (*E*)-buta-1,3-dien-1-ylbenzene (16.5 mg, 0.127 mmol) and benzyl hex-5-enoate (77.7 mg, 0.381 mmol), unpurified *Z*-butene in THF (24 wt %, 593 mg, 2.54 mmol) and a solution of **Ru-9** (1.0 mg, 0.00127 mmol, 200 μL THF). The vessel was then sealed, and

the mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of **Ru-9** (3.9 mg, 0.00508 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1~2% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.48** (31.0 mg, 0.10 mmol, 80% yield) in 97:3 *Z*:*E* ratio as colorless oil. **IR (neat):** 3061 (m), 3027 (w), 2937 (m), 1731 (s), 1493 (m), 1453 (m), 1413 (m), 1382 (m), 1310 (m), 1213 (s), 1912 (m), 1152 (m), 1073 (m), 985 (m), 946 (m), 732 (s), 694 (s) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.44−7.17 (m, 10H), 7.00 (ddd, *J* = 15.5, 11.1, 1.2 Hz, 1H), 6.52 (d, *J* = 15.5 Hz, 1H), 6.18 (t, *J* = 10.9 Hz, 1H), 5.46 (dt, *J* = 10.8, 7.7 Hz, 1H), 5.10 (s, 2H), 2.40 (t, *J* = 7.5 Hz, 2H), 2.33 (qd, *J* = 7.5, 1.4 Hz, 2H), 1.83−1.75 (m, 2H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 173.5, 137.6, 136.2, 134.2, 132.8, 131.6, 130.0, 128.7, 128.7, 128.3, 127.6, 126.5, 124.2, 66.3, 33.7, 27.4, 24.9; **HRMS[M+H]$^+$** Calcd for $C_{21}H_{23}O_2$: 307.1698, found: 307.1704.

Benzyl (5*Z*,7*E*)-8-(4-methoxyphenyl)octa-5,7-dienoate (1.49). Following the general procedure A, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with the (*E*)-1-(buta-1,3-dien-1-yl)-4-methoxybenzene (20.3 mg, 0.127 mmol) and benzyl hex-5-enoate (77.7 mg, 0.381 mmol), unpurified *Z*-butene in THF (24 wt %, 593 mg, 2.54 mmol) and a solution of **Ru-9** (1.0 mg, 0.00127 mmol, 200 μL THF). The vessel was then sealed, and the mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was

then charged with a solution of **Ru-9** (3.9 mg, 0.0051 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1~2% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.49** (23.9 mg, 0.071 mmol, 56% yield) in 97:3 *Z*:*E* ratio as colorless oil. **IR (neat):** 3029 (w), 3004 (w), 2934 (w), 2836 (w), 1731 (s), 1602 (m), 1509 (s), 1455 (m), 1303 (m), 1245 (s), 1173 (s), 1153 (s), 1115 (w), 1030 (m), 982 (m), 947 (m), 862 (m), 745 (m), 697 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 7.37−7.30 (m, 7H), 6.91−6.85 (m, 3H), 6.49 (d, *J* = 15.5 Hz, 1H), 6.18 (t, *J* = 10.9 Hz, 1H), 5.45−5.41 (m, 1H), 5.12 (s, 2H), 3.82 (s, 3H), 2.42 (t, *J* = 7.5 Hz, 2H), 2.34 (q, *J* = 7.5 Hz, 2H), 1.81 (m, 2H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 173.5, 159.3, 136.2, 132.3, 130.5, 130.4, 130.1, 128.7, 128.3, 127.7, 122.3, 114.2, 66.3, 55.4, 33.7, 27.3, 25.0; **HRMS[M+H]$^+$** Calcd for $C_{22}H_{25}O_3$: 337.1804, found: 337.1816.

(*Z*)-Di-*tert*-butyl ((hex-3-ene-1,6-diylbis(azanediyl))bis(2-oxoethane-2,1-diyl))dicarbamate (1.50). Following the general procedure A, in a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with *tert*-butyl (2-(but-3-en-1-ylamino)-2-oxoethyl)carbamate (11.4 mg, 0.0050 mmol) and *Z*-butene in THF (22 wt %, 256 mg, 1.00 mmol) and a solution of catechothiolate complex **Ru-9** (0.38 mg, 0.00050 mmol in 100 μL THF). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 4 h, after which the volatiles were removed *in vacuo*. The flask containing the residue was then charged with a solution of **Ru-9** (1.50 mg, 0.0020 mmol in 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm

pump. The resulting solution was allowed to stir for 1 h at 22 °C under vacuum, and then for another 3 h without vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (2% CH_2Cl_2 in MeOH) and filtered through a small plug of activated charcoal to afford **1.50** (9.4 mg, 0.022 mmol, 88% yield) in >98:2 *Z:E* ratio as white solid. **M.p.:** 52–53 °C; **IR (neat):** 3306 (s), 2976 (m), 2932 (s), 1698 (s), 1656 (s), 1524 (s), 1454 (m), 1365 (m), 1166 (s), 1050 (m), 864 (m), 731 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 6.62 (br, 2H), 5.45–5.40 (m, 4H), 3.77 (d, *J* = 5.5 Hz, 4H), 3.32 (q, *J* = 6.3 Hz, 4H), 2.25 (q, *J* = 6.2 Hz, 4H), 1.56–1.29 (m, 18H); **^{13}C NMR (101 MHz, $CDCl_3$):** δ 170.0, 156.4, 129.0, 80.3, 44.5, 39.0, 28.5, 27.7; **HRMS[M+H]$^+$** Calcd for $C_{20}H_{37}O_6N_4$: 429.2713, found: 429.2727.

(*S*,*Z*)-Benzyl 8-(2-((*tert*-butoxycarbonyl)amino)-3-methylbutanamido)oct-5-enoate (1.51). Following the general procedure A, in a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with (*S*)-*tert*-butyl (1-(but-3-en-1-ylamino)-3-methyl-1-oxobutan-2-yl)carbamate (27.0 mg, 0.10 mmol), benzyl hex-5-enoate (61.2 mg, 0.30 mmol, 3.00 equiv.), *Z*-2-butene in THF (24 wt %, 468 mg, 2.00 mmol) and a solution of **Ru-9** (0.76 mg, 0.001 mmol, 100 μL THF). The vessel was sealed, and the mixture was allowed to stir at 22 °C 16 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of **Ru-9** (3.00 mg, 0.004 mmol in 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified

by silica gel chromatography (20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.51** (20.8 mg, 0.047 mmol, 47% yield) in 91:9 *Z:E* ratio (determined by quantitative ^{13}C NMR, relaxation time = 13 s) ratio as colorless oil. **$[\alpha]_D^{20}$** –15.4 (*c* 0.7, MeOH); **IR (neat):** 3312 (br), 3012 (w), 2963 (m), 2934 (s), 2873 (m), 1736 (s), 1652 (s), 1525 (m), 1455 (m), 1366 (m), 1245 (m), 1163 (m), 1016 (m), 873 (m), 806 (m), 698 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 7.42–7.28 (m, 5H), 6.06 (s, 1H), 5.43 (dt, *J* = 10.5, 7.6 Hz, 1H), 5.34 (dt, *J* = 10.5, 7.4 Hz, 1H), 5.11 (s, 2H), 5.08 (s, 1H), 3.86 (dd, *J* = 8.6, 6.4 Hz, 1H), 3.30–3.20 (m, 2H), 2.35 (t, *J* = 7.3 Hz, 2H), 2.18 (q, *J* = 6.9 Hz, 2H), 2.15–2.01 (m, 3H), 1.69 (p, *J* = 7.3 Hz, 2H), 1.43 (s, 9H), 0.93 (d, *J* = 6.7 Hz, 3H), 0.89 (d, *J* = 6.7 Hz, 3H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 173.6, 171.7, 156.0, 136.1, 131.5, 128.7, 128.4, 128.4, 127.2, 79.9, 66.4, 60.2, 39.2, 33.7, 31.0, 28.5, 27.4, 26.7, 24.9, 19.5, 17.9; **HRMS[M+H]$^+$** Calcd for $C_{25}H_{39}O_5N_2$: 447.2859, found: 447.2878.

(*S*,*Z*)-Benzyl 8-(2-((*tert*-butoxycarbonyl)amino)-4-(methylthio)butanamido)oct-5-enoate (1.52). Following the general procedure A, in a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with (*S*)-*tert*-butyl (1-(but-3-en-1-ylamino)-4-(methylthio)-1-oxobutan-2-yl)carbamate (33.9 mg, 0.10 mmol), benzyl hex-5-enoate (61.2 mg, 0.30 mmol), *Z*-butene in THF (24 wt %, 472 mg, 2.02 mmol) and a solution of **Ru-9** (0.76 mg, 0.0010 mmol in 100 μL THF). The vessel was sealed, and the mixture was allowed to stir at 22 °C for 16 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the green oil residue was then charged with a solution of **Ru-9** (3.00 mg, 0.0040 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition

of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (40% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.52** (24.4 mg, 0.051 mmol, 51% yield) in >98:2 *Z:E* ratio as colorless oil. **$[\alpha]_D^{20}$** 17.5 (*c* 0.8, MeOH); **IR (neat):** 3306 (br), 3013 (w), 2972 (m), 2929 (m), 1734 (m), 1656 (s), 1524 (s), 1455 (m), 1366 (m), 1246 (s), 1164 (s), 1025 (s), 752 (m), 698 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 7.41–7.28 (m, 5H), 6.30 (br, 1H), 5.44 (dt, *J* = 10.6, 7.4 Hz, 1H), 5.34 (dt, *J* = 10.6, 7.4 Hz, 1H), 5.28 (br, 1H), 5.11 (s, 2H), 4.22 (br, 1H), 3.32–3.18 (m, 2H), 2.58–2.46 (m, 2H), 2.36 (t, *J* = 7.3 Hz, 2H), 2.24–2.15 (m, 2H), 2.11–2.03 (m, 6H), 1.92–1.85 (m 1H), 1.74–1.66 (m, 2H), 1.43 (s, 9H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 173.6, 171.5, 155.7, 136.1, 131.6, 128.7, 128.4, 128.4, 127.0, 80.1, 66.4, 53.6, 39.2, 33.7, 32.0, 30.4, 28.5, 27.3, 26.7, 24.8, 15.4; **HRMS[M+H]$^+$** Calcd for $C_{25}H_{39}O_5N_2S$: 479.2580, found: 479.2566.

Synthesis of compound 1.55

Dibenzyl (*Z*)-dec-5-enedioate (1.55). In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar is charged with benzyl hex-5-enoate (25.9 mg, 0.127 mmol) and a solution of catechothiolate complex **Ru-9** (2.0 mg, 0.00254 mmol) dissolved in THF (200 μL). The mixture was allowed to stir for 4 hrs at 22 °C, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (20% diethyl ether in hexanes) to afford olefin product **1.55** (6.3 mg, 0.018 mmol, 14% yield) in 77:23 *Z*:*E* ratio as colorless oil. **IR (neat):** 3063 (w), 3032 (w), 2954 (w), 1735 (s), 1497 (m), 1455 (m), 1235 (m), 1213 (m), 1154 (m), 738 (m), 697 (m); **^{1}H NMR (500 MHz, $CDCl_3$) *Z* isomer:** δ 7.39–7.30 (m, 10H), 5.39 (t, *J* = 4.5 Hz, 2H), 5.11 (s, 4H), 2.41−2.37

(m, 8H); **^{13}C NMR (150 MHz, $CDCl_3$) *Z* isomer:** δ 173.0, 136.1, 129.1, 128.7, 128.4, 128.3, 66.4, 34.3, 22.9. **HRMS[M+H]$^+$:** Calcd for $C_{22}H_{25}O_4$: 352.17; found:352.1755.

Preparation of compound 1.57

(*Z*)-(*Z*)-Dodec-10-en-1-yl hept-5-enoate (1.57). In a N_2-filled glove box, a solution of unpurified *Z*-2-butene in THF (27 wt %, 416 mg, 2.00 mmol) was added to an oven-dried vial containing undec-10-en-1-yl hex-5-enoate (**1.56**; 26.6 mg, 0.10 mmol), followed by a THF solution of **Ru-9** (0.76 mg, 0.001 mmol, 250 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The reaction was then quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.57** (26.2 mg, 0.089 mmol, 89% yield) in >98:2 *Z,Z:Z,E* ratio as colorless oil. **IR (neat):** 3014 (m), 2926 (s), 2855 (m), 1737 (s), 1454 (m), 1311 (m), 1238 (m), 1160 (s), 1035 (m), 699 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)** δ 5.54–5.26 (m, 4H), 4.06 (t, *J* = 6.7 Hz, 2H), 2.30 (t, *J* = 7.5 Hz, 2H), 2.08 (q, *J* = 7.3 Hz, 2H), 2.02 (q, *J* = 7.2 Hz, 2H), 1.74–1.66 (m, 2H), 1.64–1.58 (m, 6H), 1.55 (d, *J* = 5.2 Hz, 2H), 1.38–1.26 (m, 12H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 174.0, 131.0, 129.6, 125.0, 123.8, 64.6, 33.9, 29.7, 29.6, 29.60, 29.4, 28.8, 27.0, 26.3, 26.1, 24.9, 12.9; **HRMS[M+H]$^+$** Calcd for $C_{19}H_{35}O_2$: 295.2637, found: 295.2650.

Preparation of compounds 1.59 and 1.60

(*Z*)-Dodec-10-en-1-yl hex-5-enoate (1.59). In a N_2-filled glove box, a solution of unpurified *Z*-2-butene in THF (27 wt %, 10.40 g, 50.10 mmol) was added to an oven-dried vial containing undec-10-en-1-ol (852 mg, 5.00 mmol), followed by a THF solution of **Ru-9** (38.0 mg, 0.050 mmol in 250 μL THF, 1 mol %). The vessel was sealed and the mixture

was allowed to stir for 3 h at 22 °C. The reaction was then quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) to afford (*Z*)-dodec-10-en-1-ol (857.0 mg, 4.65 mmol, 93% yield) in 96:4 *Z*:*E* ratio as colorless oil, which was directly used in the next step. *N*-(3-Dimethylaminopropyl)-*N*'-ethylcarbodiimide hydrochloride (307.0 mg, 1.60 mmol) was added to an oven-dried vial containing (*Z*)-dodec-10-en-1-ol (184.0 mg, 1.00 mmol), hex-5-enoic acid (171.0 mg, 1.50 mmol) and DMAP (22.4 mg, 0.20 mmol) in dried CH_2Cl_2 (5 mL) at 0 °C. The vessel was sealed and the mixture was allowed to stir for 3 h at 22 °C. The reaction was then quenched by the addition of water (10 mL) and washed with Et_2O (20 mL×3). The organic layers were combined and washed with aqueous solution of 1N HCl (10 mL), water (10 mL) and brine (10 mL). The organic layers dried over anhydrous $MgSO_4$ and then filtered. The filtrate was concentrated and purified by silica gel chromatography (1% diethyl ether in hexanes) to afford **1.59** (267.0 mg, 0.095 mmol, 95% yield) as colorless oil. **IR (neat):** 3013 (m), 2925 (s), 2855 (m), 1736 (s), 1456 (m), 1311 (m), 1239 (m), 1160 (s), 1035 (m), 909 (m), 699 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.78 (ddt, *J* = 17.0, 10.3, 6.7 Hz, 1H), 5.50–5.32 (m, 2H), 5.03 (d, *J* = 17.1 Hz, 1H), 4.99 (d, *J* = 10.2 Hz, 1H), 4.06 (t, *J* = 6.7 Hz, 2H), 2.31 (t, *J* = 7.5 Hz, 2H), 2.09 (q, *J* = 7.2 Hz, 2H), 2.02 (q, *J* = 7.1 Hz, 2H), 1.73 (p, *J* = 7.5 Hz, 2H), 1.65–1.58 (m, 5H), 1.38–1.24 (m, 12H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 173.9, 137.9, 131.0, 123.8, 115.5, 64.6, 33.8, 33.2, 29.7, 29.6, 29.6, 29.4, 29.4, 28.8, 27.0, 26.1, 24.3, 12.9. **HRMS[M+H]$^+$** Calcd for $C_{18}H_{33}O_2$: 281.2481, found: 281.2489.

(*Z*)-Undec-10-en-1-yl hept-5-enoate (1.60). *N*-(3-Dimethylaminopropyl)-*N*'-ethylcarbodiimide hydrochloride (307.0 mg, 1.60 mmol) was added to an oven-dried vial containing undec-10-en-1-ol (255.0 mg, 1.50 mmol), *Z*-hept-5-enoic acid (**1.29**, prepared through the procedure described above, 128.0 mg, 1.00 mmol) and DMAP (22.4 mg, 0.20 mmol) in dried DCM (5 mL) at 0 °C. The vessel was sealed and the mixture was allowed to stir for 3 h at 22 °C. The reaction was quenched by the addition of water (10 mL) and washed with Et_2O (20 mL × 3). The organic layers were combined and washed with an aqueous solution of 1N HCl (10 mL), water (10 mL) and brine (10 mL). The organic layers dried over anhydrous $MgSO_4$ and then filtered. The filtrate was concentrated *in vacuo* and purified by silica gel chromatography (1% diethyl ether in hexanes) to afford **1.60** (237 mg, 0.085 mmol, 85% yield) in 98:2 *Z:E* ratio as colorless oil. **IR (neat):** 3012 (m), 2926 (s), 2855 (m), 1736 (s), 1457 (m), 1310 (m), 1253 (m), 1169 (s), 1024 (m), 912 (m), 702 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.81 (ddt, *J* = 17.0, 10.1, 6.6 Hz, 1H), 5.48 (dt, *J* = 13.5, 6.8 Hz, 1H), 5.39–5.32 (m, 1H), 4.99 (d, *J* = 17.1 Hz, 1H), 4.93 (d, *J* = 10.2 Hz, 1H), 4.06 (t, *J* = 6.8 Hz, 2H), 2.30 (t, *J* = 7.5 Hz, 2H), 2.08 (q, *J* = 7.3 Hz, 2H), 2.04 (q, *J* = 7.2 Hz, 2H), 1.69 (p, *J* = 7.4 Hz, 2H), 1.65–1.57 (m, 5H), 1.42–1.24 (m, 12H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 174.0, 139.3, 129.6, 125.0, 114.3, 64.6, 34.0, 33.9, 29.6, 29.5, 29.4, 29.2, 29.1, 28.8, 26.3, 26.1, 24.9, 12.9. **HRMS[M+H]$^+$** Calcd for $C_{18}H_{33}O_2$: 281.2481, found: 281.2476.

1.8.6 Macrocyclic ring-closing metathesis with *Z*-butene as the methylene capping agent

General procedure: In a N_2-filled glove box, a solution of unpurified *Z*-butene in THF was added to an oven-dried vial containing a bis(α)-olefin substrate (1.0 equiv.), followed

by a solution of the appropriate amount of catechothiolate complex **Ru-9** dissolved in THF. The vessel was sealed and the mixture was allowed to stir for 1–12 h at 22 °C. The reaction was monitored by ^{1}H NMR spectroscopy. After >95% conversion (disappearance of bis(α)-olefin), the volatiles were removed *in vacuo* and the resulting black residue was dissolved in THF and a solution of the appropriate amount of **Ru-9** in THF was added. The system was placed under 400 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 12–48 h at 35 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. Purification was performed by silica gel chromatography.

(*Z*)-Oxacyclohexadec-6-en-2-one (1.58). Following the general procedure, in a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (27 wt %, 416 mg, 2.01 mmol) was added to an oven-dried vial containing undec-10-en-1-yl hex-5-enoate (**1.56**, 26.6 mg, 0.10 mmol), followed by a THF solution of **Ru-9** (0.76 mg, 0.0010 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green residue was dissolved in THF (19.5 mL) and a solution of **Ru-9** (3.00 mg, 0.004 mmol, 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.58** (13.4 mg, 0.056 mmol, 56% yield) in 96:4 *Z*:*E* ratio as colorless oil. **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.51–5.25 (m, 2H), 4.15 (t, *J* = 5.5 Hz, 2H), 2.38–2.32 (m, 2H), 2.13-2.01 (4H, m), 1.78–

1.51 (m, 4H), 1.49–1.24 (m, 12H). **HRMS[M+H]$^+$** Calcd for $C_{15}H_{27}O_2$: 239.2006, found: 239.2011. The characterization data are consistent with those previously reported.[62]

(*Z*)-Oxacyclotetradec-9-en-2-one (1.61). Following the general procedure, in a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (33 wt %, 342 mg, 2.02 mmol) was added to an oven-dried vial containing hex-5-en-1-yl non-8-enoate (23.8 mg, 0.10 mmol), followed by a THF solution of **Ru-9** (0.76 mg, 0.0010 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green residue was dissolved in THF (19.5 mL) and a solution of **Ru-9** (3.00 mg, 0.0040 mmol, 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.61** (14.2 mg, 0.067 mmol, 67% yield) in 98:2 *Z:E* ratio as colorless oil. **IR (neat):** 3001 (m), 2925 (m), 2858 (m), 1733 (s), 1456 (m), 1249 (s), 1085 (m), 990 (m), 896 (m), 713 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.48 (*J* = 10.8, 7.8 Hz, 1H), 5.27 (dt, *J* = 10.8, 7.9 Hz, 1H), 4.14 (t, *J* = 5.8 Hz, 2H), 2.42–2.32 (m, 2H), 2.10–1.93 (m, 4H), 1.81–1.70 (m, 2H), 1.69–1.58 (m, 2H), 1.51–1.36 (m, 4H), 1.33–1.22 (m, 4H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 174.0, 129.9, 129.9, 62.7, 35.5, 27.7, 27.6, 27.2, 26.8, 26.0, 25.7, 25.5, 24.8. **HRMS[M+H]$^+$** Calcd for $C_{13}H_{23}O_2$: 211.1698, found: 211.1699.

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(62) Yu, M.; Wang, C.; Kyle, A. F.; Jakubec, P.; Dixon, D. J.; Schrock, R. R.; Hoveyda, A. H. *Nature* **2011**, *479*, 88–93.

(*Z*)-Oxacyclopentadec-7-en-2-one (1.62). Following the general procedure, in a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (33 wt %, 342 mg, 2.02 mmol) was added to an oven-dried vial containing non-8-en-1-yl hept-6-enoate (25.2 mg, 0.10 mmol), followed by a THF solution of **Ru-9** (0.76 mg, 0.0010 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green residue was dissolved in THF (19.5 mL) and a solution of **Ru-9** (3.00 mg, 0.0040 mmol, 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.62** (15.1 mg, 0.067 mmol, 67% yield) in 98:2 *Z:E* ratio as colorless oil. **IR (neat):** 3005 (m), 2927 (m), 2857 (m), 1732 (s), 1459 (m), 1232 (m), 1144 (m), 1061 (m), 969 (w), 719 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.41 (dt, *J* = 10.8, 7.5 Hz, 1H), 5.35 (dt, *J* = 10.8, 7.4 Hz, 1H), 4.14 (t, *J* = 5.3 Hz, 2H), 2.34 (t, *J* = 6.7 Hz, 2H), 2.01 (q, *J* = 7.6 Hz, 4H), 1.75–1.61 (m, 4H), 1.45–1.30 (m, 10H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 174.1, 130.8, 129.2, 64.3, 34.5, 29.4, 28.2, 28.0, 27.2, 27.2, 27.0, 25.6, 25.5, 25.3. **HRMS[M+H]$^+$** Calcd for $C_{14}H_{25}O_2$: 225.1855, found: 225.1866.

(*Z*)-Oxacyclohexadec-11-en-2-one (1.63). Following the general procedure, in a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (33 wt %, 342 mg, 2.02 mmol) was added to an oven-dried vial containing hex-5-en-1-yl undec-10-enoate (26.6 mg, 0.10 mmol), followed by a THF solution of **Ru-9** (0.76 mg, 0.0010 mmol, 100 μL THF). The

vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green residue was dissolved in THF (19.5 mL) and a solution of **Ru-9** (3.00 mg, 0.0040 mmol, 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) and filtered through a plug of activated charcoal to afford **1.63** (16.6 mg, 0.070 mmol, 70% yield) in 98:2 *Z:E* ratio as colorless oil. **^{1}H NMR (500 MHz, $CDCl_3$):** δ 5.45–5.30 (m, 2H), 4.14 (t, *J* = 6.3 Hz, 2H), 2.41–2.27 (m, 2H), 2.10–2.01 (m, 4H), 1.68–1.63 (m, 4H), 1.46–1.37 (m, 2H), 1.37–1.19 (m, 10H); **HRMS[M+H]$^+$** Calcd for $C_{15}H_{27}O_2$: 239.2011, found: 239.2000. The characterization data are consistent with those reported previously.[63]

(*Z*)-Azacyclohexadec-6-en-2-one (1.64). Following the general procedure, in a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (33 wt %, 342 mg, 2.02 mmol) was added to an oven-dried vial containing *N*-(undec-10-en-1-yl)hex-5-enamide (25.1 mg, 0.10 mmol), followed by a THF solution of **Ru-9** (0.76 mg, 0.0010 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green residue was dissolved in THF (19.5 mL) and a solution of **Ru-9** (3.00 mg, 0.0040 mmol, 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum, after which the reaction was quenched by

(63) Fürstner, A.; Langemann, K. *J. Org. Chem.* **1996**, *61*, 3942–3943.

the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (25% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.64** (12.3 mg, 0.055 mmol, 55% yield) in 98:2 *Z:E* selectivity as white solid. **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.53 (br, 1H), 5.42–5.28 (m, 2H), 3.34 (dt, *J* = 6.0, 5.6 Hz, 2H), 2.22–2.18 (m, 2H), 2.12–2.06 (m, 2H), 2.05–1.98 (m, 2H), 1.77–1.65 (m, 2H), 1.56–1.43 (m, 2H), 1.43–1.25 (m, 12H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 172.9, 130.9, 129.1, 39.1, 36.5, 29.1, 27.8, 27.5, 27.4, 26.7, 26.6, 26.3, 26.0, 25.9, 25.7; **HRMS[M+H]$^+$** Calcd for $C_{15}H_{28}ON$: 238.2171, found: 238.2174. The characterization data are consistent with those previously reported.[64]

(*Z*)-Cycloheptadec-9-enol (1.65). Following the general procedure, in a N_2-filled glove box, a solution of unpurified *Z*-2-butene in THF (33 wt %, 342 mg, 2.02 mmol) was added to an oven-dried vial containing nonadeca-1,18-dien-10-ol (29.4 mg, 0.10 mmol), followed by a THF solution of **Ru-9** (0.76 mg, 0.0010 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green residue was dissolved in THF (19.5 mL) and a solution of **Ru-9** (4.9 mg, 0.0065 mmol in 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (20% ethyl acetate in hexanes) and

(64) Wang, C.; Yu, M.; Kyle, A. F.; Jakubec, P.; Dixon, D. J.; Schrock, R. R.; Hoveyda, A. H. *Chem. Eur. J.* **2013**, *19*, 2726–2740.

filtered through a small plug of activated charcoal to afford **1.65** (14.1 mg, 0.053 mmol, 53% yield) in 96:4 *Z:E* selectivity (determined by quantitative ^{13}C NMR, relaxation time = 13 s) as white solid. **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.38–5.29 (m, 2H), 3.72 (p, *J* = 6.0 Hz, 1H), 2.15–1.95 (m, 4H), 1.60–1.40 (m, 4H), 1.39–1.22 (m, 21H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 130.3, 70.6, 35.8, 29.2, 28.3, 28.1, 28.0, 26.9, 23.6. **HRMS[M-H_2O+H]$^+$** Calcd for $C_{17}H_{31}$: 235.2426, found: 235.2424. The characterization data are consistent with those reportedpreviously[7].

(*Z*)-Oxacyclononadec-9-en-2-one (1.66). Following the general procedure, in a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (33 wt %, 342 mg, 2.02 mmol) was added to an oven-dried vial containing undec-10-en-1-yl non-8-enoate (30.8 mg, 0.10 mmol), followed by a THF solution of **Ru-9** (0.76 mg, 0.0010 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green residue was dissolved in THF (19.5 mL) and a solution of **Ru-9** (3.00 mg, 0.0040 mmol in 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.66** (18.2 mg, 0.065 mmol, 65% yield) in 96:4 *Z*:*E* ratio as colorless oil. **IR (neat):** 3002 (m), 2927 (s), 2855 (s), 1736 (s), 1461 (m), 1345 (w), 1248 (m), 1081 (m), 718 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.44–5.26 (m, 2H), 4.12 (t, *J* = 5.6 Hz, 2H), 2.32 (t, *J* = 6.9 Hz, 2H), 2.05–1.95 (m, 4H), 1.71–1.57 (m, 4H), 1.46–1.22 (m, 18H). **^{13}C NMR (150 MHz, $CDCl_3$):**

δ 174.2, 130.3, 130.0, 64.3, 34.8, 29.8, 29.3, 29.2, 29.0, 28.9, 28.7, 28.1, 28.0, 27.3, 26.2, 26.1, 25.5. **HRMS[M+H]$^+$** Calcd for $C_{18}H_{33}O_2$: 281.2481, found: 281.2493.

(*Z*)-Oxacyclohenicos-11-en-2-one (1.67). Following the general procedure, in a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (33 wt %, 342 mg, 2.02 mmol) was added to an oven-dried vial containing undec-10-en-1-yl undec-10-enoate (33.4 mg, 0.10 mmol), followed by a THF solution of **Ru-9** (0.76 mg, 0.0010 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green residue was dissolved in THF (19.5 mL) and a solution of **Ru-9** (3.00 mg, 0.0040 mmol, 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.67** (18.3 mg, 0.060 mmol, 60% yield) in 96:4 *Z*:*E* ratio as colorless oil. **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.45–5.30 (m, 2H), 4.11 (t, *J* = 5.7 Hz, 2H), 2.31 (t, *J* = 6.9 Hz, 2H), 2.09–1.94 (m, 4H), 1.72–1.58 (m, 4H), 1.43–1.24 (m, 22H); **HRMS[M+H]$^+$** Calcd for $C_{20}H_{37}O_2$: 309.2794, found: 309.2807. The characterization data are consistent with those reported previously.[65]

(*Z*)-Azacyclohenicos-11-en-2-one (1.68). Following the general procedure, in a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (33 wt %, 342 mg, 2.02 mmol) was added to an oven-dried vial containing *N*-(undec-10-en-1-yl)undec-10-enamide (33.5 mg,

(65) Litinas, K. E.; Salteris, B. E. *J. Chem. Soc., Perkin Trans. 1* **1997**, 2869−2872.

0.10 mmol), followed by a THF solution of **Ru-9** (0.76 mg, 0.0010 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green oil residue was dissolved in THF (19.5 mL) and a solution of **Ru-9** (3.00 mg, 0.0040 mmol, 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (25% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.68** (17.6 mg, 0.057 mmol, 57% yield) in 98:2 *Z*:*E* selectivity as white solid. **IR (neat):** 3287 (br), 3087 (m), 3002 (m), 2922 (s), 2852 (s), 1639 (s), 1556 (s), 1465 (m), 1436 (m), 1355 (m), 1278 (w), 721 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.49 (s, 1H), 5.39–5.30 (m, 2H), 3.28 (q, *J* = 5.9 Hz, 2H), 2.16 (t, *J* = 6.6 Hz, 2H), 2.04–1.95 (m, 4H), 1.67–1.59 (m, 2H), 1.50–1.47 (m, 2H), 1.40–1.22 (m, 22H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 173.3, 130.3, 130.1, 39.4, 37.3, 29.6, 29.5, 29.4, 29.1, 29.1, 29.0, 28.7, 28.7, 28.6, 26.8, 26.7, 26.6, 26.1. **HRMS[M+H]$^+$** Calcd for $C_{20}H_{38}ON$: 308.2953, found: 308.2953.

(*Z*)-2-(2-Oxoazacyclohenicos-11-en-1-yl)acetic acid (1.69). Following the general procedure for MRCM reaction, in a N_2-filled glove box, a solution of unpurified *Z*-butene (**3**) in THF (33 wt %, 342 mg, 2.02 mmol) was added to an oven-dried vial containing 2-(*N*-(undec-10-en-1-yl)undec-10-enamido)acetic acid (19.7 mg, 0.050 mmol), followed by a THF solution of **Ru-9** (0.38 mg, 0.00050 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green residue was dissolved in THF (9.5 mL) and a solution of **Ru-9** (1.50

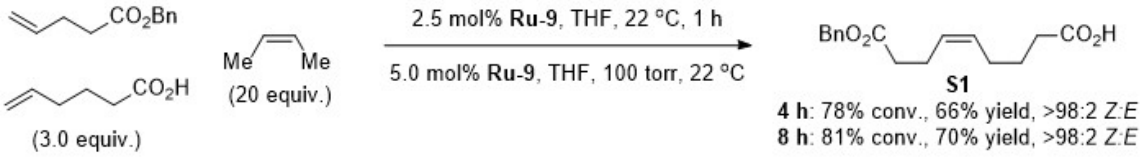
mg, 0.0020 mmol, 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (dichloromethane/MeOH/AcOH: 200/4/1) and filtered through a small plug of activated charcoal to afford **1.69** (7.5 mg, 0.020 mmol, 40% yield) in 97:3 *Z*:*E* ratio as colorless oil. **IR (neat):** 3000 (m), 2919 (s), 2851 (s), 1723 (m), 1585 (s), 1463 (m), 1251 (s), 1092 (w), 874 (w), 723 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 9.81 (br, 1H), 5.40□5.26 (m, 2H), 4.05 (s, 2H), 3.33 (t, *J* = 7.7 Hz 2H), 2.38 (*J* = 7.6 Hz 2H), 2.03 (q, *J* = 6.1 Hz, 4H), 1.77–1.53 (m, 4H), 1.40–1.20 (m, 22H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 175.3, 172.8, 130.2, 130.2, 49.9, 49.1, 32.6, 29.5, 29.5, 29.5, 29.2, 29.1, 29.0, 28.9, 28.7, 28.3, 27.1, 27.0, 26.3, 25.4; **HRMS[M+H]$^+$** Calcd for $C_{22}H_{40}O_3N$: 366.3008, found: 366.3022.

Macrocyclic ring-closing metathesis of compound 1.58 in the presence of 4-acetylbenzaldehyde: In a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (24 wt %, 236 mg, 1.01 mmol) was added to an oven-dried vial containing undec-10-en-1-yl hex-5-enoate (**1.56**, 13.3 mg, 0.050 mmol) and 4-acetylbenzaldehyde (**1.70**, 7.4 mg, 0.050 mmol), followed by a THF solution of **Ru-9** (0.38 mg, 0.00050 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green residue was dissolved in THF (9.5 mL) and a solution of **Ru-9** (1.50 mg, 0.0020 mmol, 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 22 °C under vacuum, after which the reaction was quenched by

the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) to afford macrocyclic olefin product **1.58** (6.0 mg, 0.025 mmol, 50% yield) in 98:2 *Z*:*E* ratio as colorless oil.

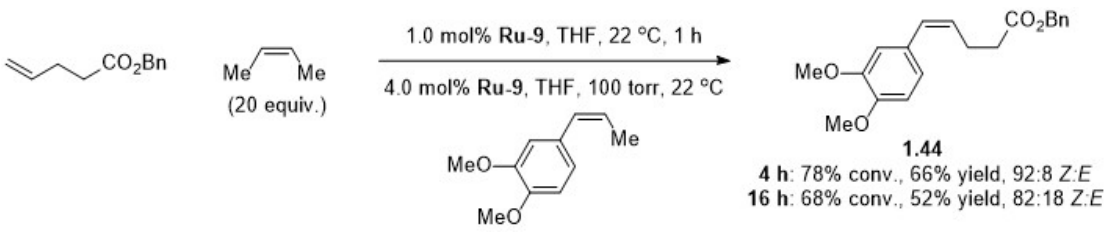
1.8.7 Influence of time on *Z* selectivity

a. Influence of time on *Z* selectivity in homocoupling and cross-metathesis



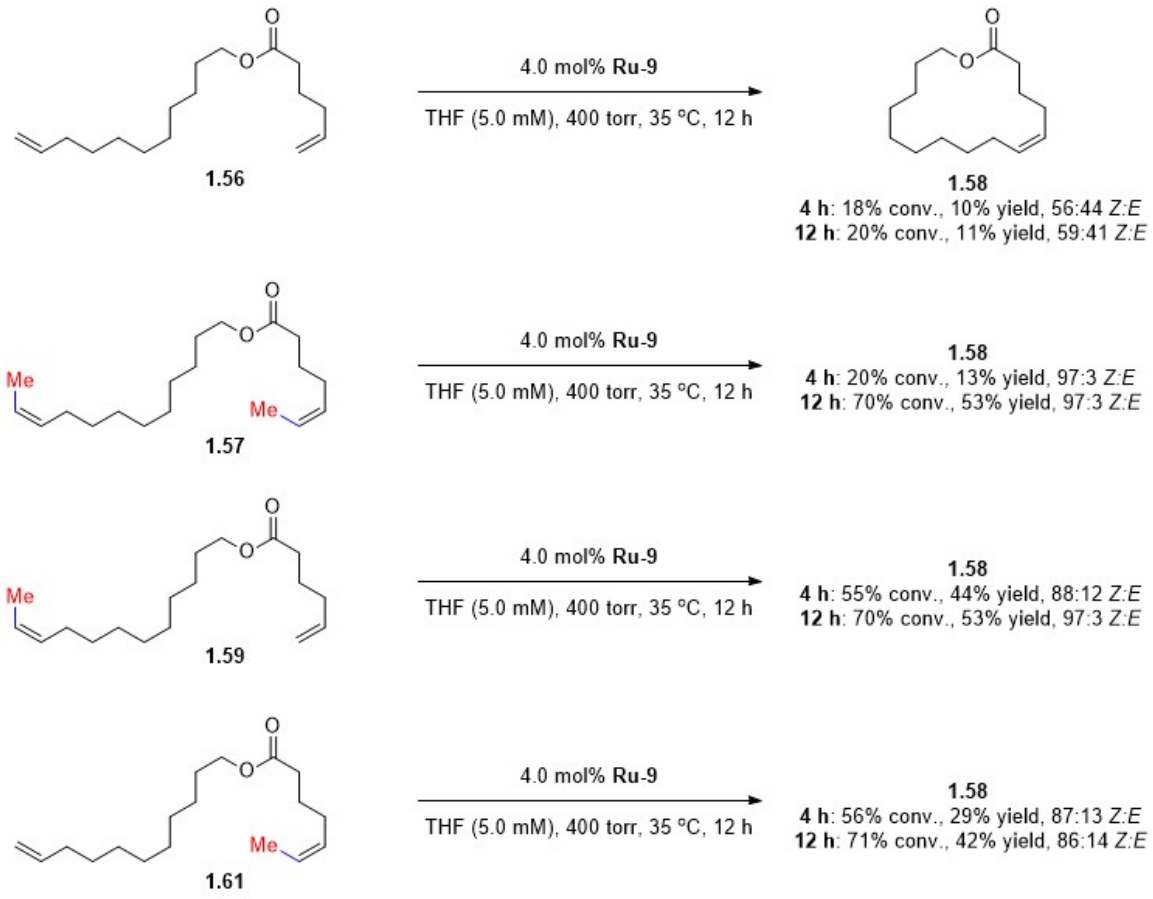
(*Z*)-9-(Benzyloxy)-9-oxonon-5-enoic acid (S1). Following the general procedure A, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with benzyl pent-4-enoate (25.4 mg, 0.127 mmol) and hex-5-enoic acid (43.5 mg, 0.38 mmol), unpurified *Z*-butene in THF (22 wt %, 650 mg, 2.54 mmol) and a THF solution (200 μL) of **Ru-9** (1.0 mg, 0.00127 mmol). The vessel was sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr for 2 mins). The flask containing the residue was then charged with a solution of **Ru-9** (3.9 mg, 0.00508 mmol) in THF (200 μL) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 8 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford the desired product **S1** (24.6 mg, 0.089 mmol, 70% yield) in >98:2 *Z*:*E* ratio as colorless oil. **IR (neat):** 3009 (m), 2926 (s), 1734 (s), 1703 (s), 1498 (m), 1455 (m), 1381 (m), 1237 (m), 1148 (s), 958 (m), 697 (m) cm^{-1}; **^{1}H NMR**

(400 MHz, $CDCl_3$): δ 7.45–7.28 (m, 5H), 5.49–5.27 (m, 2H), 5.12 (s, 2H), 2.46–2.29 (m, 6H), 2.14–2.07 (m, 2H), 1.69 (p, *J* = 7.5 Hz, 2H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 179.7, 173.1, 136.1, 130.1, 128.8, 128.7, 128.4, 128.3, 66.4, 34.4, 33.5, 26.6, 24.6, 22.9; **HRMS[M+H]$^+$:** Calcd for $C_{16}H_{21}O_4$: 277.1440, Found: 277.1452.



(*Z*)-Benzyl 5-(3,4-dimethoxyphenyl)pent-4-enoate (1.44). Following the general procedure 2, in a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with benzyl pent-4-enoate (28.5 mg, 0.050 mmol) and *Z*-2-butene (**3**) in THF (24 wt %, 236 mg, 1.01 mmol) and a solution of **Ru-9** (0.38 mg, 0.0005 mmol in 100 μL THF). The vessel was sealed, and the mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with (*Z*)-1,2-dimethoxy-4-(prop-1-en-1-yl)benzene (8.9 mg, 0.05 mmol), followed by a solution of **Ru-9** (1.50 mg, 0.002 mmol, 200 μL THF) and the system was placed under 100 torr of vacuum generated from a diaphragm pump. The solution was allowed to stir for 16 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting dark oil residue was purified by silica gel chromatography (5% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford olefin product **1.44** (8.5 mg, 0.026 mmol, 52% yield) in 82:18 *Z:E* ratio as colorless oil.

b. Influence of time on *Z* selectivity in macrocyclic ring-closing metathesis



In a N_2-filled glove box, a THF solution of **Ru-9** (1.50 mg, 0.0020 mmol in 500 μL THF) was added to an oven-dried vial containing **1.56** (0.05 mmol) and THF (9.50 mL). The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was dissolved in $CDCl_3$ and subjected to ^1H NMR analysis. Conversion refers to the disappearance of the starting material; yield refers to the conversion to macrocyclic alkene **1.58**.

1.8.8 Stereoselective synthesis of compound 1.73

(*Z*)-3-(Prop-1-en-1-yl)benzaldehyde (1.77). In a N_2-filled glove box, to a solution of 3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzaldehyde (464.0 mg, 2.00 mmol), was

added (*Z*)-1-bromoprop-1-ene (290.0 mg, 2.40 mmol), *tetra-n*-butylammonium bromide (TBAB, 772.0 mg, 2.40 mmol, 10 mL toluene) and $Pd(PPh_4)_3$ (46.0 mg, 0.040 mmol), followed by an aqueous solution of KOH (3 M, 2.2 mL, 6.6 mmol) . The vessel was sealed and the mixture was allowed to stir for 3 h at 80 °C in the dark. The solution was passed through a pad of celite with ether as eluent. The filtrate was concentrated *in vacuo* and the resulting brown oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) to afford (*Z*)-3-(prop-1-en-1-yl)benzaldehyde (**1.77**, 234.0 mg, 1.60 mmol, 80% yield) as colorless oil. **IR (neat):** 2981 (m), 2936 (m), 2829 (m), 2732 (m), 1696 (s), 1604 (m), 1483 (m), 1447 (m), 1377 (m), 1275 (m), 1187 (m), 801 (m), 753 (m), 692 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 10.00 (s, 1H), 7.77 (s, 1H), 7.72 (d, *J* = 7.5 Hz, 1H), 7.53 (d, *J* = 7.6 Hz, 1H), 7.48 (t, *J* = 7.6 Hz, 1H), 6.46 (d, *J* = 11.6 Hz, 1H), 5.88 (dq, *J* = 11.6, 7.2 Hz, 1H), 1.90 (dd, *J* = 7.2, 1.7 Hz, 3H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 192.4, 138.6, 136.5, 134.8, 129.9, 128.9, 128.6, 128.6, 127.8, 14.66; **HRMS[M+H]$^+$** Calcd for $C_{10}H_{11}O$: 147.0810, found: 147.0808.

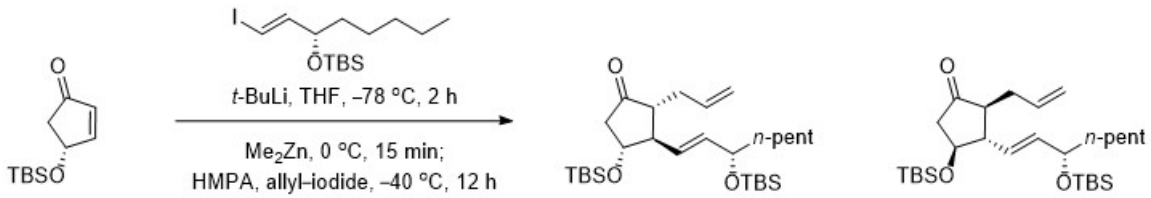
(*Z*)-1-(3-(Prop-1-en-1-yl)phenyl)hexan-1-ol (1.78). Under N_2 protection, a frame-dried flask was charged with Mg turnings (41.0 mg, 1.71 mmol) in THF (5 mL), followed by $BrCH_2CH_2Br$ (13.2 mg, 0.050 mmol). After 2 minutes, *n*-$C_5H_{11}Br$ (211.0 mg, 1.40 mmol) in THF (3 mL) was added slowly via a syringe under reflux. The mixture was refluxed for 2 hours, and then cooled to –78 °C. (Z)-3-(prop-1-en-1-yl)benzaldehyde **1.73** (102.2 mg, 0.70 mmol) in THF (3 mL) was added. The mixture was allowed to warm to 0 °C within 1 h, after which the reaction was quenched with brine and washed with Et_2O (20 mL × 3). The organic layers were dried over anhydrous $MgSO_4$ and then filtered. The filtrate was concentrated and the resulting colorless oil residue and purified by silica gel

chromatography (5% ethyl acetate in hexanes) to afford **1.78** (134.2 mg, 0.62 mmol, 88% yield) as colorless oil. **IR (neat):** 3428 (br), 3016 (s), 2954 (m), 2930 (s), 2858 (m), 1602 (w), 1483 (m), 1402 (m), 1367 (m), 1112 (m), 1054 (m), 897 (s), 804 (m), 702 (s) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.32 (t, *J* = 7.6 Hz, 1H), 7.27 (s, 1H), 7.22 (d, *J* = 7.2 Hz, 1H), 7.20 (d, *J* = 7.3 Hz, 1H), 6.44 (d, *J* = 11.6 Hz, 1H), 5.80 (dq, *J* = 11.6, 7.2 Hz, 1H), 4.67 (t, *J* = 5.5 Hz, 1H), 1.90 (dd, *J* = 7.2, 1.8 Hz, 3H), 1.86–1.64 (m, 3H), 1.47–1.37 (m, 1H), 1.35–1.25 (m, 5H), 0.87 (t, *J* = 6.9 Hz, 3H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 145.0, 137.9, 130.0, 128.4, 128.1, 127.1, 126.6, 124.2, 74.9, 39.2, 31.9, 25.7, 22.7, 14.8, 14.2; **HRMS[M-H_2O+H]$^+$** Calcd for $C_{15}H_{21}$: 201.1643, found: 201.1634.

(*Z*)-Methyl 6-(3-(1-hydroxyhexyl)phenyl)hex-5-enoate (1.73). Following general procedure B (see above), in a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with the methyl hex-5-enoate (19.2 mg, 0.15 mmol), unpurified *Z*-butene in THF (17 wt %, 334 mg, 1.01 mmol), followed by a THF solution of **Ru-9** (0.38 mg, 0.00050 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo*, and the vial containing the residue was charged (*Z*)-1-(3-(prop-1-en-1-yl)phenyl)hexan-1-ol (10.9 mg, 0.050 mmol), followed by a THF solution of **Ru-9** (1.50 mg, 0.00020 mmol, 200 μL THF) and the mixture was placed under 100 torr of vacuum generated from a diaphragm pump. The solution was allowed to stir for 4 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. Purification of the dark oil residue by silica gel chromatography (5% ethyl acetate in hexanes) afforded **1.73** (8.5 mg, 0.028 mmol, 56% yield) in 96:4 *Z*:*E* ratio as colorless oil. **IR (neat):** 3435 (br), 3008 (m), 2952 (m), 2930 (s), 2858 (m), 1737 (s),

1483 (m), 1457 (m), 1367 (m), 1117 (m), 1055 (m), 899 (m), 806 (m), 704 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.30 (t, *J* = 7.6 Hz, 1H), 7.26 (s, 1H), 7.19 (d, *J* = 7.7 Hz, 1H), 7.16 (d, *J* = 7.6 Hz, 1H), 6.46 (d, *J* = 11.7 Hz, 1H), 5.64 (dt, *J* = 11.7, 7.4 Hz, 1H), 4.66 (t, *J* = 5.8 Hz, 1H), 3.64 (s, 3H), 2.36 (t, *J* = 7.4 Hz, 2H), 2.34 (t, *J* = 7.4 Hz, 2H), 2.04 (br, 1H), 1.89–1.63 (m, 4H), 1.48–1.40 (m, 1H), 1.34–1.26 (m, 5H), 0.87 (t, *J* = 7.0 Hz, 3H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 174.1, 145.1, 137.7, 131.8, 129.9, 128.4, 127.9, 126.4, 124.4, 74.8, 51.7, 39.2, 33.6, 31.9, 28.1, 25.7, 25.1, 22.7, 14.2; **HRMS[M-H_2O+H]$^+$** Calcd for $C_{19}H_{27}O_2$: 287.2011, found: 287.1999.

1.8.9 Stereoselective synthesis of prostaglandins E_2 and $F_{2\alpha}$



S2

(2*R*,3*R*,4*R*)-2-allyl-4-((*tert*-butyldimethylsilyl)oxy)-3-((*S*,*E*)-3-((*tert*-butyldimethylsilyl)oxy)oct-1-en-1-yl)cyclopentan-1-one & (2*S*,3*S*,4*S*)-2-allyl-4-((*tert*-butyldimethylsilyl)oxy)-3-((*S*,*E*)-3-((*tert*-butyldimethylsilyl)oxy)oct-1-en-1-yl)cyclopentan-1-one (S2). To a solution of (*S*,*E*)-*tert*-butyl((1-iodooct-1-en-3-yl)oxy)dimethylsilane (276.0 mg, 0.75 mmol) in THF (1.2 mL) was added *t*-BuLi (1.7 M, THF, 0.88 mL, 1.50 mmol) at –78 °C. The mixture was allowed to stir for 2 h after which Me_2Zn (2.0 M, toluene, 0.38 mL, 0.76 mmol) was added. The mixture was allowed to warm to and stir at 0 °C for 30 min, after which it was allowed to cool to –78 °C. A solution of *rac*-4-((*tert*-butyldimethylsilyl)oxy)cyclopent-2-en-1-one (106.0 mg, 0.5 mmol) in THF (0.8 mL) was slowly added to the mixture by the use of a syringe pump within an hour (–

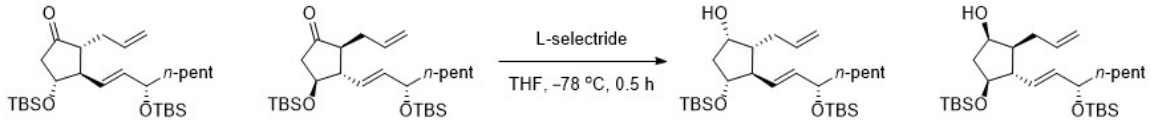
78 °C). HMPA (0.56 mL) and allyl iodide (0.15 mL) were then added, and the mixture was allowed to stir at –40 °C for an additional 18 h. At this time, the reaction was quenched by addition of a saturated solution of NH_4Cl after which it was washed with ethyl acetate (20 mL × 3). The organic layers were combined and washed with brine, dried over anhydrous $MgSO_4$, concentrated *in vacuo* and the resulting yellow oil purified by silica gel chromatography (1% ethyl acetate in hexanes) to afford **S2** (168.0 mg, 68% yield) as colorless oil (mixture of diastereomers). The isomers were inseparable by silica gel chromatography and used directly in the next step. **IR (neat):** 2955 (m), 2929 (m), 2856 (m), 1746 (m), 1471 (m), 1462 (m), 1361 (m), 1250 (m), 1112 (m), 1004 (m), 967 (m), 937 (m), 877 (s), 733 (s), 668 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.79−5.66 (m, 2H), 5.63−5.37 (m, 4H), 5.04−5.00 (m, 4H), 4.14−4.00 (m, 4H), 2.63 (dd, J = 18.2, 6.9 Hz, 2H), 2.56−2.40 (m, 4H), 2.33−2.22 (m, 2H), 2.20−2.11 (m, 2H), 2.10−2.00 (m, 2H), 1.58−1.38 (m, 4H), 1.41−1.19 (m, 12H), 0.94−0.83 (m, 42H), 0.05−0.02 (m, 24H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 215.5, 215.4, 137.3, 136.7, 135.2, 135.0, 129.0, 128.6, 117.6, 117.4, 73.5, 73.4, 73.3, 72.9, 53.6, 52.5, 52.4, 47.9, 47.8, 38.7, 38.6, 32.0, 32.0, 32.0, 31.8, 26.0, 25.9, 25.9, 25.9, 25.2, 24.9, 22.8, 18.4, 18.2, 18.1, 14.2, 14.2, −4.1, −4.1, −4.4, −4.5, −4.5, −4.5, −4.6, −4.6; **HRMS[M+NH_4]$^+$** Calcd for $C_{28}H_{58}O_3Si_2N$: 512.3955; found: 512.3968.

(2*R*,3*R*,4*R*)-2-Allyl-4-hydroxy-3-((*S*,*E*)-3-hydroxyoct-1-en-1-yl)cyclopentan-1-one (1.79). To the solution of **S2** (32.4 mg, 0.070 mmol) in CH_3CN (1.5 mL) was added hydrogen fluoride pyridine (70%, 0.3 mL) at 22 °C and the mixture was allowed to stir for 15 min. The reaction was quenched by the addition of a saturated solution of $NaHCO_3$ and washed with ethyl acetate (10 mL × 3). The organic layers were combined and washed with brine, dried over anhydrous Na_2SO_4, concentrated and purified by silica gel

chromatography (50% ethyl acetate in hexanes) to afford **1.79** (8.0 mg, 46% yield) as colorless oil. Note: the two diastereomers were separated by silica gel chromatography at this stage. **$[\alpha]_D^{22}$** –78.3 (*c* 0.59, $CHCl_3$); **IR (neat):** 3374 (br), 2955 (m), 2927 (m), 2857 (m), 1736 (s), 1604 (w), 1458 (m), 1334 (m), 1259 (m), 1160 (m), 1073 (s), 1002 (m), 968 (s), 914 (s) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.77–5.59 (m, 2H), 5.51 (dd, *J* = 15.3, 8.8 Hz, 1H), 5.07–4.98 (m, 2H), 4.18–3.98 (m, 2H), 3.48 (br, 1H), 2.74 (ddd, *J* = 18.5, 7.5, 1.2 Hz, 1H), 2.55–2.35 (m, 3H), 2.34–2.25 (m, 1H), 2.19 (dd, *J* = 18.6, 9.8 Hz, 1H), 2.14–2.06 (m, 1H), 1.67–1.44 (m, 2H), 1.36−1.25 (m, 6H), 0.96–0.85 (t, *J* = 6.8 Hz, 3H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 213.9, 137.2, 134.8, 131.6, 117.7, 73.3, 72.0, 54.3, 53.8, 46.1, 37.5, 31.8, 31.6, 25.3, 22.8, 14.2; **HRMS[M□H_2O+H]$^+$** Calcd for $C_{16}H_{25}O_2$: 249.1855, found: 249.1865.

Prostaglandin E_2. In a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (22 wt %, 184.0 mg, 0.72 mmol) was added to an oven-dried vial containing (2*R*,3*R*,4*R*)-2-allyl-4-hydroxy-3-((*S*,*E*)-3-hydroxyoct-1-en-1-yl)cyclopentanone **1.79** (9.6 mg, 0.036 mmol), followed by a THF solution of **Ru-9** (0.54 mg, 0.00072 mmol in 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 16 h at 22 °C. In another oven-dried vial, a mixture of *Z*-butene in THF (22 wt %, 184.0 mg, 0.72 mmol), hex-5-enoic acid (**1.28**, 12.3 mg, 0.11 mmol) and **Ru-9** (0.27 mg, 0.00036 mmol, 100 μL THF) was allowed to stir for 1 h at 22 °C. The mixtures were combined and the volatiles were removed *in vacuo*. To the resulting green oil was added a solution of **Ru-9** (4.1 mg, 0.0054 mmol, 200 μL THF). The vessel was then connected to a 100 torr vacuum generated from a diaphragm pump, and the solution was allowed to stir for 1 h at 22 °C under 100 torr, and then for 7 h under 400 torr. At this time, the reaction was quenched by the addition of wet

(undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (dichloromethane/MeOH/AcOH (v/v/v 200/2/1)) and filtered through a plug of activated charcoal with ethyl acetate as eluent to afford prostaglandin E_2 (6.4 mg, 0.0182 mmol, 51% yield) in >98:2 *Z:E* ratio as off-white solid. **$[\alpha]_D^{20}$** –60.0 (*c* 0.15, EtOH); **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.68 (dd, *J* = 15.4, 6.5 Hz, 1H), 5.58 (dd, *J* = 15.3, 8.2 Hz, 1H), 5.47–5.34 (m, 2H), 4.20–4.10 (m, 1H), 4.05 (dd, *J* = 16.7, 9.5 Hz, 1H), 2.75 (dd, *J* = 17.9, 7.3 Hz, 1H), 2.47–1.93 (m, 9H), 1.82–1.43 (m, 4H), 1.40–1.20 (m, 6H), 0.89 (t, *J* = 6.6 Hz, 3H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 214.4, 177.6, 136.7, 130.9, 126.9, 73.2, 72.5, 54.6, 53.6, 46.4, 37.2, 33.2, 31.8, 26.4, 25.4, 25.3, 24.6, 22.8, 14.2; [note: two olefin carbon signals overlap at 130.9 ppm]; **HRMS[M-H_2O+H]$^+$** Calcd for $C_{20}H_{31}O_4$: 335.2222, found: 335.2231. The characterization data are consistent with those of commercially available prostaglandin E_2 (Aldrich) and those reported previously.[66]



S2 **S3**

(1*S*,2*R*,3*R*,4*R*)-2-allyl-4-((*tert*-butyldimethylsilyl)oxy)-3-((*S*,*E*)-3-((*tert*-butyldimethylsilyl)oxy)oct-1-en-1-yl)cyclopentan-1-ol & **(1*R*,2*S*,3*S*,4*S*)-2-allyl-4-((*tert*-butyldimethylsilyl)oxy)-3-((*S*,*E*)-3-((*tert*-butyldimethylsilyl)oxy)oct-1-en-1-yl)cyclopentan-1-ol (S3).** To compound **S2** (40.9 mg, 0.080 mmol) in THF (2.0 mL) was added L-selectride (1M in THF, 0.12 mL) at –78 °C and the resulting mixture was allowed to stir for 30 min. The reaction was quenched by addition of a saturated solution of NH_4Cl

(66) Zanoni, G.; Valli, M.; Bendjeddou, L.; Porta, A.; Bruno, P.; Vidari, G. *J. Org. Chem.*, **2010**, *75*, 8311–8314.

and washed with ethyl acetate (10 mL × 3). The organic layers were combined, washed with brine, dried with anhydrous Na_2SO_4, concentrated *in vacuo* and the resulting brown oil residue purified by silica gel chromatography (1% ethyl acetate in hexanes) to afford **S3** (39.0 mg, 95% yield) as a colorless oil (mixture of diastereoisomers). The diastereoisomers could not be separated by silica gel chromatography and were therefore used directly in the next step. **IR (neat):** 2955 (m), 2928 (m), 2856 (m), 1746 (m), 1471 (m), 1462 (m), 1250 (m), 1112 (m), 1004 (m), 966 (m), 912 (m), 877 (m), 833 (s), 773 (s), 668 (m) cm^{-1} ; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.94−5.79 (m, 2H), 5.50−5.41 (m, 2H), 5.39−5.27 (m, 2H), 5.15−5.02 (m, 2H), 5.01−4.93 (m, 2H), 4.18−4.11 (m, 2H), 4.10−3.93 (m, 4H), 2.62 (dd, *J* = 18.2, 6.9 Hz, 2H), 2.42−2.32 (m, 2H), 2.32−2.24 (m, 2H), 2.24−2.13 (m, 2H), 1.95−1.87 (m, 2H), 1.86−1.80 (m, 2H), 1.60−1.38 (m, 2H), 1.36−1.20 (m, 10H), 0.94–0.85 (m, 42H), 0.14–0.02 (m, 24H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 138.1, 138.0, 135.0, 134.7, 131.1, 130.8, 115.4, 115.4, 80.1, 80.0, 74.7, 74.5, 73.7, 73.4, 56.5, 56.5, 51.6, 51.4, 43.2, 43.1, 38.7, 38.6, 33.5, 33.3, 32.0, 26.1, 26.0, 25.2, 25.1, 22.8, 18.4, 18.0, 18.0, 14.2, 14.2, □4.1, □4.1, □4.4, □4.5,□□4.6, □4.6, □4.7, □4.7; **HRMS[M+H]$^+$** Calcd for $C_{28}H_{57}O_3Si_2$: 497.3846, found: 497.3866.

(1*R*,3*S*,4*R*,5*R*)-4-Allyl-5-((*S*,*E*)-3-hydroxyoct-1-en-1-yl)cyclopentane-1,3-diol (1.80). To **S3** (35.0 mg, 0.070 mmol) in CH_3CN (1.5 mL) was added HF•pyridine and the solution was allowed to stir for 10 min. The reaction was quenched at this time by addition of a saturated solution of $NaHCO_3$ and resulting mixture was washed with ethyl acetate (10 mL × 3). The organic layers were combined, washed with brine, dried over Na_2SO_4, concentrated *in vacuo* and the yellow oil purified by silica gel chromatography (50% ethyl acetate in hexanes) to afford the desired product **1.80** (7.3 mg, 34% yield) as a colorless

oil. The diastereomers were separable by silica gel chromatography at this stage. **$[\alpha]_D^{22}$** +10.2 (*c* 0.46, $CHCl_3$); **IR (neat):** 3341 (br), 2956 (m), 2927 (m), 2858 (m), 1727 (s), 1437 (m), 1375 (m), 1245 (m), 1182 (m), 1078 (m), 1045 (m), 1021 (m), 994 (s), 909 (s), 732 (s) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 5.90–5.80 (m, 1H), 5.57 (dd, *J* = 15.3, 6.9 Hz, 1H), 5.48 (dd, *J* = 15.3, 8.8 Hz, 1H), 5.10 (dd, *J* = 17.1, 1.7 Hz, 1H), 5.07–4.99 (m, 1H), 4.22 (br, 1H), 4.07 (q, *J*= 6.6 Hz, 1H), 4.00–3.92 (m, 1H), 2.51 (br, 1H), 2.40–2.14 (m, 4H), 1.95 (br, 2H), 1.78 (dd, *J* = 14.8, 2.9 Hz, 1H), 1.66–1.44 (m, 3H), 1.38−1.27 (m, 6H), 0.92–0.87 (t, *J* = 6.8 Hz, 3H); **^{13}C NMR (125 MHz, $CDCl_3$):** δ 137.5, 135.3, 132.4, 116.0, 78.3, 73.3, 73.1, 56.1, 49.9, 42.9, 37.5, 32.6, 31.9, 25.4, 22.8, 14.2; **HRMS[M-H_2O+H]$^+$** Calcd for $C_{16}H_{27}O_2$: 251.2011, found: 251.2024.

Prostaglandin $F_{2\alpha}$. In a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (22 wt %, 102.4 mg, 0.40 mmol) was added to an oven-dried vial containing (1*R*,3*S*,4*R*,5*R*)-4-allyl-5-((*S*,*E*)-3-hydroxyoct-1-en-1-yl)cyclopentane-1,3-diol **1.80** (5.4 mg, 0.02 mmol), followed by **Ru-9** (0.30 mg in THF, 0.0004 mmol in 100 μL THF, 2.0 mol %). The vessel was sealed and the mixture was allowed to stir for 4 h at 22 °C. In another oven-dried vial, the mixture of *Z*-butene in THF (22 wt %, 102.4 mg, 0.40 mmol), hex-5-enoic acid (**1.28**, 6.8 mg, 0.060 mmol) and **Ru-9** (0.15 mg, 0.00020 mmol in 100 μL THF) was allowed to stir for 1 h at 22 °C. The mixtures were combined and the volatiles were removed *in vacuo*. To the resulting green residue was added a solution of **Ru-9** (2.3 mg, 0.0030 mmol, 200 μL THF). The vessel was then connected to a 100 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 1 h at 22 °C under 100 torr, and then for 12 h at 22 °C at ambient pressure, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil

residue was purified by silica gel chromatography (dichloromethane/MeOH/AcOH (v/v/v 200/2/1)) and filtered through a small plug of activated charcoal with ethyl acetate as eluent to afford prostaglandin $F_{2\alpha}$ (4.2 mg, 0.0119 mmol, 59% yield) in >98:2 *Z:E* ratio as colorless oil. **[α]D 20** □□□□□ (*c* 0.21, THF); **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.57 (dd, *J* = 15.3, 6.5 Hz, 1H), 5.51 (dd, *J* = 15.3, 8.5 Hz, 1H), 5.50□5.42 (m, 1H), 5.40□5.32 (m, 1H), 5.10□4.35 (br, 1H), 4.18 (t, *J* = 4.4 Hz, 1H), 4.11 (q, *J* = 6.8 Hz, 2H), 3.98□3.93 (m, 1H), 2.38□2.27 (m, 3H), 2.25–2.17 (m, 2H), 2.16–2.09 (m, 3H), 1.77 (d, *J* = 14.9 Hz, 1H), 1.73–1.62 (m, 2H), 1.62–1.53 (m, 1H), 1.53–1.43 (m, 2H), 1.41–1.25 (m, 6H), 0.88 (t, *J* = 6.7 Hz, 3H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 177.2, 134.6, 132.4, 129.6, 129.1, 77.9, 73.0, 72.8, 55.6, 50.5, 42.8, 37.0, 32.9, 31.7, 26.2, 25.3, 25.2, 24.5, 22.6, 14.0; **HRMS[M-H_2O+H]$^+$** Calcd for $C_{20}H_{33}O_4$: 337.2379, found: 337.2391. The characterization data are consistent with those previously reported.[67]

1.8.10 Stereoselective synthesis of macrocyclic stapled peptide 23

(5*R*,8*R*,13*R*,*Z*)-Methyl 5-benzyl-13-((*S*)-2-((*tert*-butoxycarbonyl)amino)-3-(4-hydroxyphenyl)propanamido)-3,6,14-trioxo-1,4,7-triazacyclotetradec-10-ene-8-carboxylate (1.82). In a N_2-filled glove box, a solution of unpurified *Z*-butene in THF (33 wt %, 170.0 mg, 1.00 mmol) was added to an oven-dried vial containing (6*S*,9*R*,15*S*,18*R*)-methyl 9,18-diallyl-15-benzyl-6-(4-hydroxybenzyl)-2,2-dimethyl-4,7,10,13,16-pentaoxo-3-oxa-5,8,11,14,17-pentaazanonadecan-19-oate **1.81** (34.7 mg, 0.050 mmol), followed by a solution of **Ru-9** (0.76 mg, 0.0010 mmol in 200 μL THF). The vial was sealed and the mixture was allowed to stir for 12 h at 22 °C. The volatiles were removed *in vacuo* and the green solid was dissolved in THF (800 μL) and a solution of **Ru-9** (3.78 mg, 0.0050 mmol

(67) Sheddan, N. A.; Mulzer, J. *Org. Lett.* **2006**, *8*, 3102–3104.

in 200 μL THF) was added. The mixture was allowed to stir for 48 h at 35 °C, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black solid residue was purified by silica gel chromatography (3% MeOH in CH_2Cl_2) afford **1.82** (24.0 mg, 0.036 mmol, 72% yield) in >98:2 *Z:E* selectivity as off-white solid. **$[\alpha]_D^{20}$** +34.2 (*c* 0.76, MeOH); **^{1}H NMR (600 MHz, DMSO-d_6 at 37 °C):** δ 9.08 (s, 1H), 8.84 (d, *J* = 5.5 Hz, 1H), 8.83 (d, *J* = 6.4 Hz, 1H), 8.08 (d, *J* = 7.7 Hz, 1H), 7.27 (d, *J* = 6.8 Hz, 1H), 7.27–7.25 (m, 4H), 7.22–7.13 (m, 1H), 7.01 (d, *J* = 7.4 Hz, 2H), 6.70 (d, *J* = 8.0 Hz, 1H), 6.63 (d, *J* = 8.2 Hz, 2H), 5.29 (t, *J* = 10.8 Hz, 1H), 5.16 (t, *J* = 10.8 Hz, 1H), 4.35–4.27 (m, 2H), 4.24 (ddd, *J* = 11.4, 8.1, 3.3 Hz, 1H), 4.10 (d, *J* = 5.8 Hz, 1H), 3.82 (dd, *J* = 13.3, 5.1 Hz, 1H), 3.67 (s, 3H), 3.18 (d, *J* = 14.6 Hz, 1H), 3.16–3.10 (m, 1H), 2.89–2.71 (m, 3H), 2.67–2.55 (m, 2H), 2.31 (d, *J* = 14.7 Hz, 1H), 1.85 (d, *J* = 10.2 Hz, 1H), 1.31 (s, 9H); **HRMS[M+H]$^+$** Calcd for $C_{34}H_{44}N_5O_9$: 666.3134, found: 666.3131. The characterization data are consistent with those previously reported[11].

1.8.11 Cross-metathesis and macrocyclic ring-closing metathesis with *E*-butene as methylene capping agent

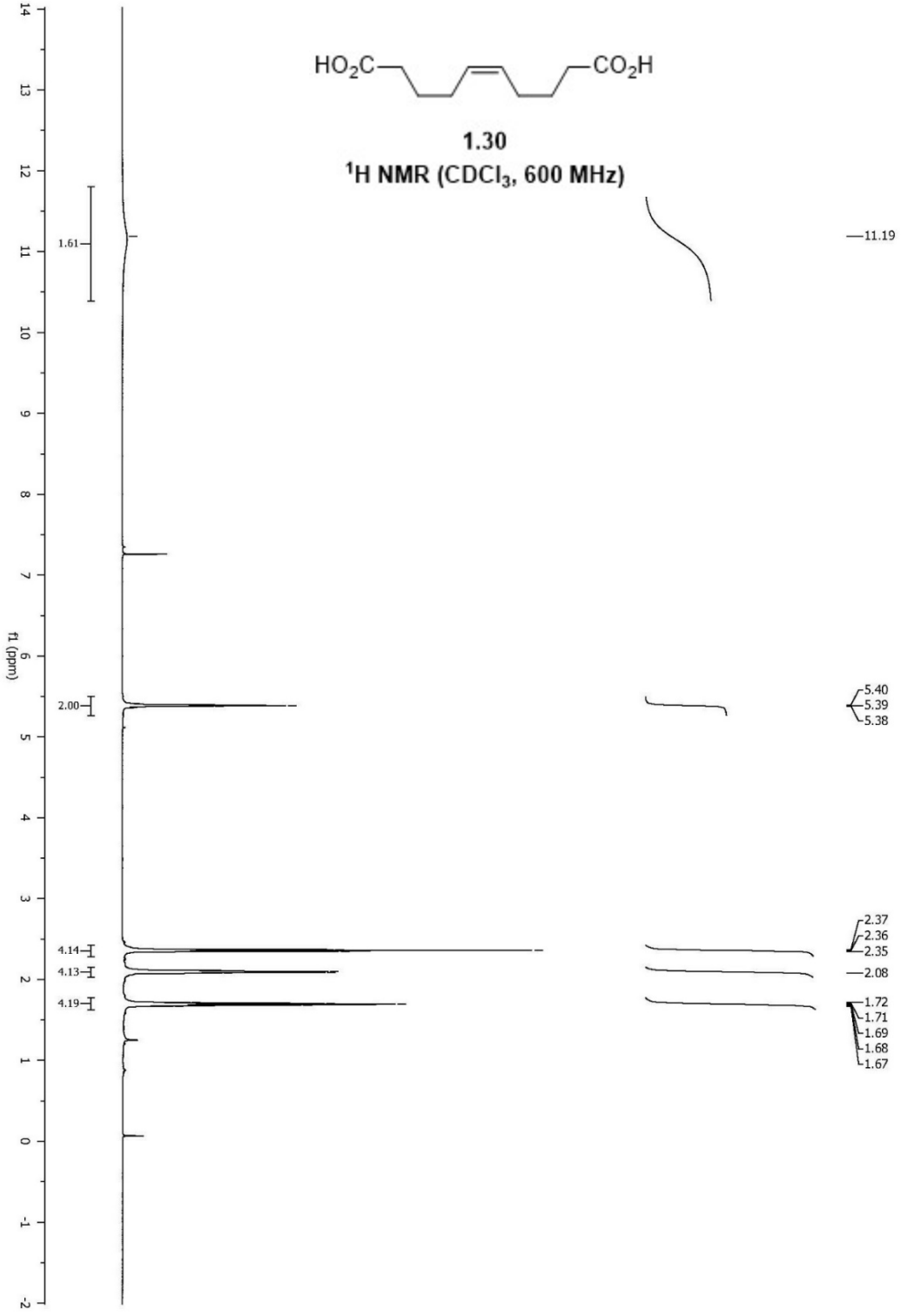
Benzyl (*E*)-12-hydroxydodec-4-enoate (1.86). In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with benzyl pent-4-enoate (**1.85**, 28.5 mg, 0.15 mmol) and 8-non-1-ol (**1.83**, 7.1 mg, 0.05 mmol), unpurified *E*-2-butene in THF (30 wt %, 698 mg, 3.75 mmol) and a solution of **Ru-11** (3.0 mg, 0.00375 mmol, 200 μL THF). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with a solution of **Ru-11** (2.1 mg, 0.0025 mmol in 200 μL THF) and the

system was placed under 100 torr of vacuum generated from a diaphragm pump. The resulting solution was allowed to stir for 4 h at 22 °C under vacuum, after which the reaction was quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford **1.86** (10.0 mg, 0.033 mmol, 66% yield) in 96:4 *E*:*Z* ratio as colorless oil. **IR (neat)**: 3387 (br), 2925 (s), 2853 (m), 1735 (s), 1497 (w), 1455 (m), 1345 (m), 1213 (m), 1158 (s), 1059 (m), 1002 (m), 968 (m), 913 (m), 749 (m), 697 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.43–7.29 (m, 5H), 5.50–5.35 (m, 2H), 5.11 (s, 2H), 3.63 (t, *J* = 6.6 Hz, 2H), 2.67–2.38 (m, 2H), 2.39–2.29 (m, 2H), 1.95 (q, *J* = 6.5 Hz, 2H), 1.61−1.53 (m, 3H), 1.46–1.13 (m, 8H); **^{13}C NMR (125 MHz, $CDCl_3$)**: δ 173.21, 136.23, 132.00, 128.67, 128.30, 128.30, 128.01, 77.41, 77.16, 76.91, 66.26, 63.20, 34.56, 32.93, 32.57, 29.45, 29.38, 29.17, 28.05, 25.83; **HRMS[M+H]$^+$** Calcd for $C_{19}H_{29}O_3$: 305.213, found: 305.2117.

(*E*)-oxacyclohexadec-6-en-2-one (1.87). In a N_2-filled glove box, a solution of unpurified *E*-butene (**3**) in THF (23 wt %, 608 mg, 2.50 mmol) was added to an oven-dried vial containing undec-10-en-1-yl hex-5-enoate (**1.56**, 13.3 mg, 0.05 mmol), followed by a THF solution of **Ru-11** (1.60 mg, 0.0020 mmol, 100 μL THF). The vessel was sealed and the mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed *in vacuo* and the resulting green residue was dissolved in THF (9.5 mL) and a solution of **Ru-11** (2.40 mg, 0.0030 mmol, 500 μL THF) was added. The vessel was then connected to a 400 torr vacuum generated from a diaphragm pump. The solution was allowed to stir for 12 h at 35 °C under vacuum and then 12 h at 35 ºC without vacuum, after which the reaction was

quenched by the addition of wet (undistilled) diethyl ether and the volatiles were removed *in vacuo*. The resulting black oil residue was purified by silica gel chromatography (1% diethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford **1.87** (6.2 mg, 0.026 mmol, 52% yield) in 95:5 *E*:*Z* ratio as colorless oil. **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.38–5.28 (m, 2H), 4.12 (t, *J* = 5.3 Hz, 2H), 2.35 (t, *J* = 7.3 Hz, 2H), 2.12–2.00 (m, 4H), 1.77–1.68 (m, 2H), 1.68–1.62 (m, 2H), 1.47–1.21 (m, 12H). The characterization data are consistent with those previously reported[18].

1.8.12 NMR spectra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11.19
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5.39
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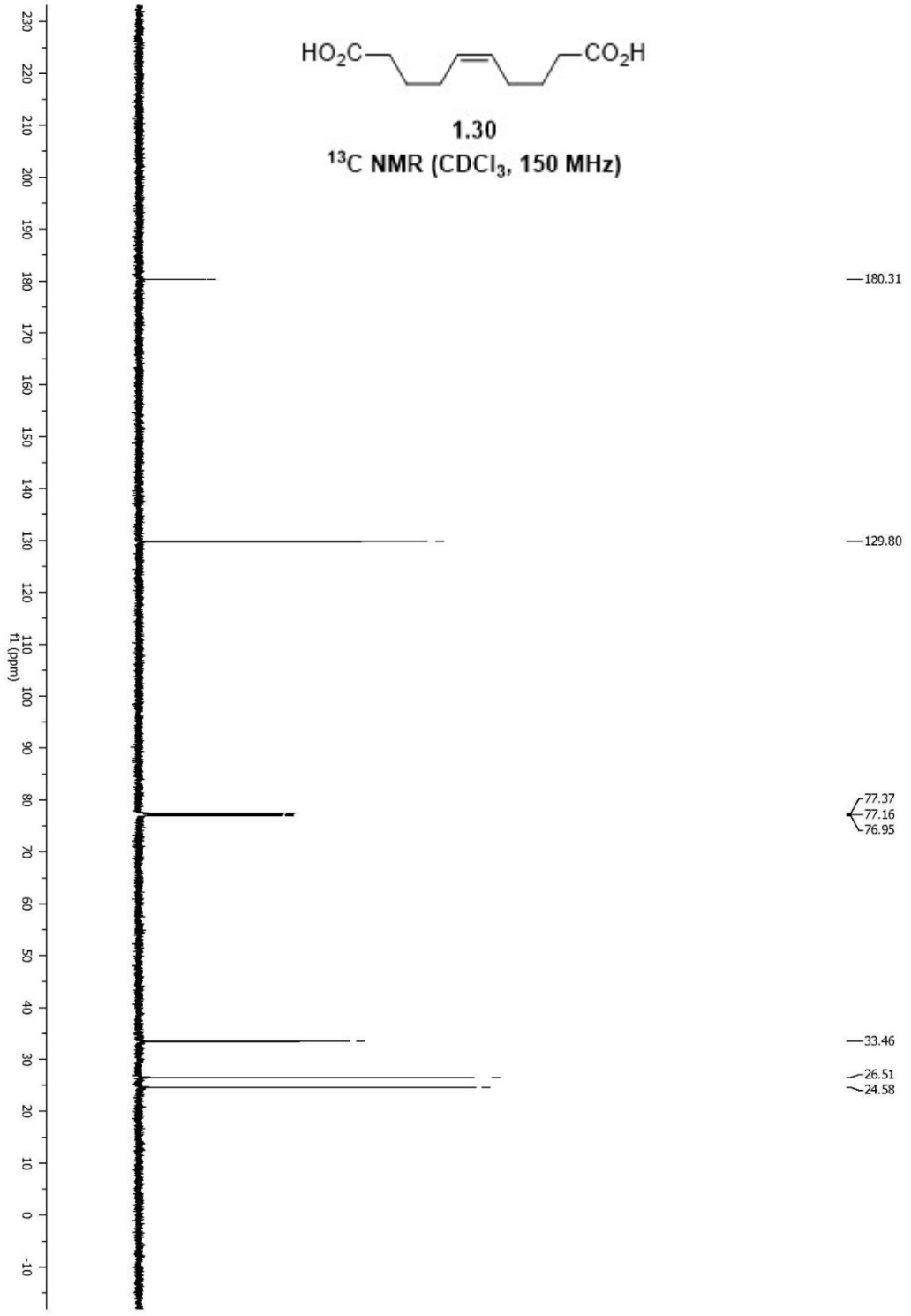
1.69
1.68
1.67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CO2H
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77.16
76.95
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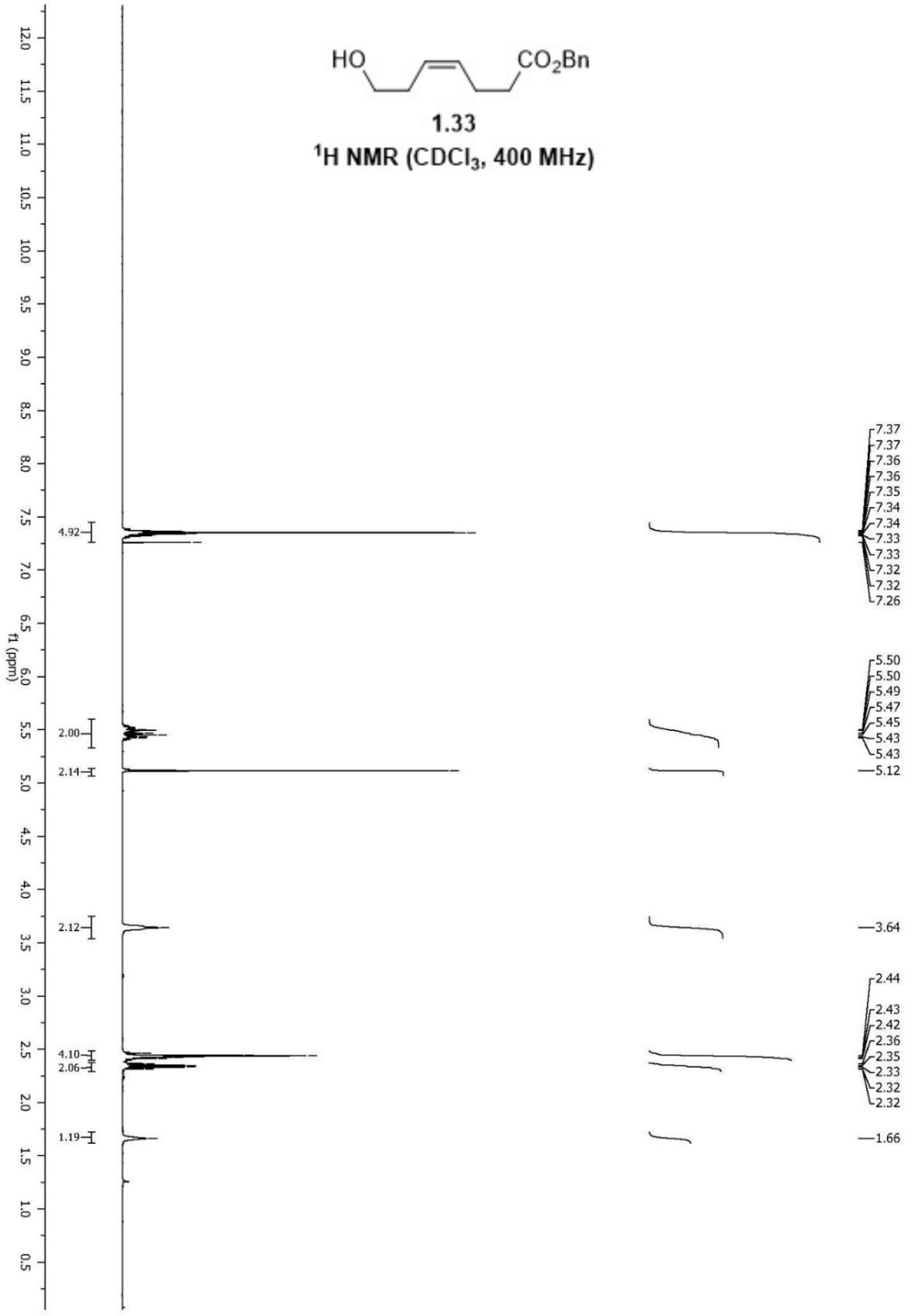
26.51
24.58
f1 (ppm)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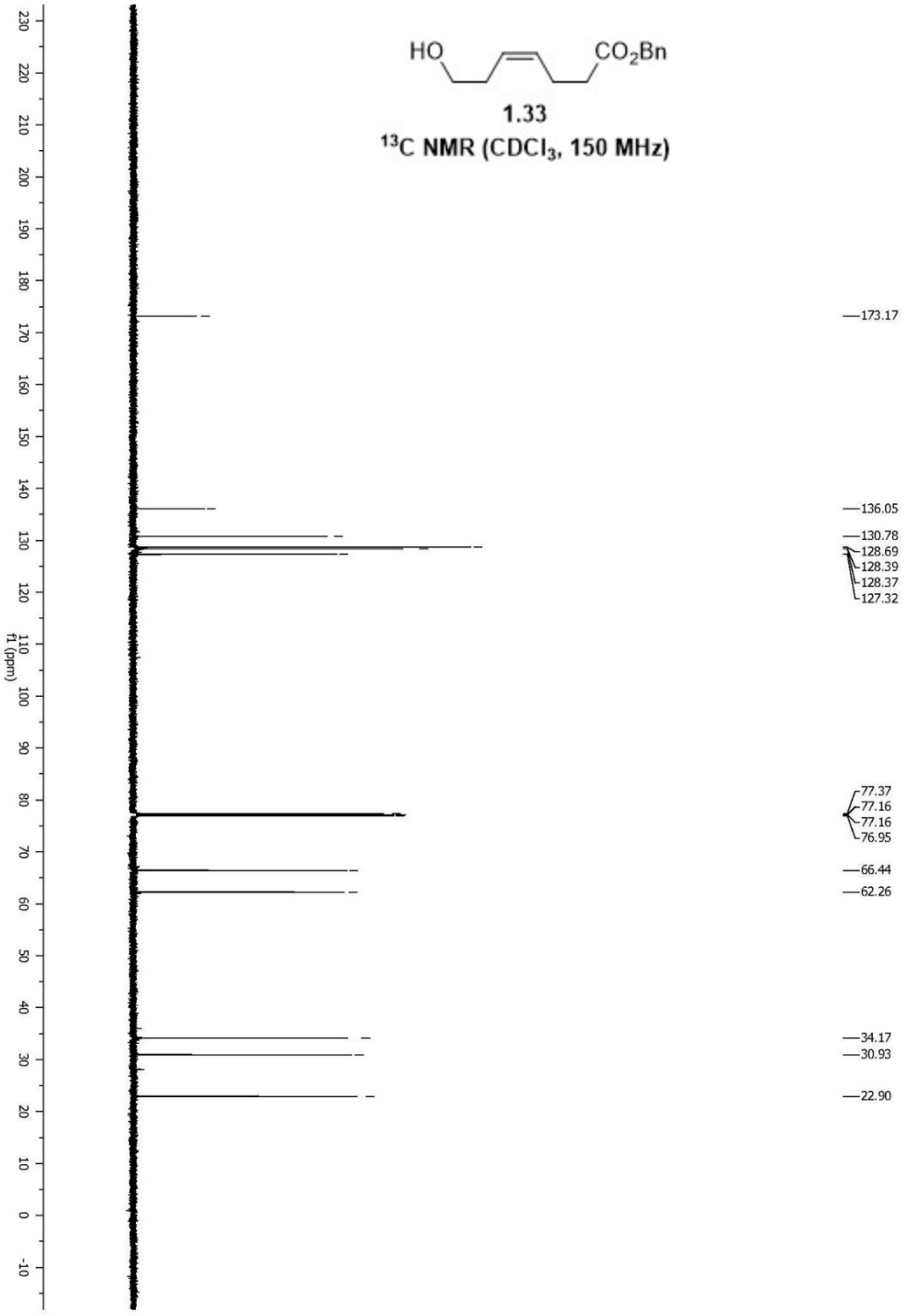
2.32
1.66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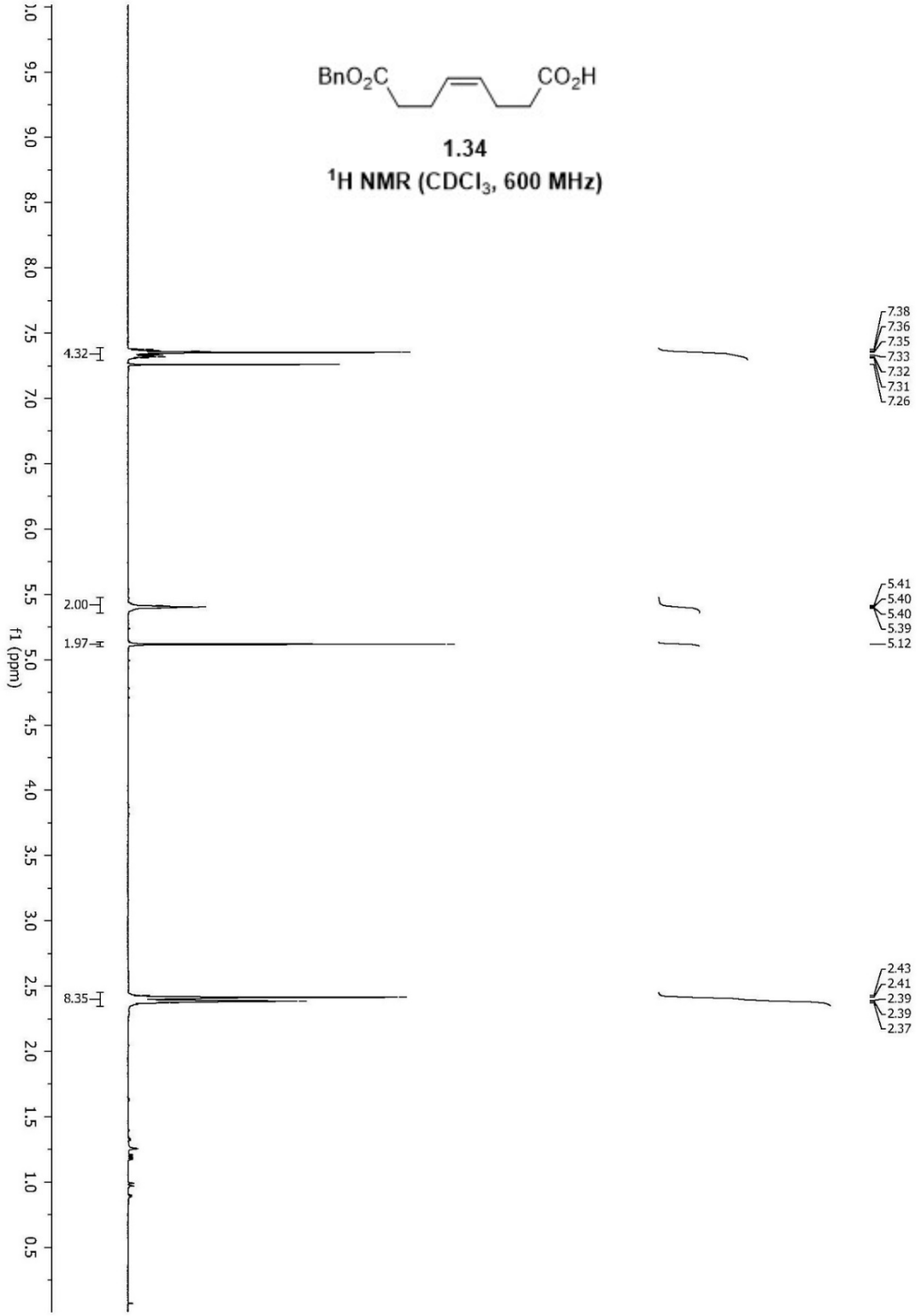
30.93
22.90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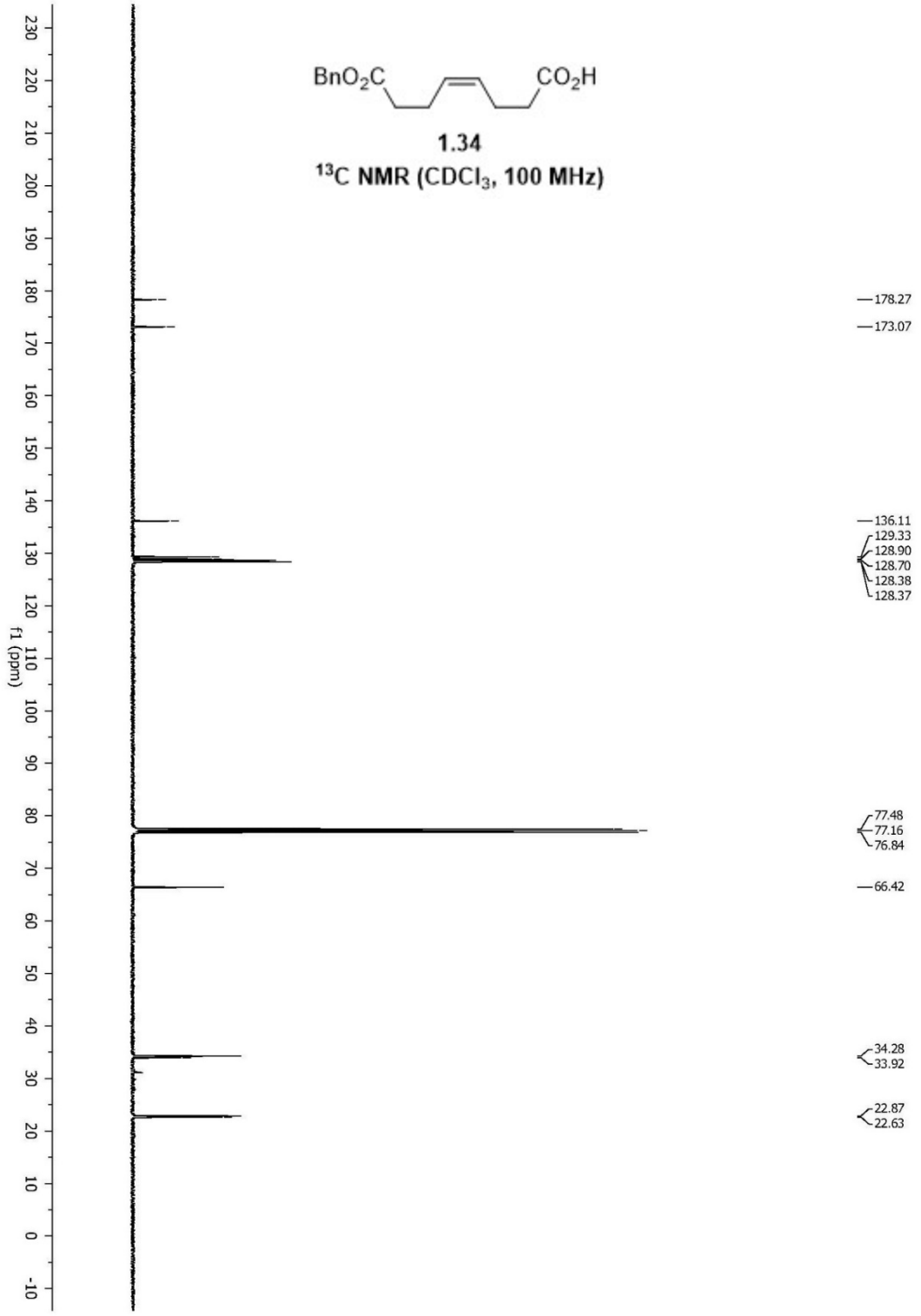
2.39
2.37
f1 (ppm)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CO2H
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128.90
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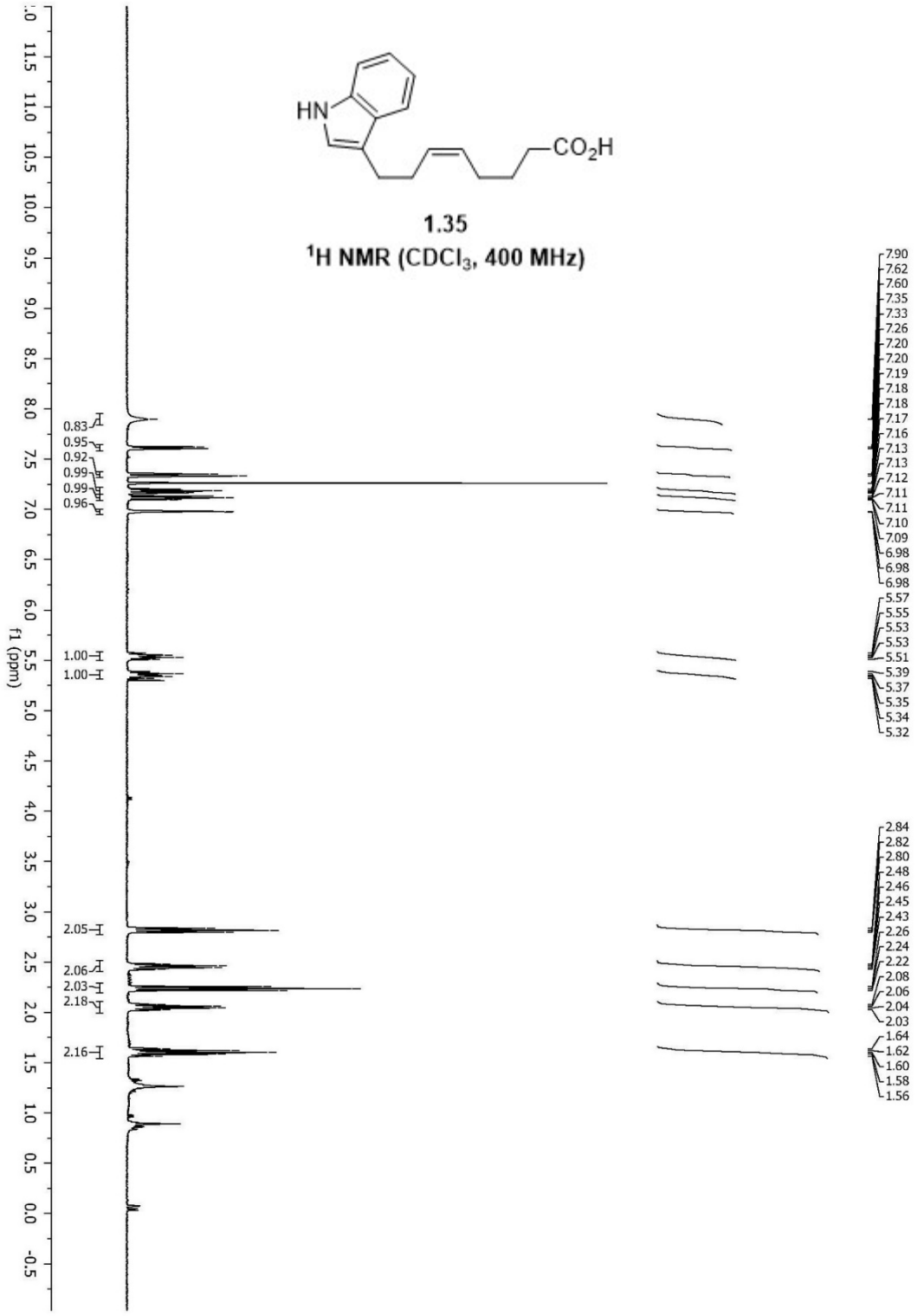
34.28
33.92
22.87
22.63
f1 (ppm)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f1 (ppm)
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0.99
0.99
0.96
1.00
1.00
2.05
2.06
2.03
2.18
2.16
7.90
7.62
7.60
7.35
7.33
7.26
7.20
7.20
7.19
7.18
7.18
7.17
7.16
7.13
7.13
7.12
7.11
7.11
7.10
7.09
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6.98
6.98
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5.55
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5.53
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5.39
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5.34
5.32
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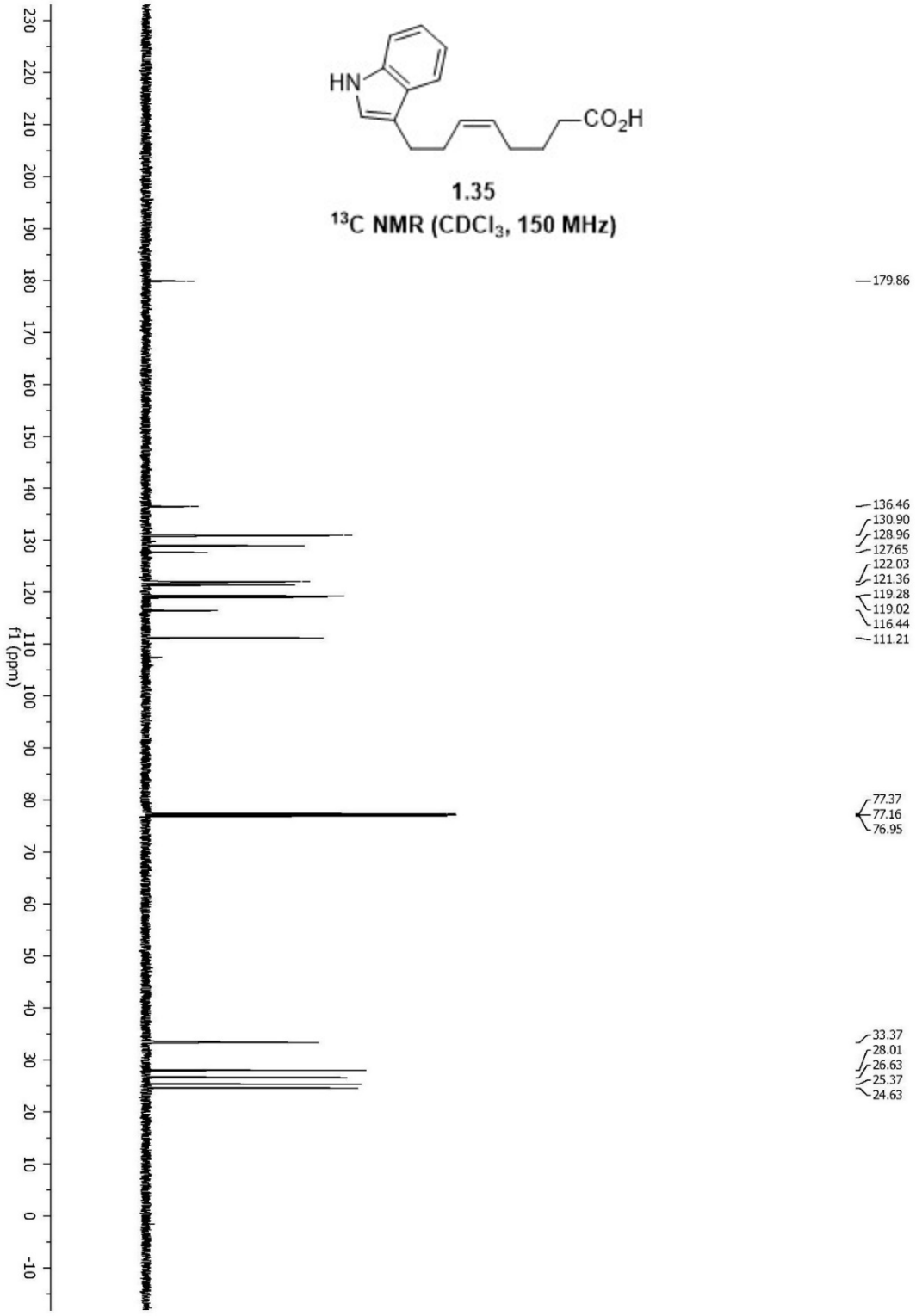
1.56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26.63
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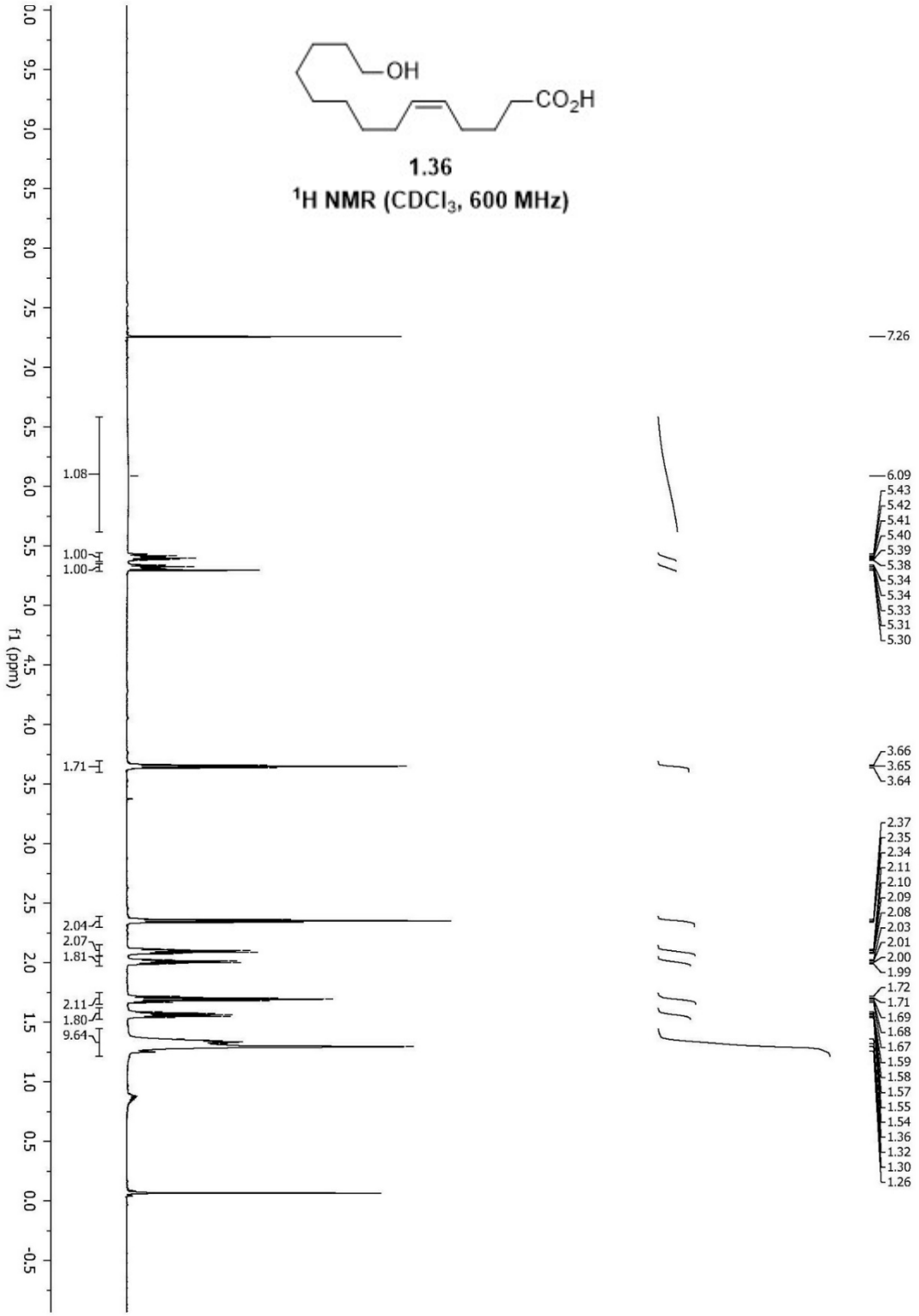
f1 (ppm)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CO2H
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5.39
5.38
5.34
5.34
5.33
5.31
5.30
3.66
3.65
3.64
2.37
2.35
2.34
2.11
2.10
2.09
2.08
2.03
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1.99
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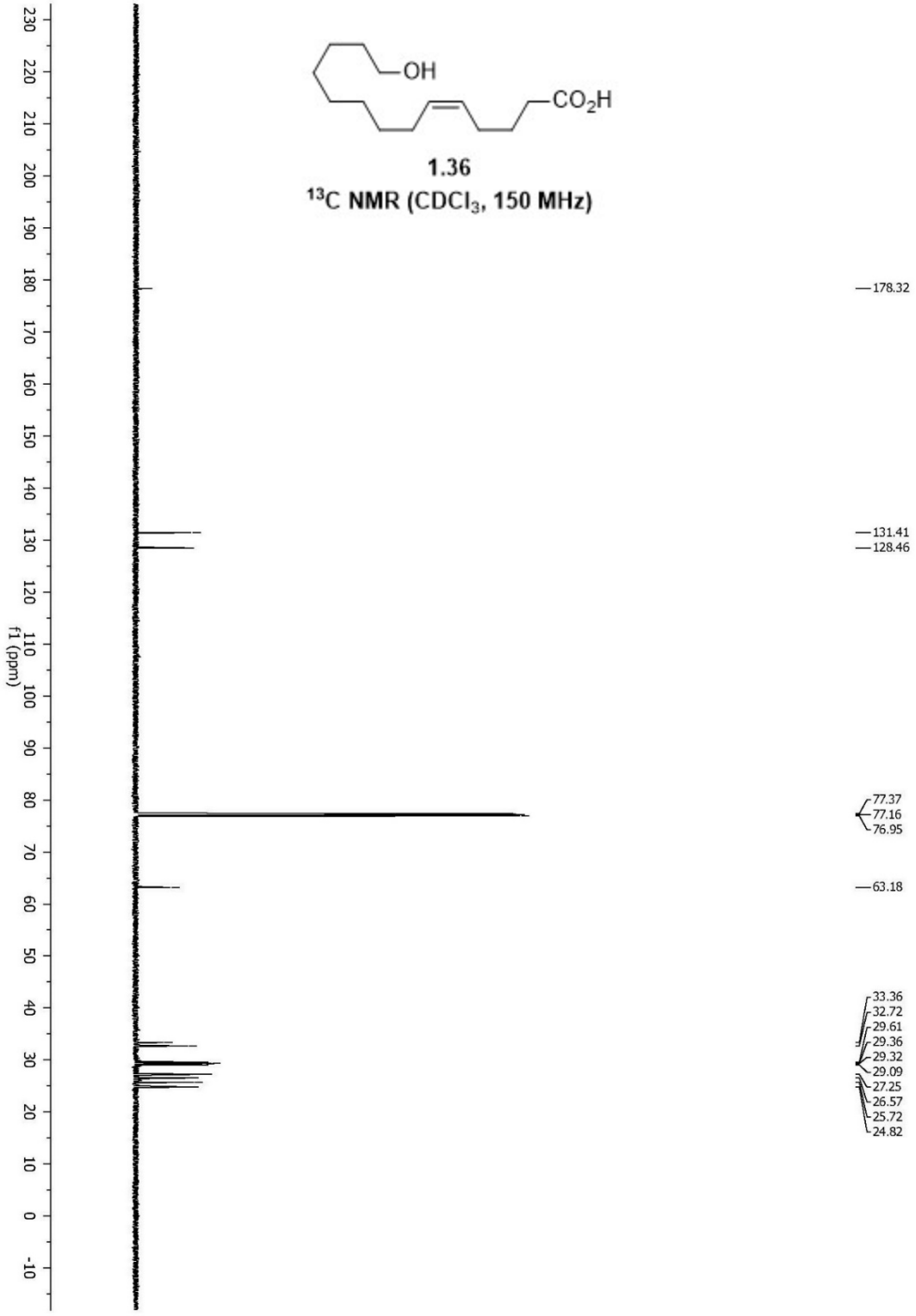
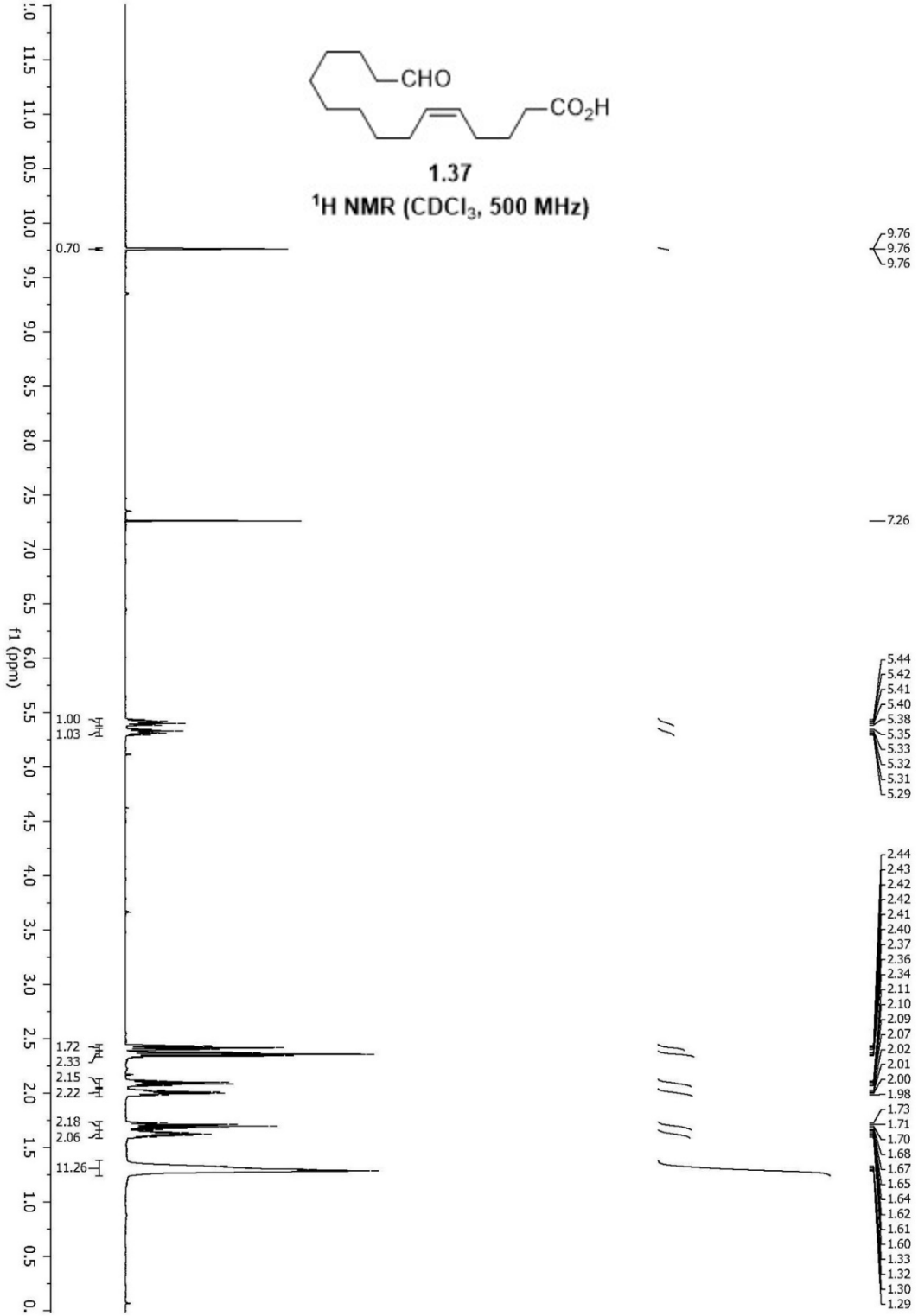
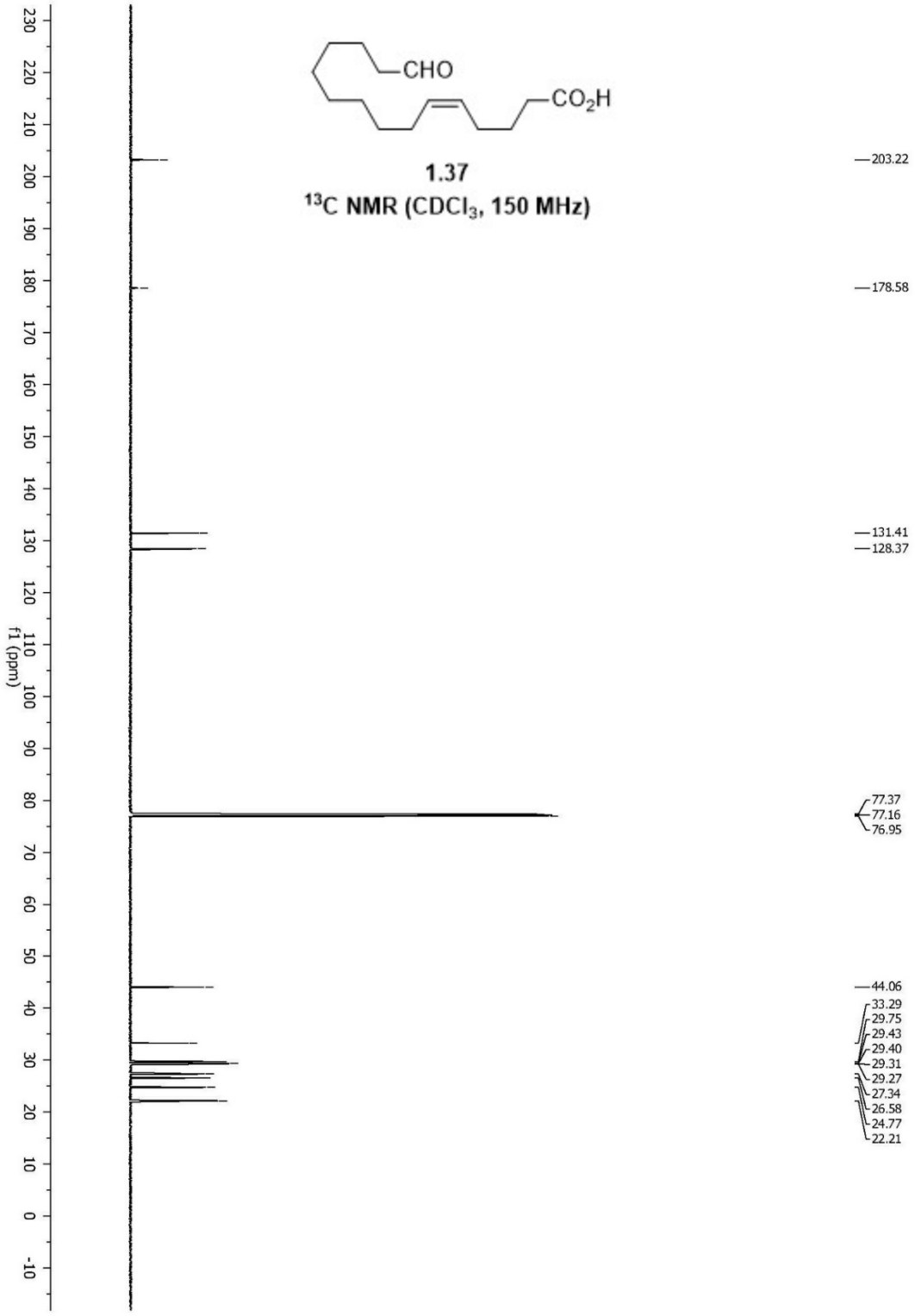
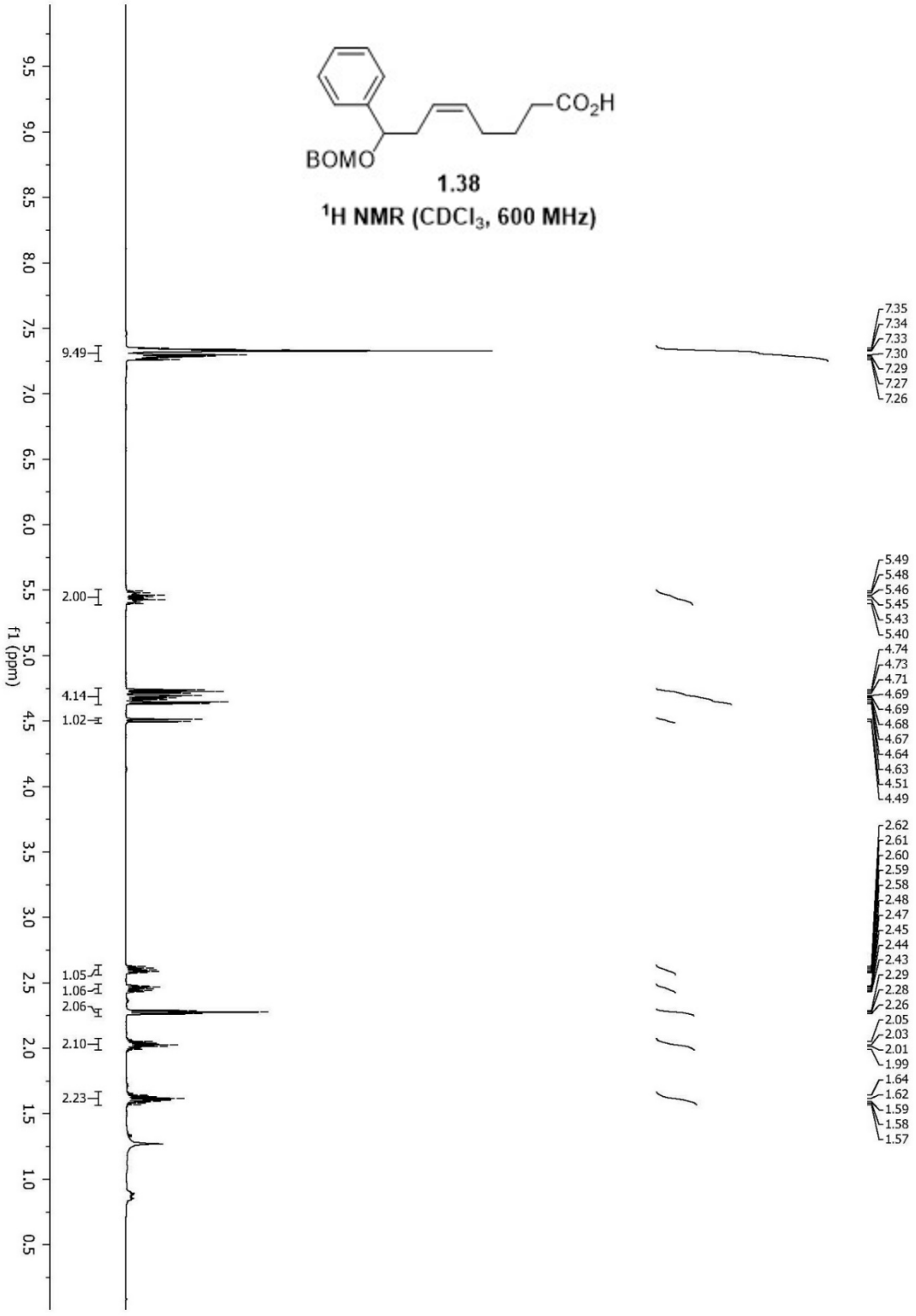
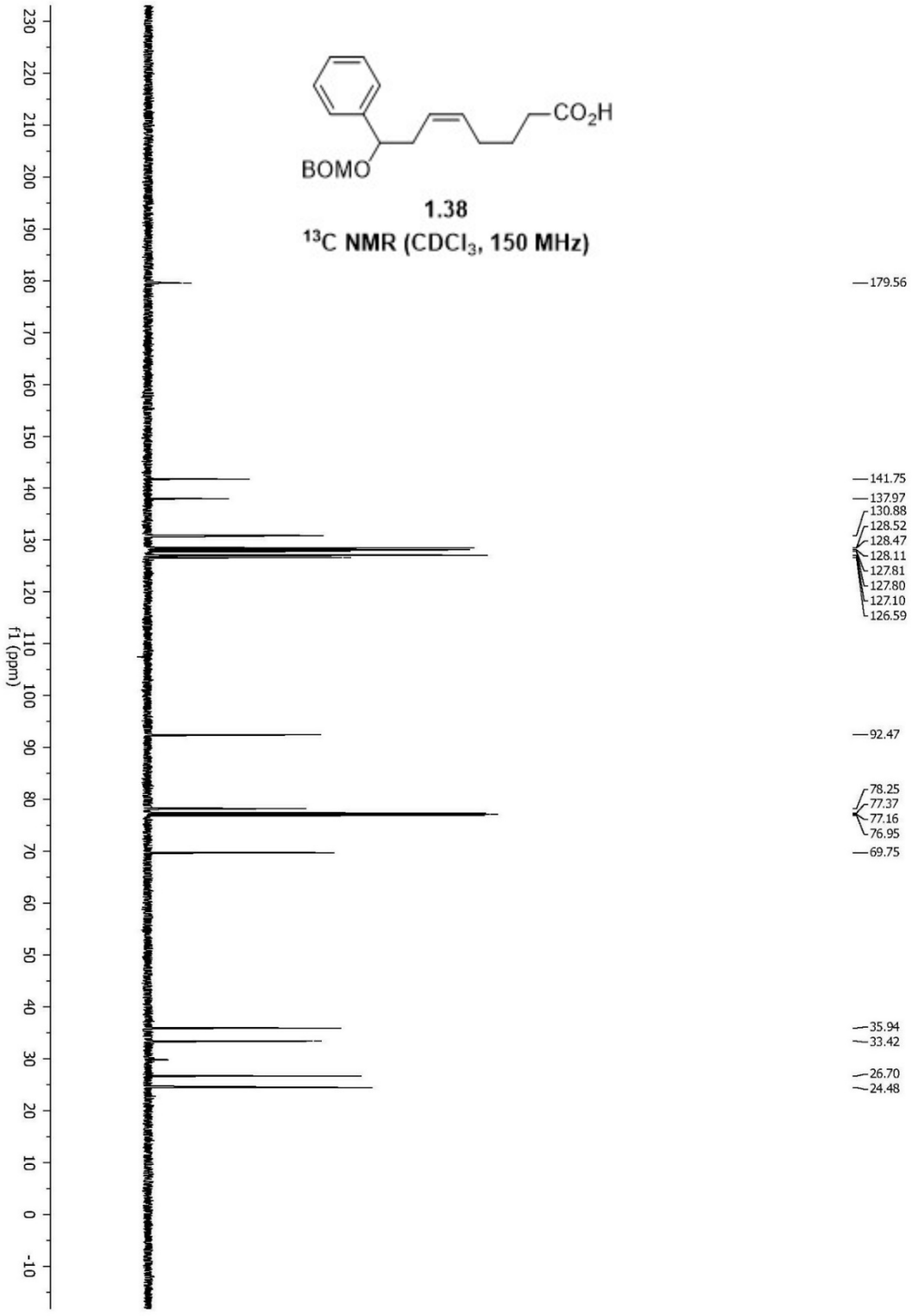
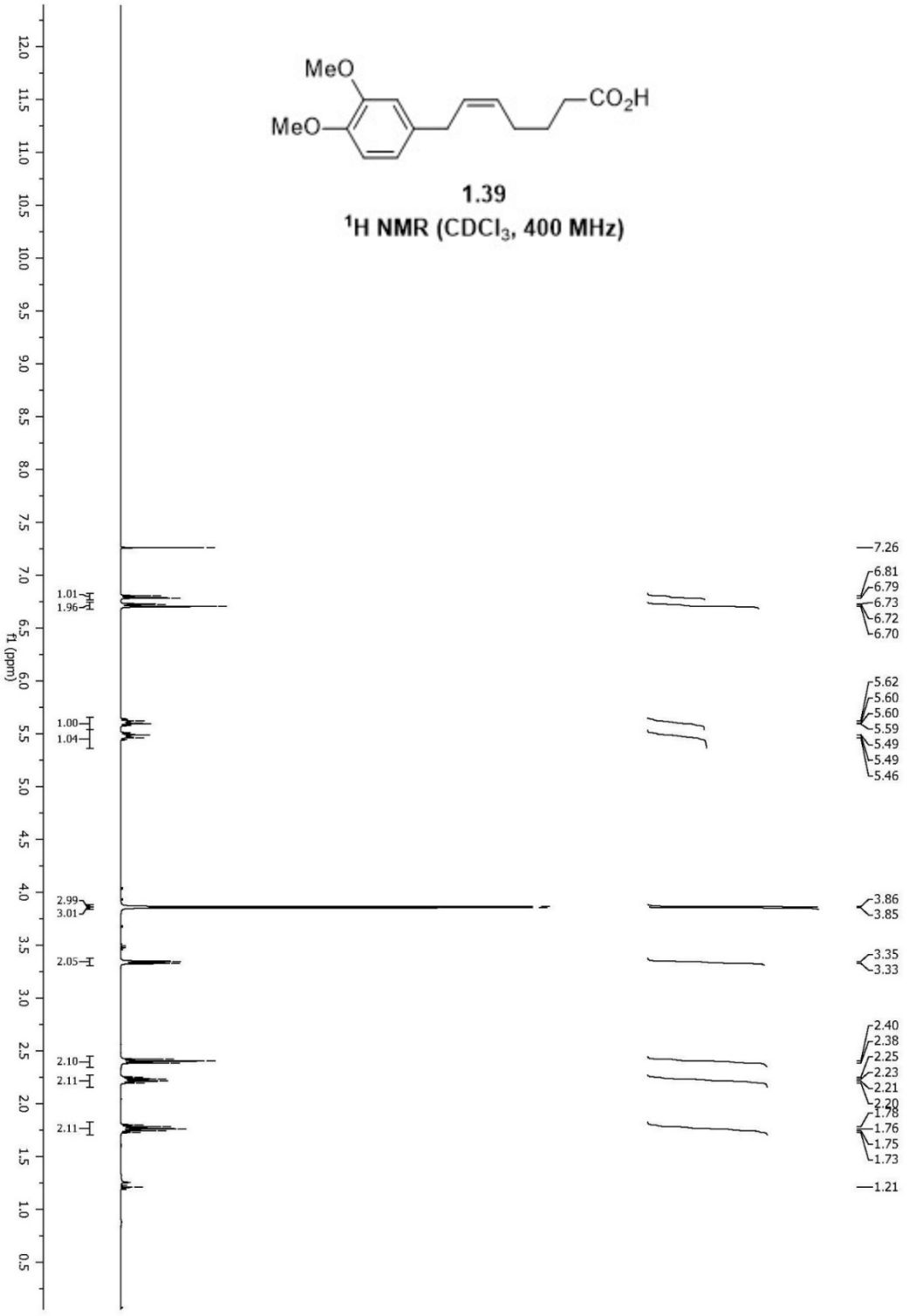

OH
CO2H
1.36
13C NMR (CDCl3, 150 MHz)
178.32
131.41
128.46
77.37
77.16
76.95
63.18
33.36
32.72
29.61
29.36
29.32
29.09
27.25
26.57
25.72
24.82
f1 (ppm)

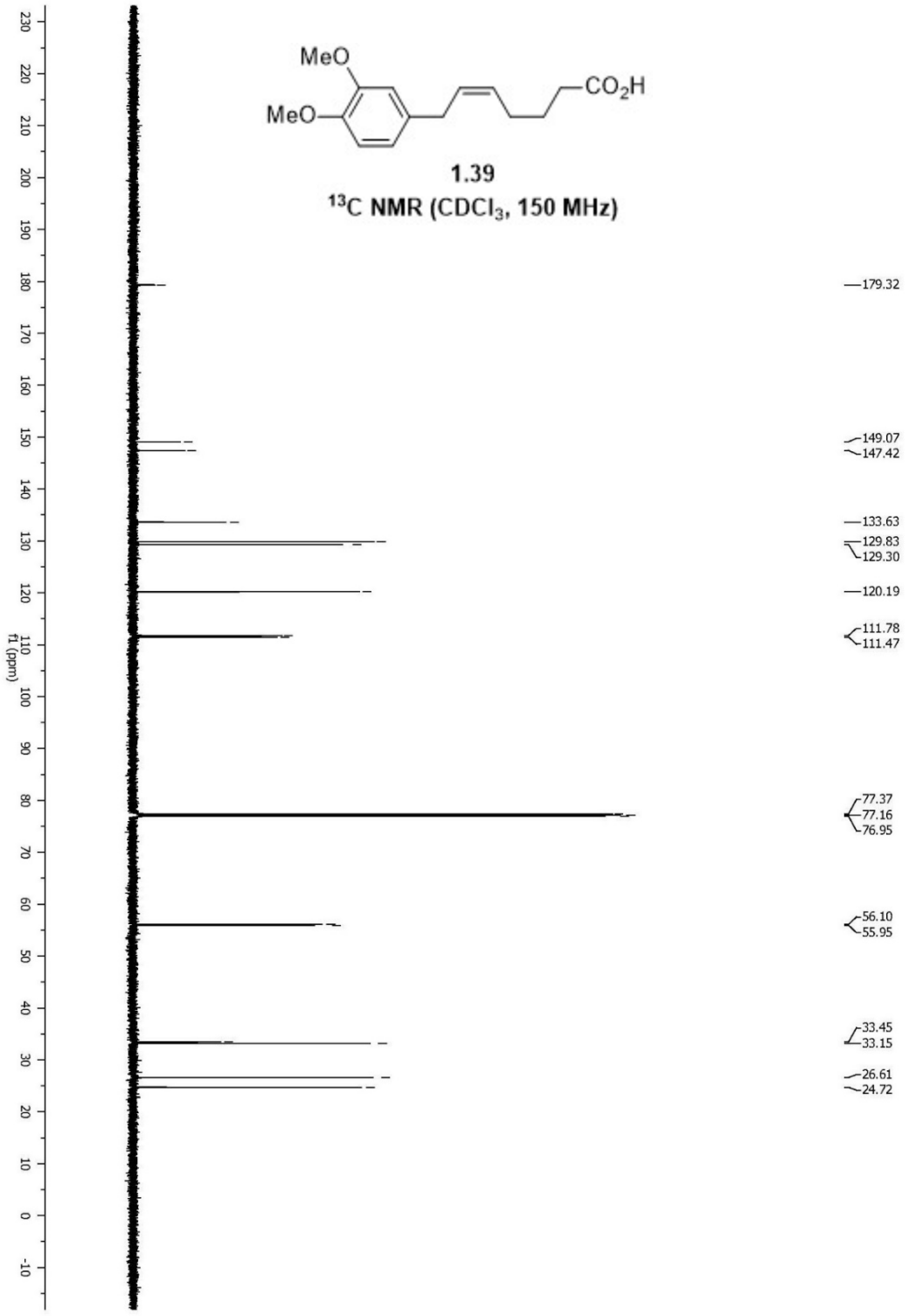

CHO
CO2H
1.37
1H NMR (CDCl3, 500 MHz)
f1 (ppm)
0.70
1.00
1.03
1.72
2.33
2.15
2.22
2.18
2.06
11.26
9.76
9.76
9.76
7.26
5.44
5.42
5.41
5.40
5.38
5.35
5.33
5.32
5.31
5.29
2.44
2.43
2.42
2.42
2.41
2.40
2.37
2.36
2.34
2.11
2.10
2.09
2.07
2.02
2.01
2.00
1.98
1.73
1.71
1.70
1.68
1.67
1.65
1.64
1.62
1.61
1.60
1.33
1.32
1.30
1.29

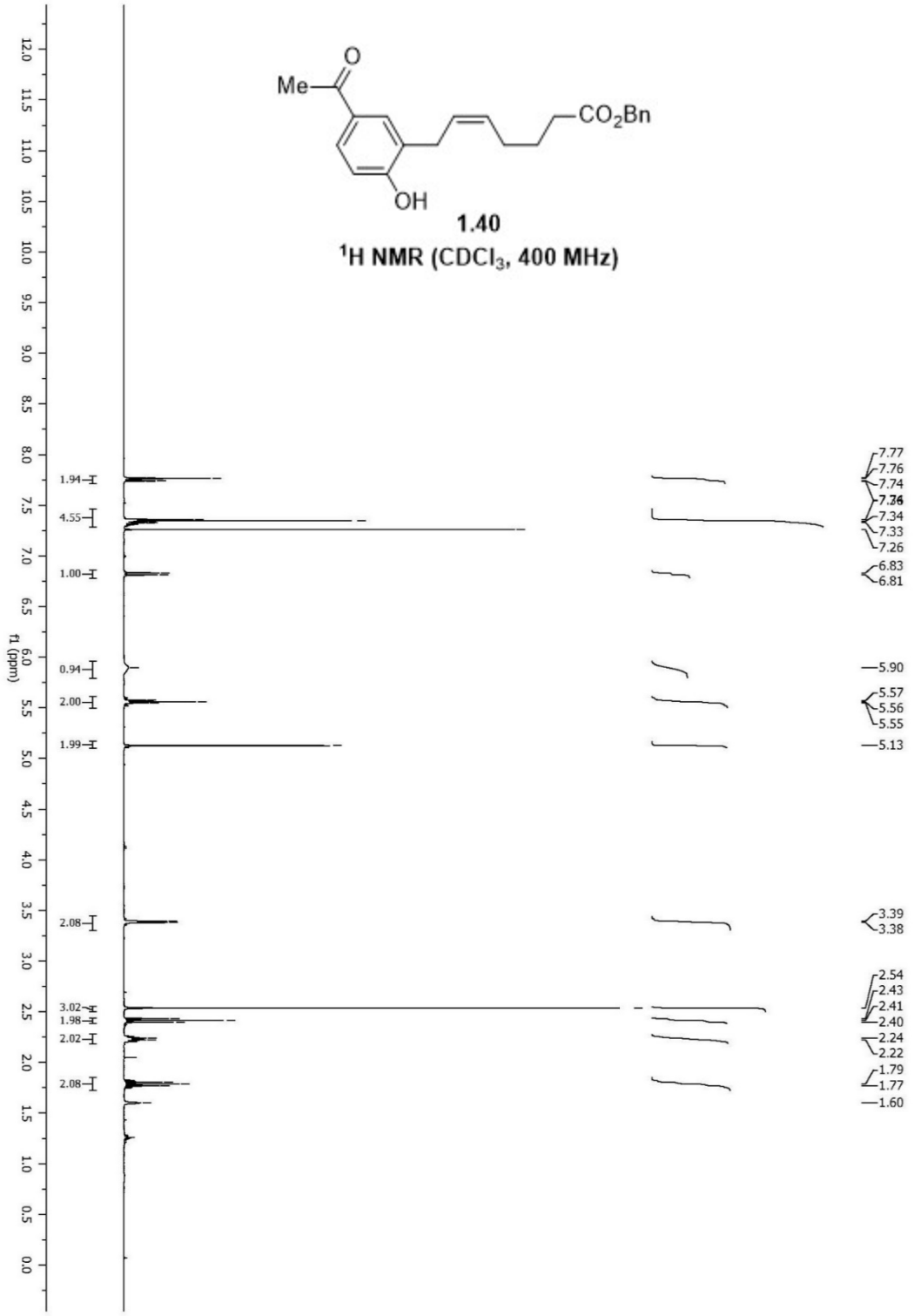

CHO
CO2H
1.37
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
203.22
178.58
131.41
128.37
77.37
77.16
76.95
44.06
33.29
29.75
29.43
29.40
29.31
29.27
27.34
26.58
24.77
22.21

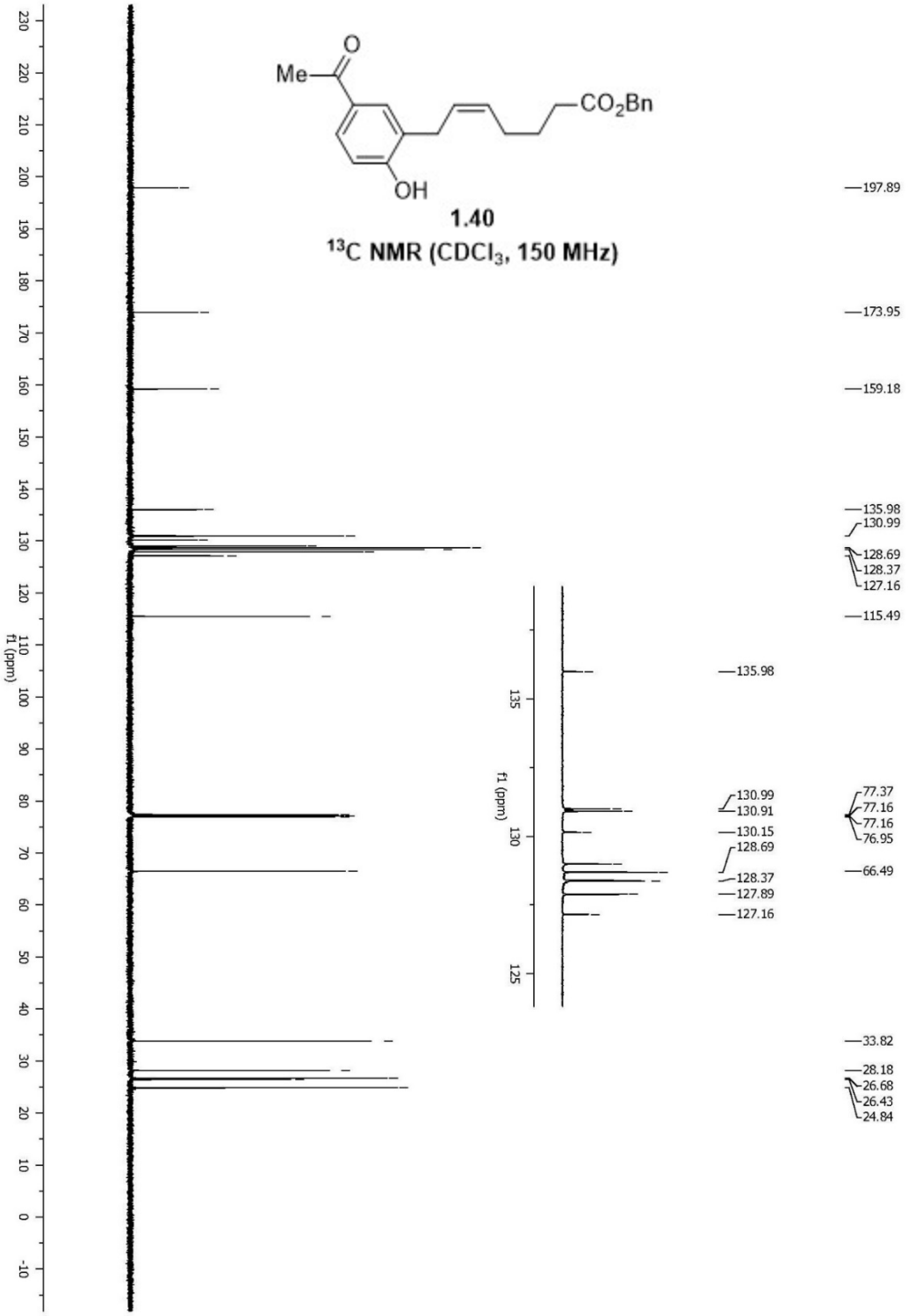

BOMO
CO_2H
1.38
^{1}H NMR ($CDCl_3$, 600 MHz)
f1 (ppm)
9.49
2.00
4.14
1.02
1.05
1.06
2.06
2.10
2.23
7.35
7.34
7.33
7.30
7.29
7.27
7.26
5.49
5.48
5.46
5.45
5.43
5.40
4.74
4.73
4.71
4.69
4.69
4.68
4.67
4.64
4.63
4.51
4.49
2.62
2.61
2.60
2.59
2.58
2.48
2.47
2.45
2.44
2.43
2.29
2.28
2.26
2.05
2.03
2.01
1.99
1.64
1.62
1.59
1.58
1.57

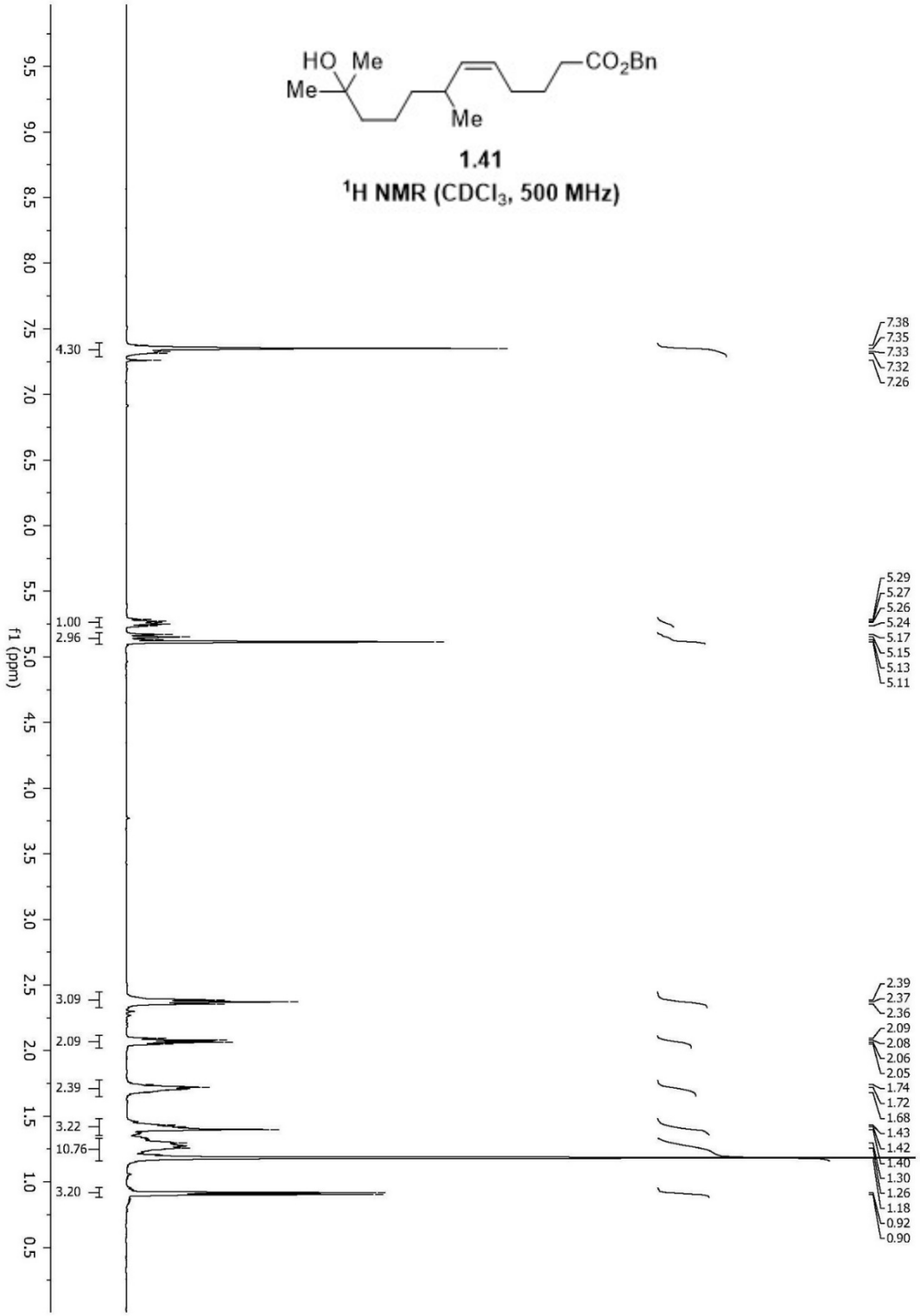

BOMO
CO2H
1.38
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
179.56
141.75
137.97
130.88
128.52
128.47
128.11
127.81
127.80
127.10
126.59
92.47
78.25
77.37
77.16
76.95
69.75
35.94
33.42
26.70
24.48

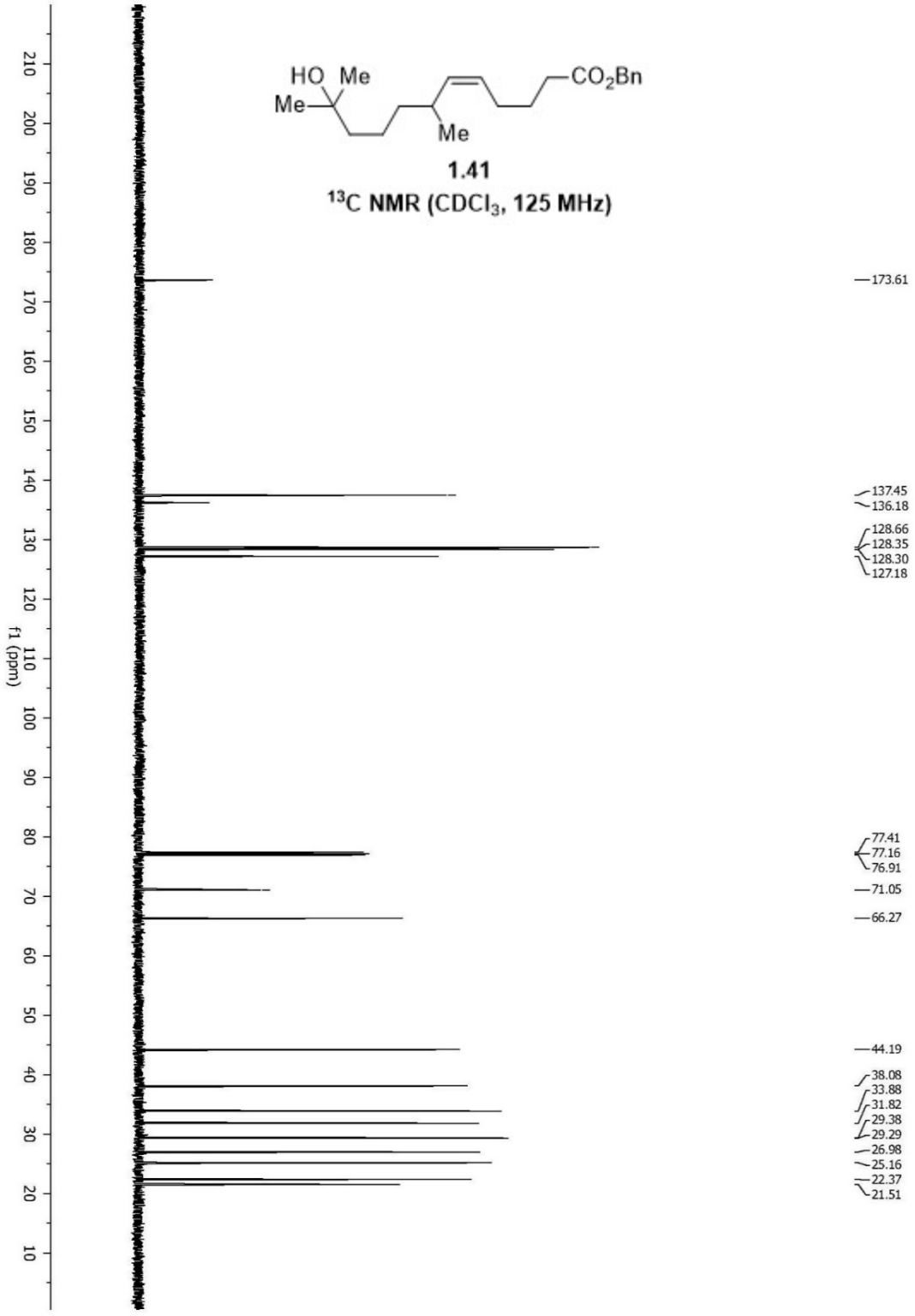

MeO
MeO
CO2H
1.39
1H NMR (CDCl3, 400 MHz)
f1 (ppm)
1.01
1.96
1.00
1.04
2.99
3.01
2.05
2.10
2.11
2.11
7.26
6.81
6.79
6.73
6.72
6.70
5.62
5.60
5.60
5.59
5.49
5.49
5.46
3.86
3.85
3.35
3.33
2.40
2.38
2.25
2.23
2.21
2.20
1.78
1.76
1.75
1.73
1.21

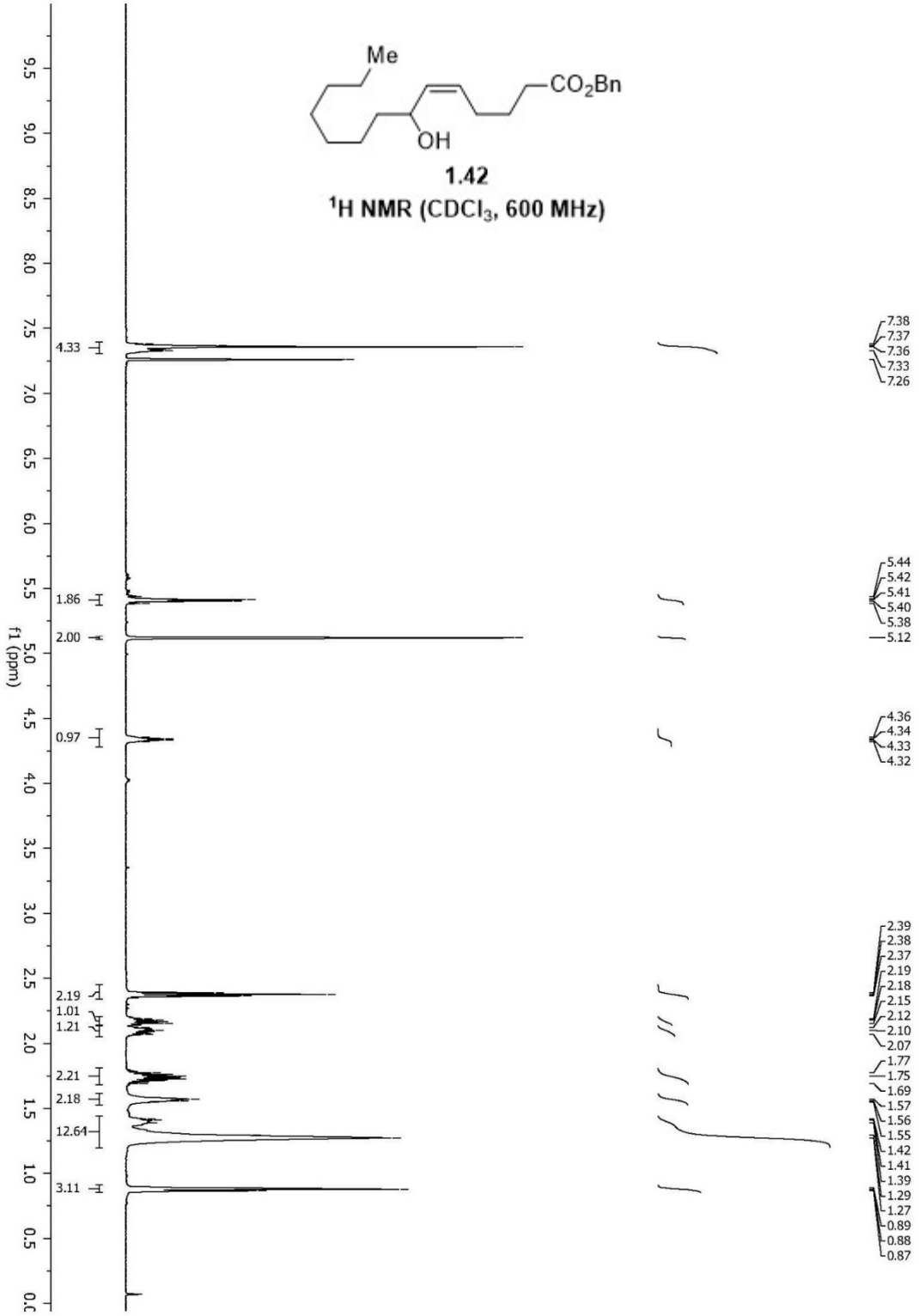

MeO
MeO
CO2H
1.39
13C NMR (CDCl3, 150 MHz)
179.32
149.07
147.42
133.63
129.83
129.30
120.19
111.78
111.47
77.37
77.16
76.95
56.10
55.95
33.45
33.15
26.61
24.72
f1 (ppm)

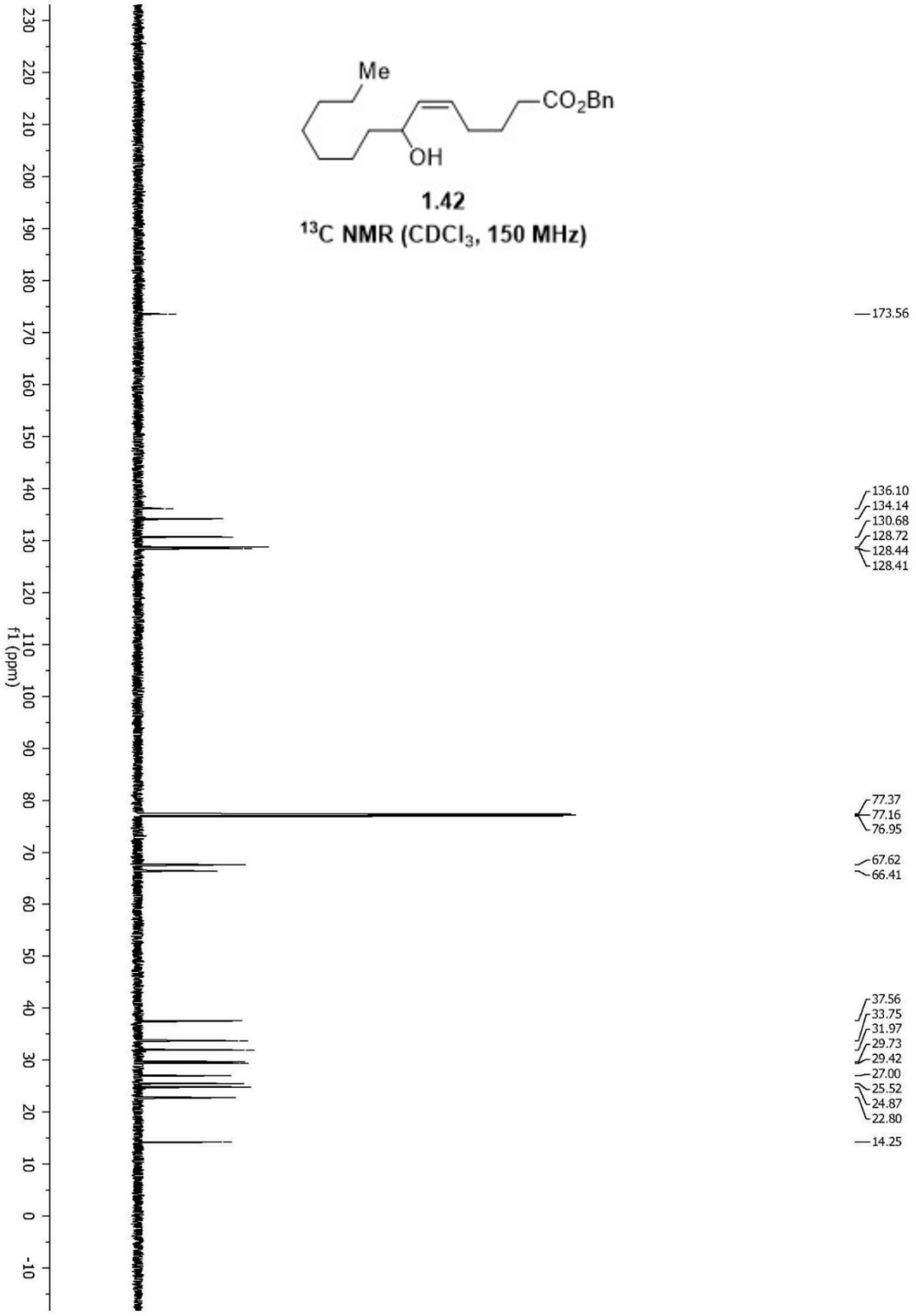

Me
O
CO2Bn
OH
1.40
1H NMR (CDCl3, 400 MHz)
f1 (ppm)
1.94
4.55
1.00
0.94
2.00
1.99
2.08
3.02
1.98
2.02
2.08
7.77
7.76
7.74
7.36
7.34
7.33
7.26
6.83
6.81
5.90
5.57
5.56
5.55
5.13
3.39
3.38
2.54
2.43
2.41
2.40
2.24
2.22
1.79
1.77
1.60

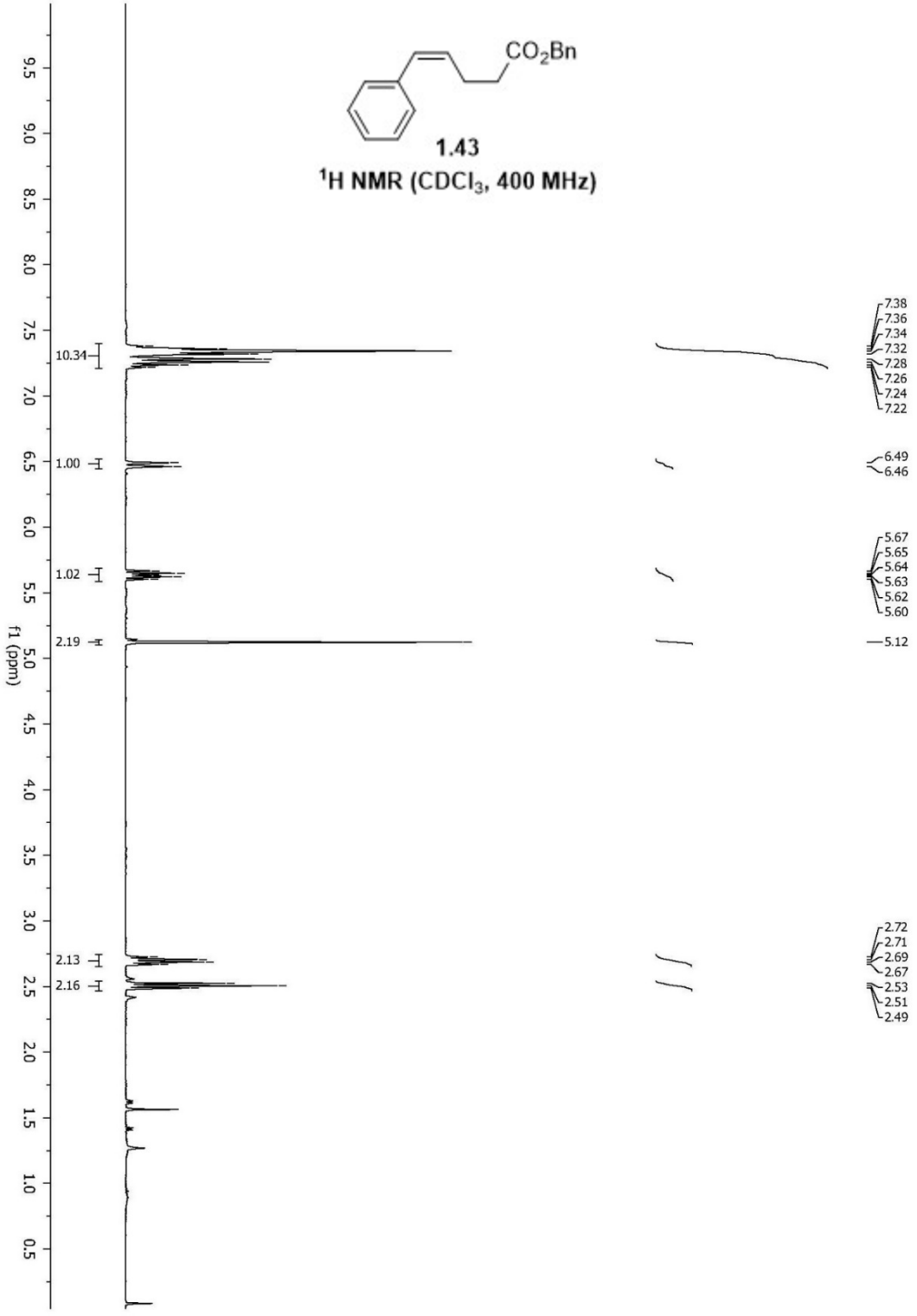

Me
O
CO2Bn
OH
1.40
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
197.89
173.95
159.18
135.98
130.99
128.69
128.37
127.16
115.49
77.37
77.16
77.16
76.95
66.49
33.82
28.18
26.68
26.43
24.84
130.91
130.15
127.89

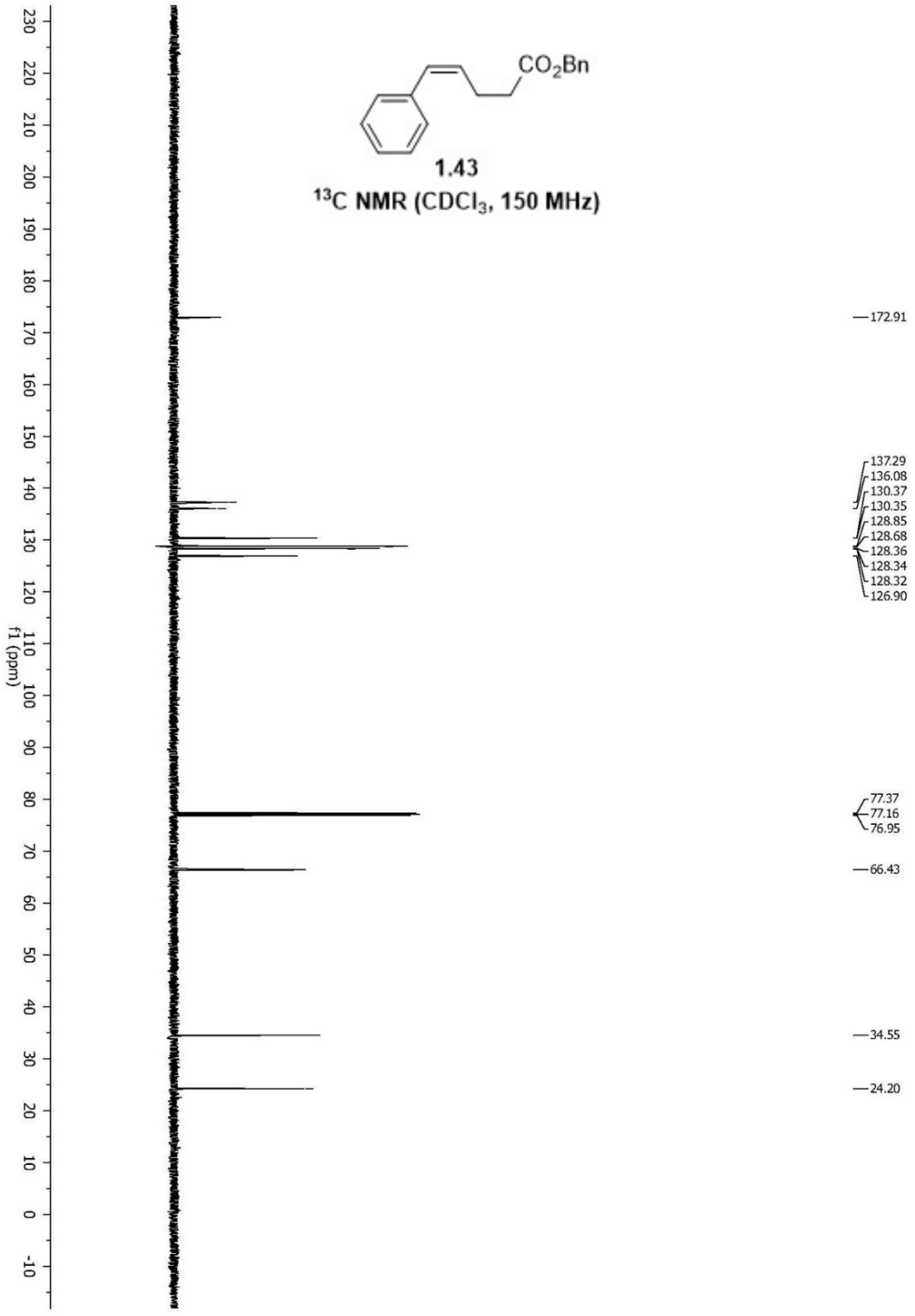

HO Me
Me
CO2Bn
Me
1.41
1H NMR (CDCl3, 500 MHz)
f1 (ppm)
4.30
1.00
2.96
3.09
2.09
2.39
3.22
10.76
3.20
7.38
7.35
7.33
7.32
7.26
5.29
5.27
5.26
5.24
5.17
5.15
5.13
5.11
2.39
2.37
2.36
2.09
2.08
2.06
2.05
1.74
1.72
1.68
1.43
1.42
1.40
1.30
1.26
1.18
0.92
0.90

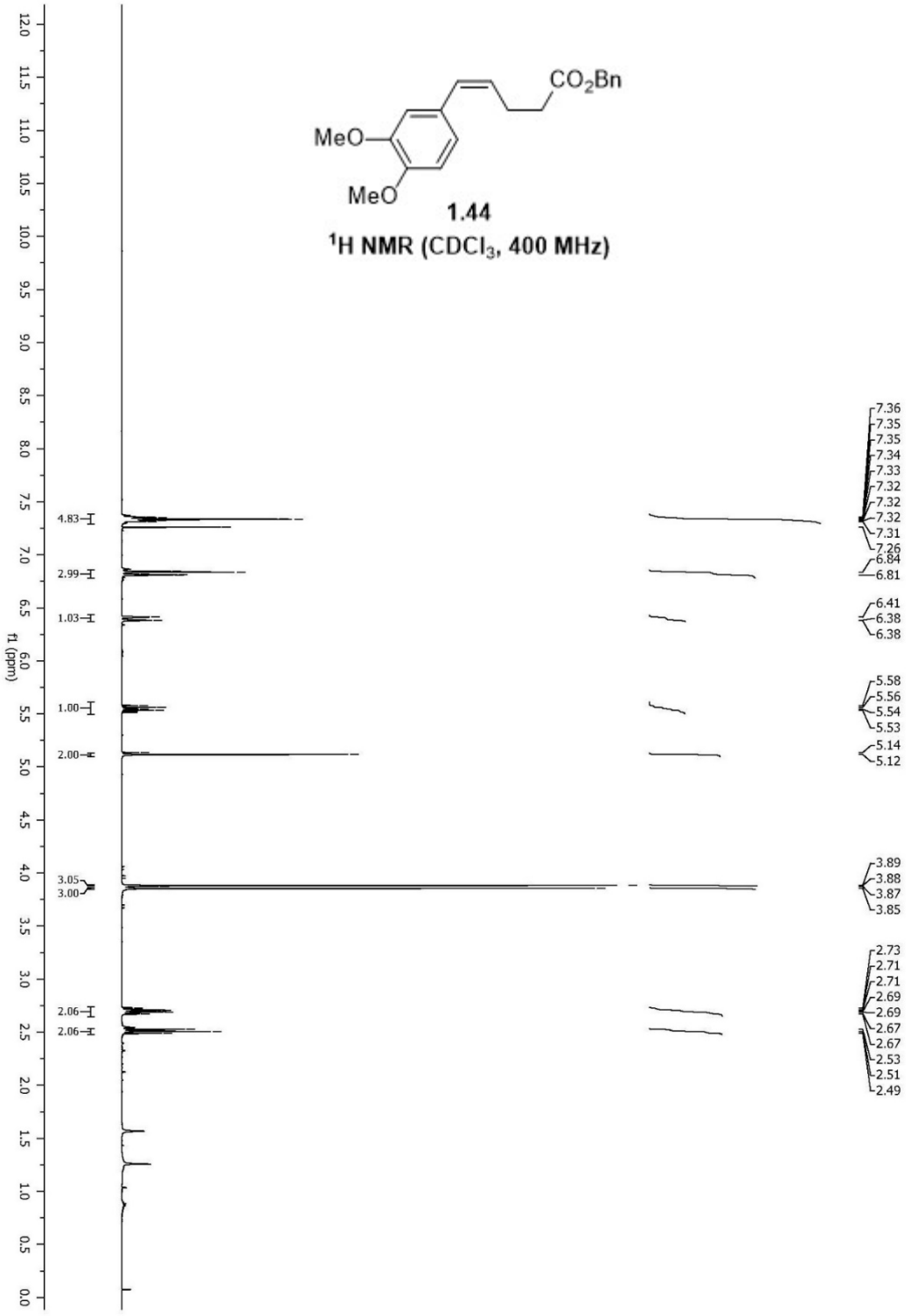

HO Me
Me
CO2Bn
Me
1.41
13C NMR (CDCl3, 125 MHz)
f1 (ppm)
173.61
137.45
136.18
128.66
128.35
128.30
127.18
77.41
77.16
76.91
71.05
66.27
44.19
38.08
33.88
31.82
29.38
29.29
26.98
25.16
22.37
21.51

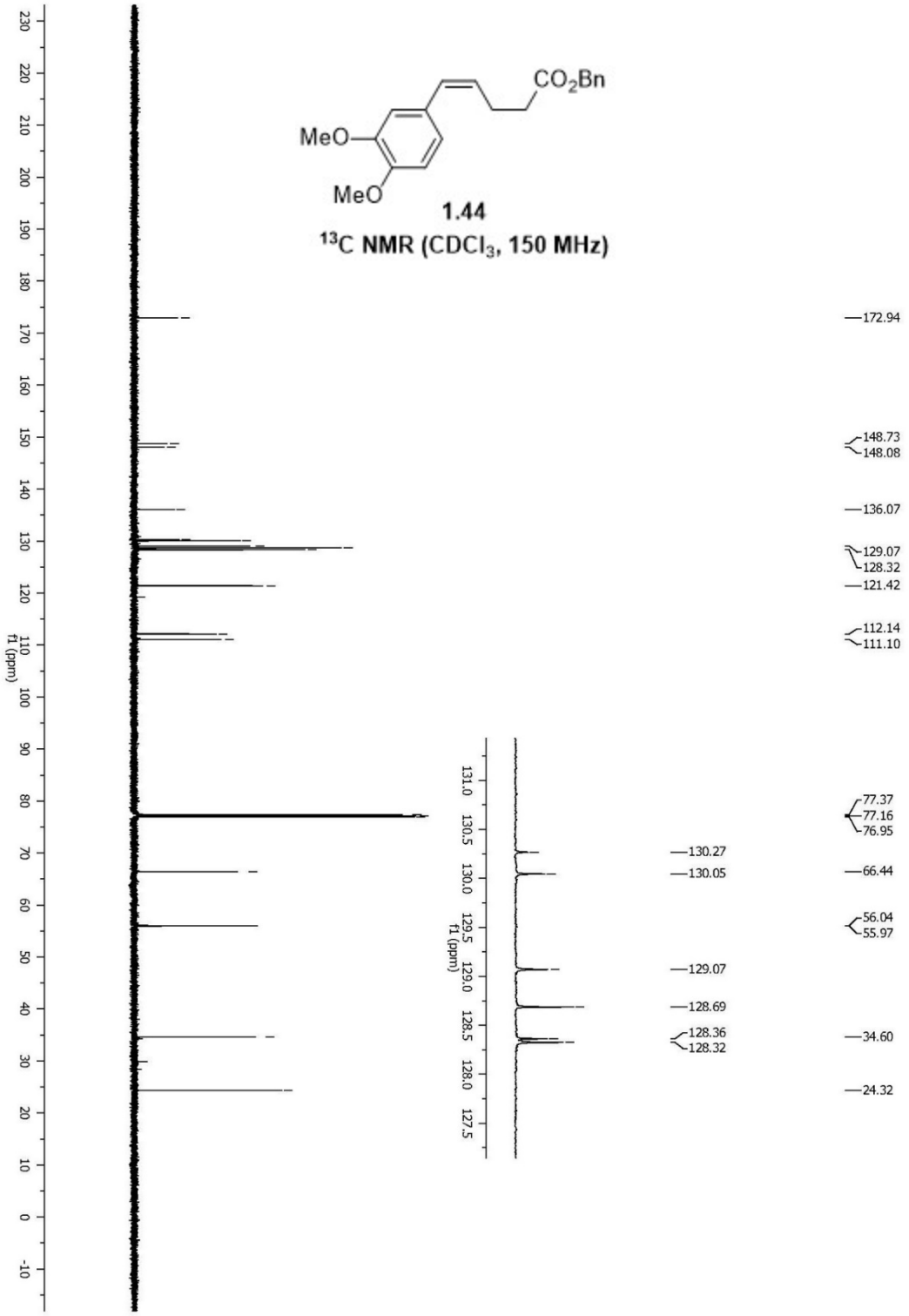

Me
CO2Bn
OH
1.42
1H NMR (CDCl3, 600 MHz)
f1 (ppm)
4.33
1.86
2.00
0.97
2.19
1.01
1.21
2.21
2.18
12.64
3.11
7.38
7.37
7.36
7.33
7.26
5.44
5.42
5.41
5.40
5.38
5.12
4.36
4.34
4.33
4.32
2.39
2.38
2.37
2.19
2.18
2.15
2.12
2.10
2.07
1.77
1.75
1.69
1.57
1.56
1.55
1.42
1.41
1.39
1.29
1.27
0.89
0.88
0.87

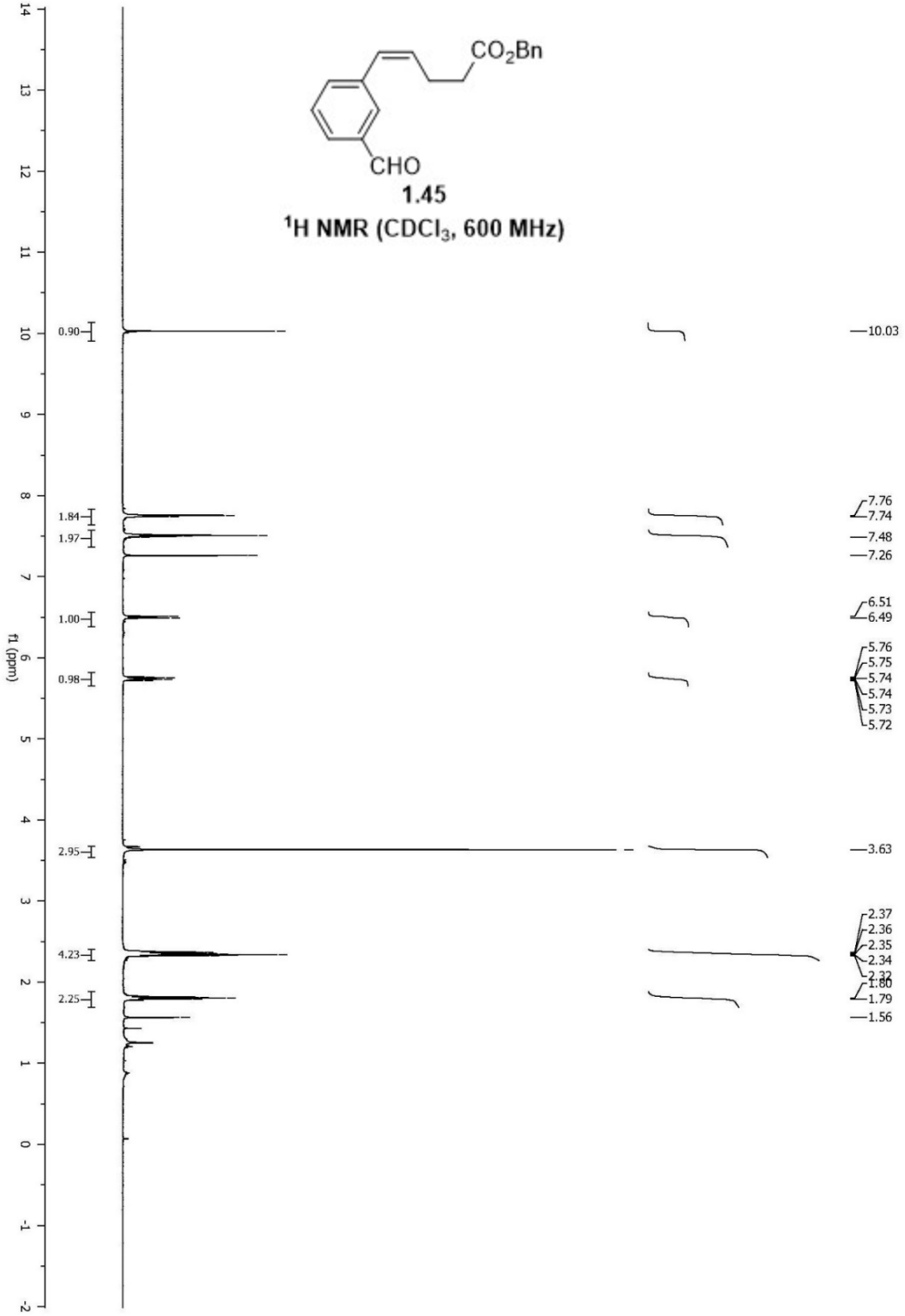

Me
CO2Bn
OH
1.42
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
173.56
136.10
134.14
130.68
128.72
128.44
128.41
77.37
77.16
76.95
67.62
66.41
37.56
33.75
31.97
29.73
29.42
27.00
25.52
24.87
22.80
14.25

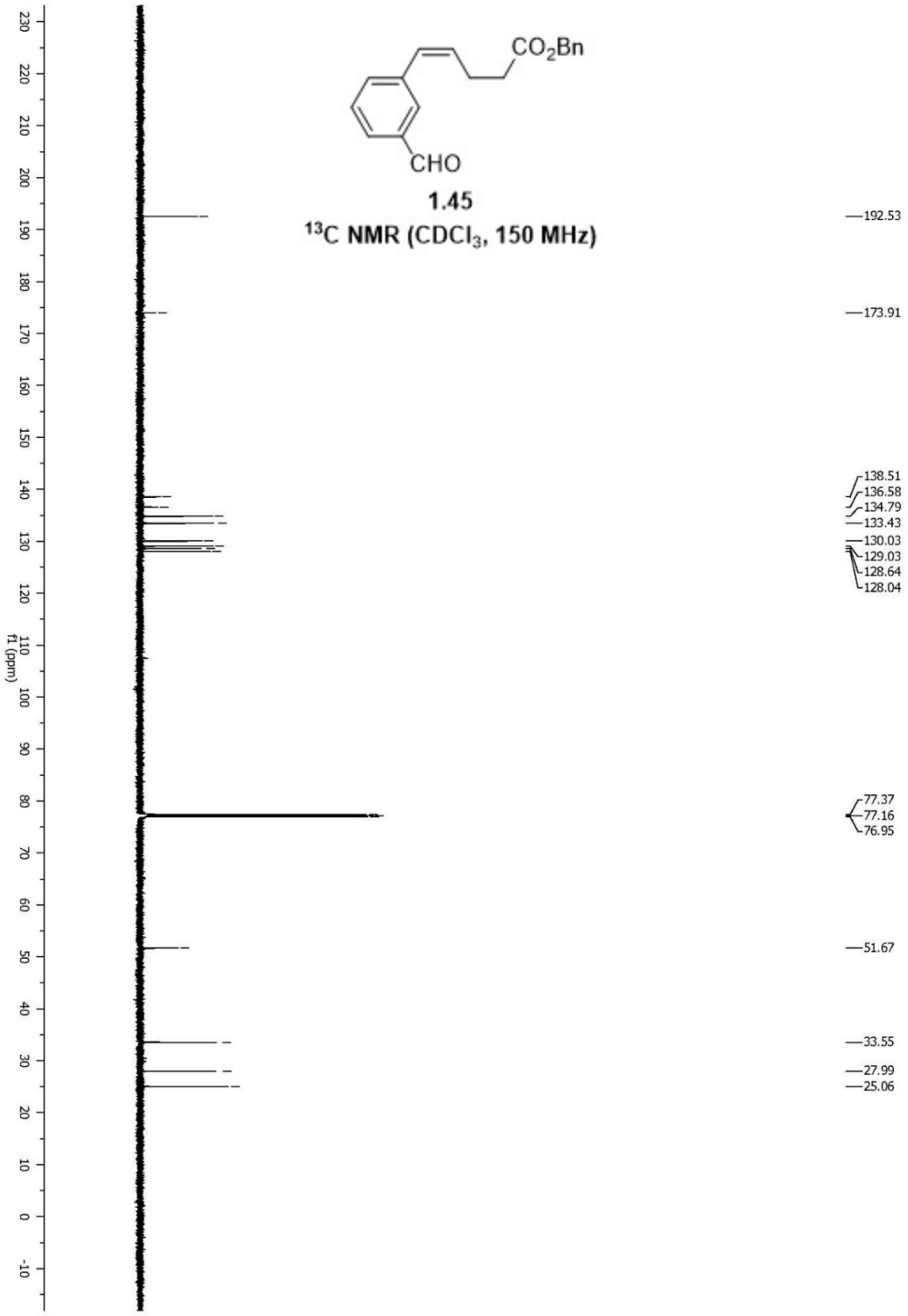

CO2Bn
1.43
1H NMR (CDCl3, 400 MHz)
f1 (ppm)
10.34
1.00
1.02
2.19
2.13
2.16
7.38
7.36
7.34
7.32
7.28
7.26
7.24
7.22
6.49
6.46
5.67
5.65
5.64
5.63
5.62
5.60
5.12
2.72
2.71
2.69
2.67
2.53
2.51
2.49

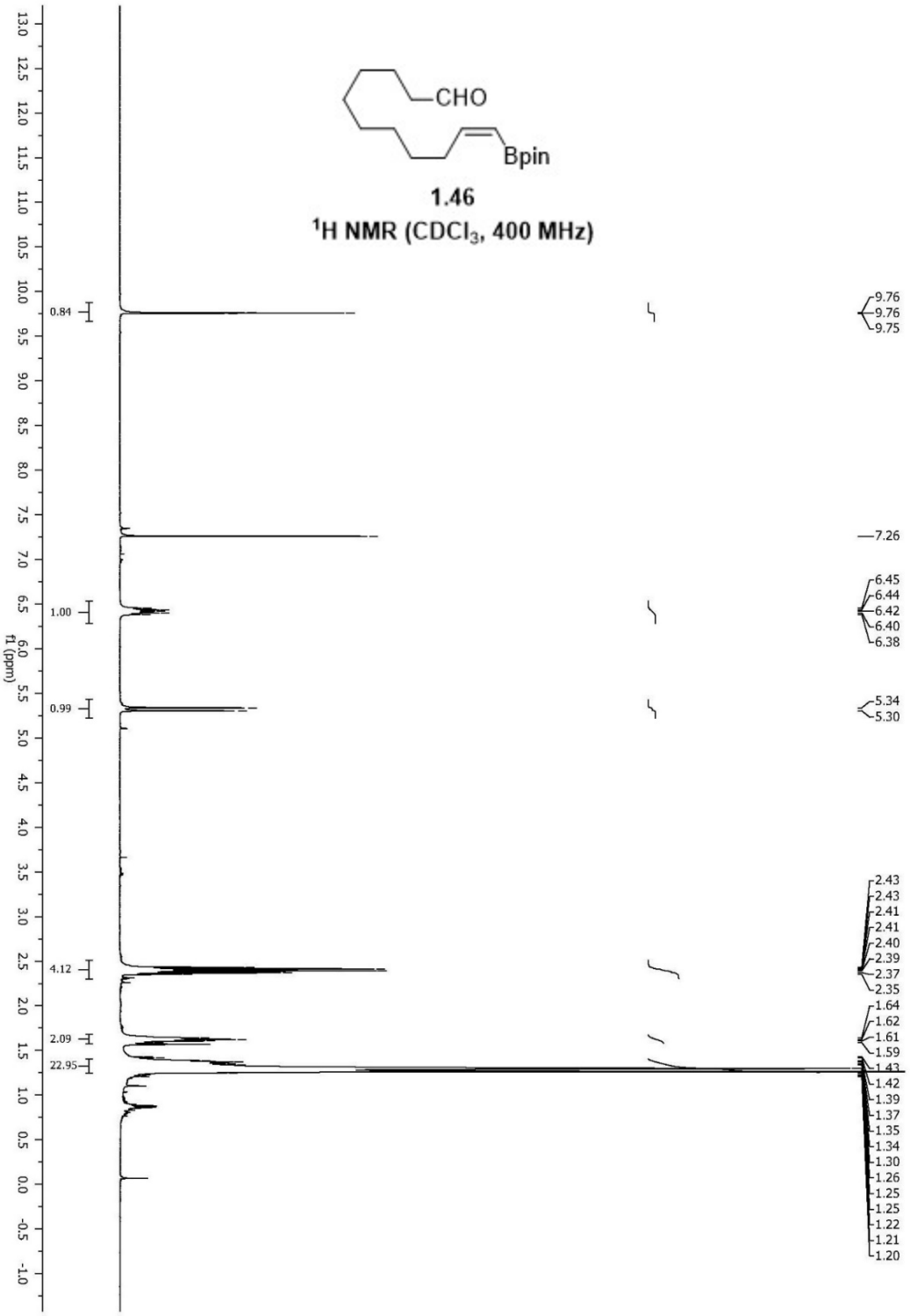

CO2Bn
1.43
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
172.91
137.29
136.08
130.37
130.35
128.85
128.68
128.36
128.34
128.32
126.90
77.37
77.16
76.95
66.43
34.55
24.20

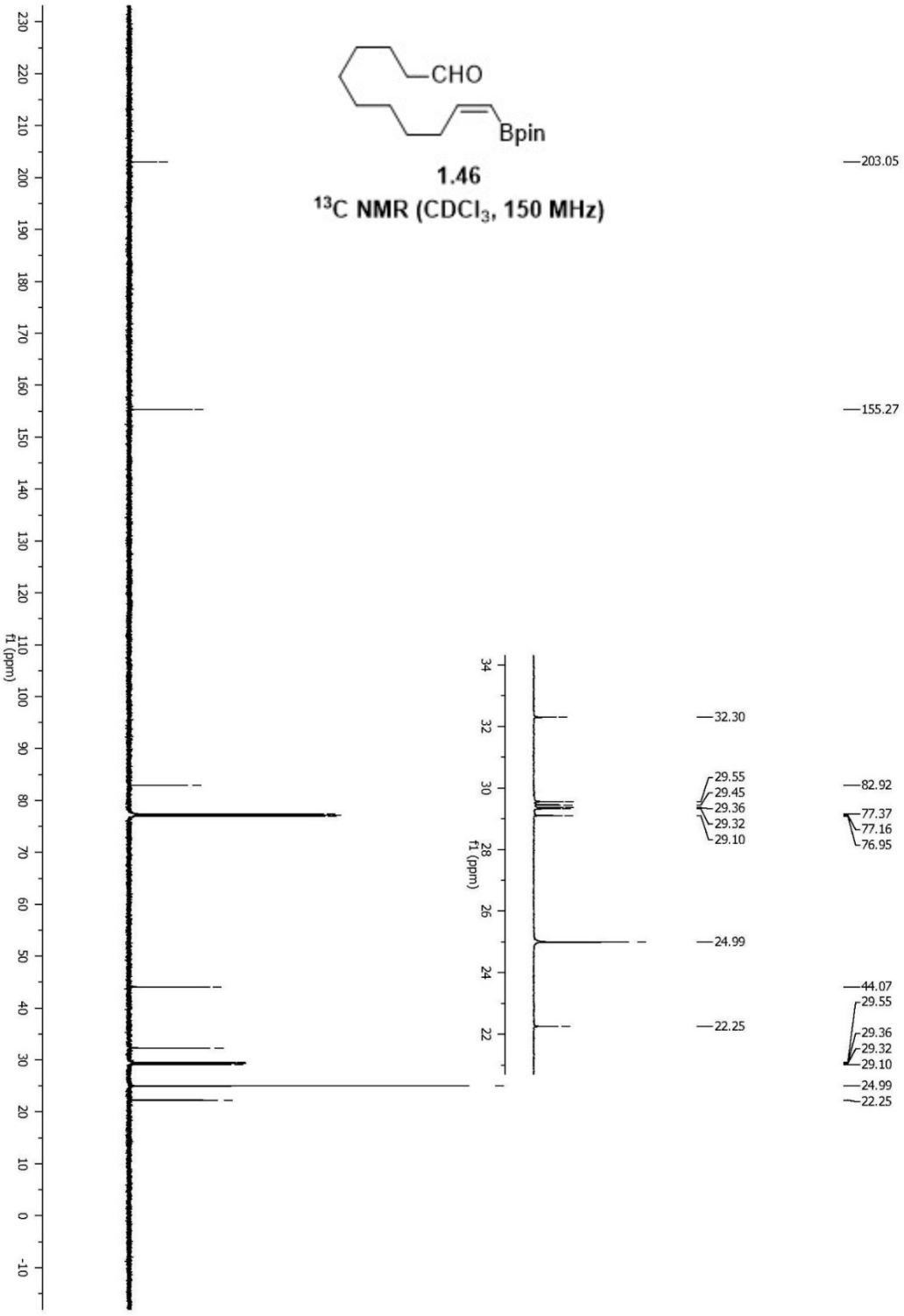

CO2Bn
MeO
MeO
1.44
1H NMR (CDCl3, 400 MHz)
f1 (ppm)
4.83
2.99
1.03
1.00
2.00
3.05
3.00
2.06
2.06
7.36
7.35
7.35
7.34
7.33
7.32
7.32
7.32
7.31
7.26
6.84
6.81
6.41
6.38
6.38
5.58
5.56
5.54
5.53
5.14
5.12
3.89
3.88
3.87
3.85
2.73
2.71
2.71
2.69
2.69
2.67
2.67
2.53
2.51
2.49

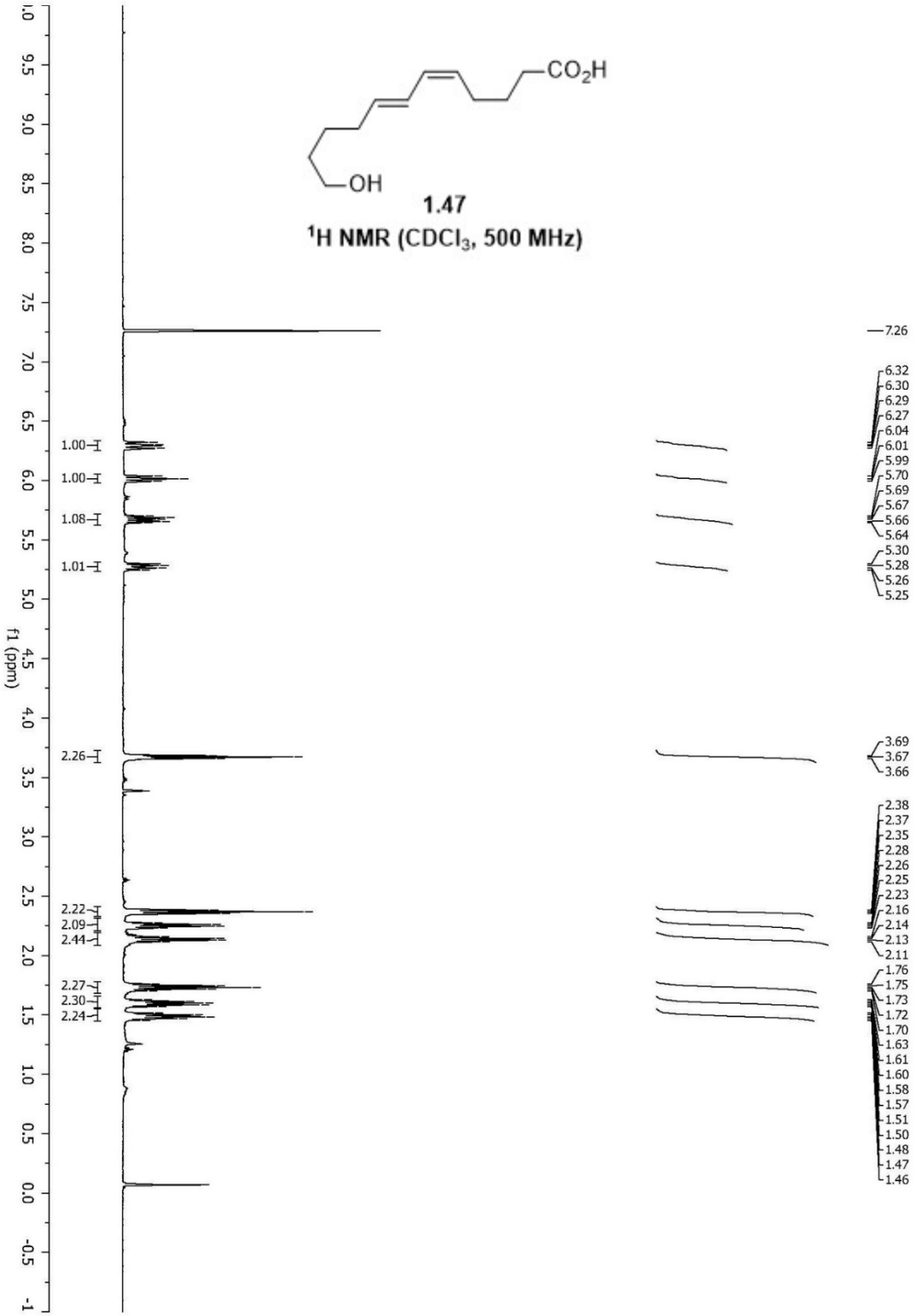

CO2Bn
MeO
MeO
1.44
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
172.94
148.73
148.08
136.07
129.07
128.32
121.42
112.14
111.10
77.37
77.16
76.95
130.27
130.05
66.44
56.04
55.97
129.07
128.69
128.36
128.32
34.60
24.32

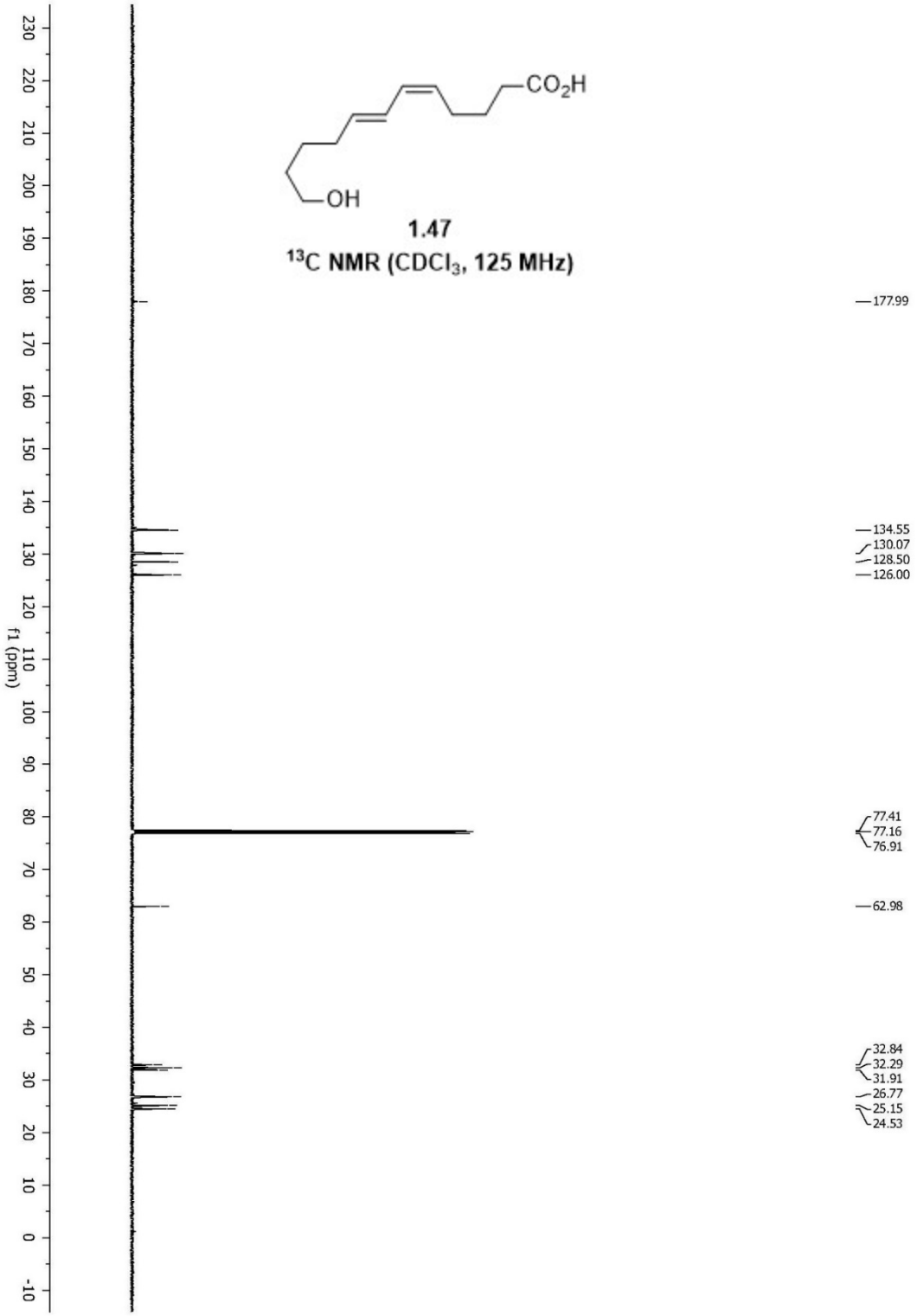

CO2Bn
CHO
1.45
1H NMR (CDCl3, 600 MHz)
f1 (ppm)
0.90
1.84
1.97
1.00
0.98
2.95
4.23
2.25
10.03
7.76
7.74
7.48
7.26
6.51
6.49
5.76
5.75
5.74
5.74
5.73
5.72
3.63
2.37
2.36
2.35
2.34
2.32
1.80
1.79
1.56

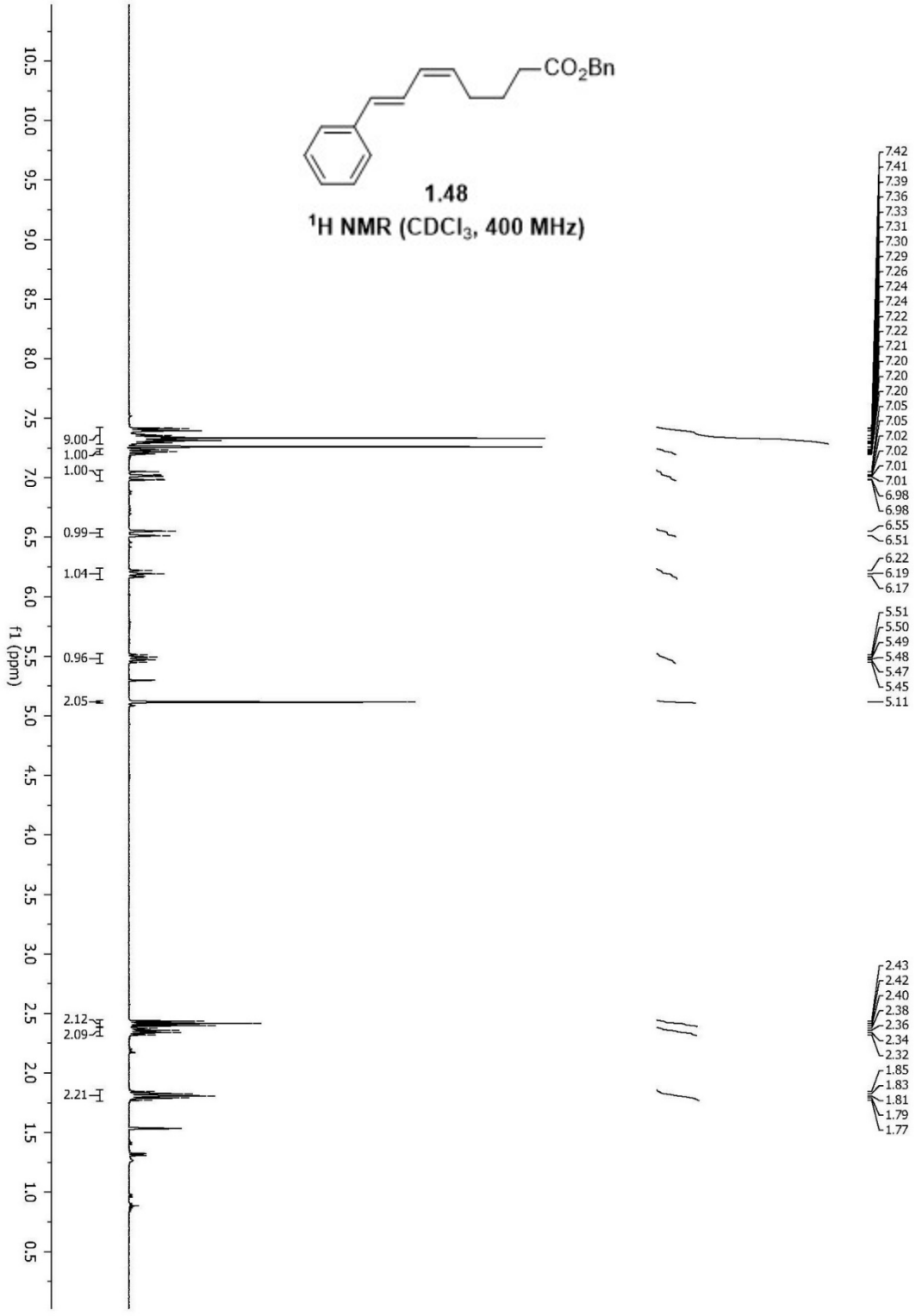

CO2Bn
CHO
1.45
13C NMR (CDCl3, 150 MHz)
192.53
173.91
138.51
136.58
134.79
133.43
130.03
129.03
128.64
128.04
77.37
77.16
76.95
51.67
33.55
27.99
25.06
f1 (ppm)

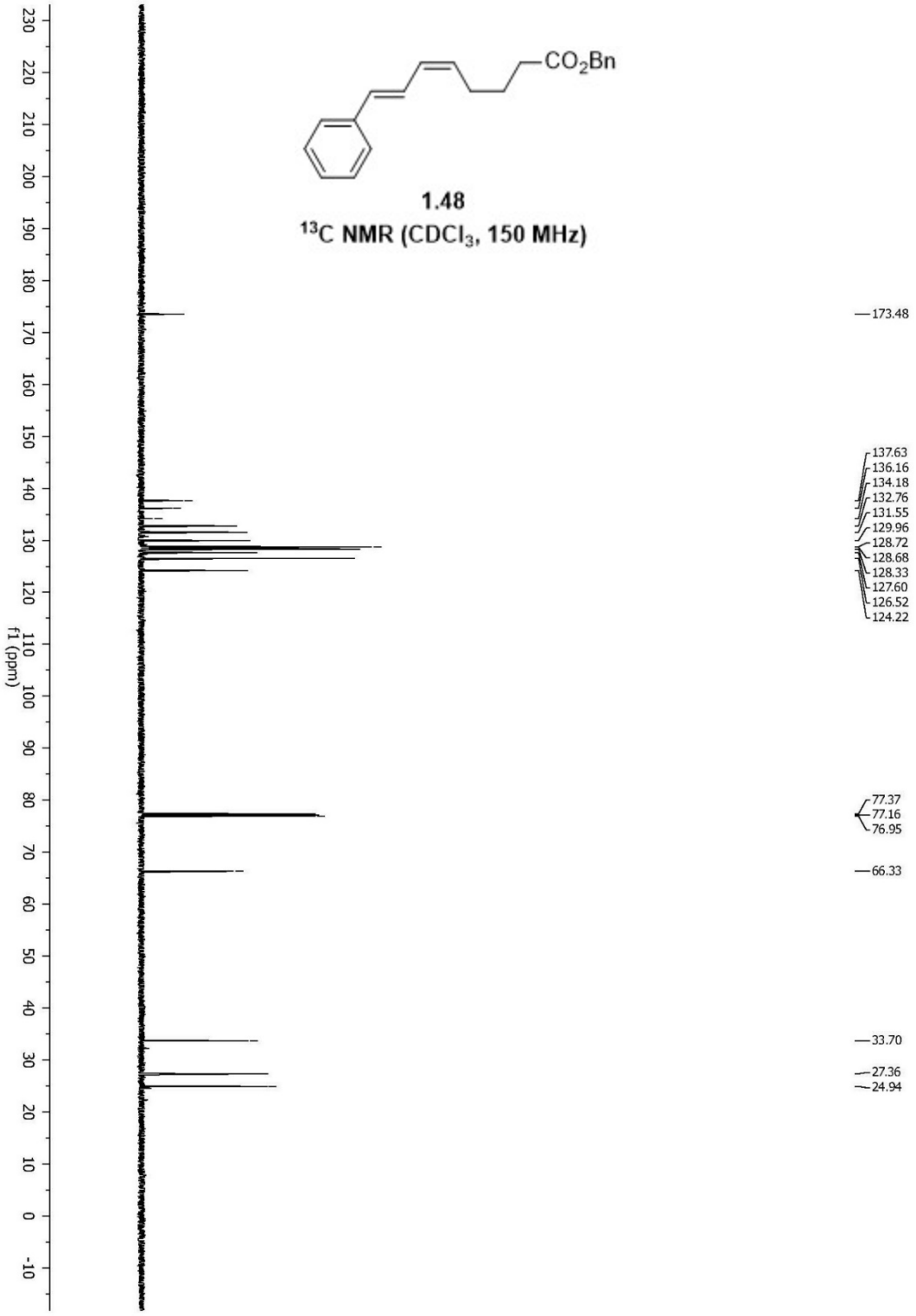

CHO
Bpin
1.46
¹H NMR (CDCl₃, 400 MHz)
f1 (ppm)
0.84
1.00
0.99
4.12
2.09
22.95
9.76
9.76
9.75
7.26
6.45
6.44
6.42
6.40
6.38
5.34
5.30
2.43
2.43
2.41
2.41
2.40
2.39
2.37
2.35
1.64
1.62
1.61
1.59
1.43
1.42
1.39
1.37
1.35
1.34
1.30
1.26
1.25
1.25
1.22
1.21
1.20

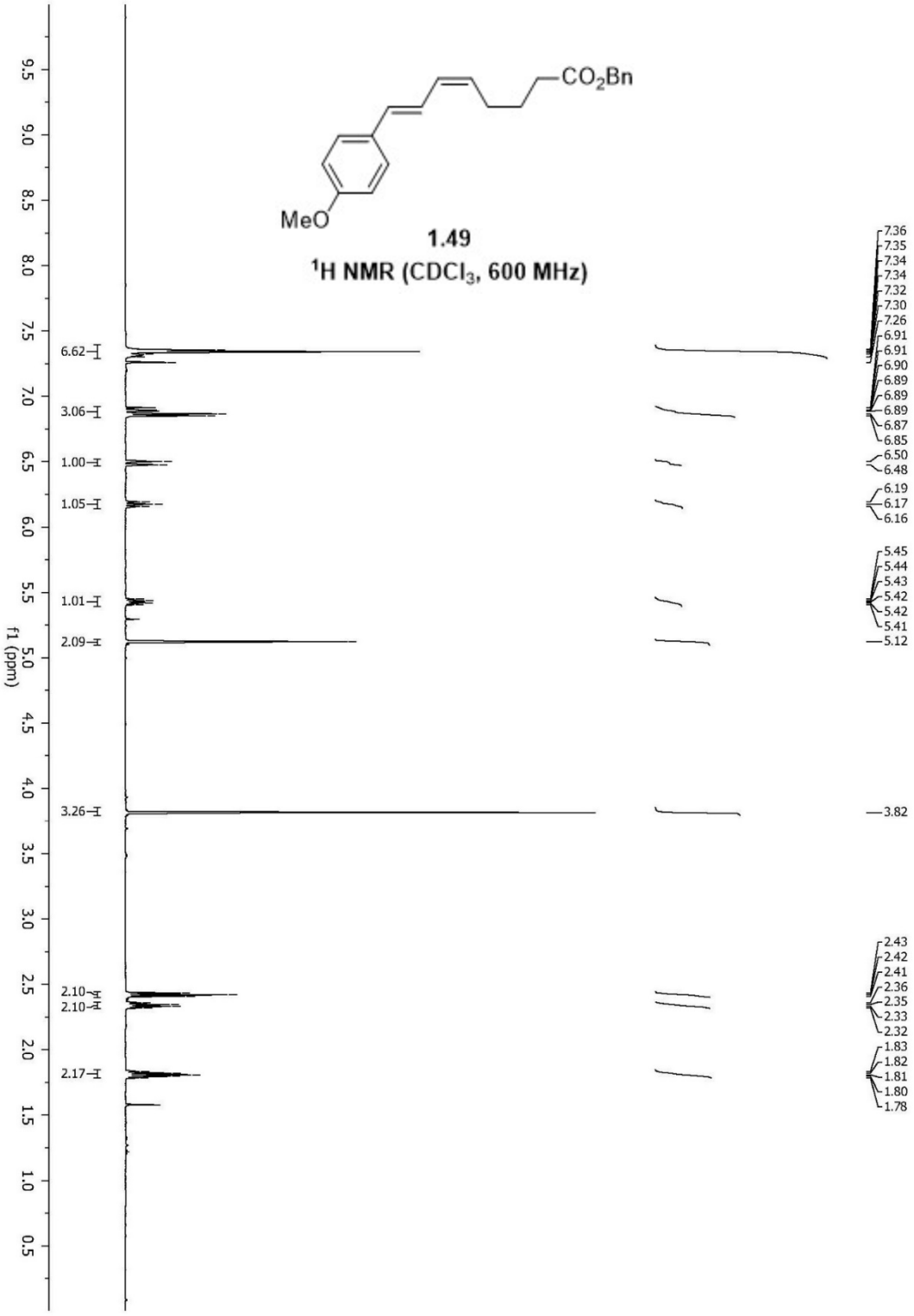

CHO
Bpin
1.46
^{13}C NMR ($CDCl_3$, 150 MHz)
f1 (ppm)
203.05
155.27
32.30
29.55
29.45
29.36
29.32
29.10
24.99
22.25
82.92
77.37
77.16
76.95
44.07
29.55
29.36
29.32
29.10
24.99
22.25

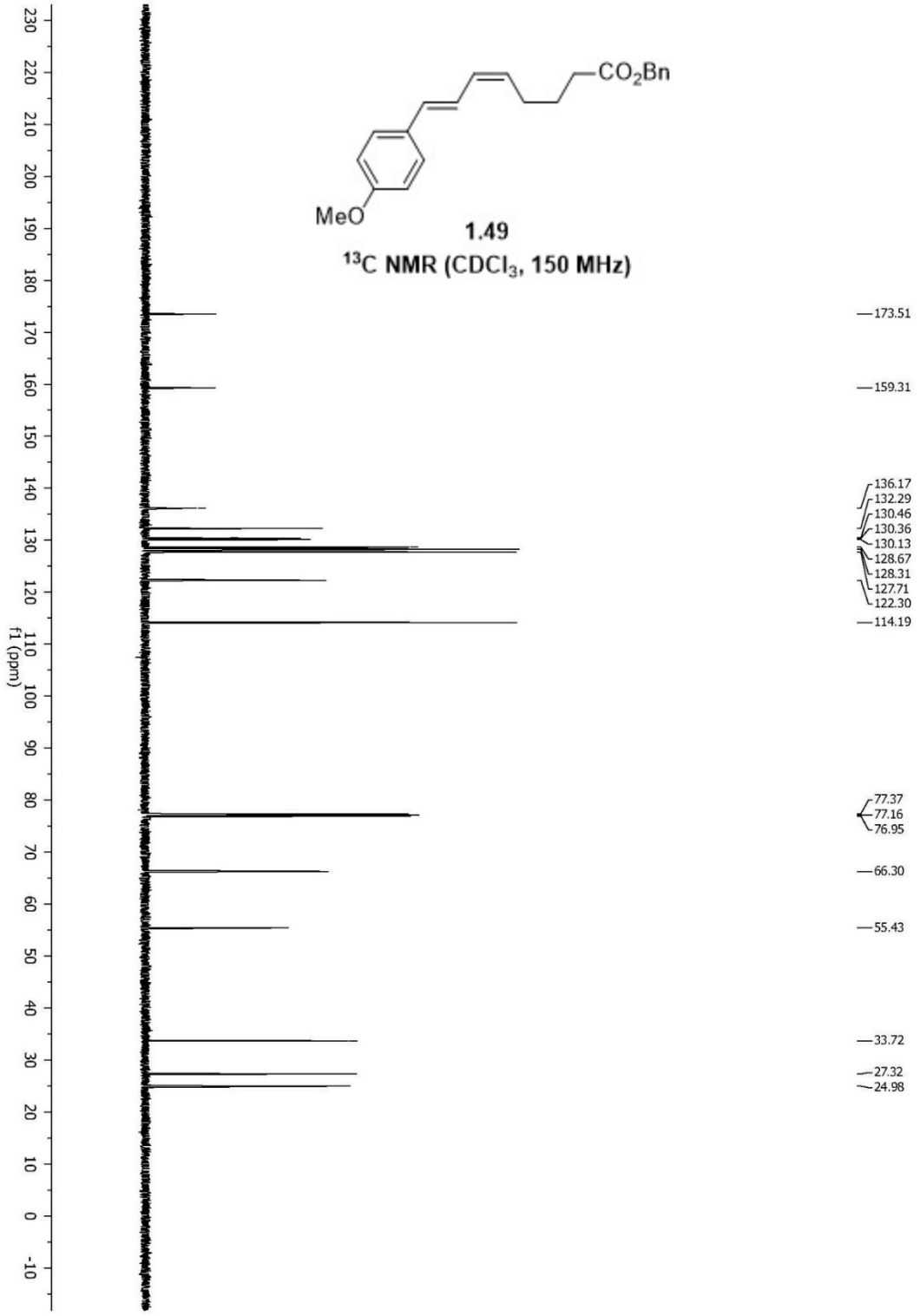

CO2H
OH
1.47
1H NMR (CDCl3, 500 MHz)
f1 (ppm)
1.00
1.00
1.08
1.01
2.26
2.22
2.09
2.44
2.27
2.30
2.24
7.26
6.32
6.30
6.29
6.27
6.04
6.01
5.99
5.70
5.69
5.67
5.66
5.64
5.30
5.28
5.26
5.25
3.69
3.67
3.66
2.38
2.37
2.35
2.28
2.26
2.25
2.23
2.16
2.14
2.13
2.11
1.76
1.75
1.73
1.72
1.70
1.63
1.61
1.60
1.58
1.57
1.51
1.50
1.48
1.47
1.46

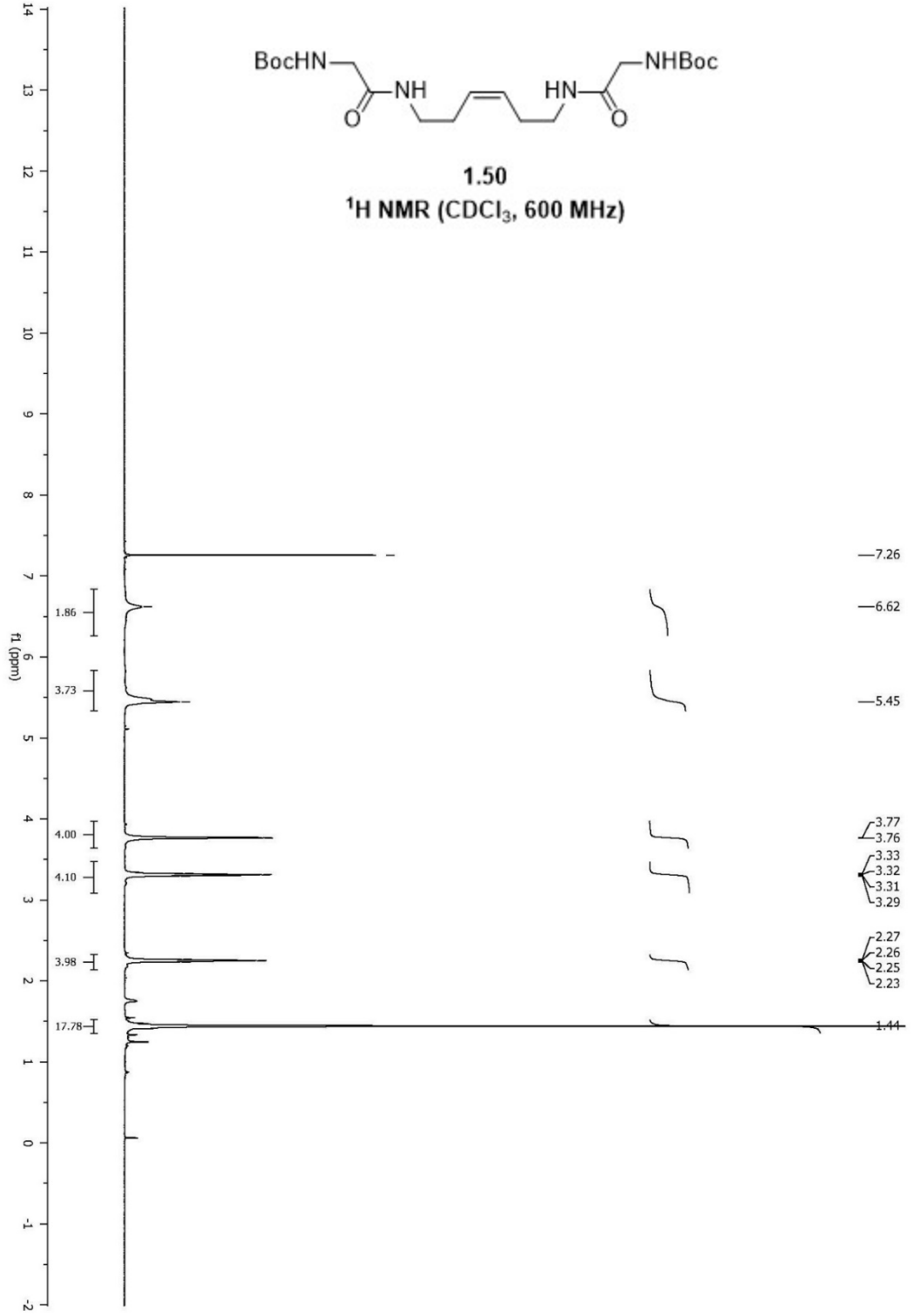

CO2H
OH
1.47
13C NMR (CDCl3, 125 MHz)
177.99
134.55
130.07
128.50
126.00
77.41
77.16
76.91
62.98
32.84
32.29
31.91
26.77
25.15
24.53
f1 (ppm)

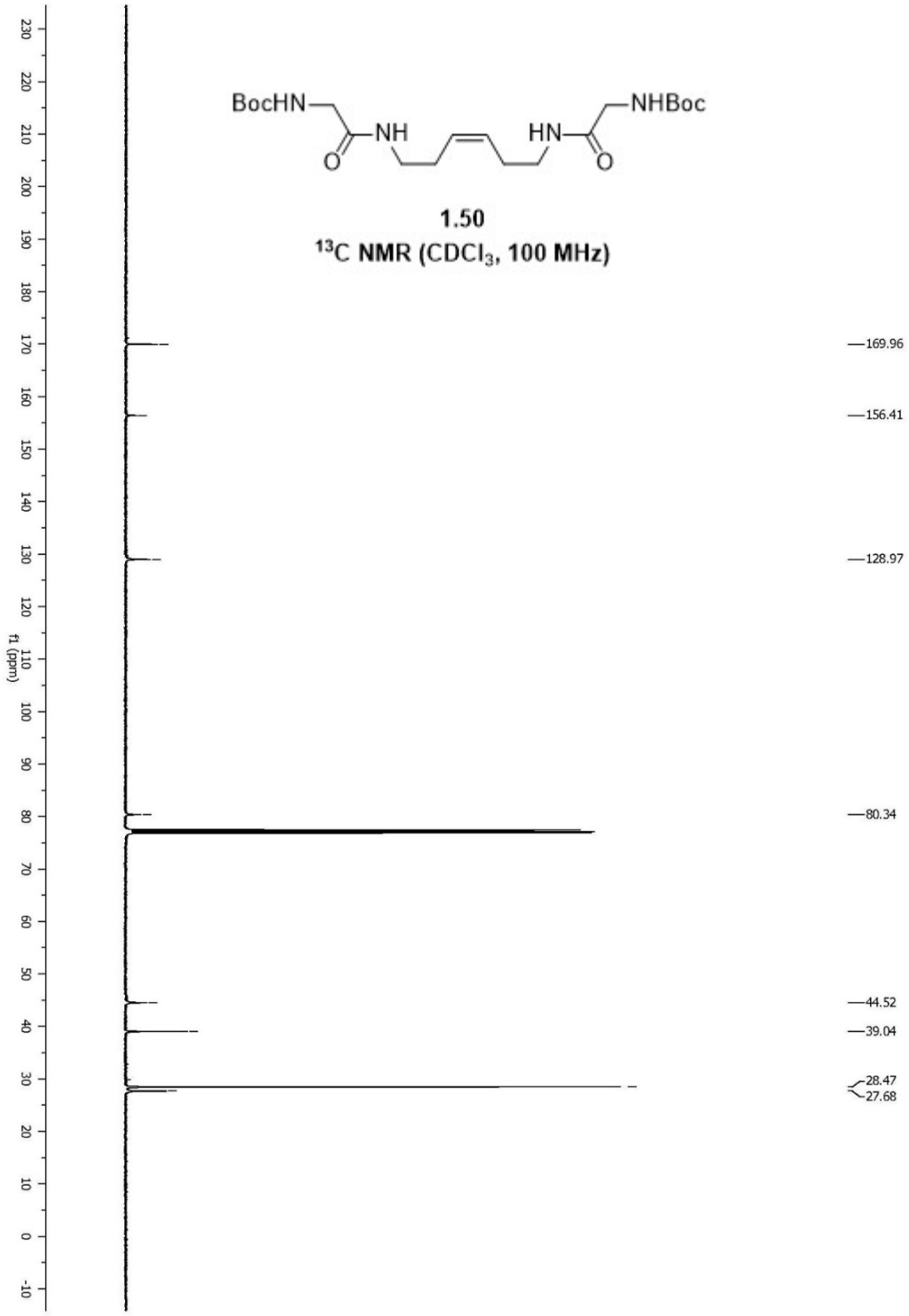

CO2Bn
1.48
1H NMR (CDCl3, 400 MHz)
f1 (ppm)
9.00
1.00
1.00
0.99
1.04
0.96
2.05
2.12
2.09
2.21
7.42
7.41
7.39
7.36
7.33
7.31
7.30
7.29
7.26
7.24
7.24
7.22
7.22
7.21
7.20
7.20
7.20
7.05
7.05
7.02
7.02
7.01
7.01
6.98
6.98
6.55
6.51
6.22
6.19
6.17
5.51
5.50
5.49
5.48
5.47
5.45
5.11
2.43
2.42
2.40
2.38
2.36
2.34
2.32
1.85
1.83
1.81
1.79
1.77

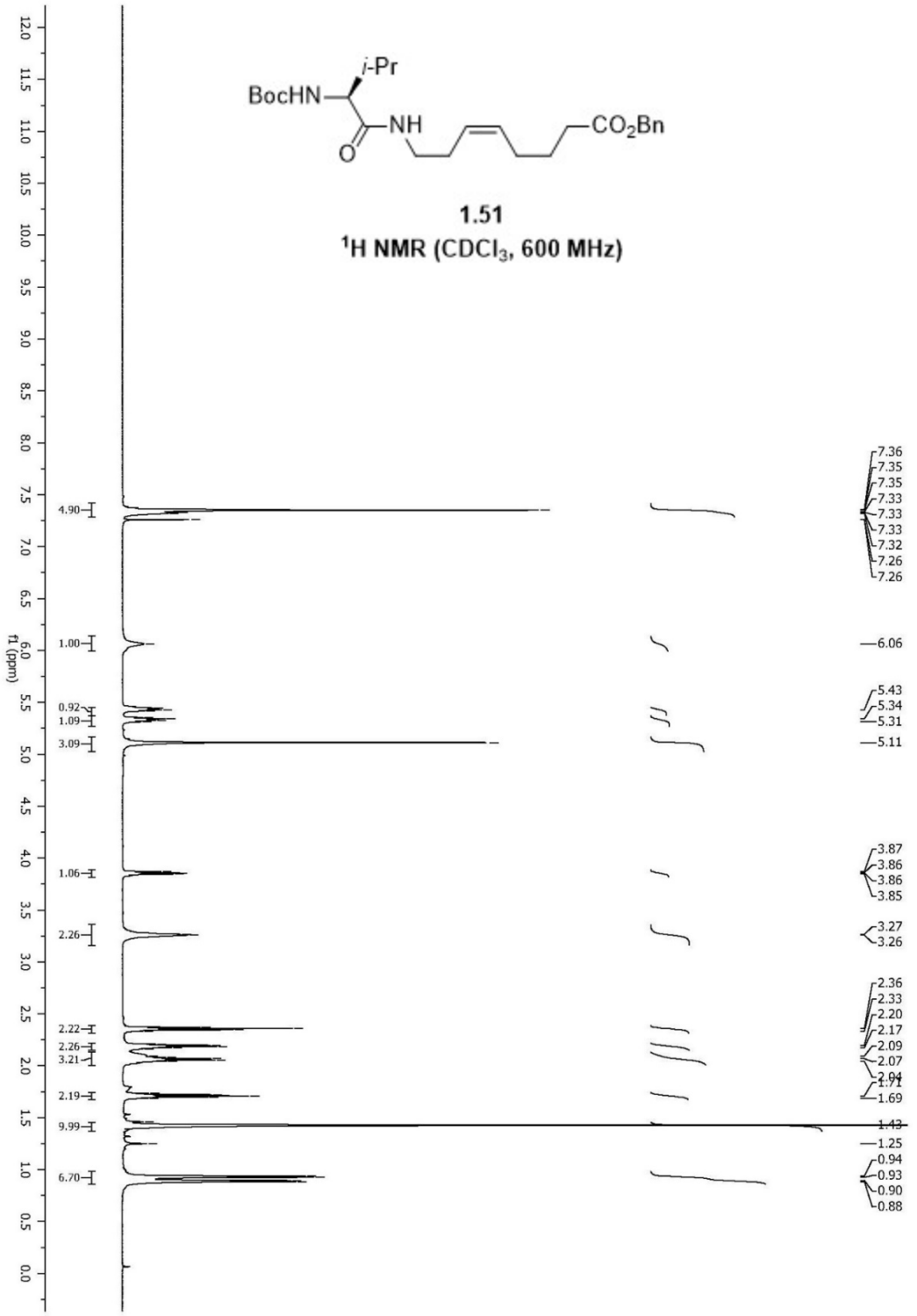

CO2Bn
1.48
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
173.48
137.63
136.16
134.18
132.76
131.55
129.96
128.72
128.68
128.33
127.60
126.52
124.22
77.37
77.16
76.95
66.33
33.70
27.36
24.94

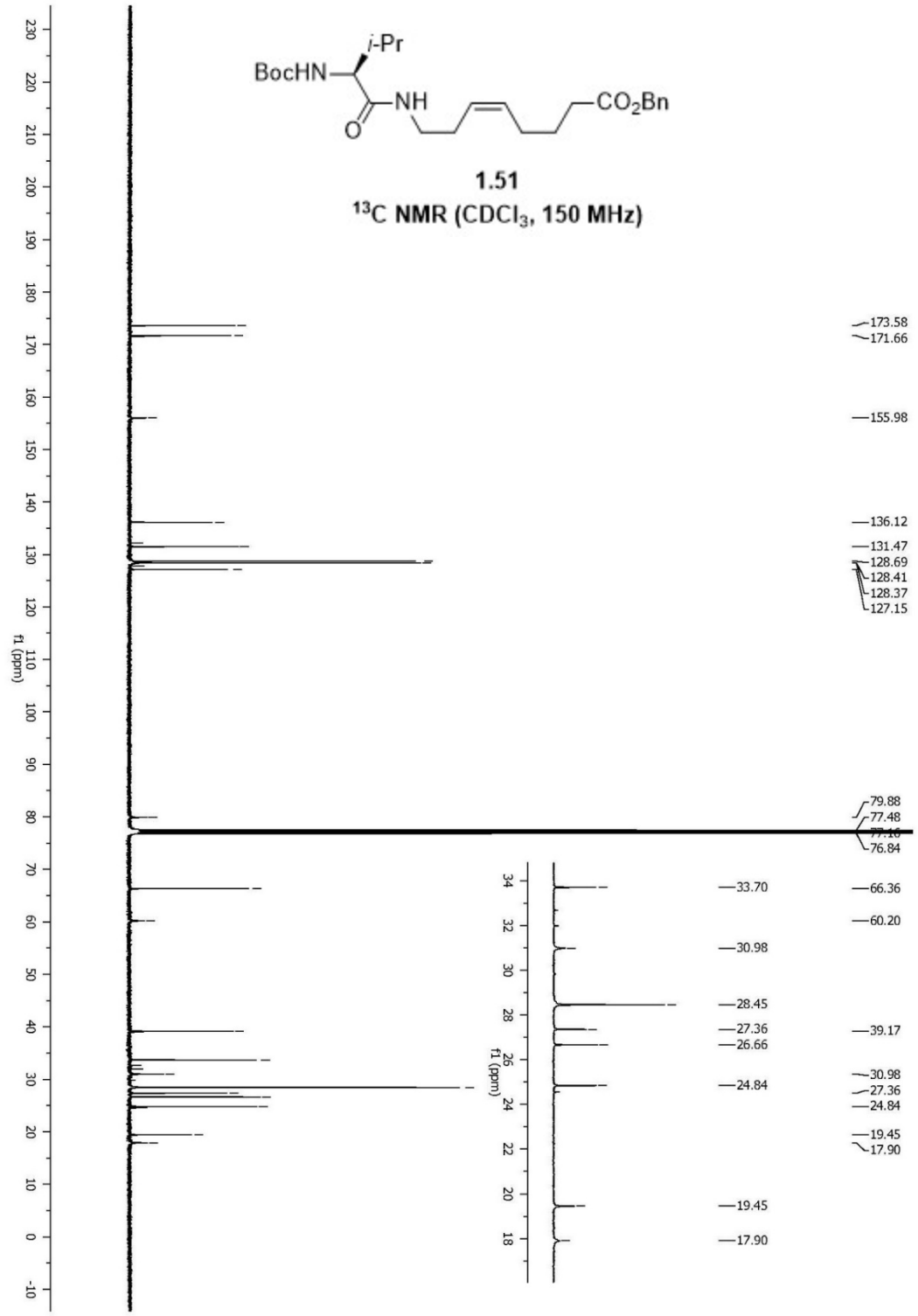

CO2Bn
MeO
1.49
1H NMR (CDCl3, 600 MHz)
f1 (ppm)
6.62
3.06
1.00
1.05
1.01
2.09
3.26
2.10
2.10
2.17
7.36
7.35
7.34
7.34
7.32
7.30
7.26
6.91
6.91
6.90
6.89
6.89
6.89
6.87
6.85
6.50
6.48
6.19
6.17
6.16
5.45
5.44
5.43
5.42
5.42
5.41
5.12
3.82
2.43
2.42
2.41
2.36
2.35
2.33
2.32
1.83
1.82
1.81
1.80
1.78

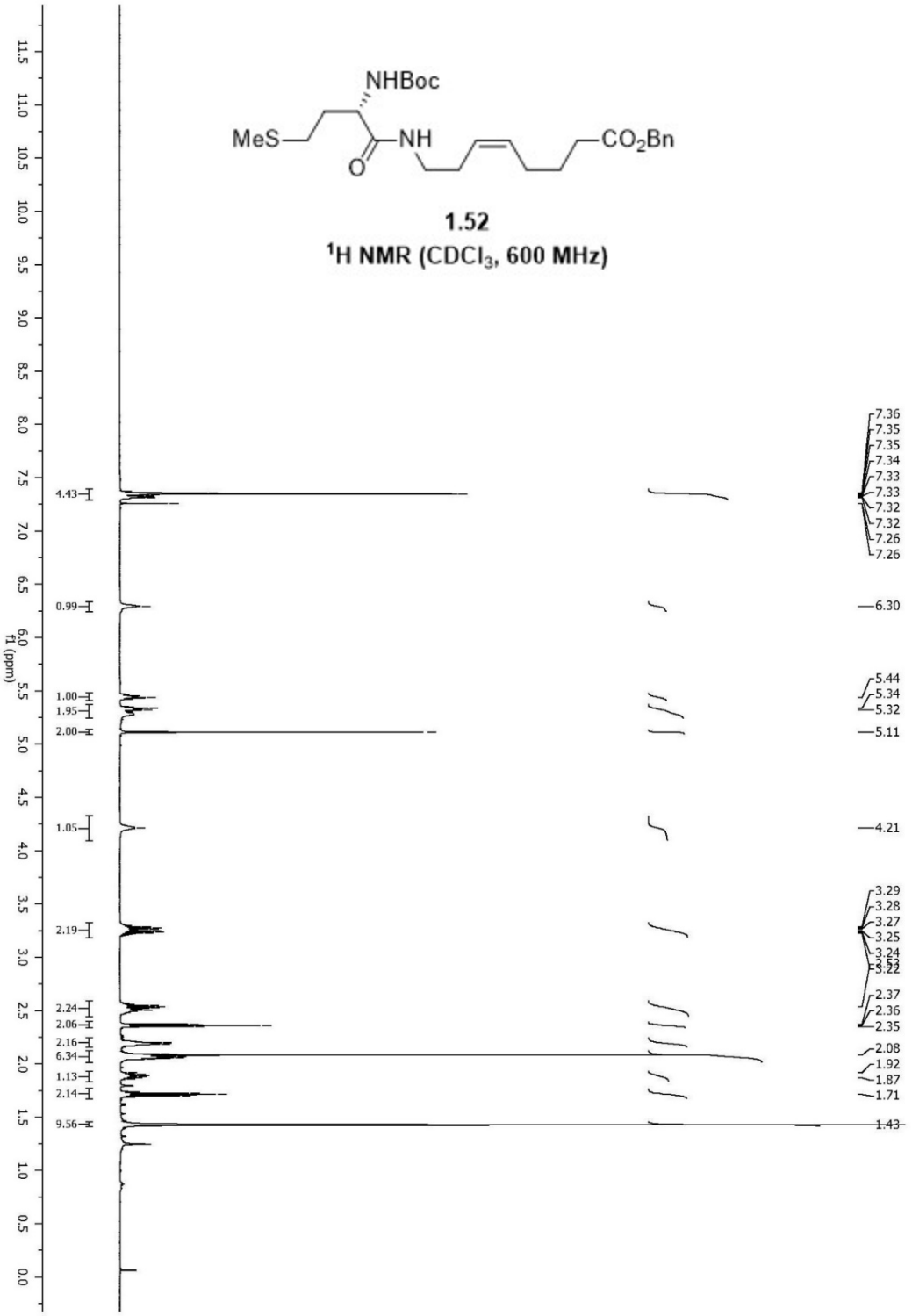

CO2Bn
MeO
1.49
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
173.51
159.31
136.17
132.29
130.46
130.36
130.13
128.67
128.31
127.71
122.30
114.19
77.37
77.16
76.95
66.30
55.43
33.72
27.32
24.98

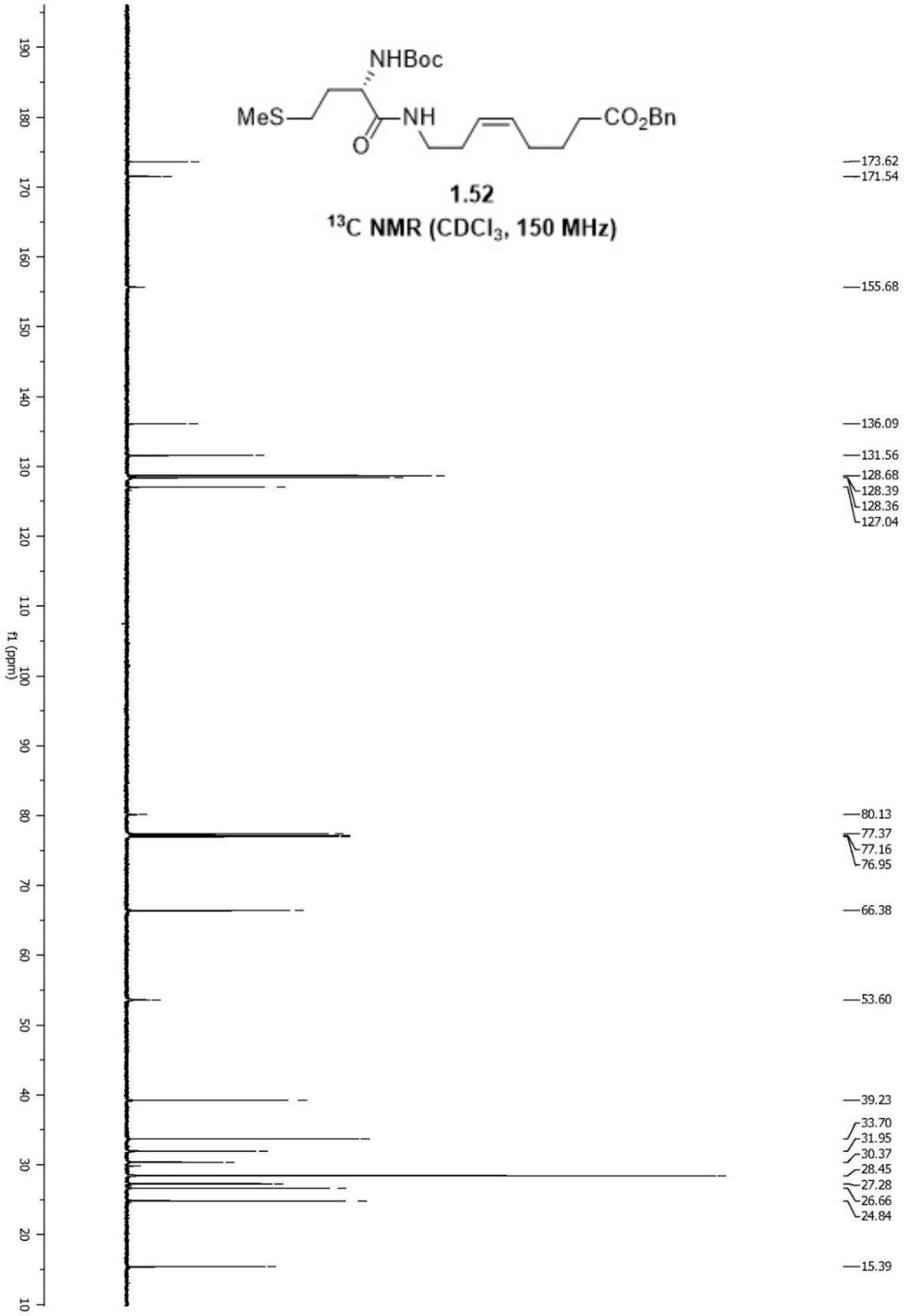

BocHN
NH
HN
NHBoc
O
O
1.50
^{1}H NMR ($CDCl_3$, 600 MHz)
f1 (ppm)
1.86
3.73
4.00
4.10
3.98
17.78
7.26
6.62
5.45
3.77
3.76
3.33
3.32
3.31
3.29
2.27
2.26
2.25
2.23
1.44

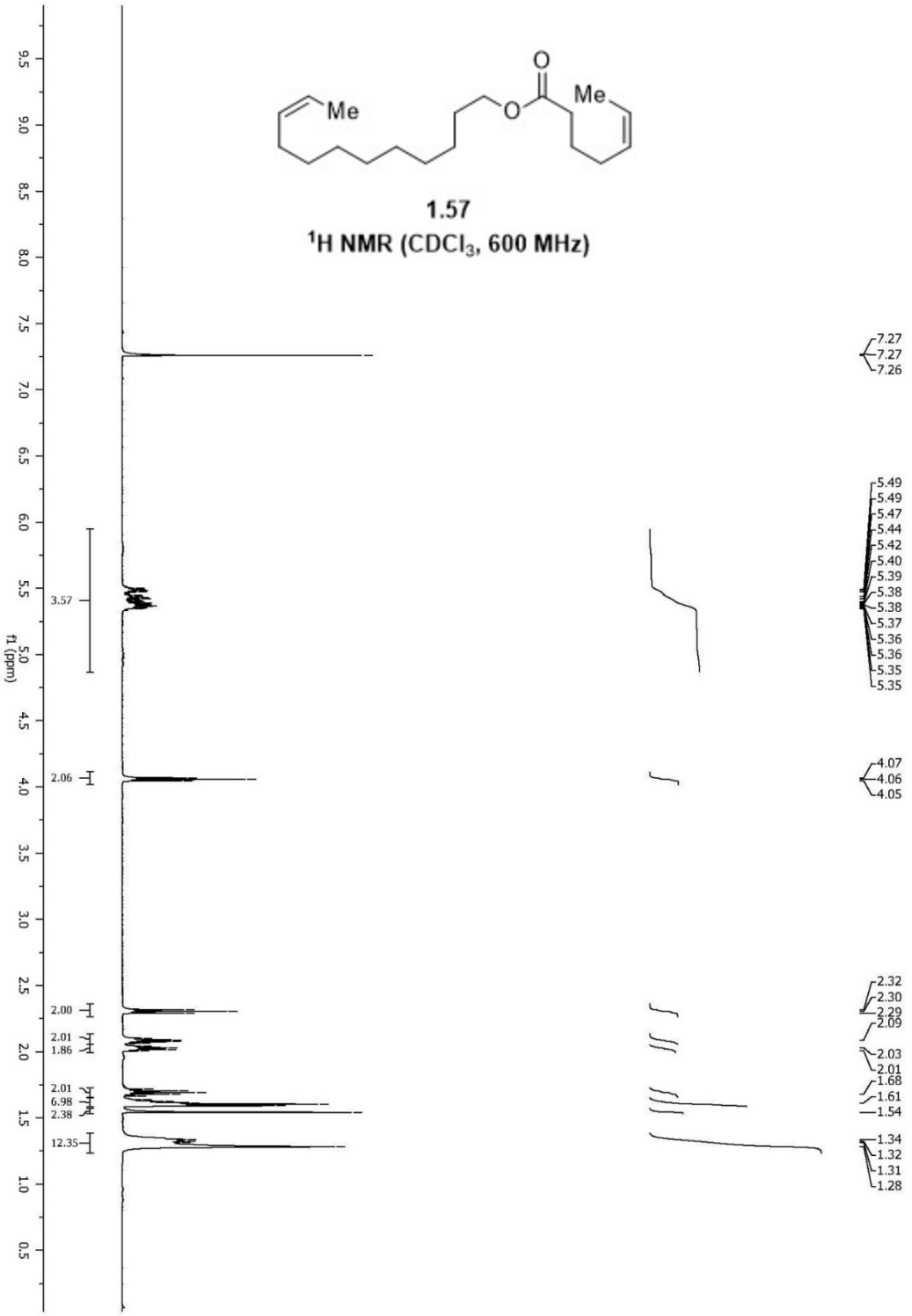

BocHN
NH
HN
NHBoc
O
O
1.50
^{13}C NMR ($CDCl_3$, 100 MHz)
f1 (ppm)
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
169.96
156.41
128.97
80.34
44.52
39.04
28.47
27.68

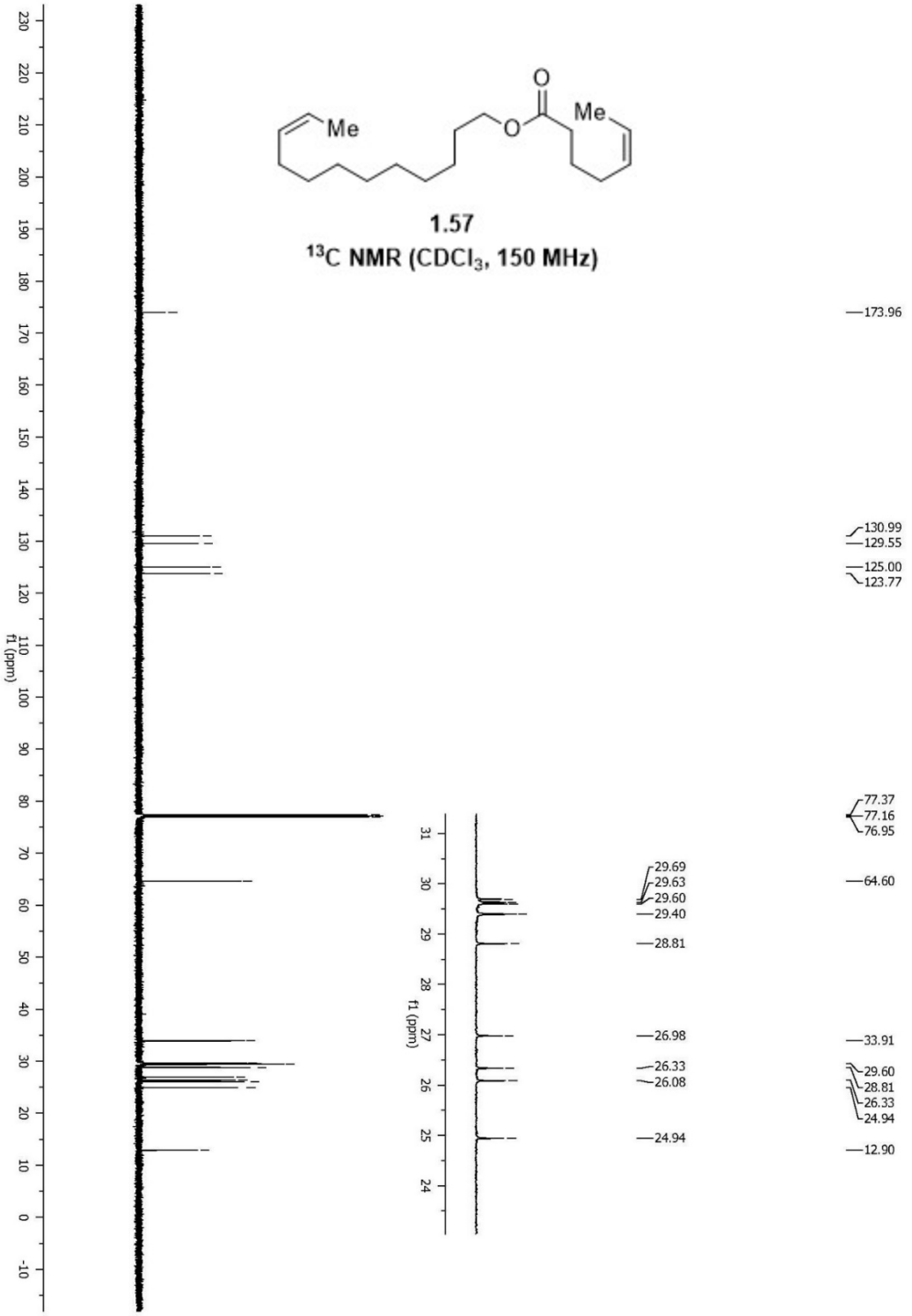

i-Pr
BocHN
NH
O
CO2Bn
1.51
1H NMR (CDCl3, 600 MHz)
f1 (ppm)
4.90
1.00
0.92
1.09
3.09
1.06
2.26
2.22
2.26
3.21
2.19
9.99
6.70
7.36
7.35
7.35
7.33
7.33
7.33
7.32
7.26
7.26
6.06
5.43
5.34
5.31
5.11
3.87
3.86
3.86
3.85
3.27
3.26
2.36
2.33
2.20
2.17
2.09
2.07
1.71
1.69
1.43
1.25
0.94
0.93
0.90
0.88

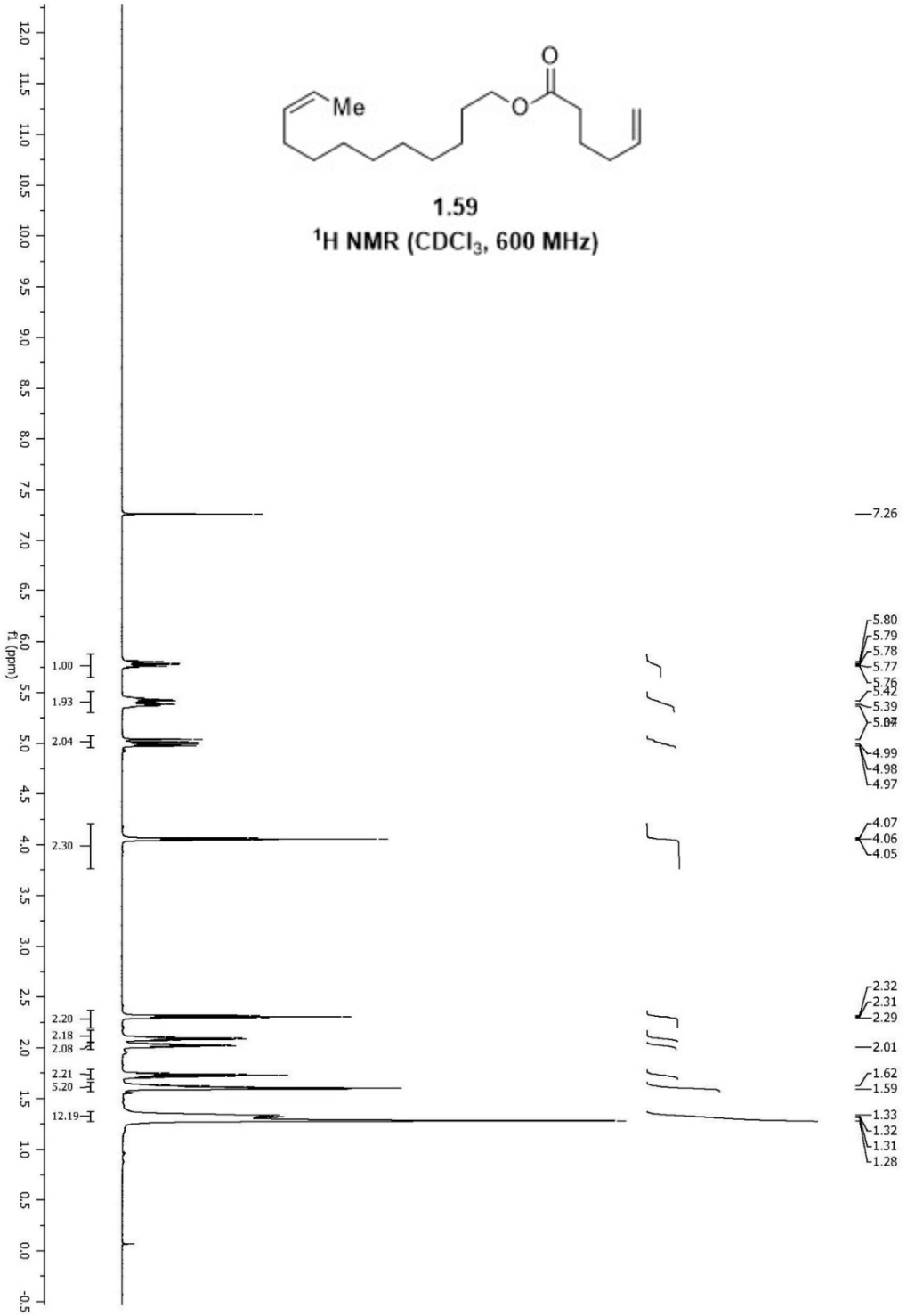

i-Pr
BocHN
NH
O
CO2Bn
1.51
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
173.58
171.66
155.98
136.12
131.47
128.69
128.41
128.37
127.15
79.88
77.48
76.84
66.36
60.20
39.17
33.70
30.98
28.45
27.36
26.66
24.84
19.45
17.90

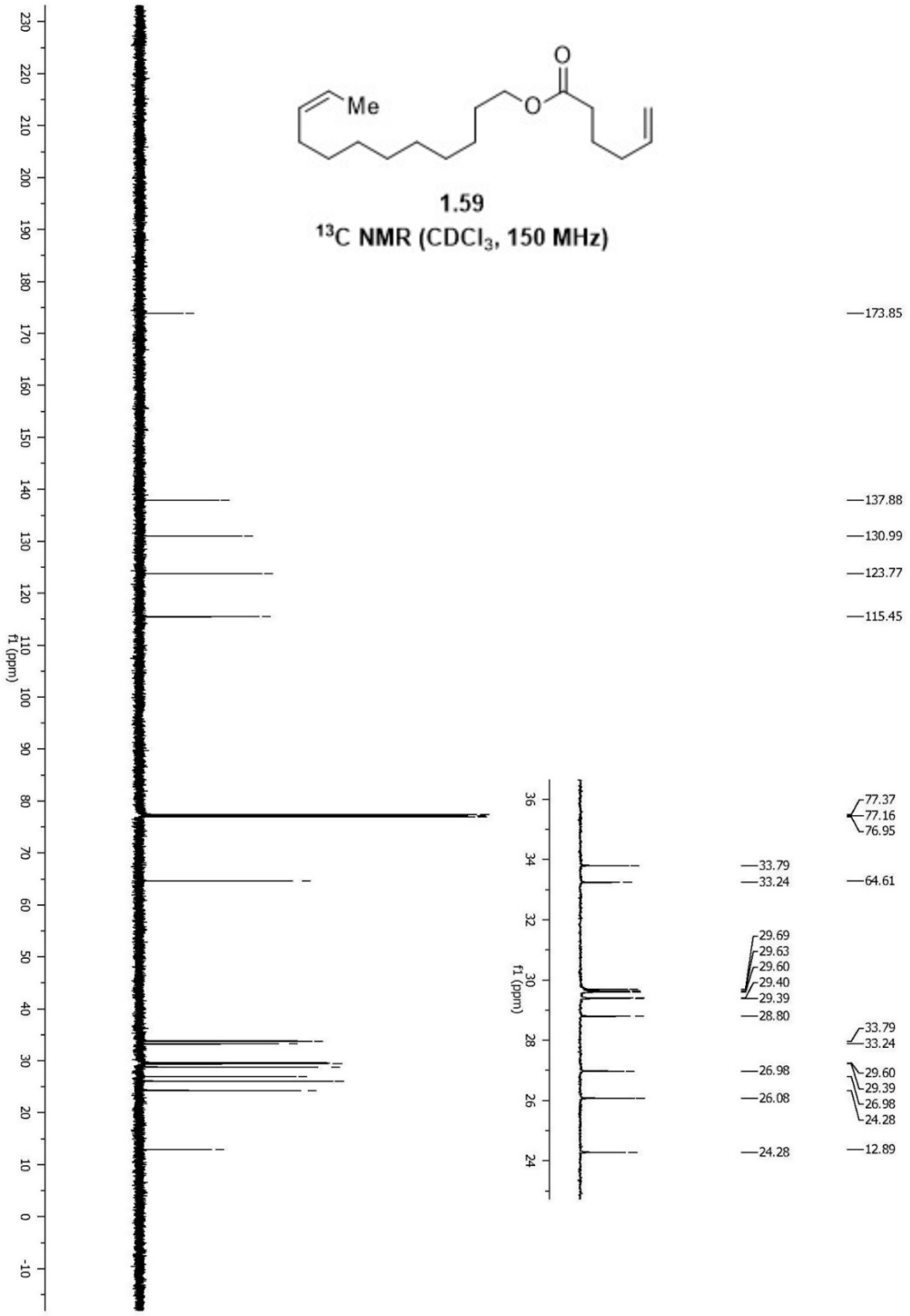

NHBoc
MeS
NH
O
CO2Bn
1.52
1H NMR (CDCl3, 600 MHz)
f1 (ppm)
4.43
0.99
1.00
1.95
2.00
1.05
2.19
2.24
2.06
2.16
6.34
1.13
2.14
9.56
7.36
7.35
7.35
7.34
7.33
7.33
7.32
7.32
7.26
7.26
6.30
5.44
5.34
5.32
5.11
4.21
3.29
3.28
3.27
3.25
3.24
3.22
2.37
2.36
2.35
2.08
1.92
1.87
1.71
1.43

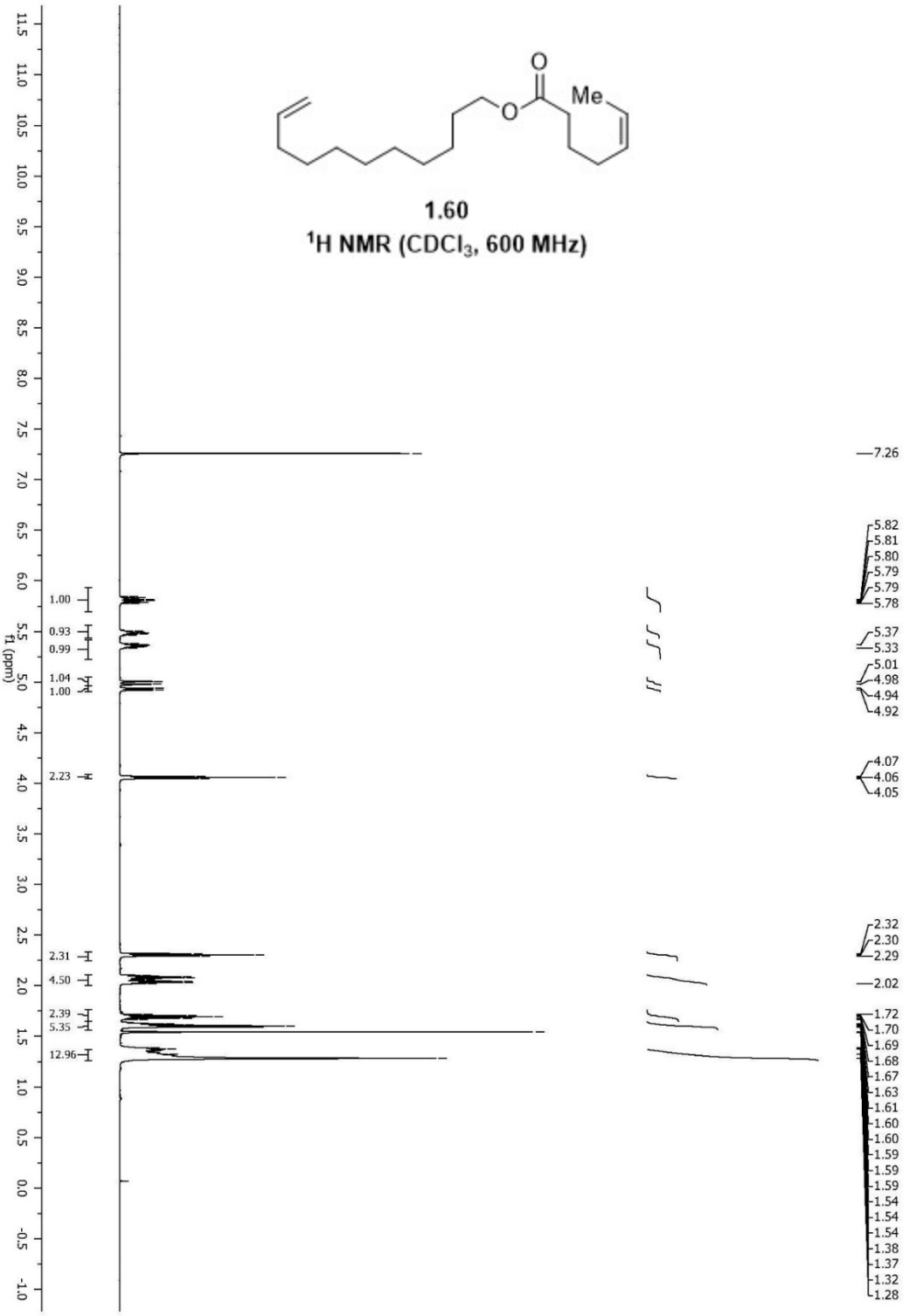

NHBoc
MeS
NH
O
CO_2Bn
1.52
^{13}C NMR ($CDCl_3$, 150 MHz)
f1 (ppm)
173.62
171.54
155.68
136.09
131.56
128.68
128.39
128.36
127.04
80.13
77.37
77.16
76.95
66.38
53.60
39.23
33.70
31.95
30.37
28.45
27.28
26.66
24.84
15.39

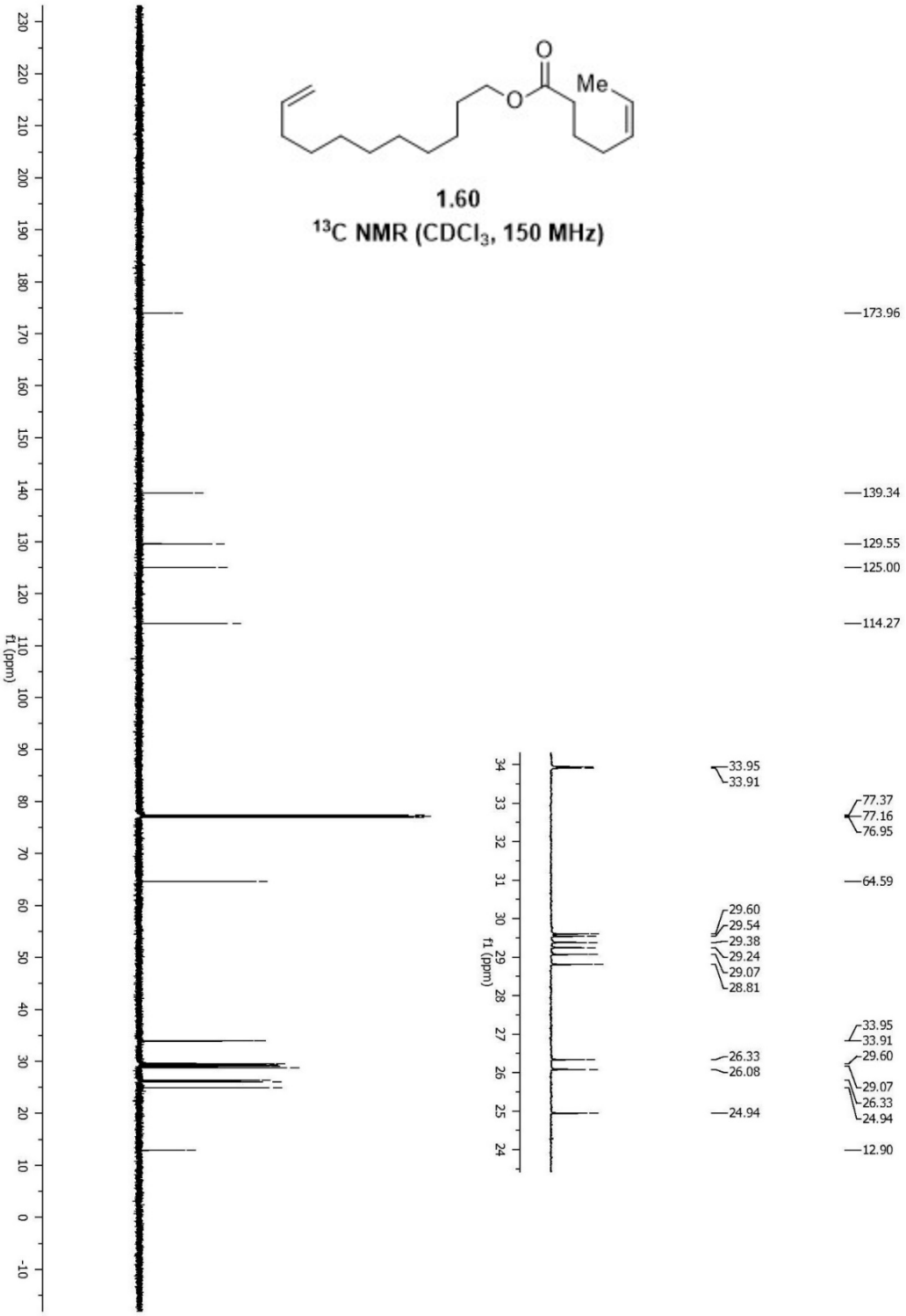

Me
O
O
Me
1.57
¹H NMR (CDCl₃, 600 MHz)
f1 (ppm)
3.57
2.06
2.00
2.01
1.86
2.01
6.98
2.38
12.35
7.27
7.27
7.26
5.49
5.49
5.47
5.44
5.42
5.40
5.39
5.38
5.38
5.37
5.36
5.36
5.35
5.35
4.07
4.06
4.05
2.32
2.30
2.29
2.09
2.03
2.01
1.68
1.61
1.54
1.34
1.32
1.31
1.28

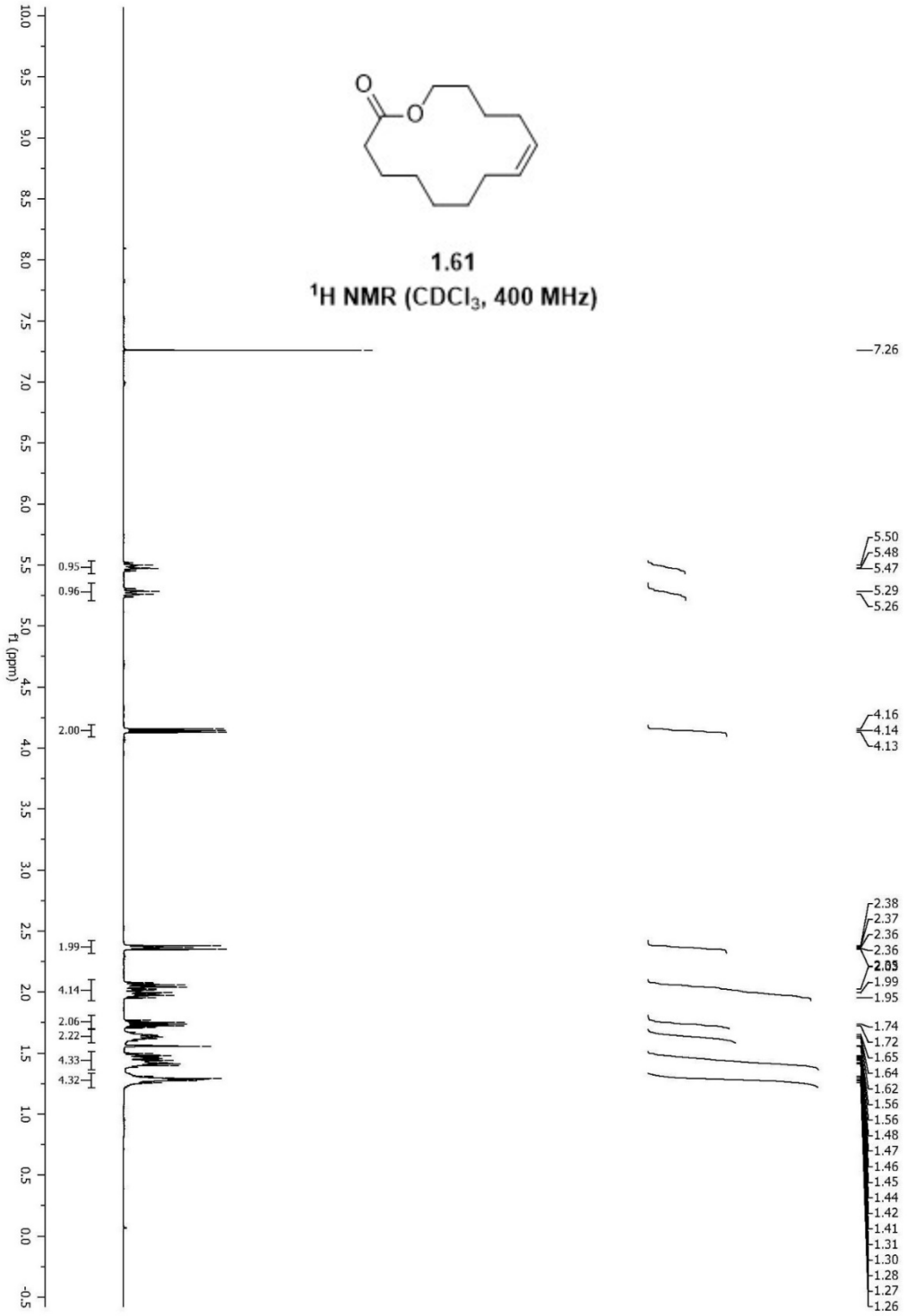

Me
O
O
Me
1.57
^{13}C NMR ($CDCl_3$, 150 MHz)
f1 (ppm)
173.96
130.99
129.55
125.00
123.77
77.37
77.16
76.95
64.60
29.69
29.63
29.60
29.40
28.81
26.98
26.33
26.08
24.94
33.91
29.60
28.81
26.33
24.94
12.90

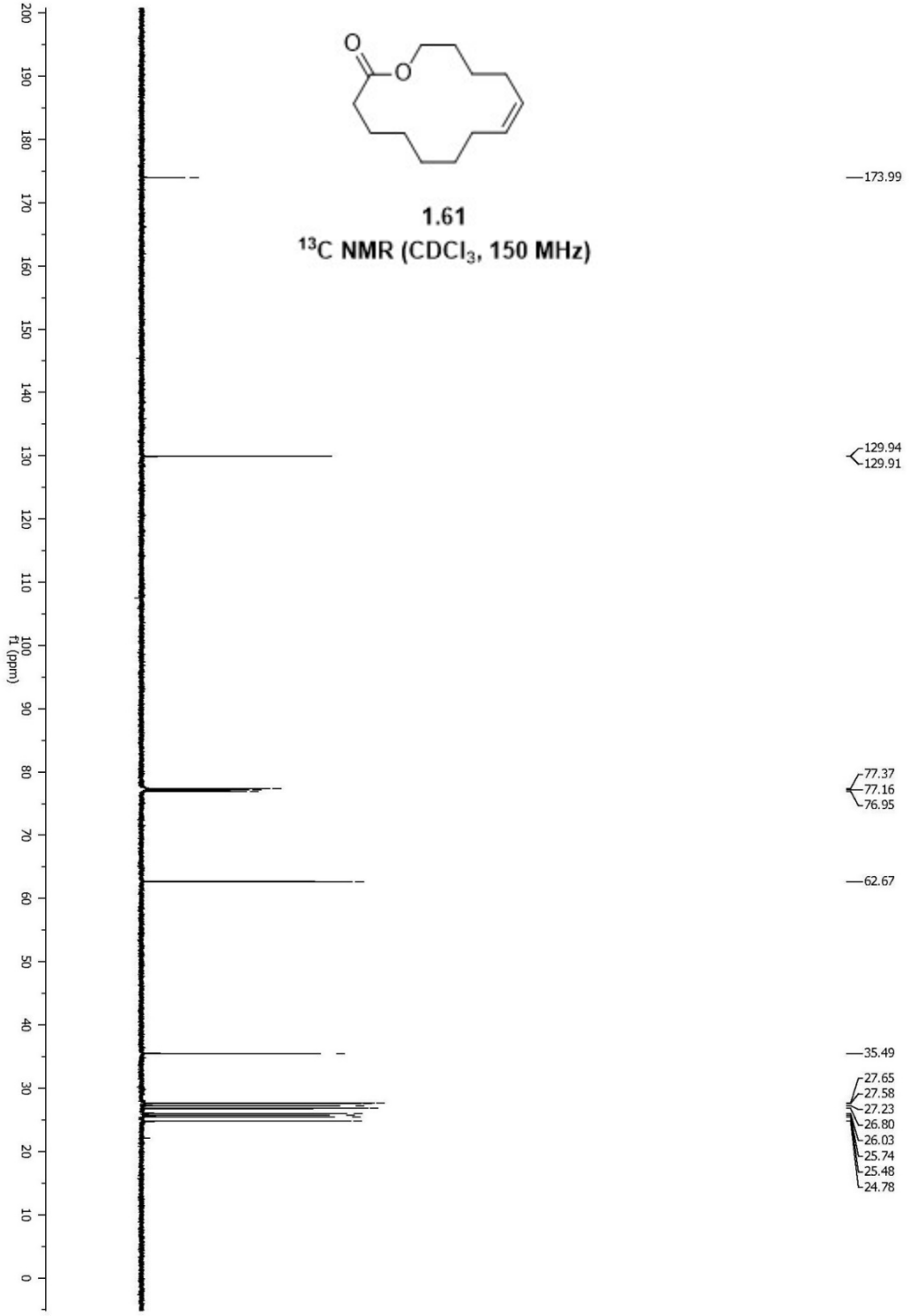

Me
O
O
1.59
¹H NMR (CDCl₃, 600 MHz)
f1 (ppm)
1.00
1.93
2.04
2.30
2.20
2.18
2.08
2.21
5.20
12.19
7.26
5.80
5.79
5.78
5.77
5.76
5.42
5.39
4.99
4.98
4.97
4.07
4.06
4.05
2.32
2.31
2.29
2.01
1.62
1.59
1.33
1.32
1.31
1.28

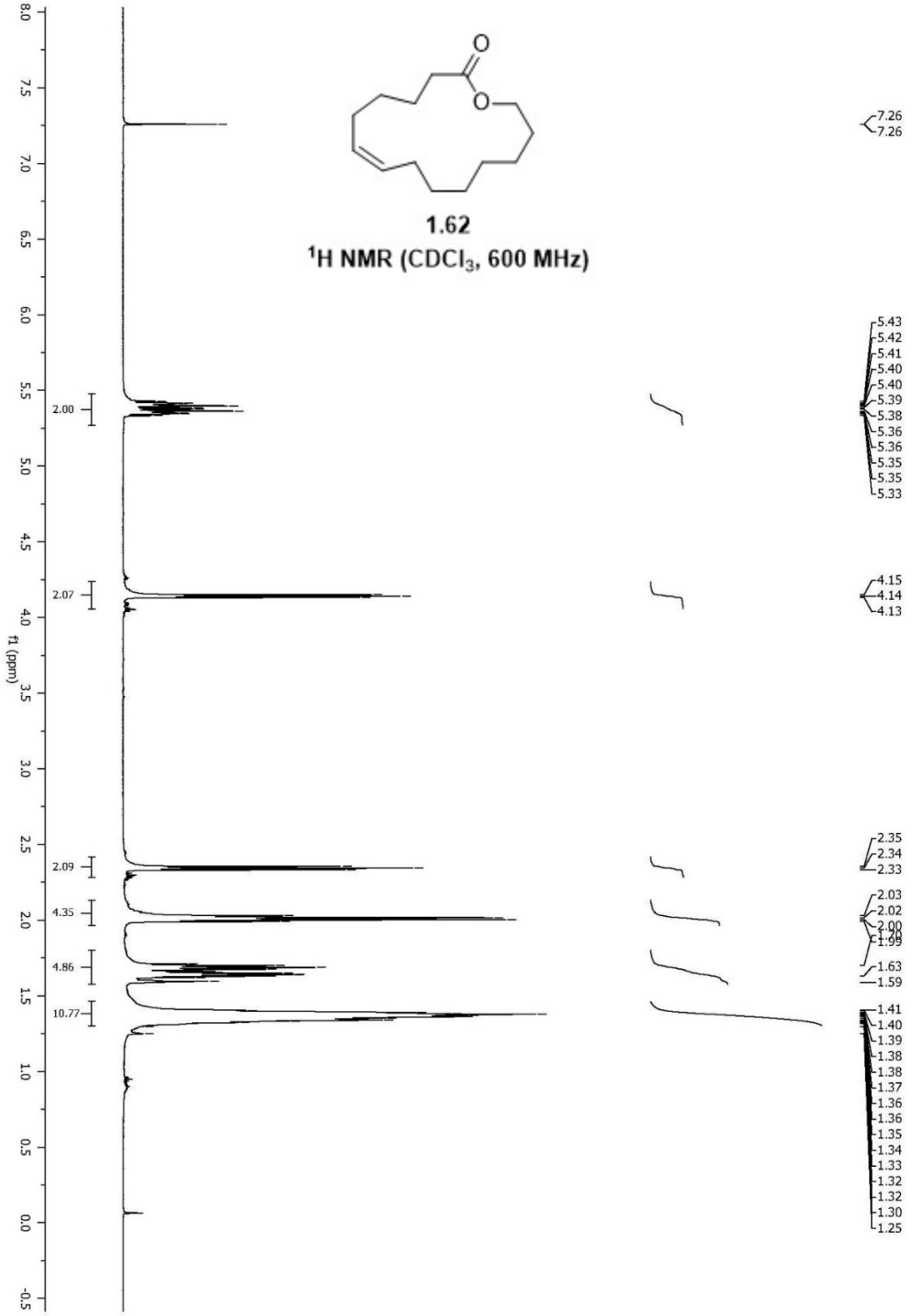

Me
O
O
1.59
^{13}C NMR ($CDCl_3$, 150 MHz)
f1 (ppm)
173.85
137.88
130.99
123.77
115.45
77.37
77.16
76.95
33.79
33.24
64.61
29.69
29.63
29.60
29.40
29.39
28.80
26.98
26.08
24.28
12.89


O
O
Me
1.60
^{1}H NMR ($CDCl_3$, 600 MHz)
f1 (ppm)
1.00
0.93
0.99
1.04
1.00
2.23
2.31
4.50
2.39
5.35
12.96
7.26
5.82
5.81
5.80
5.79
5.79
5.78
5.37
5.33
5.01
4.98
4.94
4.92
4.07
4.06
4.05
2.32
2.30
2.29
2.02
1.72
1.70
1.69
1.68
1.67
1.63
1.61
1.60
1.60
1.59
1.59
1.59
1.54
1.54
1.54
1.38
1.37
1.32
1.28


O
O
Me
1.60
^{13}C NMR ($CDCl_3$, 150 MHz)
f1 (ppm)
173.96
139.34
129.55
125.00
114.27
77.37
77.16
76.95
64.59
33.95
33.91
29.60
29.54
29.38
29.24
29.07
28.81
26.33
26.08
24.94
12.90


1.61
^{1}H NMR ($CDCl_3$, 400 MHz)
f1 (ppm)
7.26
5.50
5.48
5.47
5.29
5.26
4.16
4.14
4.13
2.38
2.37
2.36
2.36
2.05
1.99
1.95
1.74
1.72
1.65
1.64
1.62
1.56
1.56
1.48
1.47
1.46
1.45
1.44
1.42
1.41
1.31
1.30
1.28
1.27
1.26
0.95
0.96
2.00
1.99
4.14
2.06
2.22
4.33
4.32


1.61
^{13}C NMR ($CDCl_3$, 150 MHz)
173.99
129.94
129.91
77.37
77.16
76.95
62.67
35.49
27.65
27.58
27.23
26.80
26.03
25.74
25.48
24.78
f1 (ppm)


1.62
^{1}H NMR ($CDCl_3$, 600 MHz)
f1 (ppm)
2.00
2.07
2.09
4.35
4.86
10.77
7.26
7.26
5.43
5.42
5.41
5.40
5.40
5.39
5.38
5.36
5.36
5.35
5.35
5.33
4.15
4.14
4.13
2.35
2.34
2.33
2.03
2.02
2.00
1.99
1.63
1.59
1.41
1.40
1.39
1.38
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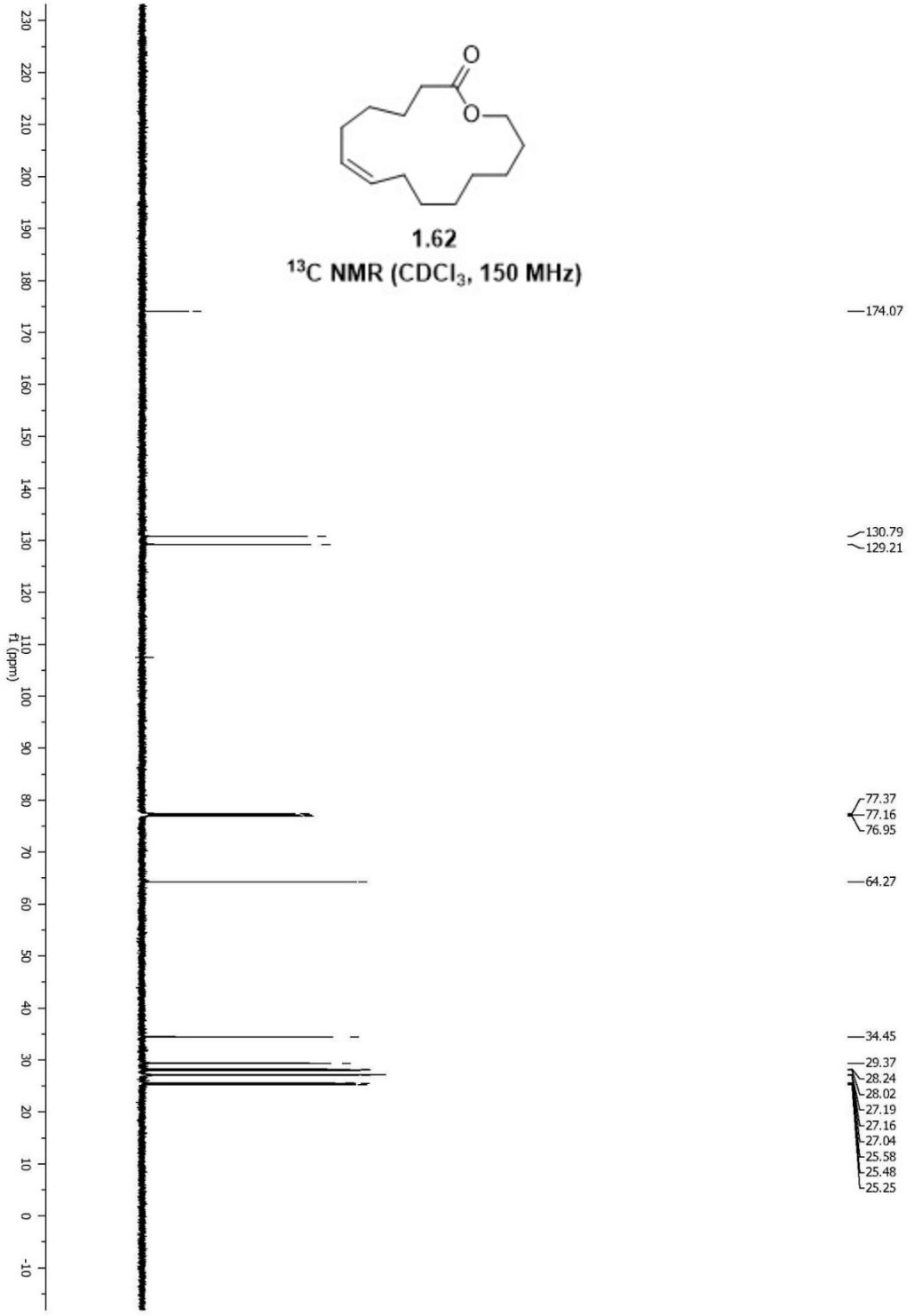
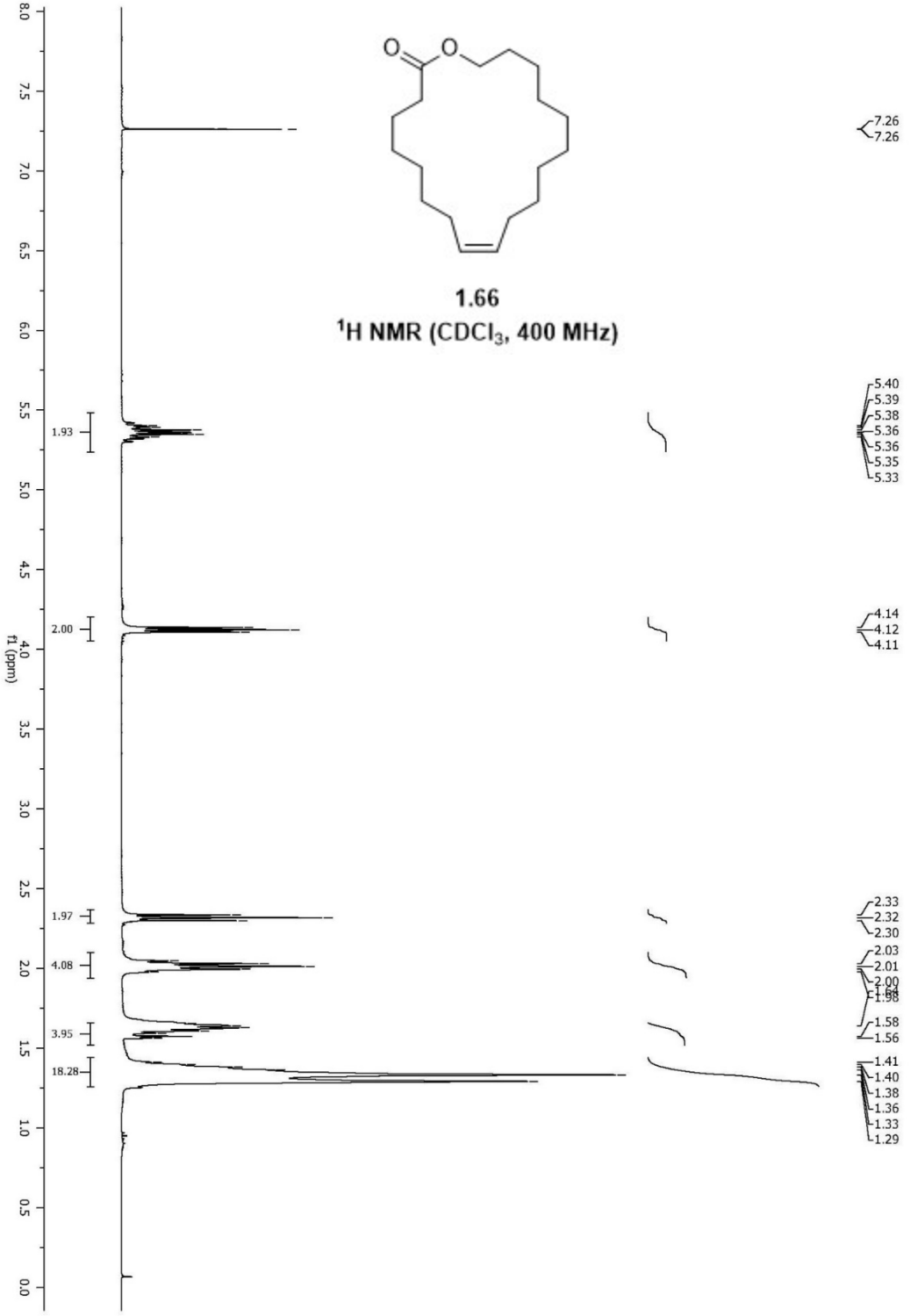
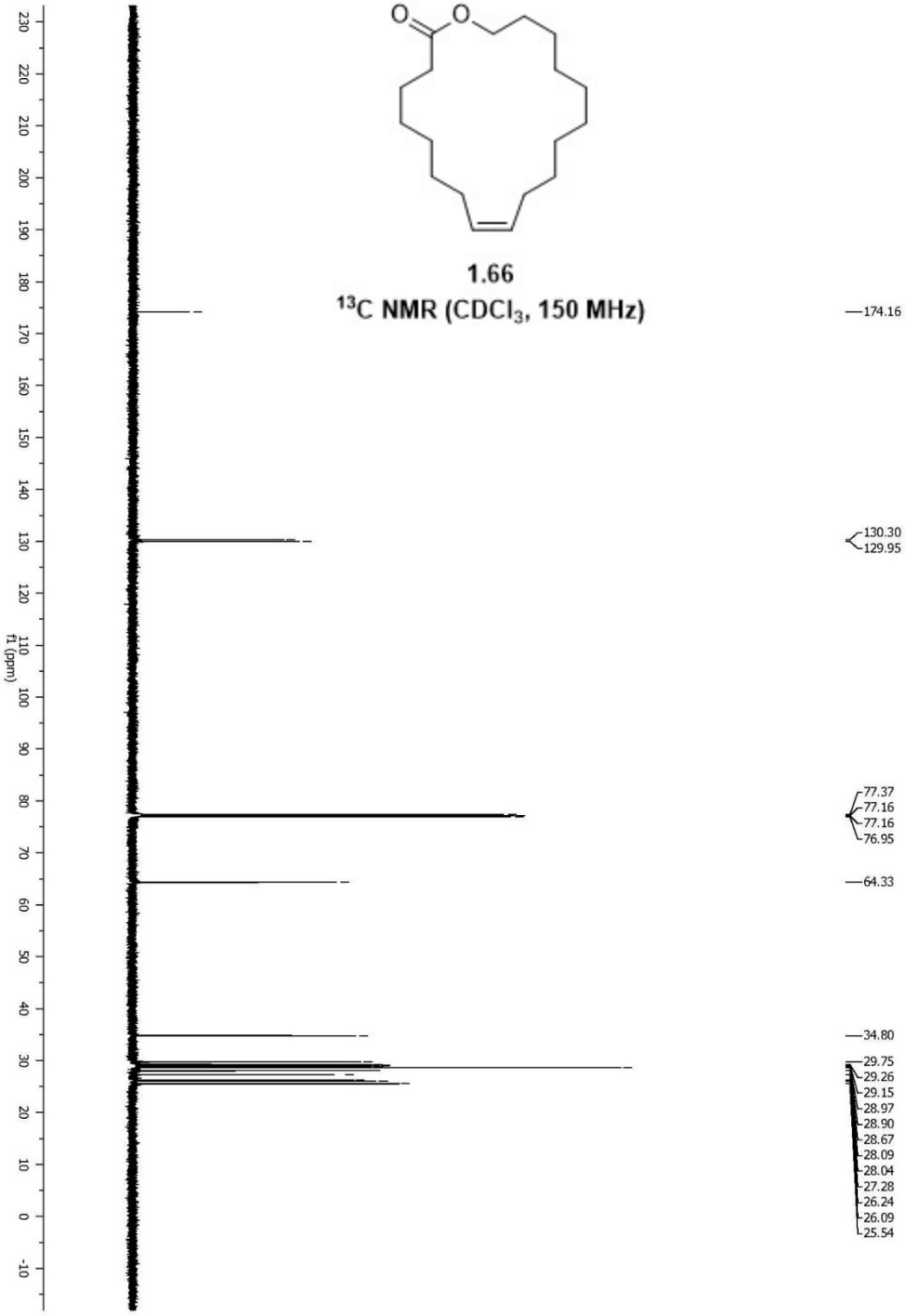
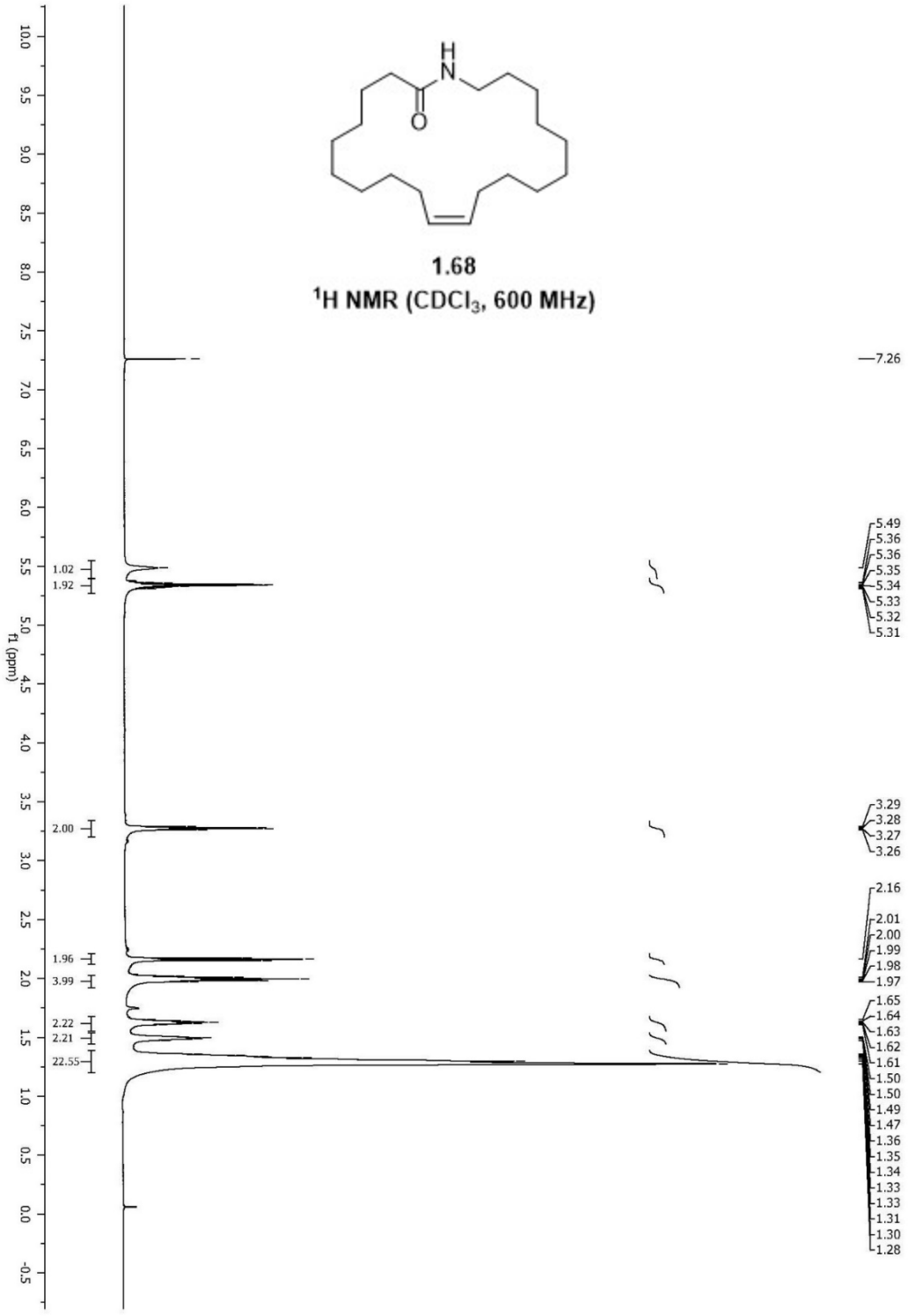
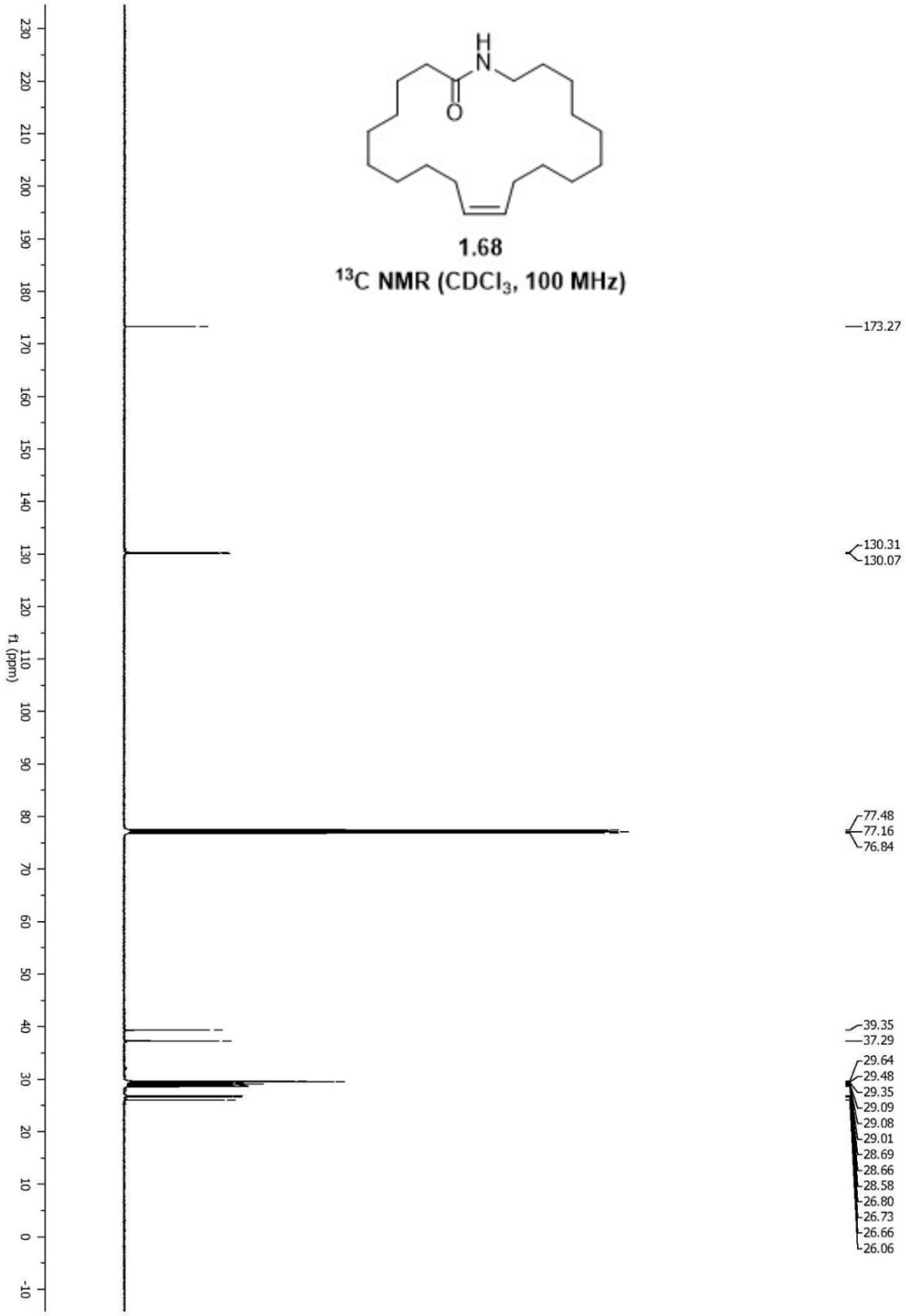
1.34
1.33
1.32
1.32
1.30
1.25

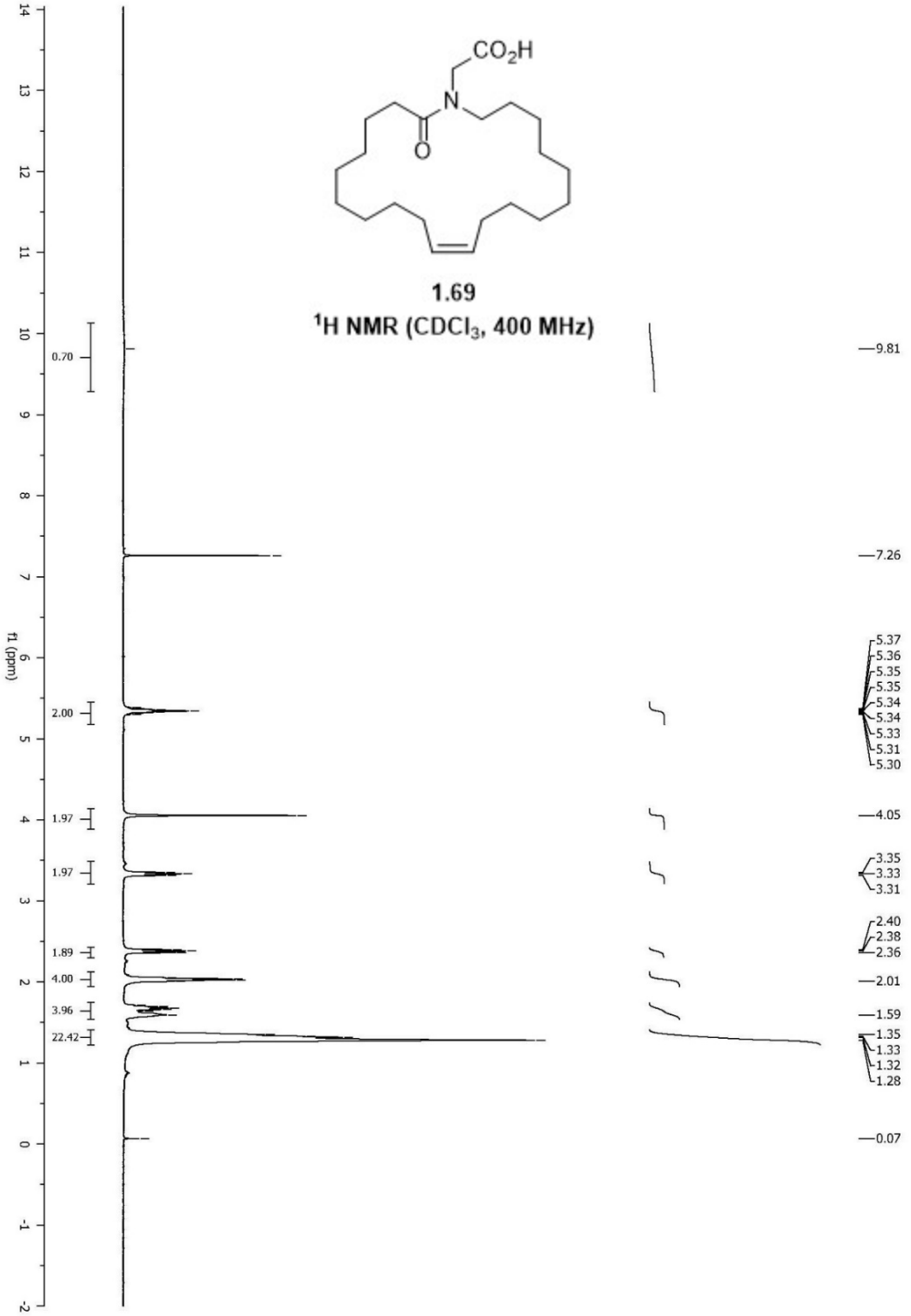

1.62
^{13}C NMR ($CDCl_3$, 150 MHz)
f1 (ppm)
174.07
130.79
129.21
77.37
77.16
76.95
64.27
34.45
29.37
28.24
28.02
27.19
27.16
27.04
25.58
25.48
25.25

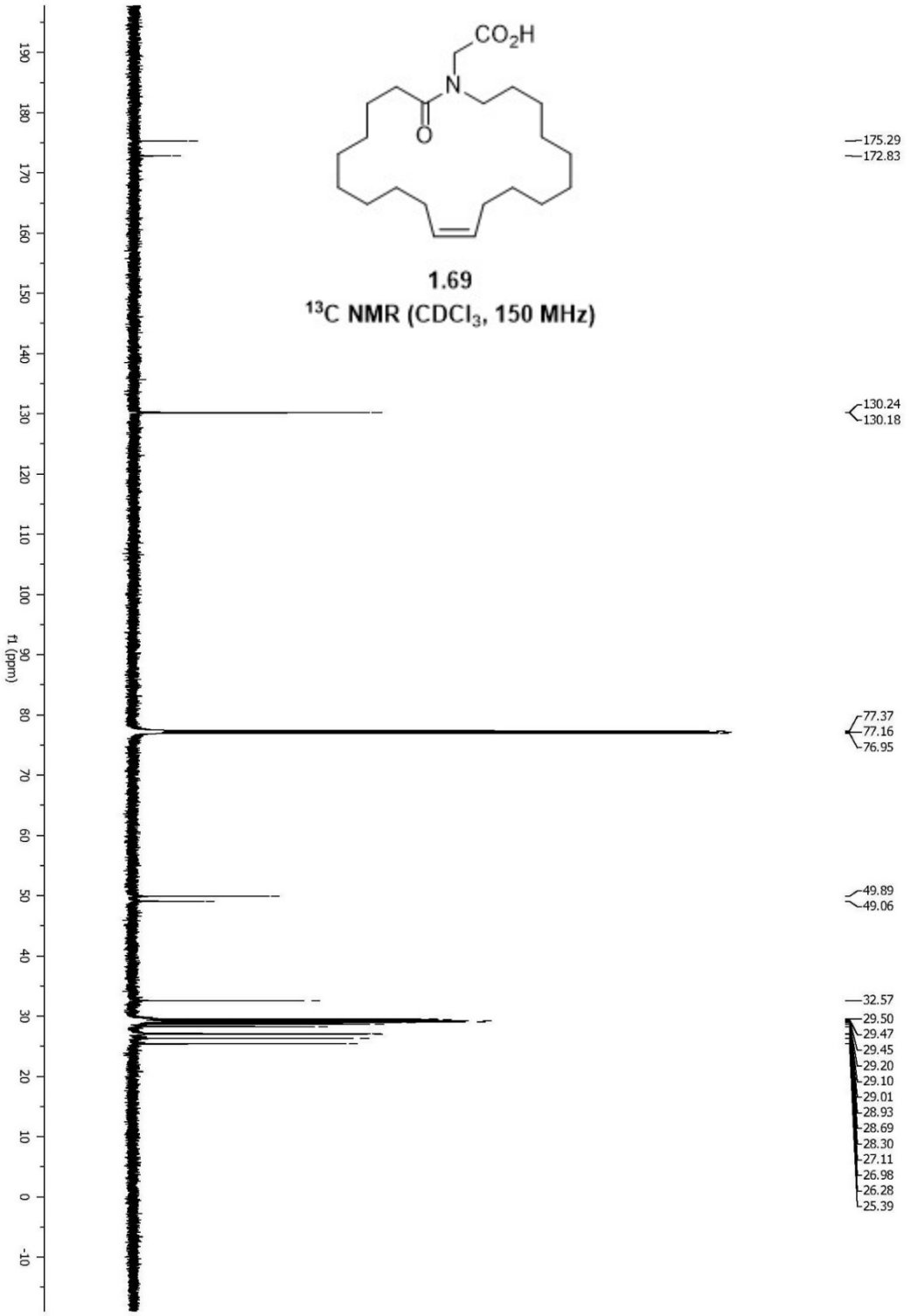

1.66
^{1}H NMR ($CDCl_3$, 400 MHz)
f1 (ppm)
1.93
2.00
1.97
4.08
3.95
18.28
7.26
7.26
5.40
5.39
5.38
5.36
5.36
5.35
5.33
4.14
4.12
4.11
2.33
2.32
2.30
2.03
2.01
2.00
1.98
1.58
1.56
1.41
1.40
1.38
1.36
1.33
1.29

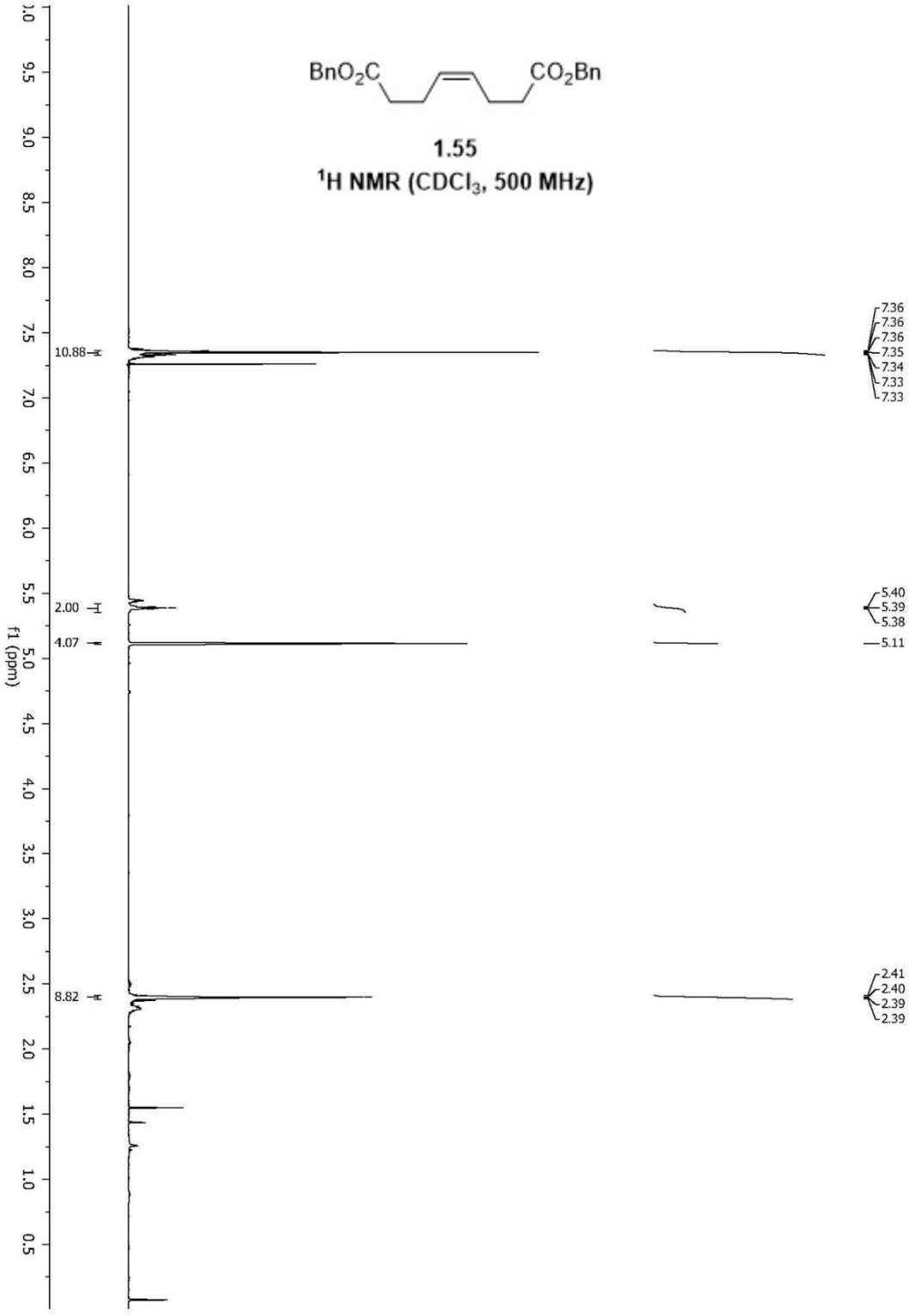

1.66
^{13}C NMR ($CDCl_3$, 150 MHz)
f1 (ppm)
174.16
130.30
129.95
77.37
77.16
77.16
76.95
64.33
34.80
29.75
29.26
29.15
28.97
28.90
28.67
28.09
28.04
27.28
26.24
26.09
25.54

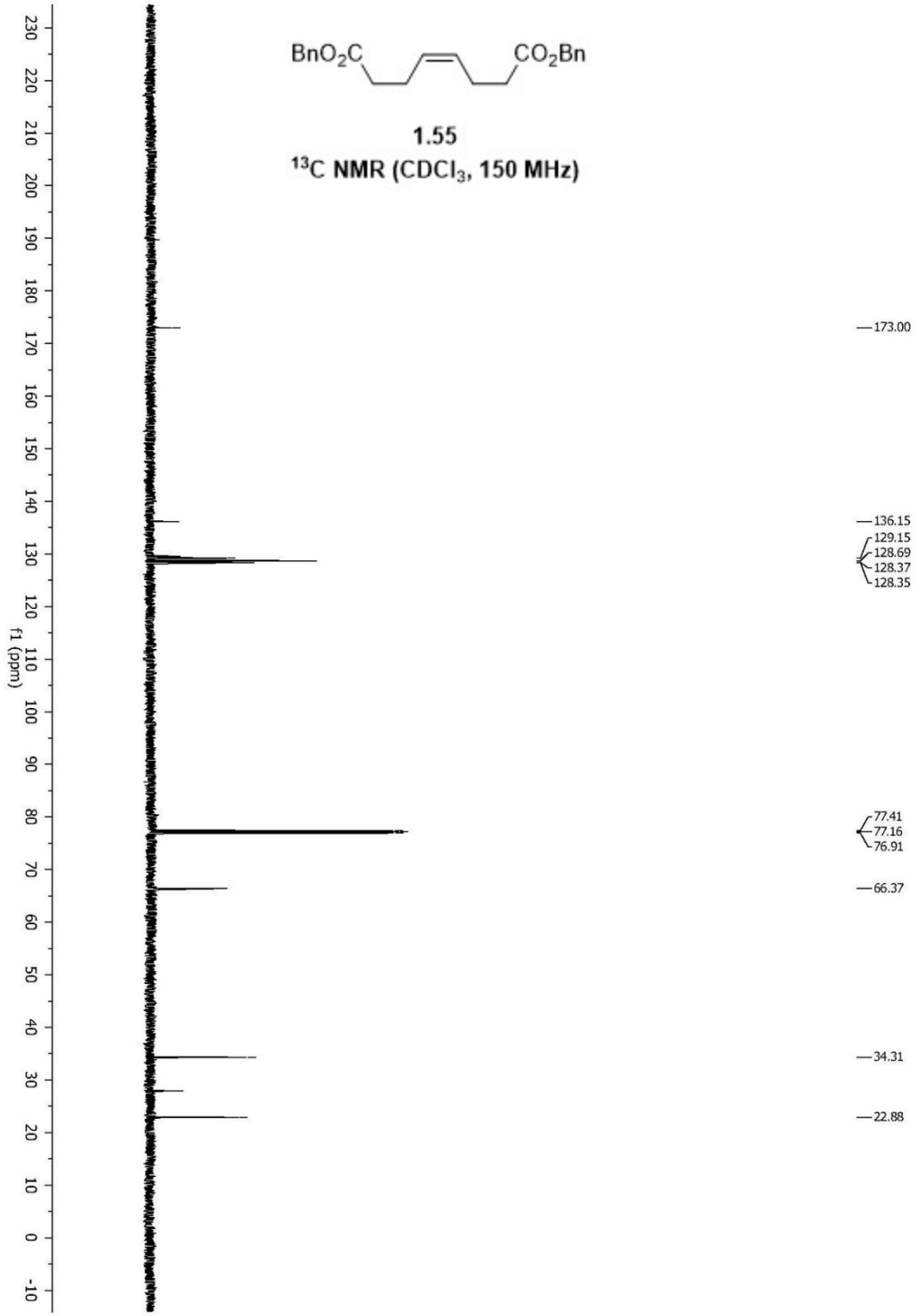

H
N
O
1.68
¹H NMR (CDCl₃, 600 MHz)
f1 (ppm)
1.02
1.92
2.00
1.96
3.99
2.22
2.21
22.55
7.26
5.49
5.36
5.36
5.35
5.34
5.33
5.32
5.31
3.29
3.28
3.27
3.26
2.16
2.01
2.00
1.99
1.98
1.97
1.65
1.64
1.63
1.62
1.61
1.50
1.50
1.49
1.47
1.36
1.35
1.34
1.33
1.33
1.31
1.30
1.28

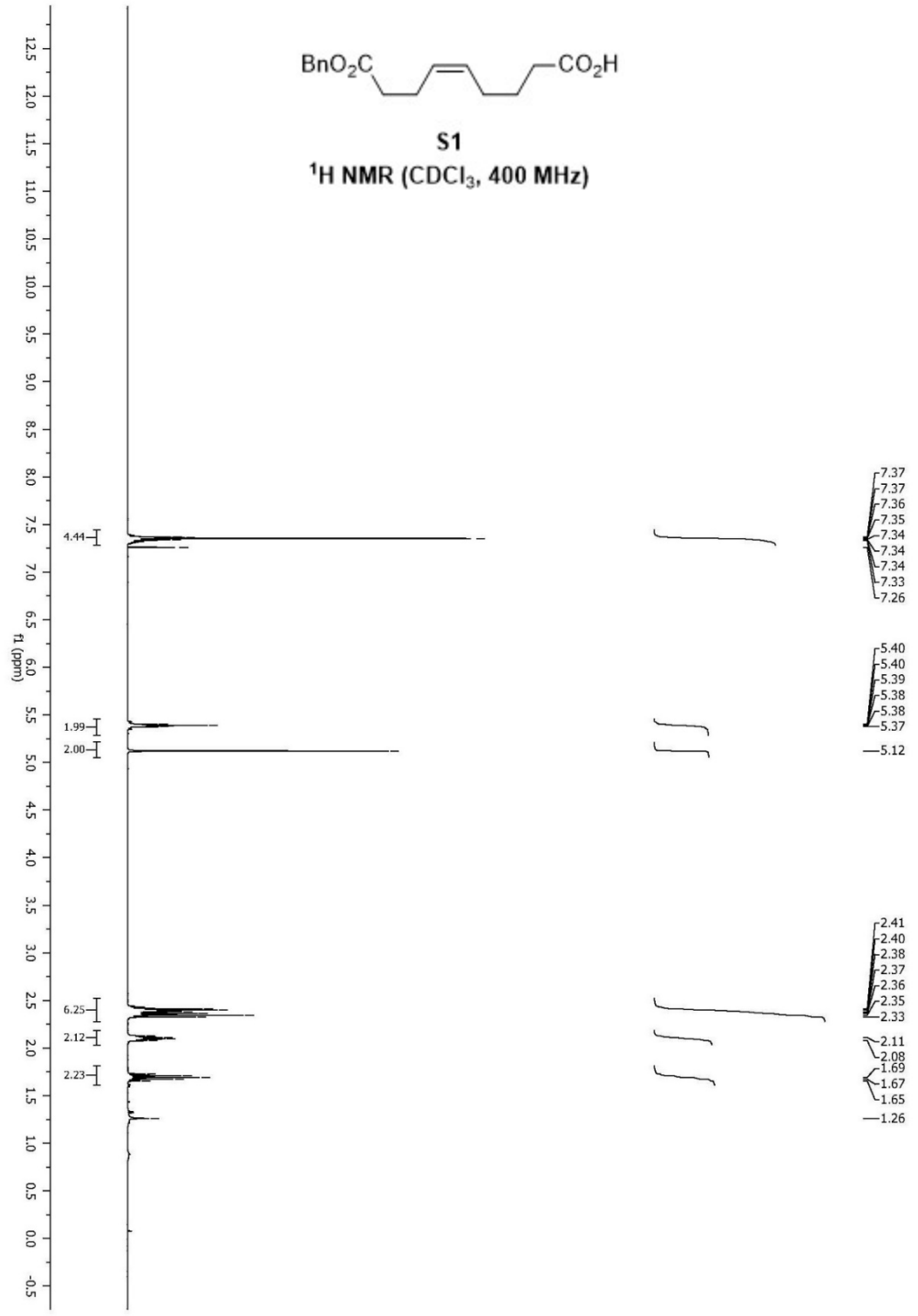

1.68
^{13}C NMR ($CDCl_3$, 100 MHz)
f1 (ppm)
173.27
130.31
130.07
77.48
77.16
76.84
39.35
37.29
29.64
29.48
29.35
29.09
29.08
29.01
28.69
28.66
28.58
26.80
26.73
26.66
26.06

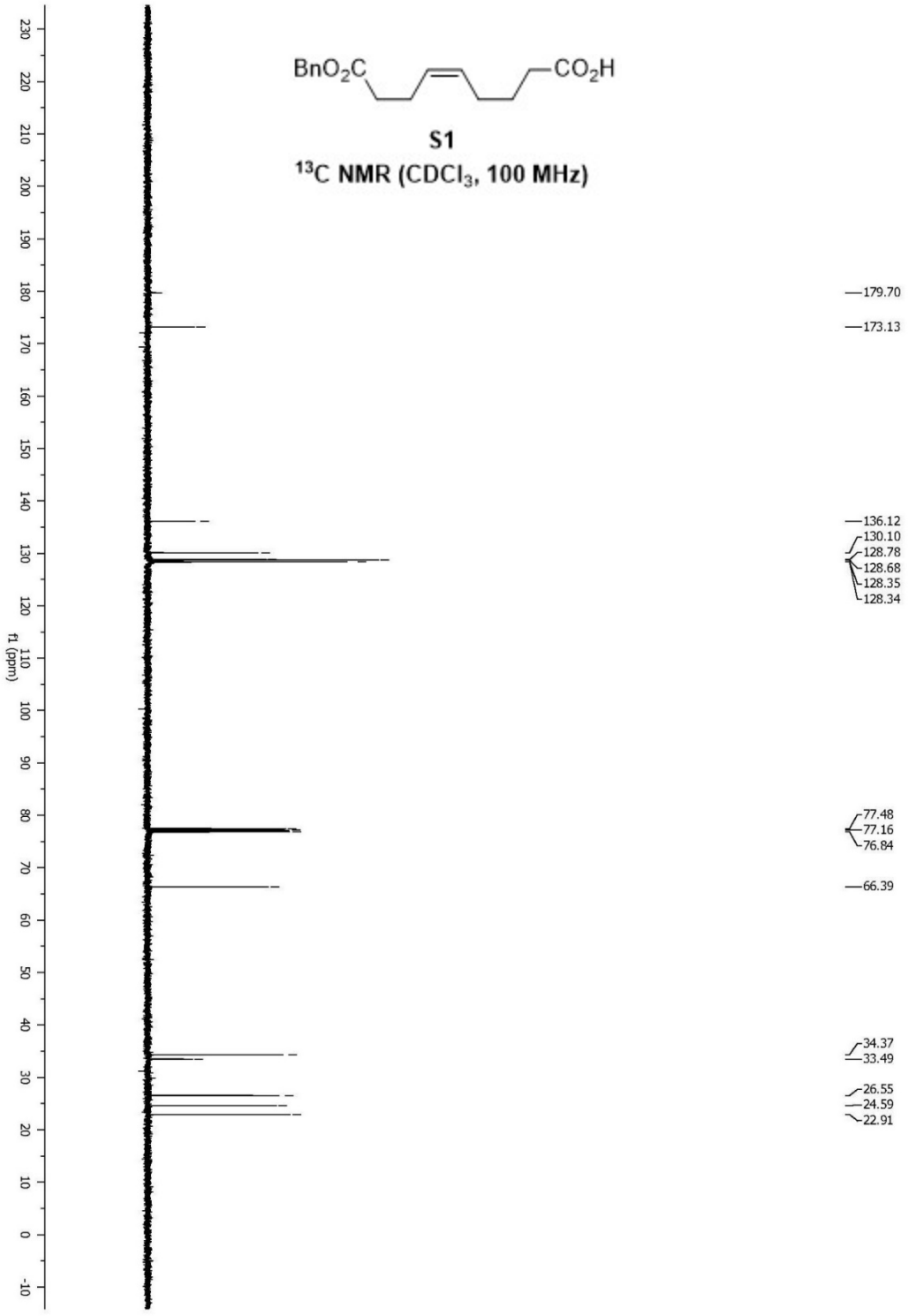

CO2H
N
O
1.69
1H NMR (CDCl3, 400 MHz)
f1 (ppm)
0.70
2.00
1.97
1.97
1.89
4.00
3.96
22.42
9.81
7.26
5.37
5.36
5.35
5.35
5.34
5.34
5.33
5.31
5.30
4.05
3.35
3.33
3.31
2.40
2.38
2.36
2.01
1.59
1.35
1.33
1.32
1.28
0.07

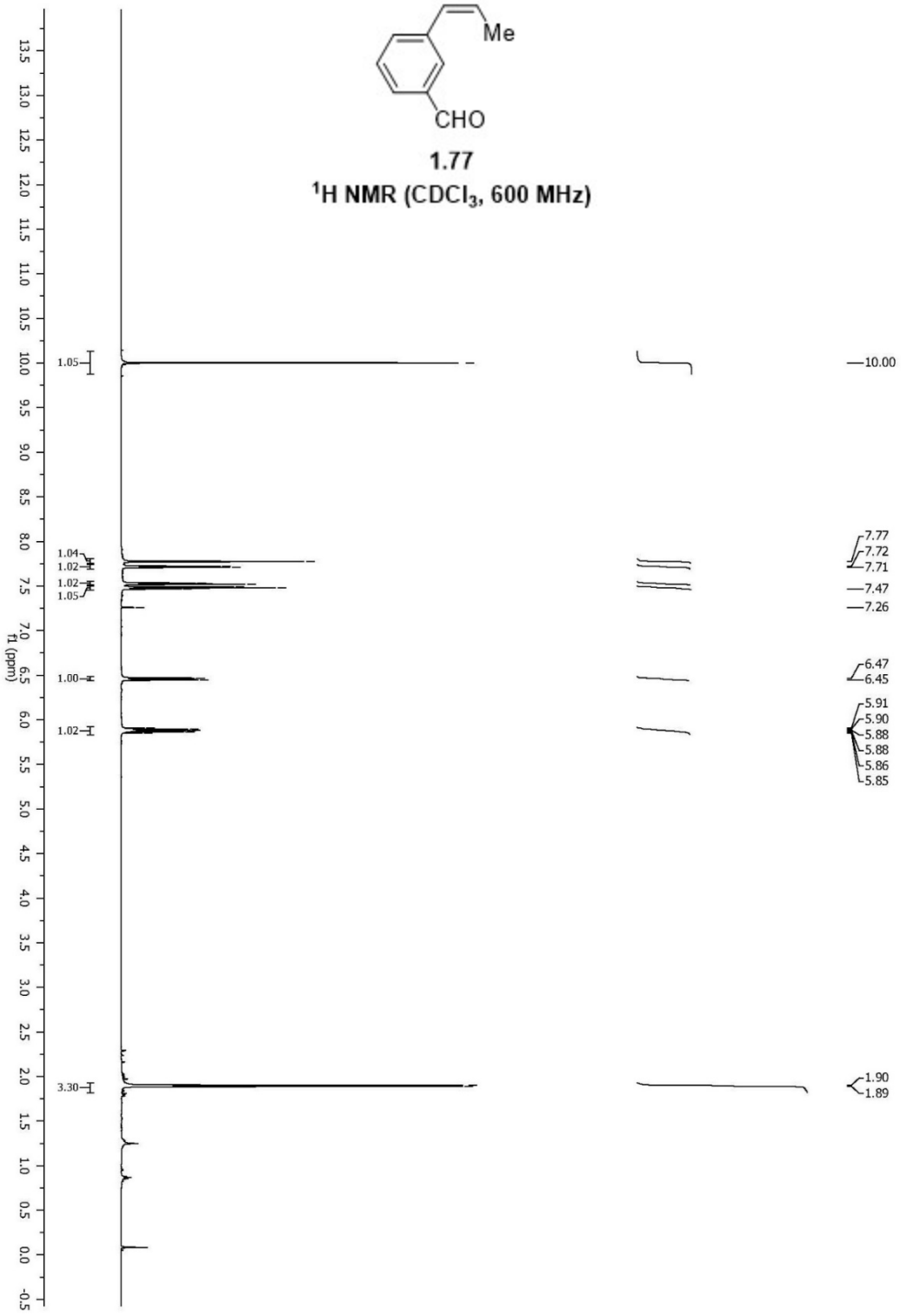

CO2H
N
O
1.69
13C NMR (CDCl3, 150 MHz)
175.29
172.83
130.24
130.18
77.37
77.16
76.95
49.89
49.06
32.57
29.50
29.47
29.45
29.20
29.10
29.01
28.93
28.69
28.30
27.11
26.98
26.28
25.39
f1 (ppm)

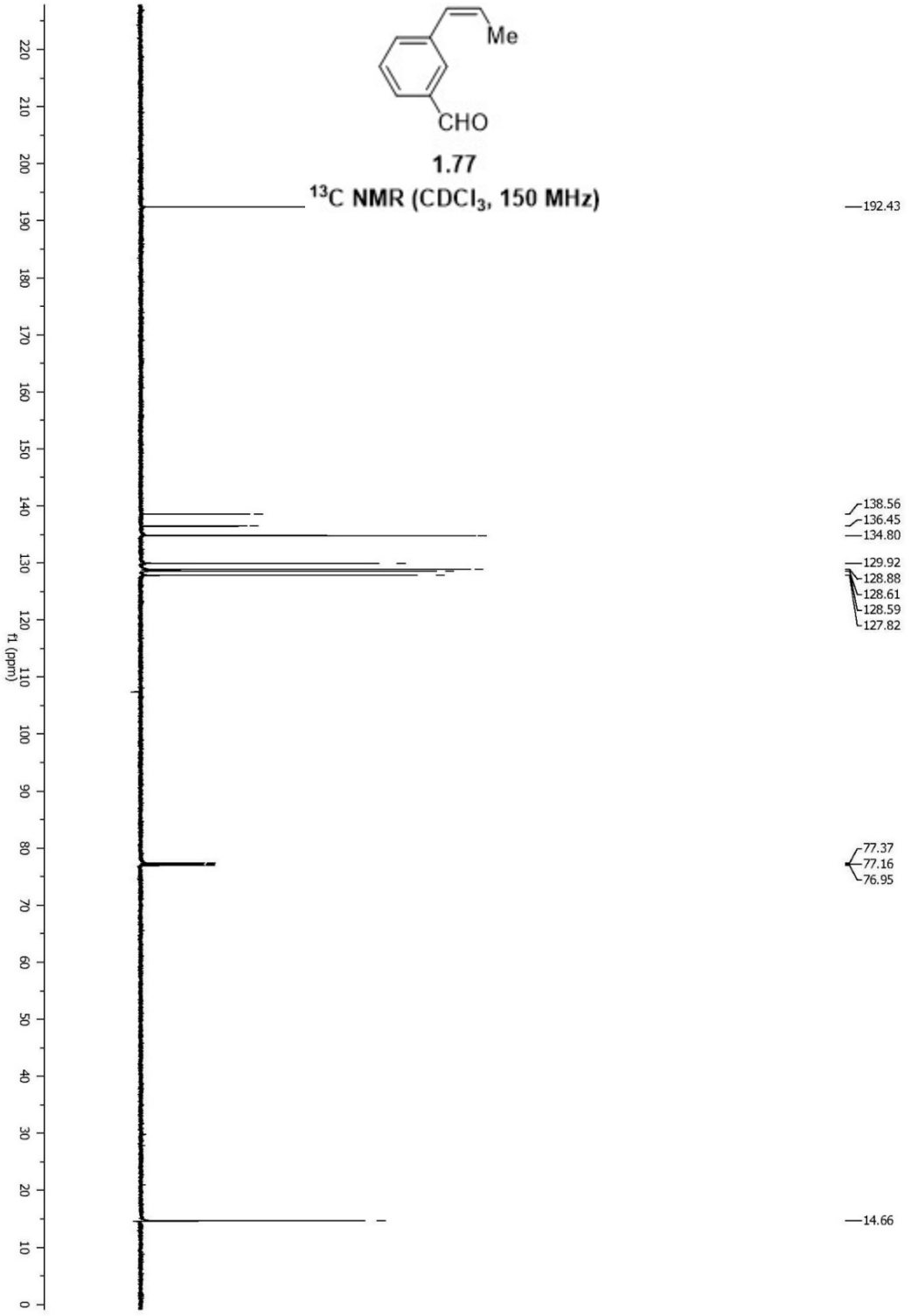

BnO2C
CO2Bn
1.55
1H NMR (CDCl3, 500 MHz)
10.88
2.00
4.07
8.82
7.36
7.36
7.36
7.35
7.34
7.33
7.33
5.40
5.39
5.38
5.11
2.41
2.40
2.39
2.39
f1 (ppm)

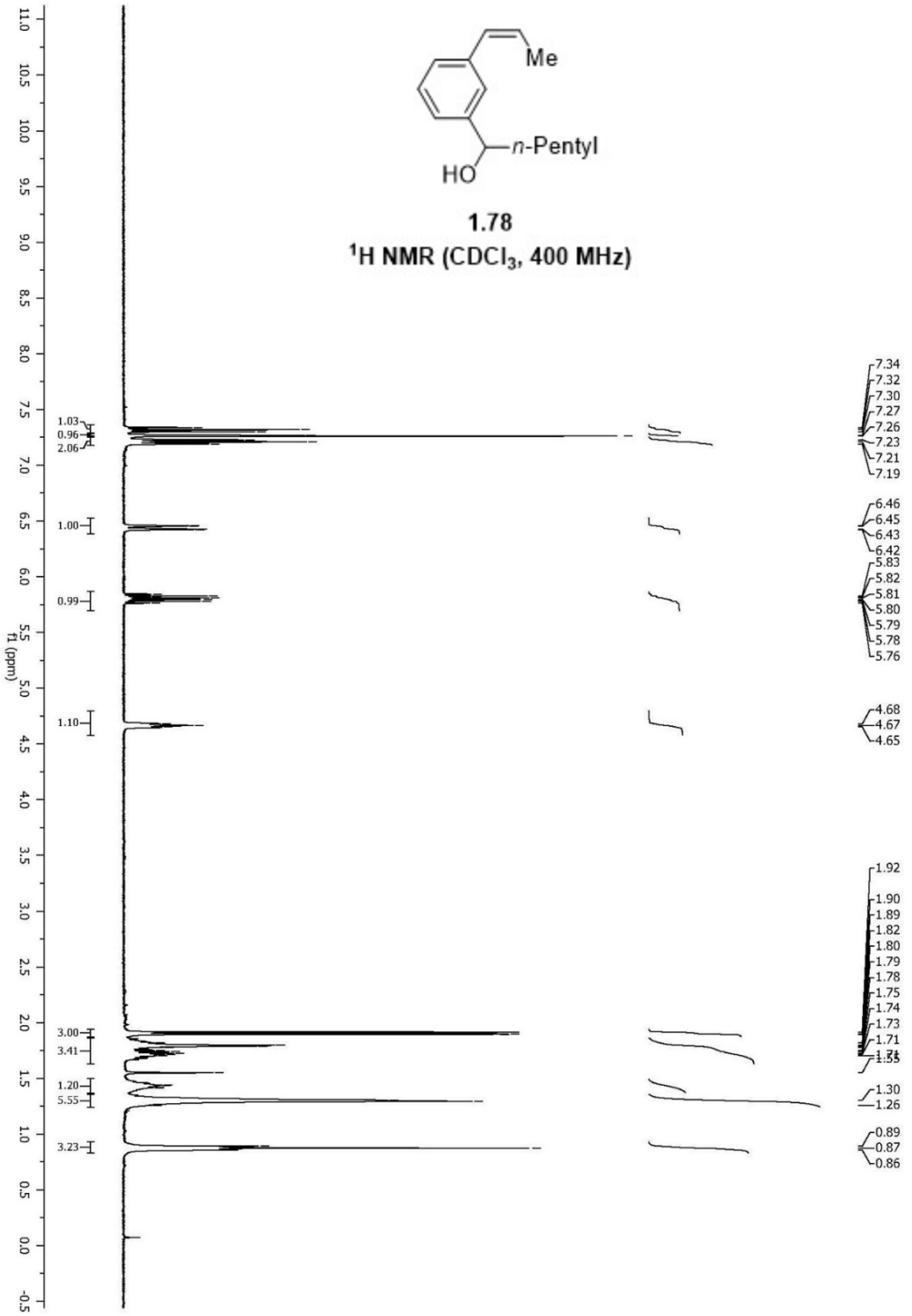

BnO2C
CO2Bn
1.55
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
173.00
136.15
129.15
128.69
128.37
128.35
77.41
77.16
76.91
66.37
34.31
22.88

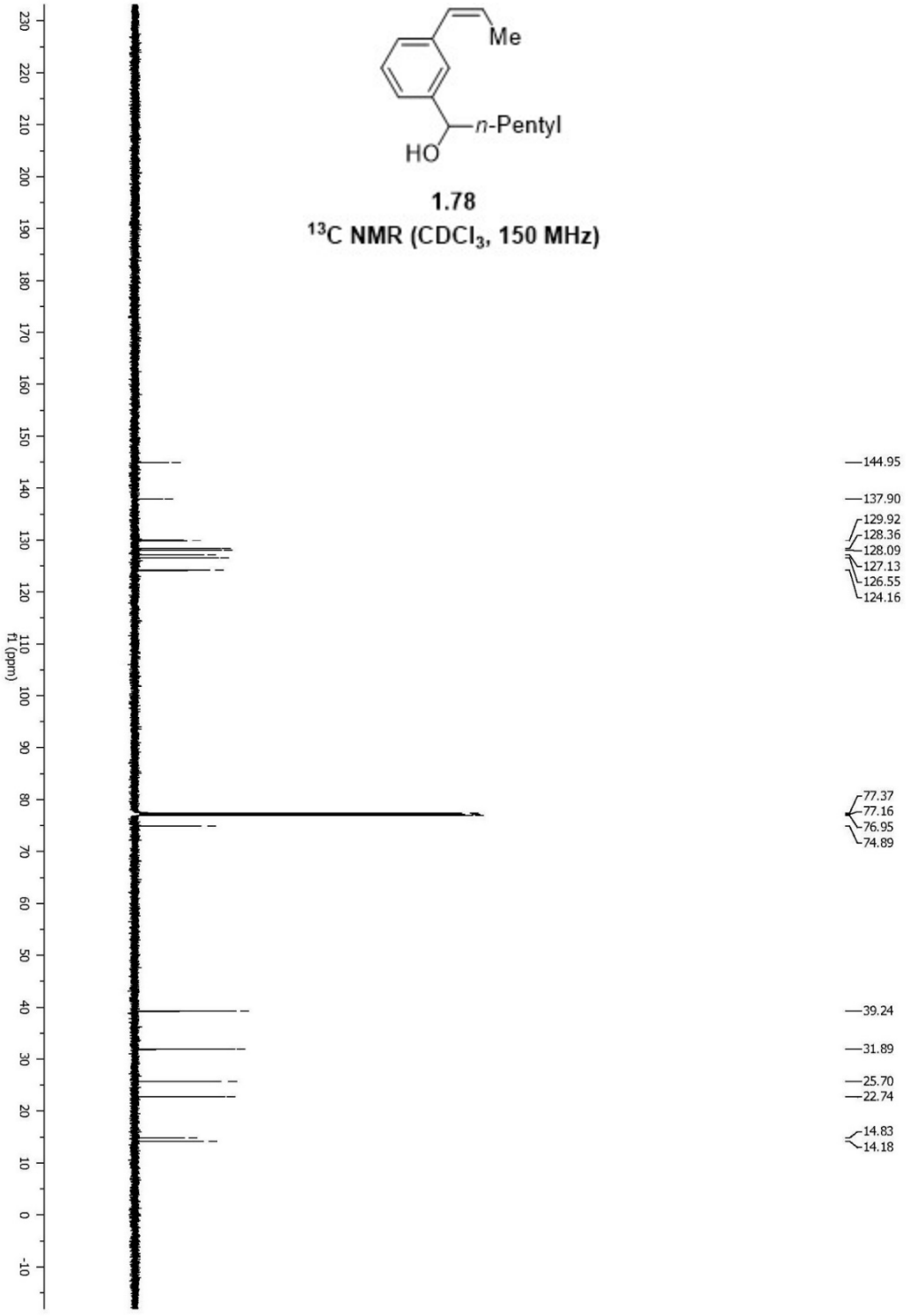

BnO2C
CO2H
S1
1H NMR (CDCl3, 400 MHz)
f1 (ppm)
4.44
1.99
2.00
6.25
2.12
2.23
7.37
7.37
7.36
7.35
7.34
7.34
7.34
7.33
7.26
5.40
5.40
5.39
5.38
5.38
5.37
5.12
2.41
2.40
2.38
2.37
2.36
2.35
2.33
2.11
2.08
1.69
1.67
1.65
1.26

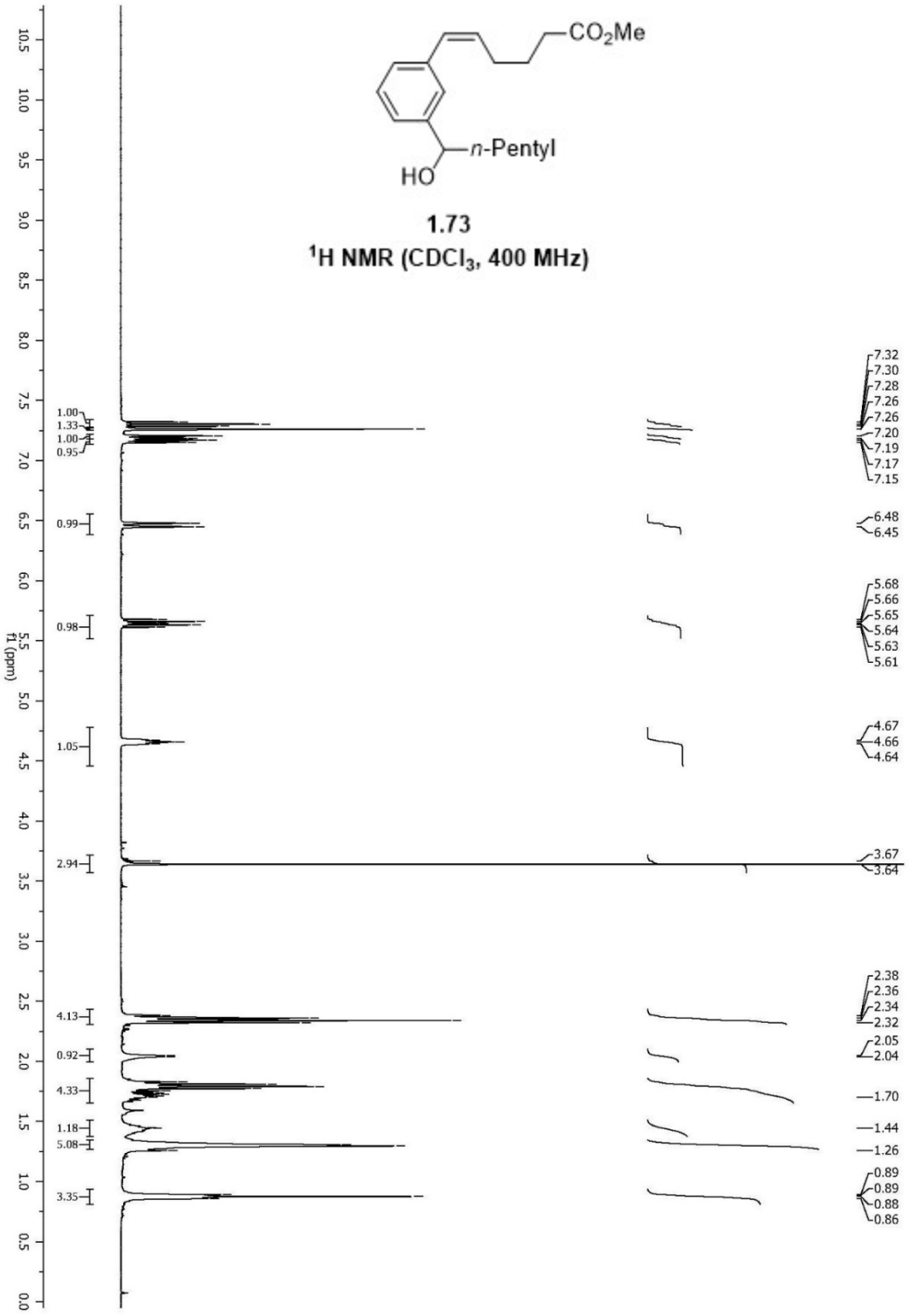

BnO2C
CO2H
S1
13C NMR (CDCl3, 100 MHz)
179.70
173.13
136.12
130.10
128.78
128.68
128.35
128.34
77.48
77.16
76.84
66.39
34.37
33.49
26.55
24.59
22.91
f1 (ppm)

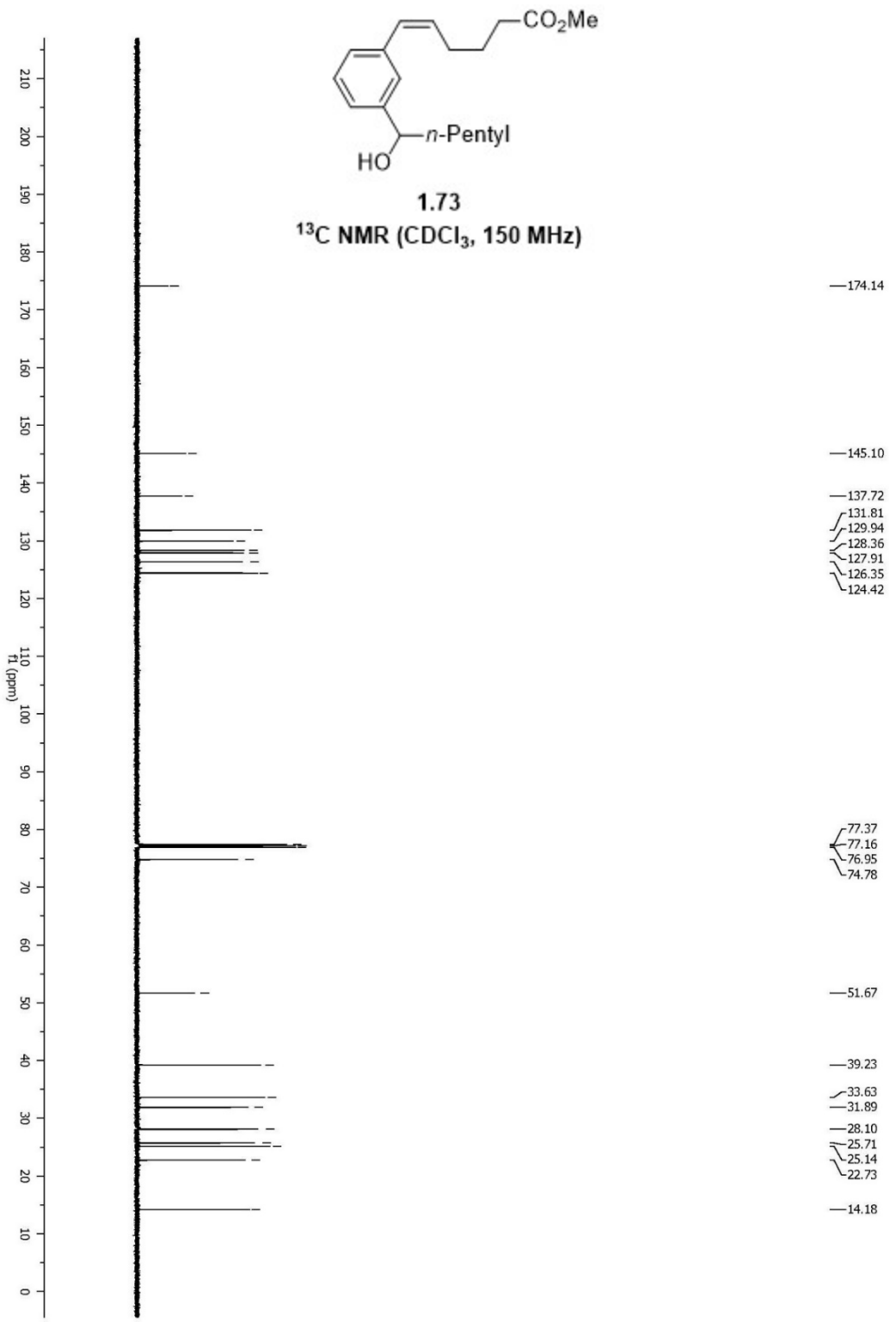

Me
CHO
1.77
^{1}H NMR ($CDCl_3$, 600 MHz)
f1 (ppm)
1.05
1.04
1.02
1.02
1.05
1.00
1.02
3.30
10.00
7.77
7.72
7.71
7.47
7.26
6.47
6.45
5.91
5.90
5.88
5.88
5.86
5.85
1.90
1.89

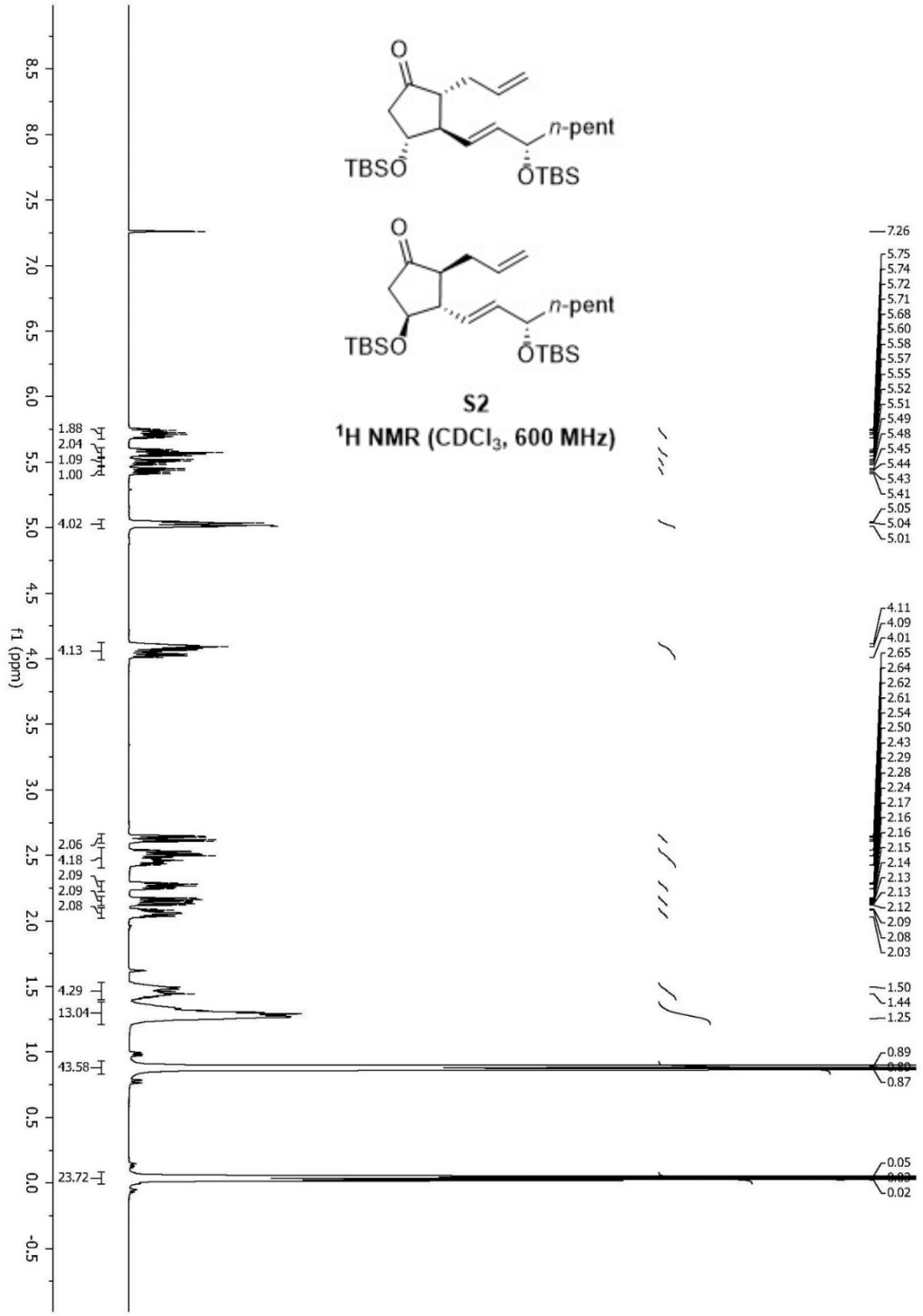

Me
CHO
1.77
^{13}C NMR ($CDCl_3$, 150 MHz)
192.43
138.56
136.45
134.80
129.92
128.88
128.61
128.59
127.82
77.37
77.16
76.95
14.66
f1 (ppm)

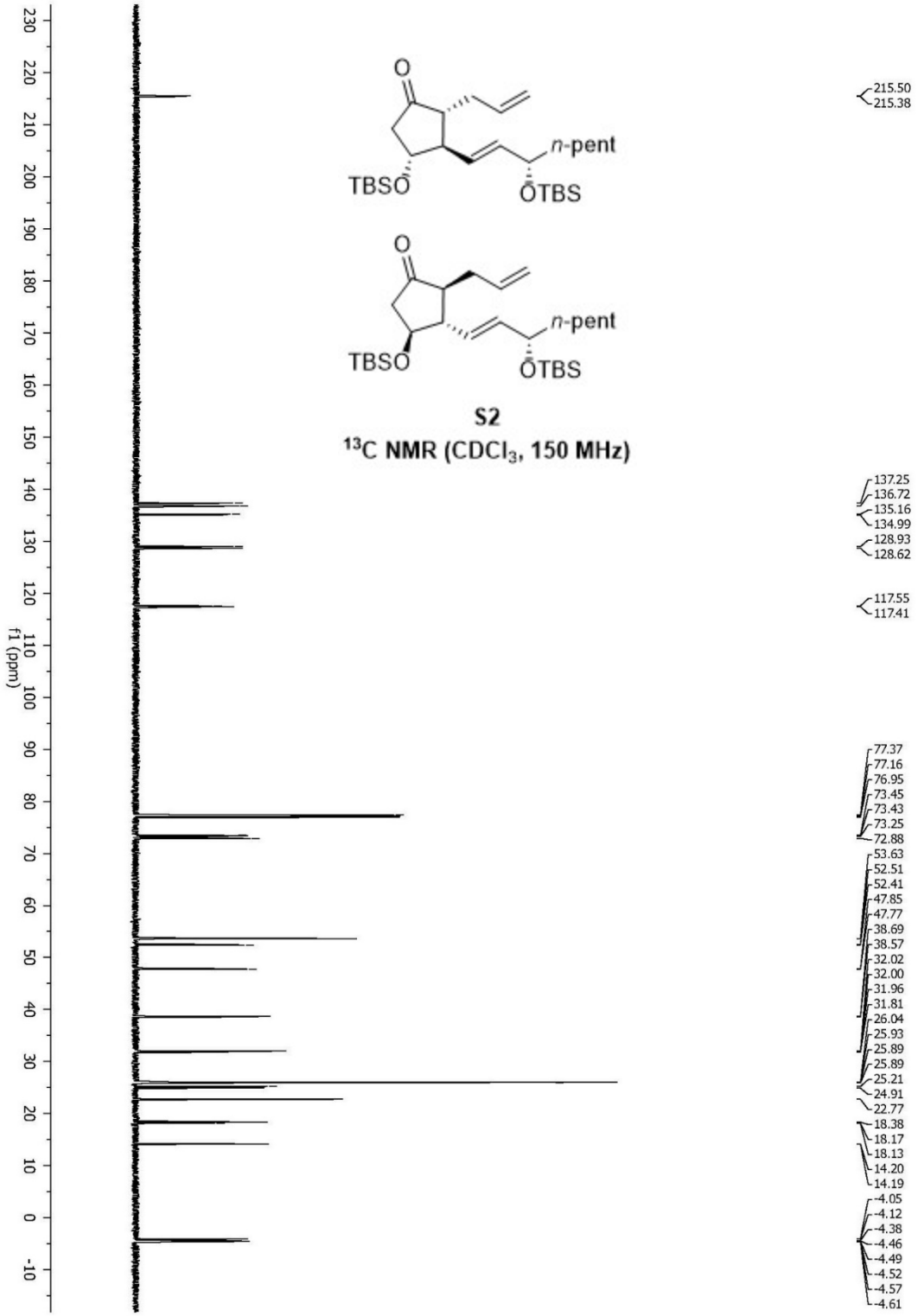

Me
n-Pentyl
HO
1.78
¹H NMR (CDCl₃, 400 MHz)
f1 (ppm)
1.03
0.96
2.06
1.00
0.99
1.10
3.00
3.41
1.20
5.55
3.23
7.34
7.32
7.30
7.27
7.26
7.23
7.21
7.19
6.46
6.45
6.43
6.42
5.83
5.82
5.81
5.80
5.79
5.78
5.76
4.68
4.67
4.65
1.92
1.90
1.89
1.82
1.80
1.79
1.78
1.75
1.74
1.73
1.71
1.30
1.26
0.89
0.87
0.86


Me
n-Pentyl
HO
1.78
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
144.95
137.90
129.92
128.36
128.09
127.13
126.55
124.16
77.37
77.16
76.95
74.89
39.24
31.89
25.70
22.74
14.83
14.18


CO2Me
n-Pentyl
HO
1.73
1H NMR (CDCl3, 400 MHz)
f1 (ppm)
7.32
7.30
7.28
7.26
7.26
7.20
7.19
7.17
7.15
6.48
6.45
5.68
5.66
5.65
5.64
5.63
5.61
4.67
4.66
4.64
3.67
3.64
2.38
2.36
2.34
2.32
2.05
2.04
1.70
1.44
1.26
0.89
0.89
0.88
0.86
1.00
1.33
1.00
0.95
0.99
0.98
1.05
2.94
4.13
0.92
4.33
1.18
5.08
3.35

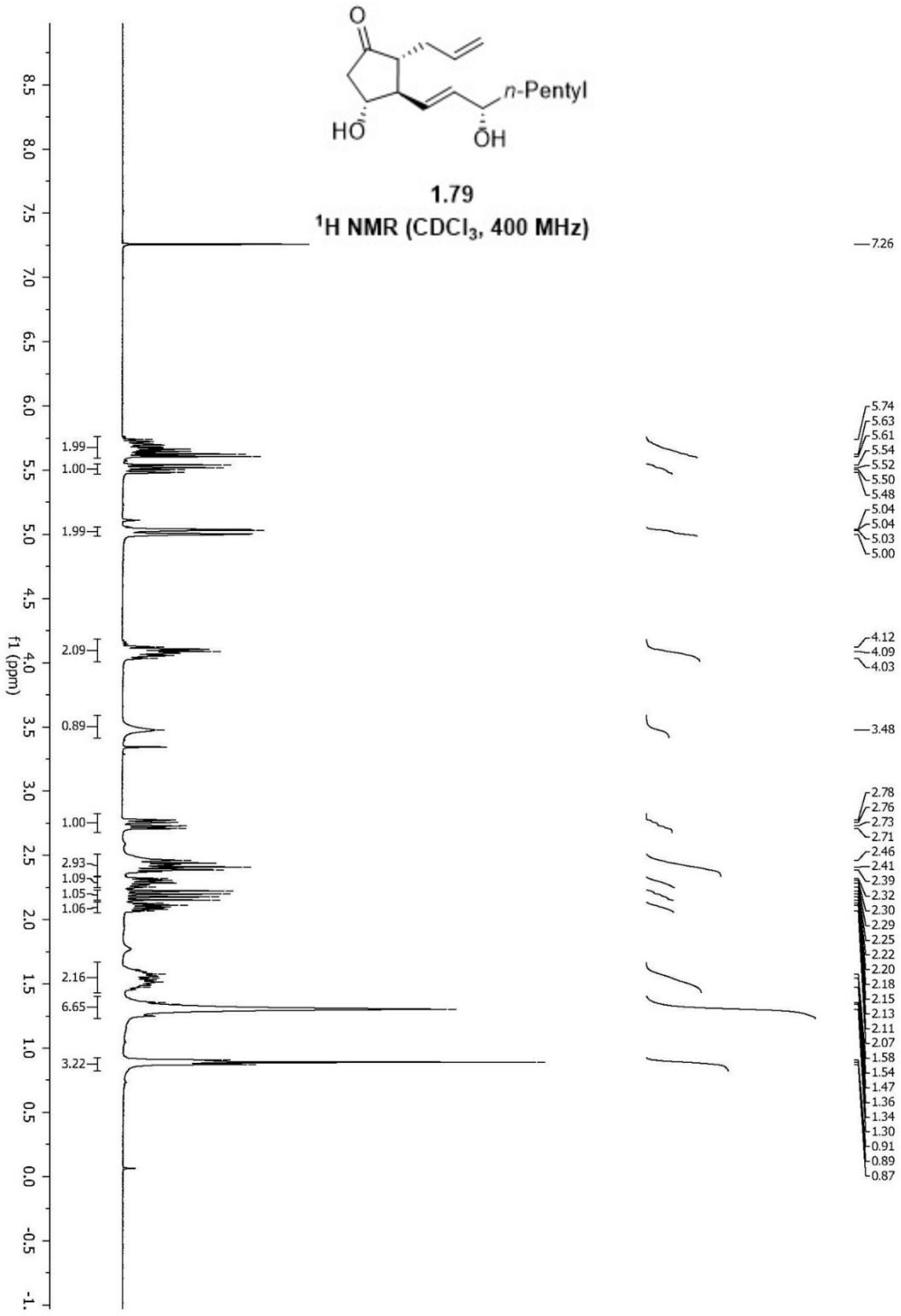

CO2Me
n-Pentyl
HO
1.73
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
174.14
145.10
137.72
131.81
129.94
128.36
127.91
126.35
124.42
77.37
77.16
76.95
74.78
51.67
39.23
33.63
31.89
28.10
25.71
25.14
22.73
14.18

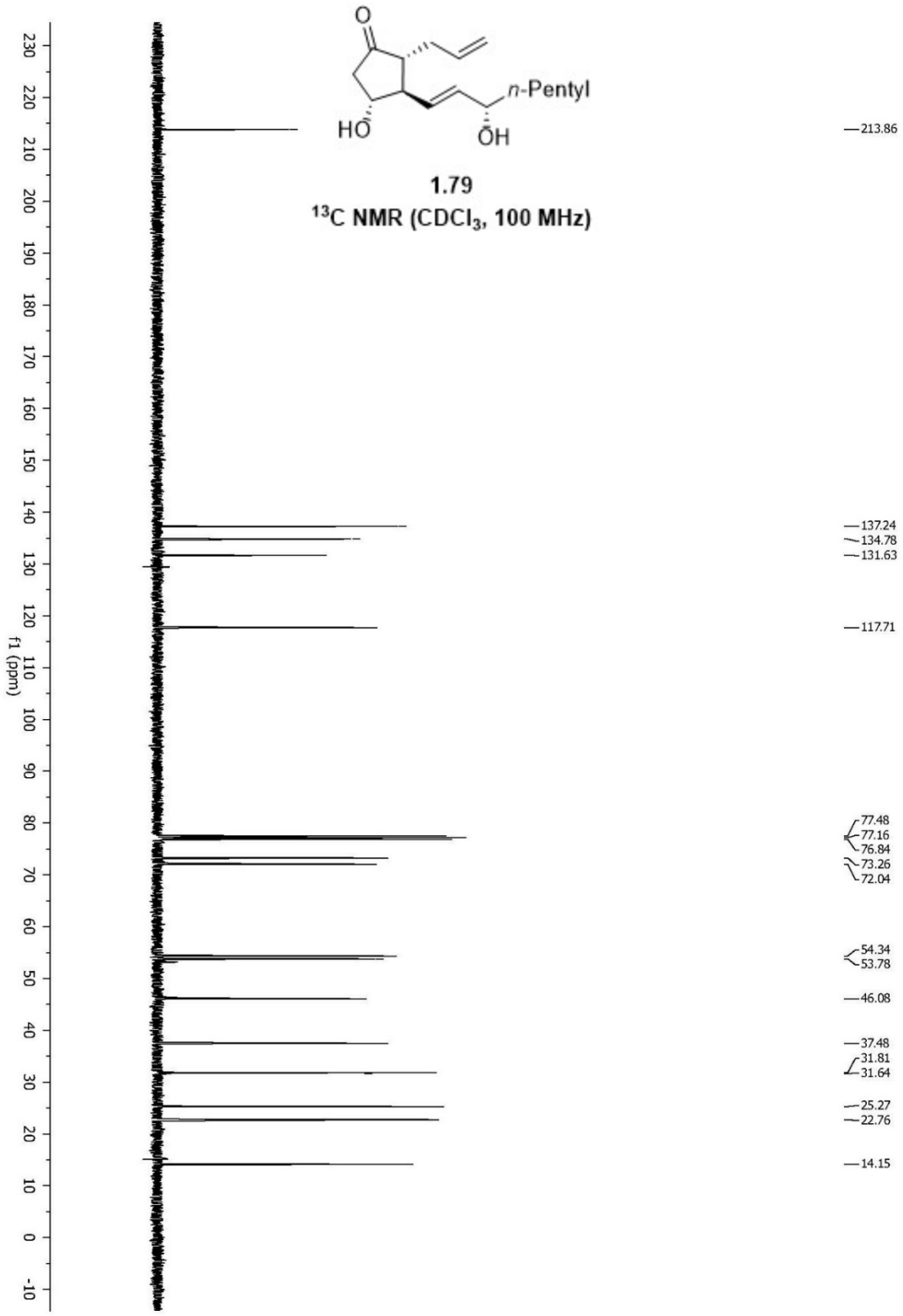

O
n-pent
TBSO
OTBS
O
n-pent
TBSO
OTBS
S2
¹H NMR (CDCl₃, 600 MHz)
f1 (ppm)
1.88
2.04
1.09
1.00
4.02
4.13
2.06
4.18
2.09
2.09
2.08
4.29
13.04
13.58
23.72
7.26
5.75
5.74
5.72
5.71
5.68
5.60
5.58
5.57
5.55
5.52
5.51
5.49
5.48
5.45
5.44
5.43
5.41
5.05
5.04
5.01
4.11
4.09
4.01
2.65
2.64
2.62
2.61
2.54
2.50
2.43
2.29
2.28
2.24
2.17
2.16
2.16
2.15
2.14
2.13
2.13
2.12
2.09
2.08
2.03
1.50
1.44
1.25
0.89
0.87
0.05
0.02

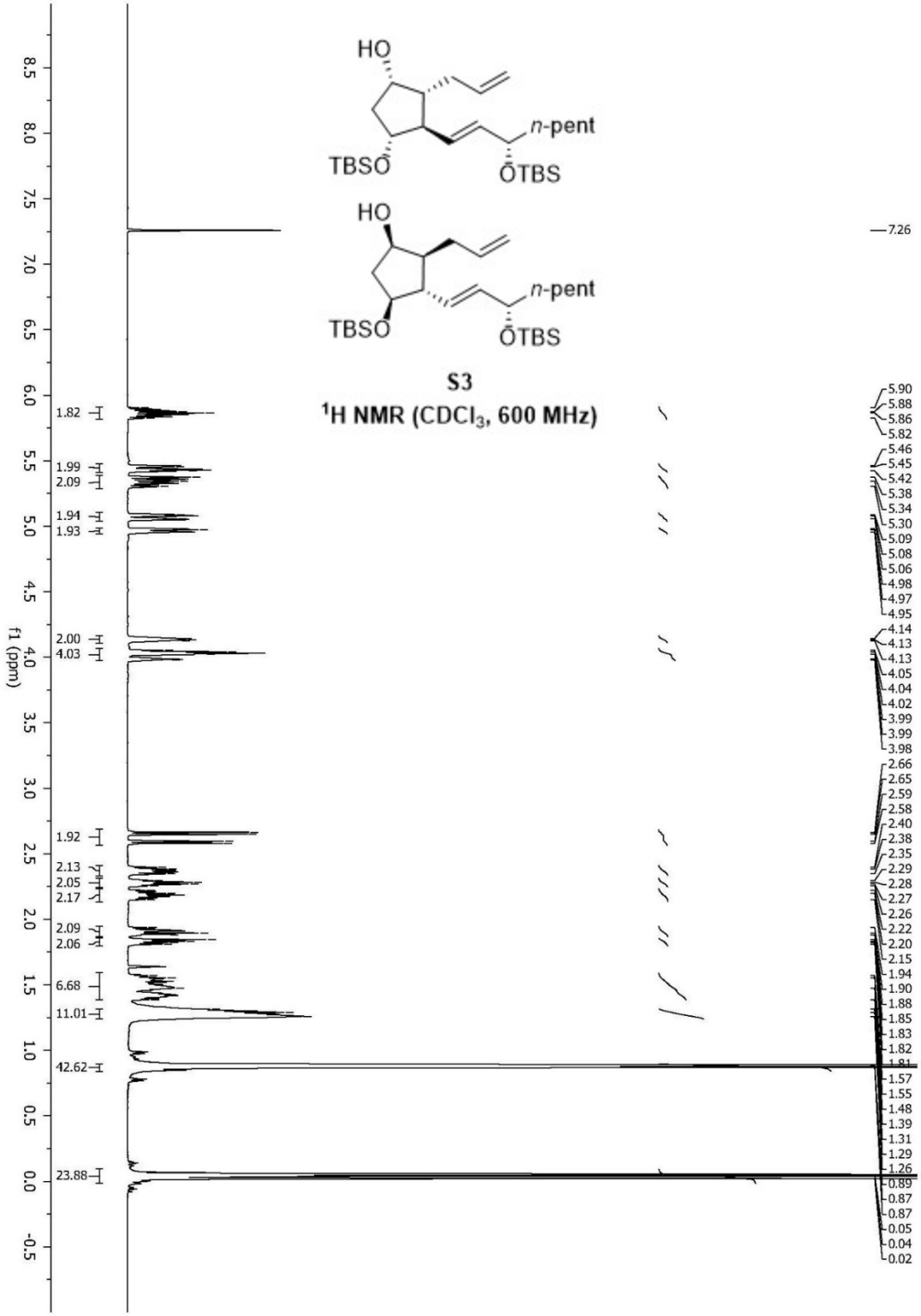


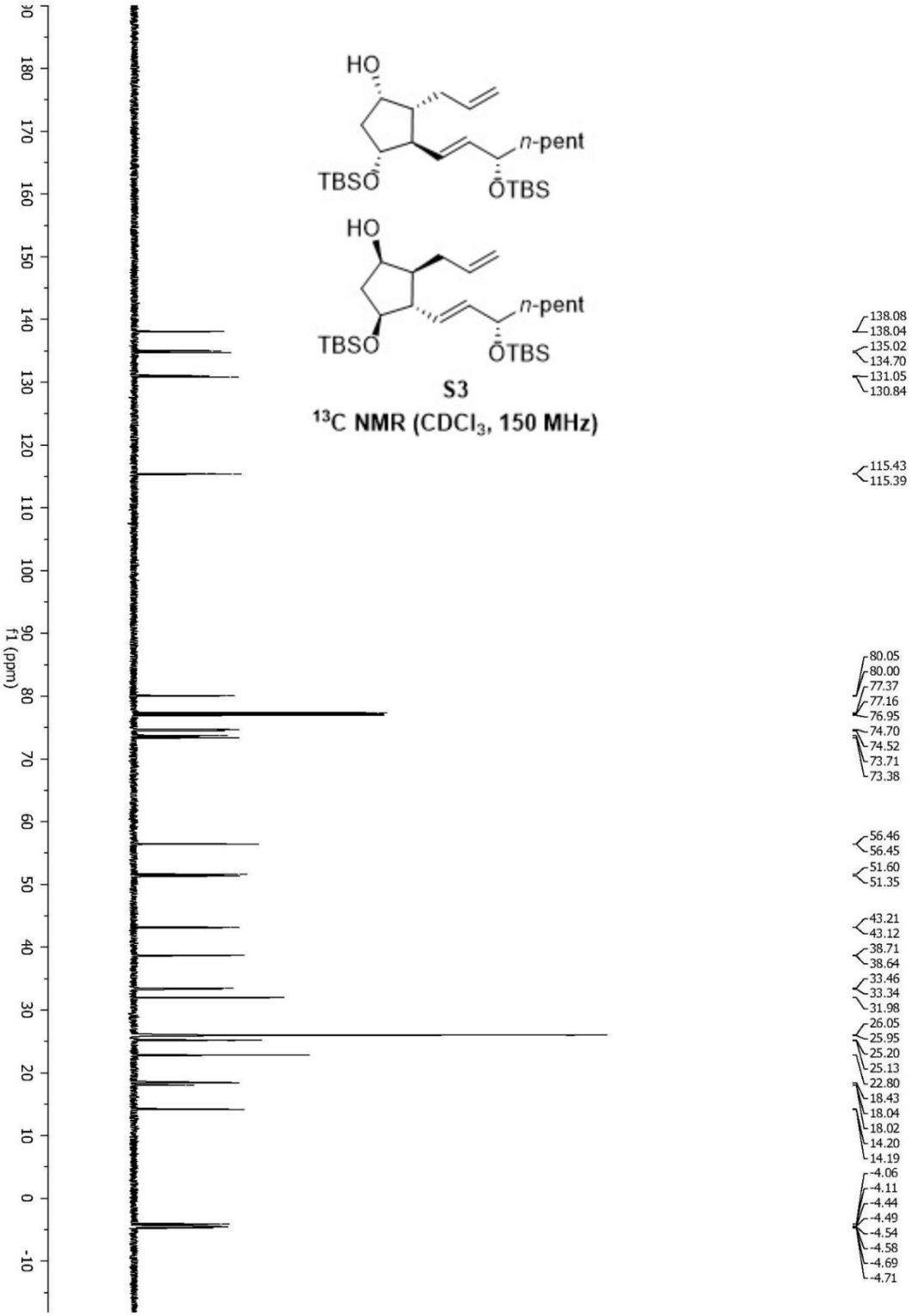
S2

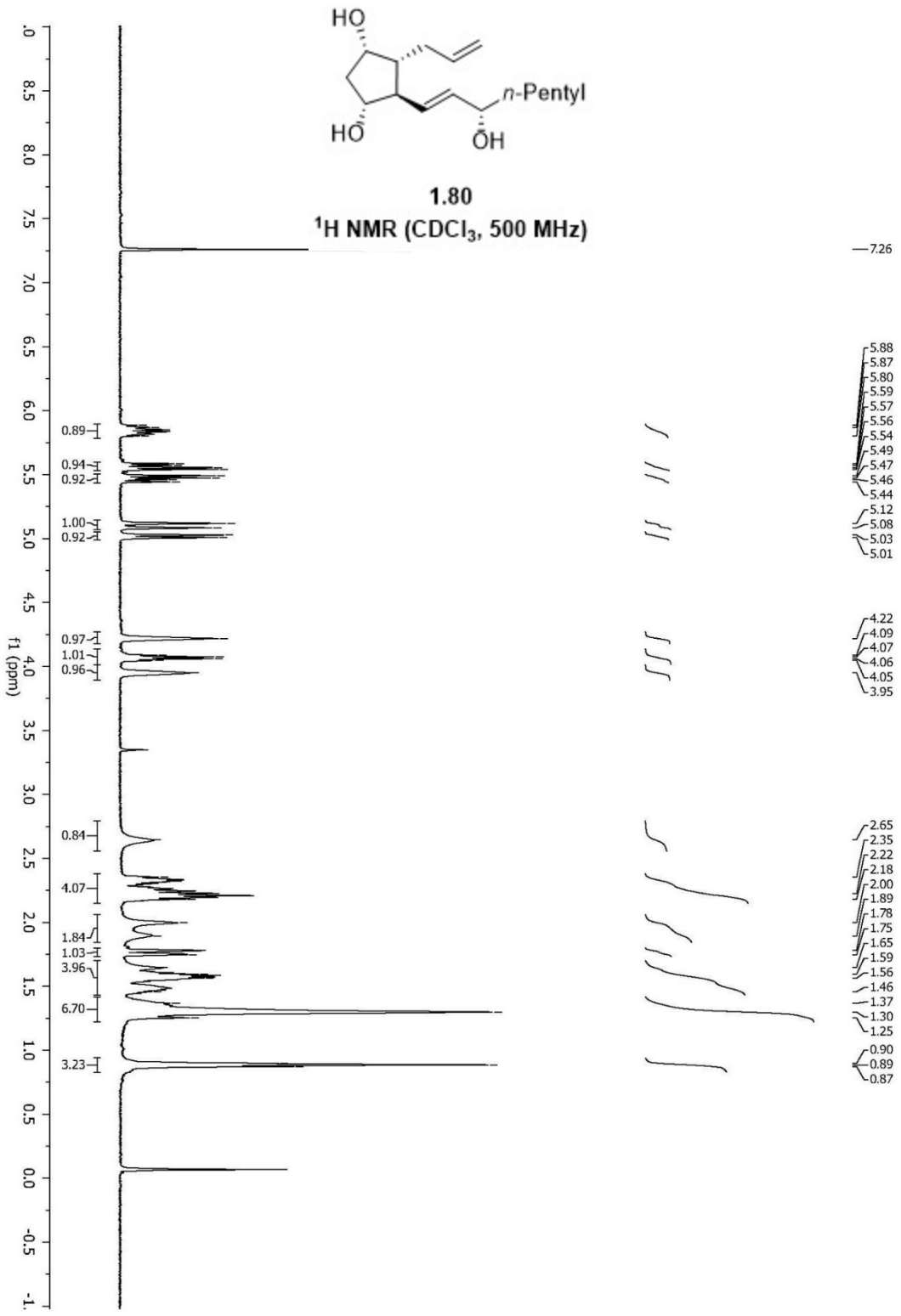
^{13}C NMR ($CDCl_3$, 150 MHz)

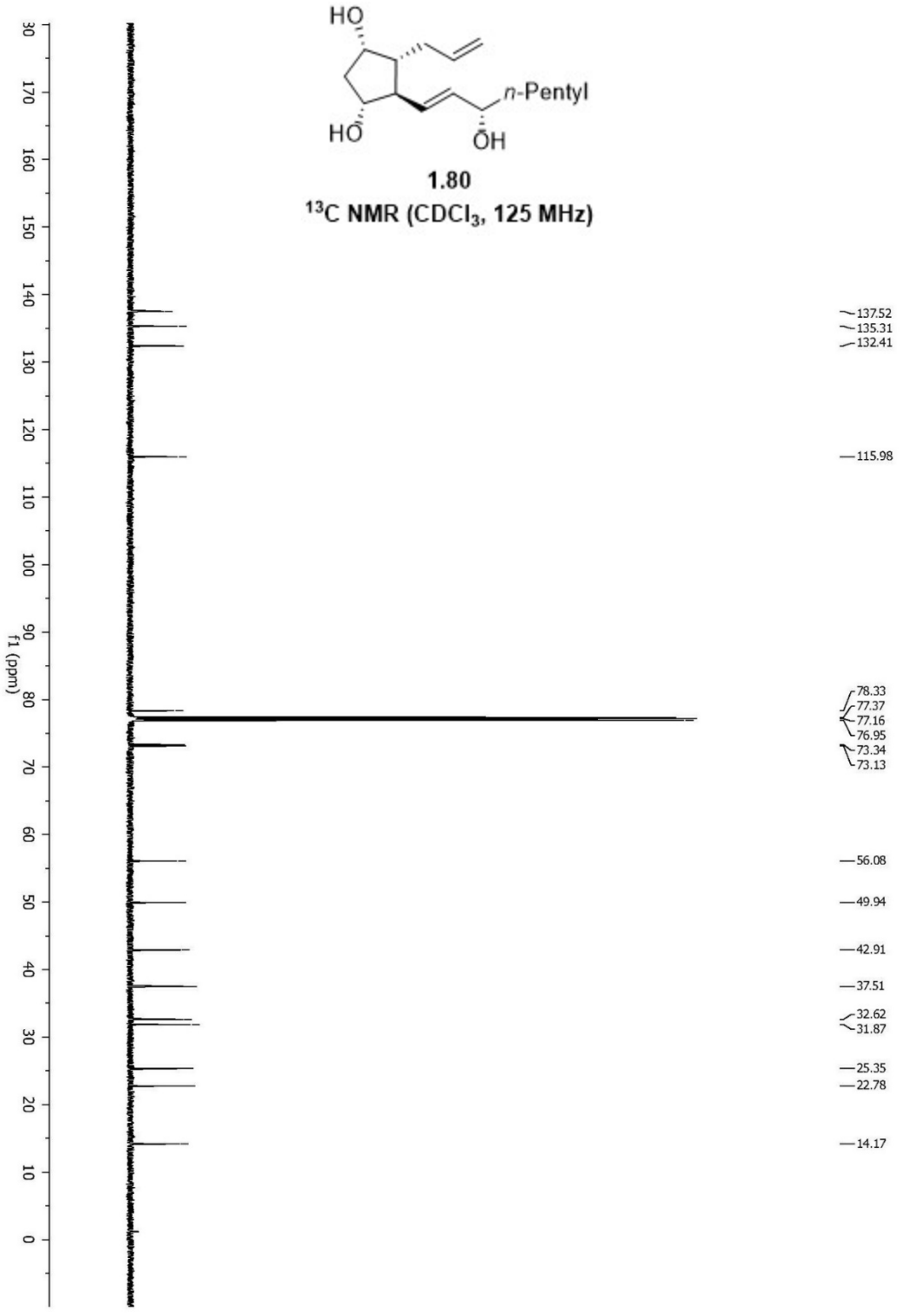

n-Pentyl
HO
OH
1.79
¹H NMR (CDCl₃, 400 MHz)
f1 (ppm)
7.26
5.74
5.63
5.61
5.54
5.52
5.50
5.48
5.04
5.04
5.03
5.00
4.12
4.09
4.03
3.48
2.78
2.76
2.73
2.71
2.46
2.41
2.39
2.32
2.30
2.29
2.25
2.22
2.20
2.18
2.15
2.13
2.11
2.07
1.58
1.54
1.47
1.36
1.34
1.30
0.91
0.89
0.87
1.99
1.00
1.99
2.09
0.89
1.00
2.93
1.09
1.05
1.06
2.16
6.65
3.22

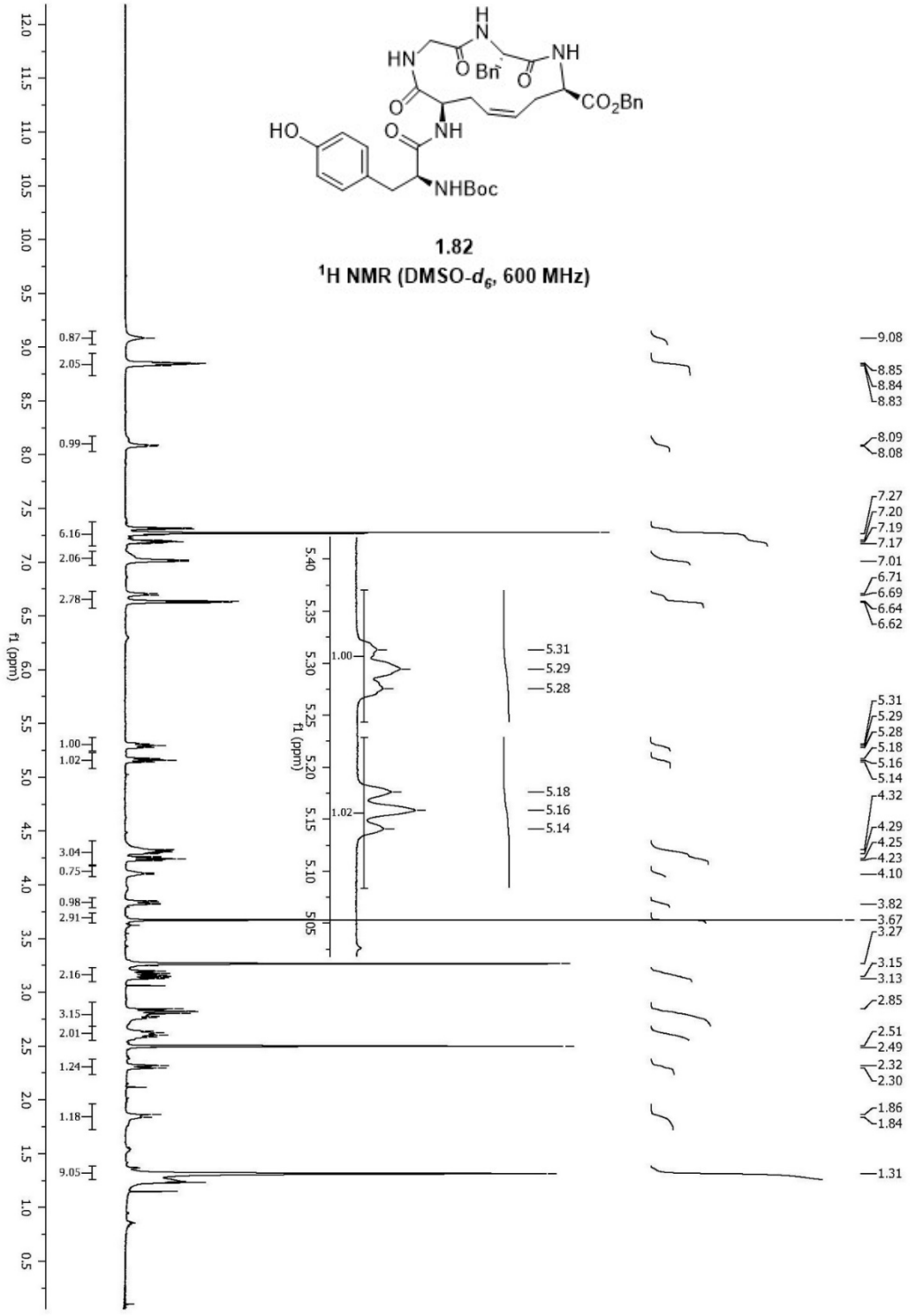

O
n-Pentyl
HO
OH
1.79
13C NMR (CDCl3, 100 MHz)
f1 (ppm)
213.86
137.24
134.78
131.63
117.71
77.48
77.16
76.84
73.26
72.04
54.34
53.78
46.08
37.48
31.81
31.64
25.27
22.76
14.15

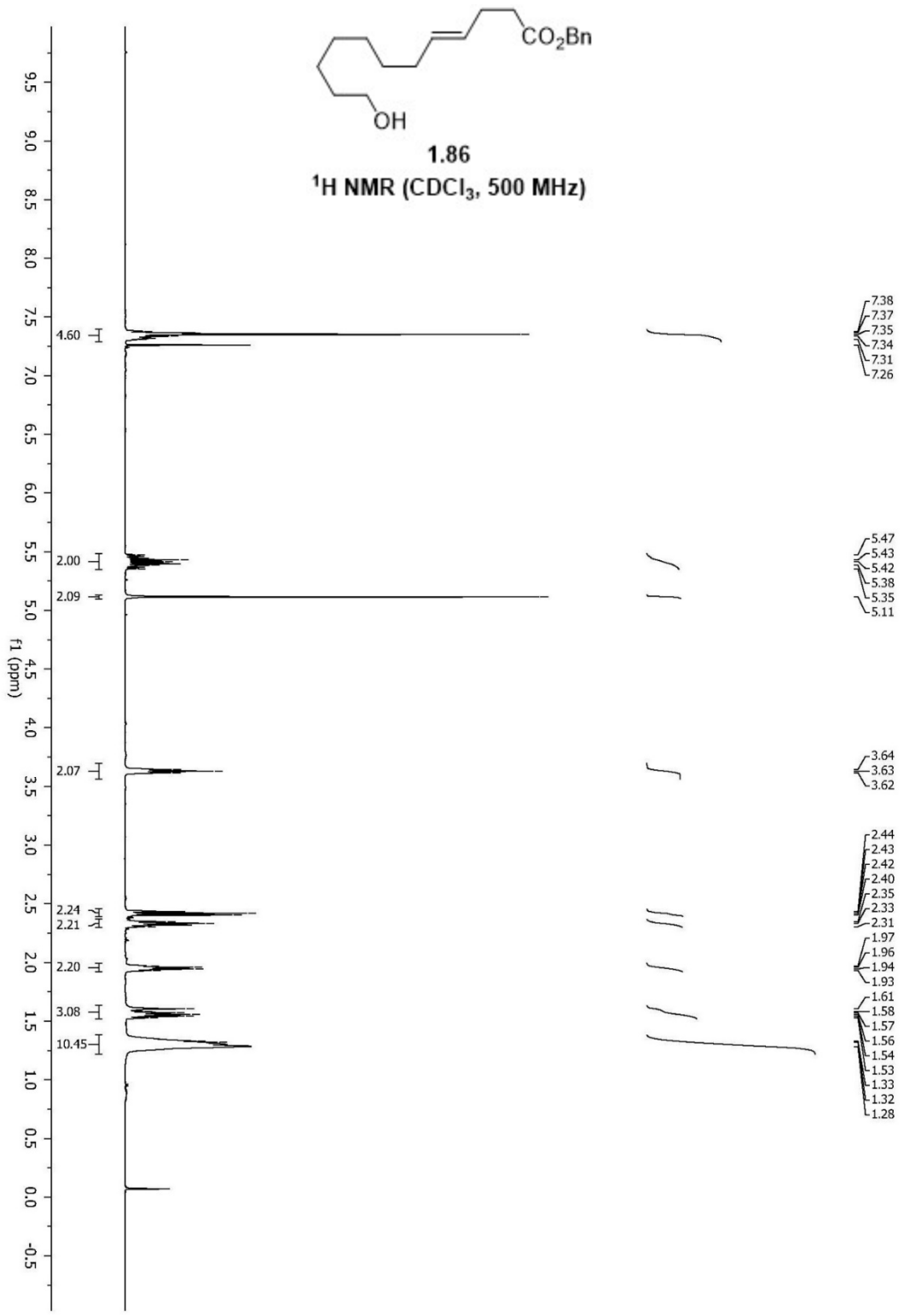

HO
n-pent
TBSO
OTBS
HO
n-pent
TBSO
OTBS
S3
¹H NMR (CDCl₃, 600 MHz)
f1 (ppm)
7.26
1.82
1.99
2.09
1.94
1.93
2.00
4.03
1.92
2.13
2.05
2.17
2.09
2.06
6.68
11.01
42.62
23.88

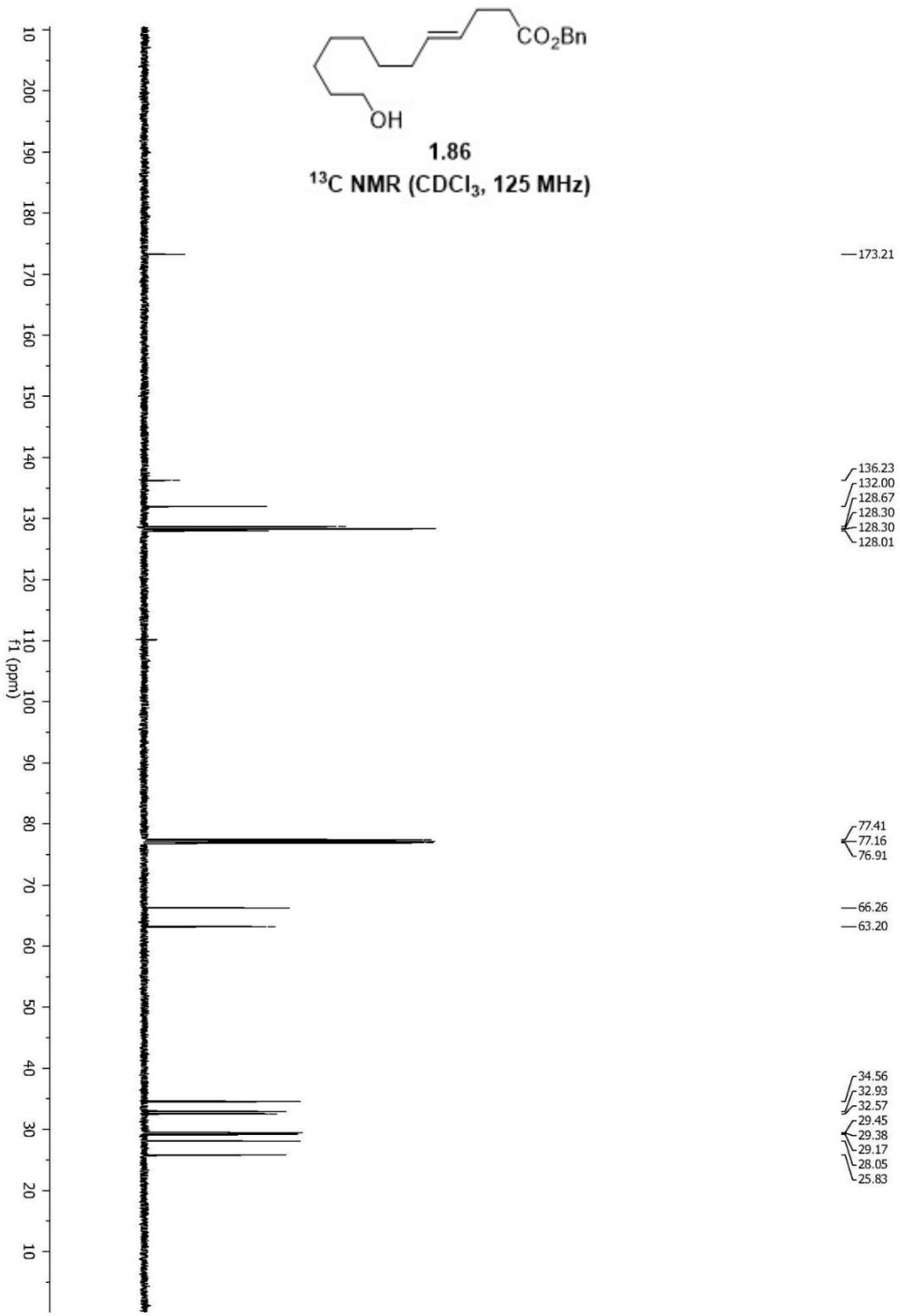

HO
n-pent
TBSO
OTBS
HO
n-pent
TBSO
OTBS
S3
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
138.08
138.04
135.02
134.70
131.05
130.84
115.43
115.39
80.05
80.00
77.37
77.16
76.95
74.70
74.52
73.71
73.38
56.46
56.45
51.60
51.35
43.21
43.12
38.71
38.64
33.46
33.34
31.98
26.05
25.95
25.20
25.13
22.80
18.43
18.04
18.02
14.20
14.19
-4.06
-4.11
-4.44
-4.49
-4.54
-4.58
-4.69
-4.71


HO
n-Pentyl
HO
OH
1.80
¹H NMR (CDCl₃, 500 MHz)
f1 (ppm)
7.26
5.88
5.87
5.80
5.59
5.57
5.56
5.54
5.49
5.47
5.46
5.44
5.12
5.08
5.03
5.01
4.22
4.09
4.07
4.06
4.05
3.95
2.65
2.35
2.22
2.18
2.00
1.89
1.78
1.75
1.65
1.59
1.56
1.46
1.37
1.30
1.25
0.90
0.89
0.87
0.89
0.94
0.92
1.00
0.92
0.97
1.01
0.96
0.84
4.07
1.84
1.03
3.96
6.70
3.23


HO
n-Pentyl
HO
OH
1.80
13C NMR (CDCl3, 125 MHz)
f1 (ppm)
137.52
135.31
132.41
115.98
78.33
77.37
77.16
76.95
73.34
73.13
56.08
49.94
42.91
37.51
32.62
31.87
25.35
22.78
14.17


1.82
¹H NMR (DMSO-d_6, 600 MHz)
f1 (ppm)


CO2Bn
OH
1.86
1H NMR (CDCl3, 500 MHz)
f1 (ppm)
4.60
2.00
2.09
2.07
2.24
2.21
2.20
3.08
10.45
7.38
7.37
7.35
7.34
7.31
7.26
5.47
5.43
5.42
5.38
5.35
5.11
3.64
3.63
3.62
2.44
2.43
2.42
2.40
2.35
2.33
2.31
1.97
1.96
1.94
1.93
1.61
1.58
1.57
1.56
1.54
1.53
1.33
1.32
1.28


CO2Bn
OH
1.86
13C NMR (CDCl3, 125 MHz)
f1 (ppm)
173.21
136.23
132.00
128.67
128.30
128.30
128.01
77.41
77.16
76.91
66.26
63.20
34.56
32.93
32.57
29.45
29.38
29.17
28.05
25.83

Chapter Two

Synthesis of Z- or E-Trisubstituted Allylic Alcohols and Ethers by Kinetically Controlled Catalytic Cross-Metathesis

2.1 Introduction

Stereochemically defined trisubstituted alkenes are commonly occurring in natural products and of considerable utility in chemical synthesis,[1] including catalytic enantioselective transformations (e.g., hydrogenation,[2] dihydroxylation,[3] allylic substitution[4] and conjugate addition).[5] Given the significance of trisubstituted alkenes, several synthesis methods have been developed for their preparation, but a number of key issues remain unaddressed. For instance, the Wittig reaction[6] cannot be used for stereoselective generation of trisubstituted alkenes, unless an α-alkoxy ketone is involved[7] or the substituents are of markedly different sizes.[8] The Horner-Wadsworth-Emmons (HWE) process[9] or the corresponding Still-Gennari variant[10] can be utilized for

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(1) (a) Negishi, E.; Huang, Z.; Wang, G.; Mohan, S.; Wang, C.; Hattori, H. *Acc. Chem. Res.* **2008***, 41*, 1474–1485. (b) Siau, W.-Y.; Zhang, Y.; Zhao, Y. *Top. Curr. Chem.* **2012**, *327*, 33–58.

(2) Shang, G.; Li, W.; Zhang, X. In *Catalytic Asymmetric Synthesis*; Ojima, I., Ed.; Wiley: New Jersey, 2010; pp 344–436.

(3) Noe, M. C.; Letavic, M. A.; Snow, S. L. In *Organic Reactions;* Denmark, S. E., Ed.; Wiley: New Jersey, 2005; pp 109–625.

(4) Basle, O.; Denicourt-Nowicki, A.; Crevisy, C.; Mauduit, M. In *Copper-Catalyzed Asymmetric Synthesis;* Alexakis, A., Krause, N., Woodward, S., Eds.; Wiley-VCH: Weinheim, 2004; pp 85–119.

(5) Alexakis, A.; Krause, N.; Woodward, S. In *Copper-Catalyzed Asymmetric Synthesis;* Alexakis, A., Krause, N., Woodward, S., Eds.; Wiley-VCH: Weinheim; 2014, pp 33–68.

(6) (a) Maryanoff, B. E.; Reitz, A. B. *Chem. Rev.* **1989**, *89*, 863–927. (b) Taber, D. F.; Meagley, R. P.; Doren, D. J. *J. Org. Chem.* **1996**, *61*, 5723–5728.

(7) Sreekumar, C.; Darst, K. P.; Still, W. C. *J. Org. Chem.* **1980**, *45*, 4260–4262.

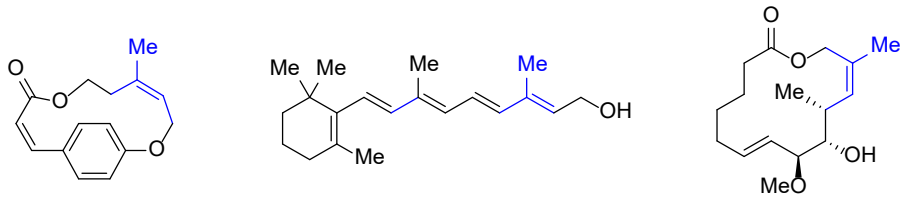
(8) Schlosser, M.; Christmann, K.-F. *Synthesis* **1969**, 38–39.

(9) Wadsworth, W. *Org. React*. **1977**, *25*, 73.

(10) Still, W. C.; Gennari, C. *Tetrahedron Lett*. **1983**, *24*, 4405–4408.

preparation of *E*- and *Z*-trisubstituted alkenes, respectively. However, these processes demand cryogenic and/or strongly basic conditions, thus limiting applicability. Other methods, such as conversion of an alkyne to a trisubstituted alkene, [11] often requires multistep sequences, harsh reaction conditions, and/or can be used to obtain one of two possible stereoisomers.

Scheme 2.1. Representative Trisubstituted Allylic Alcohols in Biologically Active Molecules



Pondaplin *(anti-tumor)* | Vitamin A1 *(diterpenoid)* | Migrastatin analog *(anti-tumor)*

Trisubstituted allylic alcohols are particularly valuable. These moieties are found in many biologically active compounds[12] (Scheme 2.1) and are among the most significant in chemical synthesis, used in key transformations such as hydroxy-directed reactions,[13] and allylic substitutions.[14] However, there are only a small number of methods for stereoselective synthesis of trisubstituted allylic alcohols. The most common entails reduction of the corresponding trisubstituted ester, typically prepared by HWE[9] or Still-

(11) For representative examples, see: (a) Fleming, I.; Newton, T. W.; Roessler, F. *J. Chem. Soc. Perkin Trans 1* **1981**, 2527–2532. (b) Trost, B. M.; Balls, Z. T. *Synthesis* **2005**, 853–887. (c) Wang, C.; Tobrman, T.; Xu, Z.; Negishi, E.-i. *Org. Lett.* **2009**, *11*, 4092–4095. (d) Mun, B.; Kim, S.; Yoon, H.; Kim, K. H.; Lee, Y. *J. Org. Chem.* **2017**, *82*, 6349–6357.

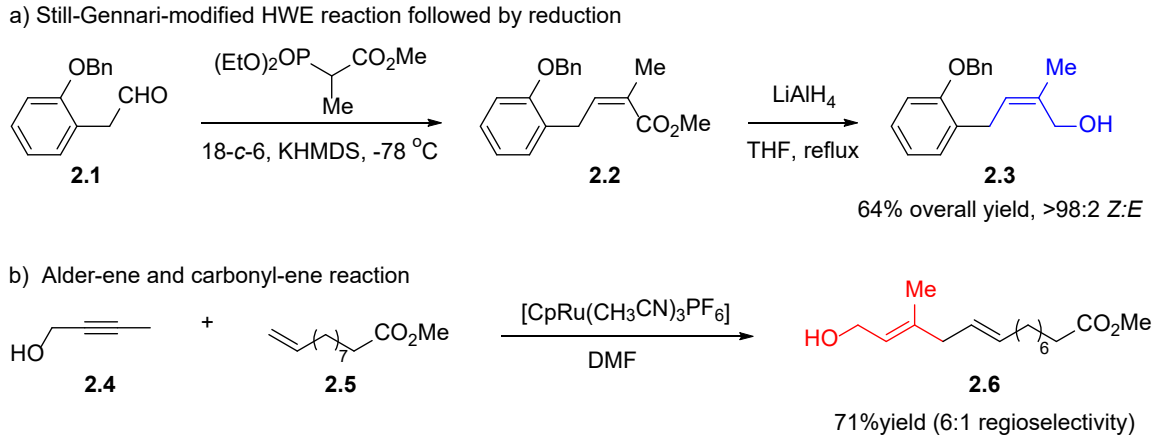
(12) (a) Wolf, G. *J. Nutr*. **2001**, *131*, 1647–1650. (b) Sabitha, G.; Swapna, R.; Babu, S.; Yadav, J. S. *Tetrahedron Lett*. **2005**, *46*, 6145–6148. (c) Giralt, E.; Re, D. L. *Molecules* **2017**, *22*, 198.

(13) (a) Hoveyda, A. H.; Evans, D. A.; Fu, G. C. *Chem. Rev*. **1993**, *93*, 1307. For recent examples, see: (b) Wu, R.; Beauchamps, M. G.; Laquidara, J. M.; Sowa, J. R., Jr. *Angew. Chem., Int. Ed*. **2012**, *51*, 2106. (c) Li, H.; Mazet, C. *J. Am. Chem. Soc*. **2015**, *137*, 10720.

(14) For reviews on substitution reactions with trisubstituted alkenes, see: (a) Trost, B. *Tetrahedron.* **2015**, *71*, 5708–5733. (a) Butt, N. A.; Zhang, W. *Chem. Soc. Rev*. **2015**, *22*, 7929–7927. (c) Cheng, Q.; Tu, H.-F.; Zheng, C.; Qu, J.-P.; Helmchen, G.; You, S.-L. *Chem. Rev*. **2019**, *119*, 1855–1969.

Gennari reactions[10] (Scheme 2.2a); as was noted, these routes require harsh reaction conditions and multistep sequences. Alder-ene and carbonyl-ene reactions[15] catalyzed by Ru complexes can be used to prepare trisubstituted allylic alcohols, but stereoselectivities are often low (Scheme 2.2b).[16]

Scheme 2.2. Methods for Stereoselective Synthesis of Trisubstituted Allylic Alcohols



2.2 Stereoselective Synthesis of Trisubstituted Alkenes by Cross-Metathesis

Catalytic cross metathesis (CM) represents a distinct and direct disconnection with considerable scope owing to compatibility of various Ru-, and Mo-based complexes to different recurring functional groups.[17] Consequently, synthesis routes involving alkene metathesis are often more concise.[18] Furthermore, transformations can be performed with reliable control of stereoselectivity.[19] There are several reports regarding the use of CM for

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(15) (a) Snider, B. B. *Acc. Chem. Res.* **1980**, *13*, 426–432. (b) Mikami, K.; Shimizu, M. *Chem. Rev*. **1992**, *92*, 1021–1050.

(16) Trost, B. M.; Shen, H. C.; Pinkerton, A. B. *Chem. Eur. J.* **2002**, *8*, 2341–2349.

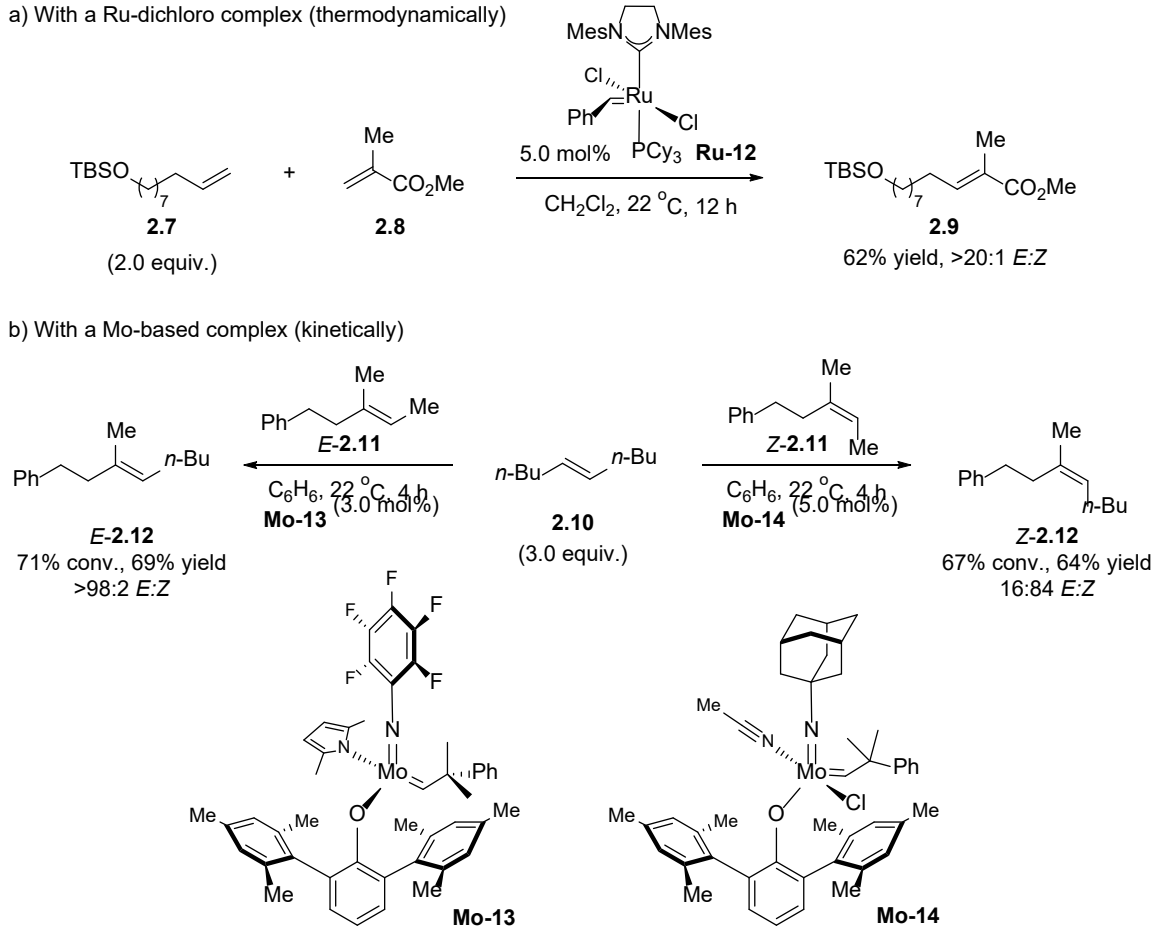
(17) *Handbook of Metathesis*; Grubbs, R. H., Wenzel, A. G., O'Leary, D. J., Khosravi, E., Eds.; Wiley-VCH: Weinheim, Germany, 2014.

(18) Yu, M.; Wang, C.; Kyle, A. F.; Jakubec, P.; Dixon, D. J.; Schrock, R. R.; Hoveyda, A. H. *Nature* **2011**, *479*, 88–93.

(19) Hoveyda, A. H. *J. Org. Chem.* **2014**, *79*, 4763–4792.

accessing trisubstituted alkenes. Some of these strategies involve Ru-based carbenes[20] and afford products selectively, depending the degree to which one isomer is energetically more favored (i.e., thermodynamic control).[20a,c,d, 21] For instance, CM of enoates or related derivatives typically furnish *E*-alkene products selectively; the example in Scheme 2.3a is illustrative.[20a]

Scheme 2.3. Stereoselective Synthesis of Trisubstituted Alkenes by Catalytic CM



(20) (a) Chatterjee, A. K.; Grubbs, R. H. *Org. Lett.* **1999**, *1*, 1751–1753. (b) Chatterjee, A. K.; Sanders, D. P.; Grubbs, R. H. *Org. Lett.* **2002**, *4*, 1939–1942. (c) Morrill, C. M.; Funk, T. W.; Grubbs, R. H. *Tetrahedron Lett.* **2004**, *45*, 7733–7736. (d) Wang, Z. J.; Jackson, W. R.; Robinson, A. J. *Org. Lett.* **2003**, *15*, 3006–3009.

(21) Cuvigny, T.; du Penhoat, H.; Julia, M. *Tetrahedron Lett.* **1980**, *21*, 1331–1334.

In 2017, Hoveyda *et al.* reported a catalytic CM method for stereoselective synthesis of trisubstituted alkenes where Mo-based complexes were used to promote reactions (Scheme 2.3b).[22] Thus, with *Z*- or *E*-trisubstituted alkenes serving as substrate (***Z*-2.11** and ***E*-2.11**, Scheme 2.3b) the desired *Z*- or *E*-trisubstituted alkenes were synthesized efficiently and stereoselectively. The study described below relate to the use of Ru-based catechothiolate complexes for stereoretentive formation of *Z*- and *E*-trisubstituted allylic alcohols and ethers.

2.3 Synthesis of Trisubstituted *Z*- and *E*-Allylic Alcohols and Ethers by Kinetically Controlled Cross-Metathesis Catalyzed by Ru-Based Complexes

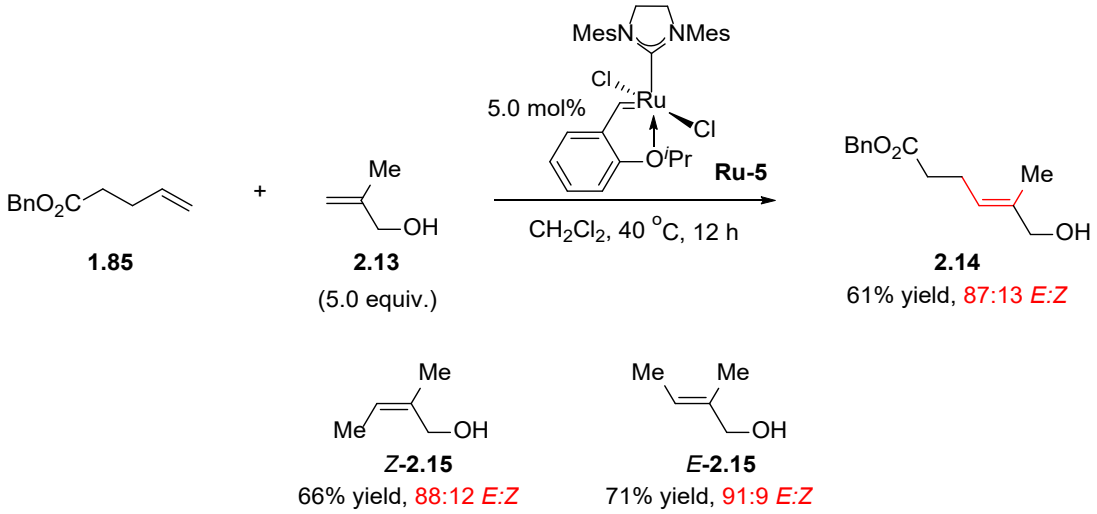
2.3.1 Initial studies

To probe the feasibility of developing a catalytic CM method for synthesis of stereodefined trisubstituted allylic alcohols, we first investigated the ability of a commonly utilized Ru-dichloro complex (**Ru-5**)[23] to promote such a transformation. We found that with

(22) Nguyen, T. T.; Koh, M. J.; Mann, T J.; Schrock, R. R.; Hoveyda, A. H. *Nature* **2017**, *552*, 347–354.

(23) Garber, S. B.; Kingsbury, J. S.; Gary, B. L.; Hoveyda, A. H. *J. Am. Chem. Soc*. **2000**, *122*, 8168–8179.

Scheme 2.4. CM for Synthesis of Trisubstituted Allylic Alcohols with a Ru-Dichloro Complex[a]



[a]Reactions were performed under N_2 atm. *Z:E* Ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

monosubstituted alkene **1.85** and 1,1-disubstituted alkene **2.13** as substrates, in the presence of 5,0 mol % **Ru-5**, allylic alcohol **2.14** may be isolated in 61% yield and 87:13 *E:Z* ratio (Scheme 2.4); the more thermodynamically favored *E* alkene was thus generated preferentially. When *Z*- or *E*-trisubstituted allylic alcohols **2.15** were used as the starting materials, the *E*-trisubstituted allylic alcohol products were again generated predominantly.

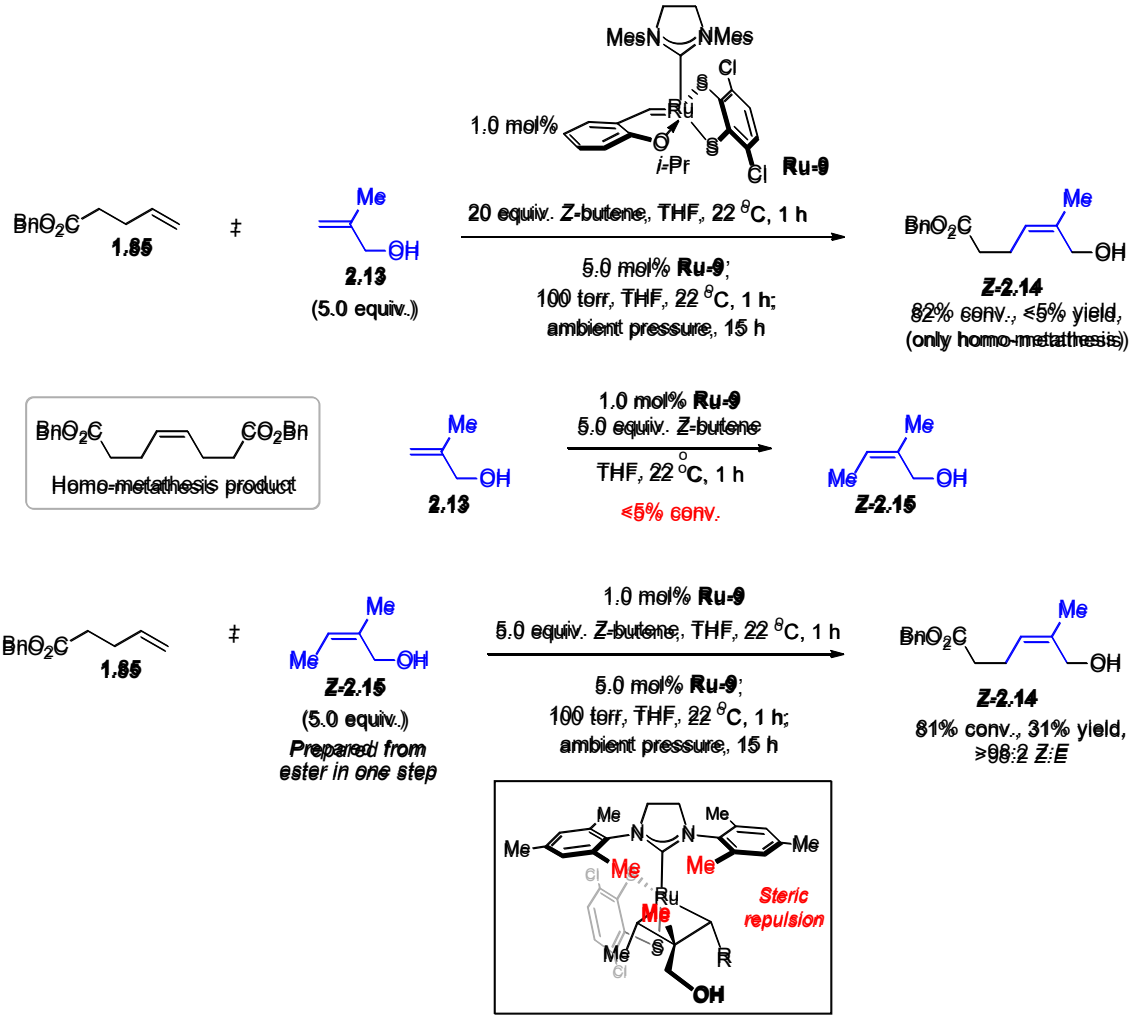
Next, we investigated the possibility of using a Ru-based catechothiolate complex[24] to promote CM reactions that generate trisubstituted alkenes (Scheme 2.5). We had previously used **Ru-9** together for *Z*-selective CM reactions where methylene capping strategy was applied to prepare 1,2-disubstituted alkenes. Here, we began by investigating the capping[25] of terminal alkenes **1.85** and **2.13** with *Z*-butene (20 equiv) in the presence

(24) (a) Khan, R. K. M.; Torker, S.; Hoveyda, A. H. *J. Am. Chem. Soc*. **2013**, *135*, 10258–10261. (b) Koh, M. J.; Khan, R. K. M.; Torker, S.; Yu, M.; Mikus, M.; Hoveyda, A. H. *Nature* **2015**, *517*, 181–186.

(25) Xu, C.; Shen, X.; Hoveyda, A. H. *J. Am. Chem. Soc*. **2017**, *139*, 10919–10928.

of 1.0 mol % **Ru-9**. Subsequent removal of excess *Z*-butene and addition of 5.0 mol % of **Ru-9** only afforded the product derived from homo-metathesis of the less hindered monosubstituted olefin **1.85**. Equally important, under the same conditions, **2.13** did not react with *Z*-butene (<5% conv; i.e., it could not be capped). The reason might be that nonproductive metathesis with *Z*-butene is significantly more facile (vs CM with 1,1-disubstitued alkene).

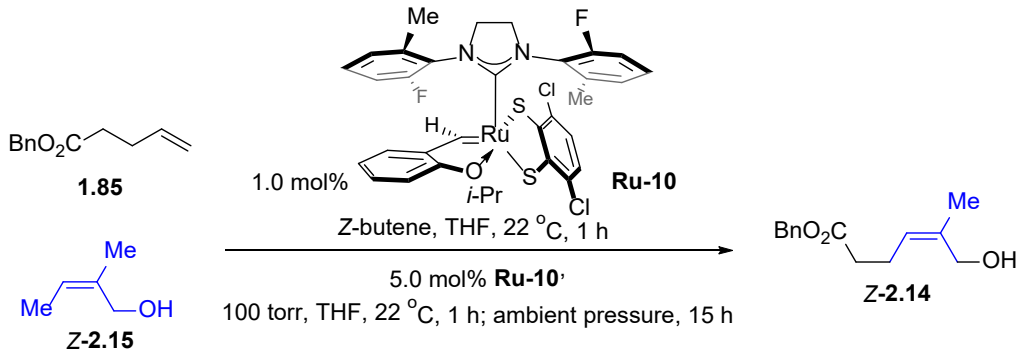
Scheme 2.5. Synthesis of Trisubstituted Allylic Alcohols through CM with a Ru Catechothiolate Complex[a]



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

We therefore opted to use *Z*-**2.15**, prepared by reduction of commercially available methyl angelate (96% yield in the presence of 3.0 equiv. of $LiAlH_4$ in ethyl ether), Thus, in the presence of *Z*-**2.15** as the cross partner, under otherwise identical conditions as described above (Scheme 2.5), the CM process proceeded to 81% conversion, affording *Z*-**2.14** in 31% yield and >98:2 *Z:E* ratio. Nonetheless, still, ~50% of the monosubstituted alkene substrate underwent homo-metathesis. We reasoned that steric pressure caused by the proximity of the catalyst's NHC ligand and metallacyclobutane's C_β substituent could lead to rate diminution (Scheme 2.5).

Scheme 2.6. Optimizations for CM with **Ru-10** for Synthesis of *Z*-Trisubstituted Allylic Alcohols[a]



entry	equiv. ***Z*-2.15**	equiv. *Z*-butene	conv(%)[b], yield(%)[c]	*Z:E*[b]
1	**5.0**	**10**	**90; 76**	**>98:2**
2	3.0	10	85; 65	>98:2
3	5.0	5.0	95; 74	>98:2
4	5.0	none	21; 15	>98:2

[a]Reactions were performed under N_2 atm. [b]Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). [c]Yields for purified products (±5%). For full details, see the Experimental Section.

Based on the above considerations, we envisioned that catalysts derived from **Ru-10**,[26] which contains a less sterically demanding NHC ligand, might prove to be more

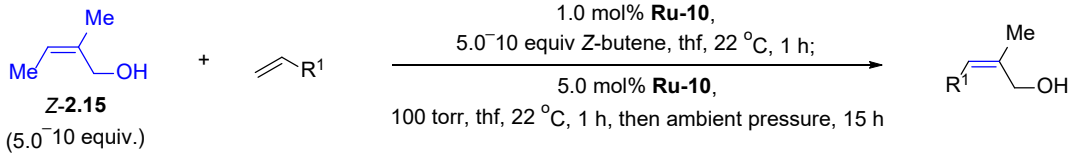
(26) For studies about **Ru-10** in other olefin metathesis reactions, see: Johns, A. M.; Ahmed, T. S.; Jackson, B. W.; Grubbs, R. H.; Pederson, R. L. *Org. Lett*. **2016**, *18*, 772–775.

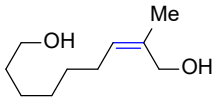
effective (Scheme 2.6). With 5.0 equivalents of *Z*-**2.15** and excess *Z*-butene (10 equiv) as the capping agent and in the presence of 6.0 mol % **Ru-10** could catalyze CM to afford product *Z*-**2.14** in 76% yield and >98:2 *Z:E* ratio (entry 1). With lower amounts of *Z*-**2.15** (3.0 equiv) efficiency was decreased (65% vs 76% yield, entry 2, and with less *Z*-butene (5.0 equiv vs 10 equiv) the transformation was equally efficient (74% vs 76% yield, entry 3). When larger excess of *Z*-butene was used, efficiency decreased considerably (15% yield, entry 4). With the optimized conditions in hand (entry 1, Table 2.6), we set out to explore the scope of the method.

2.3.2 Synthesis of *Z*- and *E*-Trisubstituted Allylic Alcohols

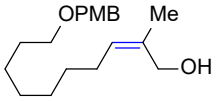
We synthesized a variety of *Z*-trisubstituted allylic alcohols in up to 81% yield and ≥98:2 *Z:E* selectivity (Scheme 2.7). Products containing a hydroxy (*Z*-**2.16**), a Lewis basic phthalimide (*Z*-**2.20**), an epoxide (*Z*-**2.21**), an aldehyde (*Z*-**2.22**), or a phenolic moiety (*Z*-**2.25**) were thus readily generated. Reactions with *β*-branched alkenes were somewhat less efficient, as indicated by the data regarding *Z*-**2.24** (40% yield) and *Z*-**2.23** (63% yield). A conjugated diene (*Z*-**2.27**) chemoselectively underwent transformation to afford the expected product in 58% and high stereoisomeric purity (98:2 *Z:E*).

Scheme 2.7. *Z*-Trisubstituted Allylic Alcohols Prepared by Catalytic CM[a]

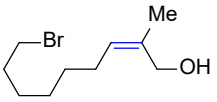




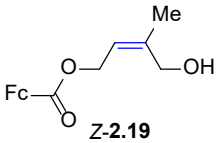
Z-2.16
92% conv., 70% yield,
>98:2 *Z*:*E*



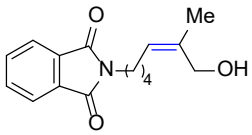
Z-2.17
95% conv., 78% yield,
>98:2 *Z*:*E*



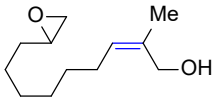
Z-2.18
95% conv., 68% yield,
>98:2 *Z*:*E*



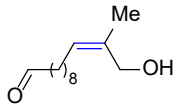
Z-2.19
87% conv., 55% yield,
>98:2 *Z*:*E*



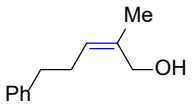
Z-2.20
92% conv., 77% yield,
>98:2 *Z*:*E*



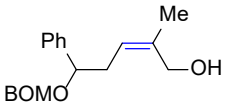
Z-2.21
90% conv., 75% yield,
>98:2 *Z*:*E*



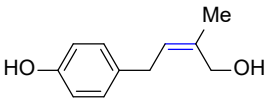
Z-2.22
95% conv., 70% yield,
>98:2 *Z*:*E*



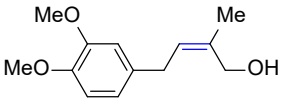
Z-2.23
83% conv., 63% yield,
>98:2 *Z*:*E*



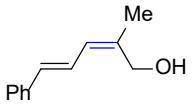
Z-2.24
75% conv., 40% yield,
>98:2 *Z*:*E*



Z-2.25
88% conv., 55% yield,
98:2 *Z*:*E*



Z-2.26
90% conv., 81% yield,
>98:2 *Z*:*E*



Z-2.27
91% conv., 58% yield,
98:2 *Z*:*E*

[a]Reactions were performed under N_2 atm. Conversion and *Z*:*E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

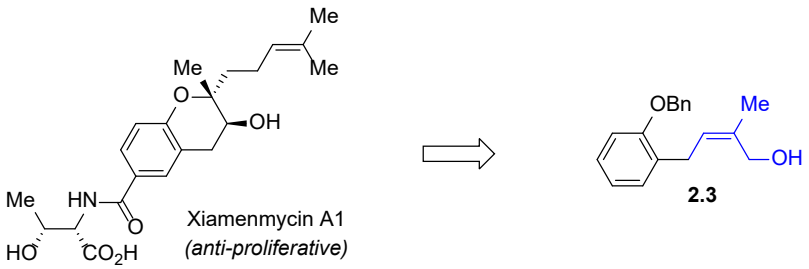
To determine the utility of the approach method, we set out to synthesize xiamenmycin A, a naturally occurring antiproliferative agent (Scheme 2.8).[27] A previously reported synthesis involved the intermediacy of *Z*-homoallylic alcohol **2.3**, which was accessed in four chemical steps.[28] Our route began with a transformation involving the protected form of a commercially available phenol (benzyl ether formation proceeded

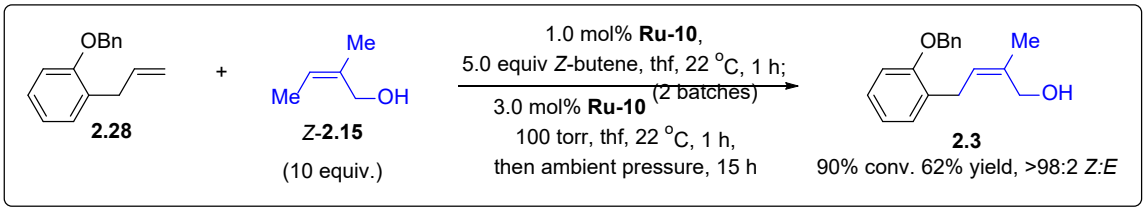
(27) M. J. Xu, X. J. Liu, Y. L. Zhao, D. Liu, Z. H. Xu, X. M. Lang, P. Ao, W. H. Lin, S. L. Yang, Z. G. Zhang and J. Xu, *Mar. Drugs*, **2012**, *10*, 639–654.

(28) Jiao, X.; Yao, Y.; Yang, B.; Liu, X.; Li, X.; Yang, H.; Li, L.; Xu, J.; Xu, M.; Xie, P. *Org. Biomol. Chem.* **2016**, *14*, 1805.

in >98% yield) and CM of benzyl ether **2.28** to afford *Z*-trisubstituted homoallylic alcohol **2.3** in 62% yield as a single stereoisomer. The two-step approach is more concise, obviating the need for as reduction of the enoate generated by Horner-Wadsworth-Emmons reaction.

Scheme 2.8. The Application to Synthesis of Xiamenmycin A1[a]

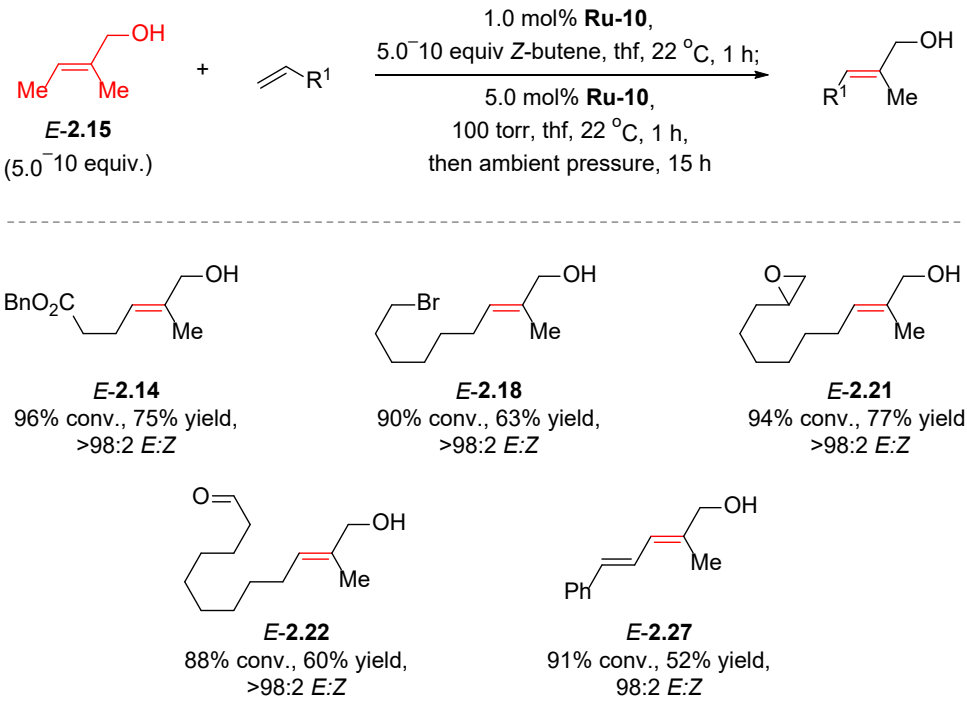




[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^1H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

By using trisubstituted *E*-**2.15**, generated readily in a similar manner as the corresponding *Z* isomer, *E*-allylic alcohols were synthesized up to 77% yield with exceptional stereocontrol (Scheme 2.9). As was the case with the corresponding *Z* isomers, the approach has reasonably broad applicability.

Scheme 2.9. *E*-Trisubsituted Allylic Alcohols Synthesized by CM[a]



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^1H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

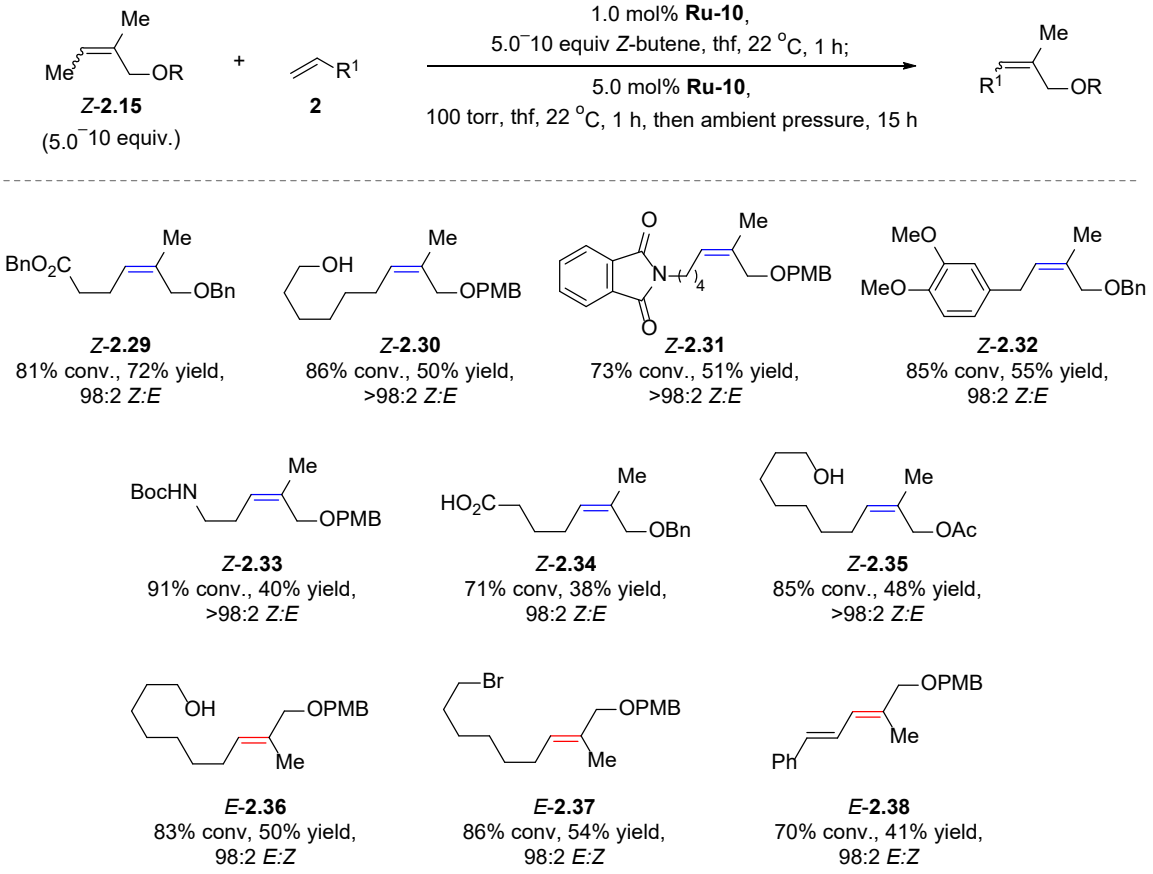
2.3.3 Synthesis of *Z*- and *E*-Trisubstituted Allylic Ethers

The catalytic approach may be applied to stereoselective formation of *Z*- or *E*-trisubstituted allylic ethers (Scheme 2.10). Thus, allylic benzyl ethers, *p*-methoxy benzyl ethers, and allylic acetates are suitable substrates. The CM reaction to generate carboxylic acid (*Z*-**2.34**) proved to be more challenging,[29] probably because of slow decomposition of the Ru carbene by the carboxylic acid group and, as a result, more of the allylic ether was needed to ensure proper efficiency (20 equiv).[30]

(29) Koh, M. J.; Khan, R. K. M.; Torker, S.; Yu, M.; Mikus, M.; Hoveyda, A. H. *Nature* **2015**, *517*, 181.

(30) Xu, C.; Shen, X.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2017**, *139*, 10919–10928.

Scheme 2.10. *Z*- and *E*-Trisubstituted Allylic Ethers and Esters Synthesized by CM[a]



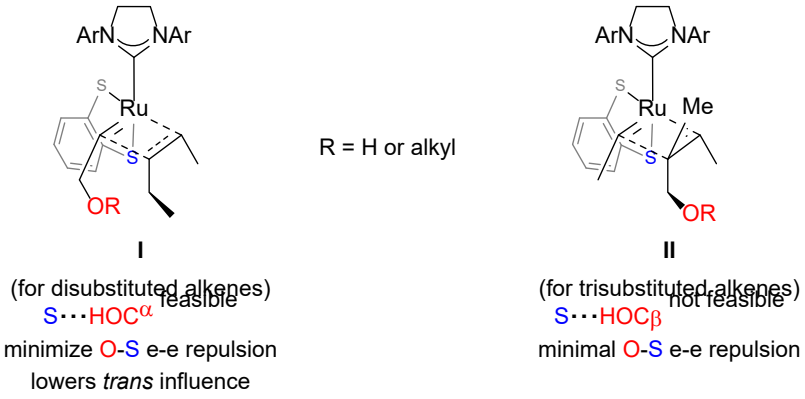
[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

It is noteworthy that, although ring-opening/cross-metathesis (ROCM) reactions with a Ru catechothiolate complex were found to be effective only with a 1,2-disubstituted allylic alcohol and not allylic ethers,[31] the reverse is the case here. The reason for this difference in reactivity might be because in metallacyclobutane (mcb) intermediate derived from a 1,2-disubstituted olefin (**I**, Scheme 2.11), the allylic hydroxy or alkoxy group is a C_α substituent, which could mean that while a hydroxy group can establish H-bonding with apical sulfide to facilitate reaction by minimizing *trans* influence (causes by apical NHC

(31) Koh, M. J.; Khan, R. K. M.; Torker, S.; Hoveyda, A. H. *Angew. Chem., Int. Ed*. **2014**, *53*, 1968.

and sulfide ligands), the same is not feasible with a corresponding ether or acetate. In contrast, for reactions that generate a trisubstituted allylic ether, the Ru mcb intermediate (**II**, Scheme 2.11) contains a Cβ-substituted allylic hydroxy or alkoxy group, suggesting that the aforementioned H-bonding interactions are unlikely to be playing a significant role. Then why is it that CM reactions that afford trisubstituted allylic ethers and acetates are efficient?

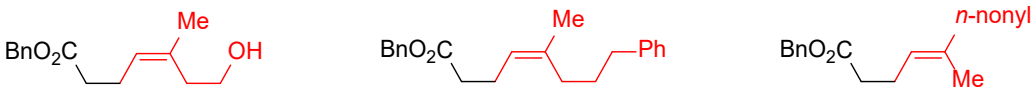
Scheme. 2.11. Comparisons for CM of Trisubstituted and Disubstituted Allylic Ethers



2.4 The Origin of Unusual Reaction Efficiency According to DFT Studies

Further explorations of the CM reactions of trisubstituted alkenes indicated that substrates involving a homoallylic alcohol derivative or other alkyl-substituted alkene didn't afford any desired products (<5% yield). Only homometathesis byproducts were observed. The findings revealed that an allylic heteroatom might be needed for enough efficiency of trisubstituted CM catalyzed by Ru catechothiolate complexes.

Scheme 2.12. An Allylic Heteroatom Is Needed for Efficient CM[a]



2.39
83% conv, <5% yield

2.40
79% conv, <5% yield

2.41
70% conv., <5% yield

[a]Same conditions as in Scheme 2.6. Conversion determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). For full details, see the Experimental Section.

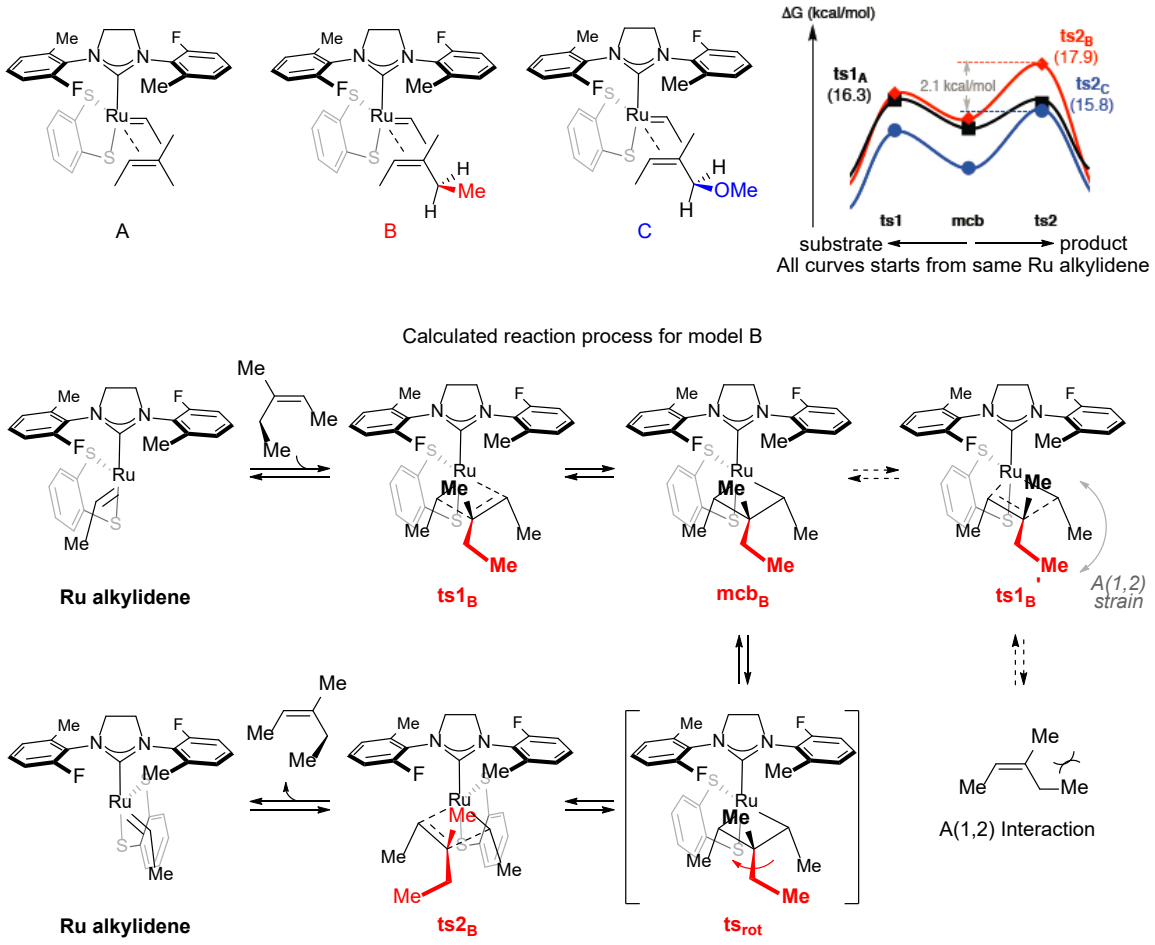
To gain better appreciation of the factors that impact the observed reactivity trends, DFT calculations were carried out (complexes lacking the two Cl substituents were used for simplicity).[32] We investigated three reaction modes, labeled A–C. Model A refers to CM involving a terminal and a trisubstituted alkene that lacks an allylic substituent. Model B corresponds to reaction of a trisbustituted alkene that contains a C-based allylic substituent (found to be inefficient CM substrates). Model C represents the transformation of a trisubstituted allylic alcohol or ether starting material.

The energy diagram for the above three reaction modes indicated the differences in the rate of metallacyclobutane formation and cleavage (**substrate→mcb→ts2→product**). The reaction involving a substrate with an allylic substituent requires the largest energy barrier for the overall conversion of the substrate to the final product. In other words, the mcb for route B appears to be more prone to revert back to the starting materials. Moreover, DFT studies revealed that the relatively high barrier for **mcb→ts2** conversion is probably that the C_β substituent is oriented in the same direction as the sulfide ligand and must undergo rotation around the C–C bond prior to metallacycle rupture (see Scheme 2.13). The eclipsing interaction associated with the aforementioned bond rotation for pathway B seems to be more severe and energetically costly compared to the same for modes A or C.

(32) For details of computational studies, see the Supporting Information.

This is likely because a Me group is larger than H or OMe. Examination of molecular models indicate that rotation of the abovementioned C_β substituent is required to avoid a costly A(1,2) allylic strain interaction[33] within the newly formed trisubstituted alkenes.

Scheme 2.13. DFT Calculations for CM of Trisubstituted Alkenes[a]



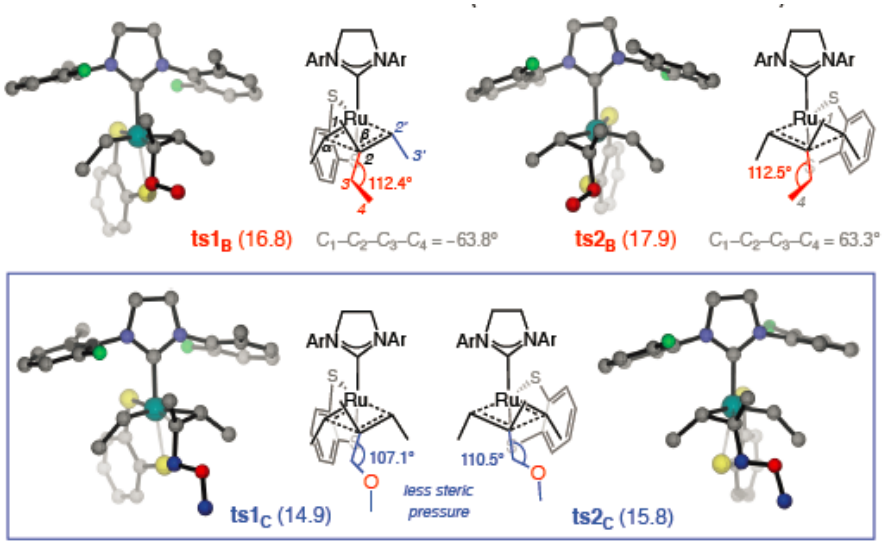
[a]DFT calucations were performed at PBE0-D3BJ/Def2TZVPP$_{thf(SMD)}$ level. For full details, see the Experimental Section. ts = transition state; mcb = metallacyclobutane; SMD = solvation model based on density.

The reactivity trend is reflected in bond angles of key transition states as well (Scheme 2.14). Owing to more significant torsional strain between the C1–C2 bond C3–

(33) Yadav, V. K. In *Steric and Stereoelectronic Effects in Organic Chemistry*; Springer: Singapore, 2016; pp 103–125.

C4 bond, the C2–C3–C4 bond angles in **ts1**$_B$ and **ts2**$_B$ are therefore wider than those in **ts1**$_C$ and **ts2**$_C$ (112.4° and 112.5° vs 107.1°and 110.5°).[34]

Scheme 2.14. Calculated Key Transition States in Model B and C[a]



[a]DFT calucations were performed at PBE0-D3BJ/Def2TZVPP$_{thf(SMD)}$ level. For full details, see the Experimental Section. ts = transition state; SMD = solvation model based on density.

2.5 Conclusions

The studies described in this chapter outline an efficient method for highly stereoselective synthesis of *Z*- and *E*-trisusbstituted allylic alcohols by the use of Ru-based catechothiolate complex. Additionally, in contrast to CM of disubstituted alkenes.*Z*- and *E*-trisusbstituted allylic ethers were prepared with similar efficiency. DFT studies indicate that an allylic heteroatom is needed for high efficiency because of lowering of steric pressure in the course of mcb formation. The investigations detailed above represents the

(34) The A value for a methyl or an ethyl group is ~1.7−1.8, whereas it is ~0.6−0.7 for a hydroxy or methoxy group. The Charton values for the latter two units are not known. See: (a) Eliel, E. L.; Wilen, S. H. *Stereochemistry of Organic Compounds*; Wiley: New Jersey, 1994; pp 696−697. (b) Charton, M. *J. Am. Chem. Soc*. **1975**, *97*, 1552. The sterimol value for a methyl or an ethyl group is 0.52, but is not known for a hydroxy or methoxy group. See: (a) Verloop, A. *Drug Design,* Vol. *III*; Arien, E. J., Ed.; Academica Press: New York, 1976. (b) Harper, K. C.; Bess, E. N.; Sigman, M. S. *Nat Chem* **2012**, *4*, 366–374. (c) Brethome, A. V.; Fletcher, S. P.; Paton, R. S. *ACS Catal*. **2019**, *9*, 2313–2323.

first – and thus far only – examples of olefin metathesis reactions that afford a trisubstituted alkene with high kinetic stereoselectivity. The ability to generate trisubstituted allylic alcohols and ethers in either stereoisomeric form is expected to be considerable utility in organic synthesis.

2.6 Experimental

2.6.1 General

Unless otherwise noted, transformations were performed with distilled and degassed solvents under an atmosphere of dry N_2, in oven (135 °C) or flame-dried glassware with standard dry box or vacuum line techniques. ^{1}H NMR spectra were recorded on a Varian Unity INOVA 400 (400 MHz), 500 (500 MHz) or a 600 (600 MHz) spectrometer. Chemical shifts are reported in ppm from tetramethylsilane with the solvent resonance resulting from incomplete deuterium incorporation as the internal standard ($CDCl_3$: δ 7.26 ppm, DMSO-d_6: δ 2.50 ppm). Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, br = broad, m = multiplet), and coupling constants (Hz), integration. ^{13}C NMR spectra were recorded on a Varian Unity INOVA 400 (100 MHz), 500 (125MHz), or 600 (150 MHz) spectrometers with complete proton decoupling. Chemical shifts are reported in ppm from tetramethylsilane with the solvent resonance as the internal standard ($CDCl_3$: δ 77.16 ppm). High-resolution mass spectrometry was performed on a Micromass LCT ESI-MS and JEOL Accu TOF Dart (positive mode) at the Boston College Mass Spectrometry Facility. Melting points were determined using a Thomas Hoover Uni-melt capillary melting point apparatus. Infrared (IR) spectra were recorded on a Bruker FTIR Alpha (ATR Mode) spectrometer, ν_{max} in cm^{-1}. Bands are characterized as broad (br), strong (s), medium (m), or weak (w). Values for

E:*Z* ratios of products were determined by analysis of ^{1}H NMR spectra.

Solvents

Tetrahydrofuran (THF) was distilled from Na/benzophenone. CH_2Cl_2 was purified under a positive pressure of dry Ar gas by a modified Innovative Technologies purification system. $CDCl_3$ was purchased from Cambridge Isotope Laboratories and stored over activated 4Å molecular sieves prior to use. Purification procedures of products were carried out with reagent grade solvents (Fisher) under bench-top conditions.

Reagents and previously reported substrates

(*Z*)-2-Butene (Aldrich) was dissolved in anhydrous thf and stored in the freezer at –50 °C; weight percent (wt%) was calculated based on the ^{1}H NMR analysis of the mixture. **4-allyl-1,2-dimethoxybenzene** (Aldrich), **4-allylphenol** (Aldrich), **8-bromo-1-octene** (Oakwood), **(*E*)-buta-1,3-dien-1-ylbenzene** (Aldrich), **but-3-en-1-ylbenzene** (Aldrich), **5-hexenoic acid** (Aldrich), **8-Nonen-1-ol** (TCI), **2-(oct-7-en-1-yl)oxirane** (Aldrich), **undec-10-enal** (Aldrich) were used as received.

1-Allyl-2-(benzyloxy)benzene (from 2-allylphenol (Aldrich)) was prepared according to a reported procedure.[35] **(1-((Benzyloxy)methoxy)but-3-en-1-yl)benzene** (from 1-phenylbut-3-en-1-ol (Aldrich)) was prepared according to a reported prodecure.[36] **Benzyl pent-4-enoate** (from 4-pentenoic acid (Aldrich)) were prepared according to reported procedures.[37] **2-(Hex-5-en-1-yl)isoindoline-1,3-dione** (from phthalimide (Aldrich)) was

(35) McManus, J. B.; Nicewicz, D. A. *J. Am. Chem. Soc*. **2017**, *139*, 2880–2883.

(36) Jiang, H.; Xu, L.-P.; Fang, Y.; Zhang, Z.-X.; Yang, Z.; Huang, Y. *Angew. Chem., Int. Ed*. **2016**, *55*, 14340−14344.

(37) Nookaraju, U.; Kumar, P. *RSC Adv.* **2015**, *5*, 63311−63317.

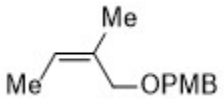
prepared according to a reported procedure.[38] **1-Methoxy-4-((non-8-en-1-yloxy)methyl)benzene** (from 8-nonen-1-ol (TCI)) was prepared analogously to a reported procedure.[39] **(*Z*)-2-Methylbut-2-en-1-ol** (from methyl angelate (TCI)) and **(*E*)-2-methylbut-2-en-1-ol** (from ethyl tiglate (TCI)) were prepared according to a reported procedure.[40] **(*Z*)-(((2-Methylbut-2-en-1-yl)oxy)methyl)benzene** (from ((*Z*)-2-methylbut-2-en-1-ol (from methyl angelate (TCI)) was prepared according to a previous procedure.[41] **(*E*)-3-methyldodec-2-ene** (from non-1-ene (Aldrich)) and **(*Z*)-(4-Methylhex-4-en-1-yl)benzene** (from allylbenzene (Aldrich)) were prepared analogously to a formerly disclosed protocol.[42] **Undec-10-en-1-yl ferrocenoate** (from ferrocenecarboxylic acid (Aldrich)) were prepared according to reported methods.[3]

Organometallic complexes

Ru-9,10 were prepared according to a previously reported procedure.[43] **Ru-5** (Aldrich) was used as received.

2.6.2 Procedure for synthesis of substrates

(*Z*)-1-Methoxy-4-(((2-methylbut-2-en-1-yl)oxy)methyl)benzene (S2.1)



To an ice-cold solution of (*Z*)-2-methylbut-2-en-1-ol (520 mg, 5.0 mmol) in THF (10 mL) was added NaH (300 mg, 60 wt% in mineral

(38) Fukuda, H.; Nishiyama, Y.; Nakamura, S.; Ohno, Y.; Eguchi, T.; Iwabuchi, Y.; Usui, T.; Kanoh, N. *Chem. Asian. J*. **2012**, *7*, 2872−2881.

(39) Kiyotsuka, Y.; Katayama, Y.; Acharya, H. P.; Hyodo, T.; Kobayashi, Y. *J. Org. Chem*. **2009**, *74*, 1939−1951.

(40) Gibson, C.; Buck, T.; Walker, M.; Bruckner, R. *Synlett*. **1998**, *2*, 201−205.

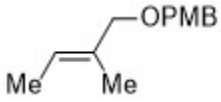
(41) Zhou, J.; Ogle, J. W.; Fan, Y.; Banphavichit, V.; Zhu, Y.; Burgess, K. *Chem. Eur. J*. **2007**, *13*, 7162−7170.

(42) Fristrup, P.; Jensen, G. H.; Andersen, M. L. N.; Tanner, D.; Norrby, P.-O. *J. Organomet. Chem*. **2006**, *691*, 2182−2198.

(43) Johns, A. M.; Ahmed, T. S.; Jackson, B. W.; Grubbs, G. H.; Pederson, R. L. *Org. Lett*. **2016**, *18*, 772−775.

oil, 7.5 mmol). The mixture was stirred at 22 °C for 30 min, after which (*n*-Bu)$_4$NI (37 mg, 0.1 mmol) and PMBCl (1.02 g, 6.5 mmol) were added. The mixture was allowed to stir at 22 °C for 12 h after which the reaction was quenched by addition of a saturated solution of aqueous NH_4Cl. The mixture was then washed with hexanes (50 mL × 3). The combined organic layers were dried over $MgSO_4$, filtered and concentrated in vacuo. The yellow resiude oil was passed through a short column of silica gel (1% ethyl acetate in hexanes) to afford the desired product **S2.1** as a colorless oil (875 mg, 4.3 mmol, 85% yield). **IR (neat)**: 3000 (w), 2932 (m), 2858 (m), 2836 (m), 1612 (m), 1585 (w), 1513 (s), 1455 (m), 1374 (m), 1331 (m), 1301 (s), 1209 (m), 1077 (m), 1036 (m), 821 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 7.29−7.26 (m, 2H), 6.95–6.85 (m, 2H), 5.52–5.40 (m, 1H), 4.39 (s, 2H), 4.00 (s, 2H), 3.81 (s, 3H), 1.77 (p, *J* = 1.5 Hz, 3H), 1.66–1.58 (m, 3H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 159.3, 132.9, 130.9, 129.5, 123.8, 113.9, 71.4, 68.0, 55.4, 21.8, 13.4; **HRMS[M+NH_4]$^+$**: Calcd for $C_{13}H_{22}O_2N$: 224.1651, found: 224.1645.

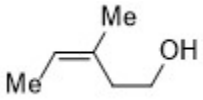
(*E*)-1-Methoxy-4-(((2-methylbut-2-en-1-yl)oxy)methyl)benzene (S2.2)



To an ice-cold solution of (*E*)-2-methylbut-2-en-1-ol (520 mg, 5.0 mmol) in thf (10 mL) was added NaH (300 mg, 60 wt% in mineral oil, 7.5 mmol). The mixture was stirred at 22 °C for 30 min, after which (*n*-Bu)$_4$NI (37 mg, 0.1 mmol) and PMBCl (1.02 g, 6.5 mmol) were added. The mixture was allowed to stir at 22 °C for 12 h after which the reaction was quenched by addition of a saturated solution of aqueous NH_4Cl. The mixture was then washed with hexanes (50 mL × 3). The combined organic layers were dried over $MgSO_4$, filtered and concentrated. The yellow residue oil was passed through a short column of silica gel (1% ethyl acetate in hexanes) to afford the desired compound **S2.2** as a colorless oil (907 mg, 4.4 mmol, 88% yield). **IR (neat)**: 3029 (w), 2994 (m), 2914 (m), 2855 (m), 2835 (m), 1612 (m), 1586 (w), 1513 (s), 1463 (m),

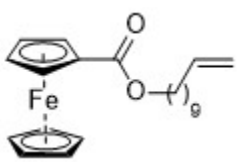
1380 (m), 1301 (m), 1247 (s), 1172 (m), 1108 (m), 1036 (m), 820 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)**: δ 7.26 (d, *J* = 8.5 Hz, 2H), 6.87 (d, *J* = 8.6 Hz, 2H), 5.50 (q, *J* = 7.0 Hz, 1H), 4.38 (s, 2H), 3.87 (s, 2H), 3.80 (s, 3H), 1.67 (s, 3H), 1.65–1.62 (m, 3H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 159.2, 133.1, 130.9, 129.5, 122.8, 113.9, 76.2, 71.3, 55.4, 13.8, 13.3; **HRMS[M+NH_4]$^+$**: Calcd for $C_{13}H_{22}O_2N$: 224.1651, found: 224.1641.

(*Z*)-3-Methylpent-3-en-1-ol (S2.3)



To a thf solution (5 mL) of (*Z*)-2-bromobut-2-ene (540 mg, 4.0 mmol) was added *t*-BuLi (4.7 mL, 1.7 M in hexanes) at □78 °C, and the solution was allowed to stir at -78 ºC for 30 min. At this point, ethylene oxide (2.7 mL, 2.5−3.3 M in thf) was added (at □78 ºC) and the mixture was allowed to warm to 22 °C within 3 h. The reaction was then quenched by addition of a saturated solution of aqueous NH_4Cl; the organic layers were subsequently washed with ether (50 mL × 3). The combined organic layers were dried over $MgSO_4$, filtered and concentrated in vacuo. The yellow residue oil was passed through a short column of silica gel (20% ethyl ether in hexanes) to afford the desired compound **S2.3** as a colorless oil (256 mg, 2.6 mmol, 64% yield). **IR (neat)**: 3334 (br, m), 2961 (m), 2924 (m), 2877 (m), 1449 (m), 1375 (m), 1092 (w), 1038 (s), 1005 (m), 861 (m), 803 (m), 573 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 5.42 (q, *J* = 6.7 Hz, 1H), 3.69 (t, *J* = 6.1 Hz, 2H), 2.34 (t, *J* = 6.6 Hz, 2H), 1.72 (s, 3H), 1.62 (d, *J* = 6.7 Hz, 3H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 132.0, 122.5, 60.7, 34.8, 23.5, 13.6; **HRMS[M+H]$^+$**: Calcd for $C_6H_{13}O$: 101.0966, found: 101.0963.

Undec-10-en-1-yl ferrocenoate (S2.4)



To a solution of ferrocenecarboxylic acid (230.0 mg, 1.0 mmol), EDC•HCl (230.0 mg, 1.2 mmol) and DMAP (12.2 mg, 0.1 mmol) in

CH_2Cl_2 (1.5 mL) was added undec-10-en-1-ol (170.3 mg, 1.0 mmol). The resulting mixture was allowed to stir for 14 h at 22 °C after which the volatiles were removed in vacuo. The brown residue oil was purified by silica gel chromatography (20% Et_2O in hexanes) to afford the desired product **S2.4** as yellow liquid (258.1 mg, 0.68 mmol; 68% yield). **IR (neat):** 2924 (s), 2853 (m), 1710 (s), 1459 (m), 1272 (s), 1133 (s), 1106 (w), 820 (w), 484 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)**: δ 5.81 (ddt, *J* = 16.9, 10.2, 6.7 Hz, 1H), 5.01–4.92 (m, 2H), 4.81–4.80 (m, 2H), 4.39−4.38 (m, 2H), 4.22–4.20 (m, 5H), 2.06–2.02 (m, 2H), 1.75–1.69 (m, 2H), 1.47–1.31(m, 14H); **^{13}C NMR (125 MHz, $CDCl_3$)**: δ 171.9, 139.3, 114.3, 71.7, 71.3, 70.2, 69.8, 64.4, 34.0, 29.7, 29.6, 29.4, 29.3, 29.1, 26.2; **HRMS[M+H]$^+$**: Calcd for $C_{22}H_{31}FeO_2$: 383.16737, Found: 383.16737.

Procedure for synthesis of *E*-2.14 with dichloro-Ru complex

Benzyl (*E*)-6-hydroxy-5-methylhex-4-enoate (*E*-2.14)

In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with benzyl pent-4-enoate (9.5 mg, 0.05 mmol) and 1,1-disubstituted olefin **2.13** (18.0 mg, 0.25 mmol), and a CH_2Cl_2 solution (200 μL) of **Ru-5** (1.6 mg, 0.0025 mmol) was added. The vessel was sealed and the mixture was allowed to stir at 40 °C for 12 h. The volatiles were removed in vacuo to leave behind yellow oil residue, which was purified by silica gel chromatography (20–50% ethyl ether in hexanes), affording *E*-**2.14** in 86:14 *E*:*Z* ratio as colorless oil (6.7 mg, 0.029 mmol, 57% yield). **IR (neat)**: 3372 (br, m), 3030 (w), 2918 (m), 2855 (m), 1731 (s), 1497 (m), 1454 (m), 1417 (m), 1381 (m), 1260 (m), 1212 (m), 1146 (s), 1065 (m), 1004 (m), 804 (m), 750 (m), 697 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.38−7.32 (m, 5H), 5.38 (t, *J* = 6.4 Hz, 1H), 5.12 (s, 2H), 3.97 (s, 2H), 2.47–2.33 (m, 4H), 1.62 (br, 4H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 173.2, 136.5, 136.2, 128.7,

128.4, 128.4, 123.7, 68.7, 66.4, 34.2, 23.3, 13.9; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{14}H_{17}O_2$: 217.1229, found: 217.1231.

2.6.3 General procedure for cross-metathesis with Ru catechothiolate complexes

In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with alkene substrates and a thf solution of **Ru-9**. The vessel was sealed and the mixture was allowed to stir at 22 °C for 1 h. The volatiles were then removed in vacuo (100 torr for 2 mins). The flask containing the residue was then charged with the trisubstituted alkene substrate, followed by the addition of a solution of **Ru-9** in thf, and the mixture was subjected to reduced pressure (100 torr) for 1 hour, and the resulting solution was allowed to stir for 15 h at 22 °C. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air. The volatiles were subsequently removed in vacuo, and the resulting residue (typically black oil) was purified by silica gel chromatography and filtered through a small plug of activated charcoal.

Scope I: *Z*-Trisubstituted allylic alcohols

Benzyl (*Z*)-6-hydroxy-5-methylhex-4-enoate (*Z*-2.14)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with benzyl pent-4-enoate (9.5 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (21.5 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed

to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.14** in >98:2 *Z*:*E* ratio as colorless oil (8.7 mg, 0.037 mmol, 74% yield). **IR (neat)**: 3410 (br, m), 2966 (m), 2942 (m), 1732 (s), 1454 (w), 1416 (m), 1381 (m), 1351 (m), 1259 (m), 1213 (m), 1145 (m), 1003 (m), 950 (m), 750 (m), 698 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.41–7.30 (m, 5H), 5.21 (t, *J* = 7.2 Hz, 1H), 5.11 (s, 2H), 4.10 (d, *J* = 4.8 Hz, 2H), 2.49–2.35 (m, 4H), 1.93 (t, *J* = 5.3 Hz, 1H), 1.78 (s, 3H); **^{13}C NMR (150 MHz, $CDCl_3$)**: *δ* 173.6, 136.8, 136.0, 128.7, 128.4, 128.4, 126.0, 66.5, 61.6, 34.2, 23.1, 21.8; **HRMS[M+H]$^+$**: Calcd for $C_{14}H_{19}O_3$: 235.1334, found: 235.1345.

(*Z*)-2-Methyldec-2-ene-1,10-diol (*Z*-2.16)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 8-nonen-1-ol (7.1 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (43.0 mg, 0.5 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl acetate in hexanes) and filtered

through a small plug of activated charcoal to afford *Z*-**2.16** in >98:2 *Z*:*E* ratio as colorless oil (6.5 mg, 0.035 mmol, 70% yield). **IR (neat)**: 3342 (br, m), 2924 (s), 2853 (m), 1456 (m), 1371 (m), 1260 (w), 1056 (m), 1007 (m), 949 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 5.30 (t, *J* = 7.6 Hz, 1H), 4.13 (s, 2H), 3.64 (t, *J* = 6.6 Hz, 2H), 2.04 (q, *J* = 7.0 Hz, 2H), 1.80 (s, 3H), 1.56 (p, *J* = 6.7 Hz, 2H), 1.42–1.29 (m, 8H); **^{13}C NMR (125 MHz, $CDCl_3$)**: δ 134.3, 129.0, 63.2, 61.8, 32.9, 30.1, 29.4, 29.3, 27.7, 25.8, 21.4; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{11}H_{21}O$: 169.1592, found: 169.1589.

(*Z*)-10-((4-Methoxybenzyl)oxy)-2-methyldec-2-en-1-ol (*Z*-2.17)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 1-methoxy-4-((non-8-en-1-yloxy)methyl)benzene (13.1 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (21.5 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.17** in >98:2 *Z*:*E* ratio as colorless oil (12.0 mg, 0.039 mmol, 78% yield). **IR (neat):** 3381 (br, m), 2926 (m), 2853 (m), 1612 (m), 1586 (w), 1512 (s), 1462 (m), 1351 (m), 1301 (m), 1246 (s), 1173 (m), 1095 (m), 1035 (m), 1007 (m), 947 (m),

820 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.26 (d, *J* = 8.4 Hz, 2H), 6.88 (d, *J* = 8.5 Hz, 2H), 5.29 (t, *J* = 7.3 Hz, 1H), 4.43 (s, 2H), 4.12 (s, 2H), 3.80 (s, 3H), 3.43 (t, *J* = 6.6 Hz, 2H), 2.03 (q, *J* = 7.1 Hz, 2H), 1.79 (s, 3H), 1.59 (p, *J* = 6.8 Hz, 2H), 1.44–1.24 (m, 8H); **^{13}C NMR (125 MHz, $CDCl_3$)**: δ 159.2, 134.3, 130.9, 129.4, 128.9, 113.9, 72.6, 70.3, 61.8, 55.4, 30.1, 29.9, 29.4, 29.3, 27.7, 26.3, 21.4; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{19}H_{29}O_2$: 289.2168, found: 289.2178.

(*Z*)-9-Bromo-2-methylnon-2-en-1-ol (*Z*-2.18)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 8-bromooct-1-ene (9.6 mg, 0.051 mmol) and a thf solution of *Z*-butene (35 wt %, 80 mg, 0.5 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (21.5 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.18** in >98:2 *Z*:*E* ratio as colorless oil (8.0 mg, 0.034 mmol, 68% yield). **IR (neat):** 3334 (br, m), 2927 (s), 2854 (s), 1453 (m), 1437 (m), 1377 (m), 1294 (m), 1005 (s), 948 (m), 725 (m), 645 (m), 562 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.30 (t, *J* = 7.4 Hz, 1H), 4.14 (s, 2H), 3.40 (t, *J* = 6.8 Hz, 2H), 2.05 (q, *J* = 7.0 Hz, 2H), 1.91–1.81 (m, 2H), 1.81–1.79 (m, 3H),

1.49–1.26 (m, 7H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 134.5, 128.7, 61.7, 34.1, 32.9, 29.9, 28.5, 28.1, 27.6, 21.4; **HRMS[M+NH_4]$^+$**: Calcd for $C_{10}H_{23}BrNO$: 252.0963, Found: 252.0970.

(*Z*)-4-Hydroxy-3-methylbut-2-en-1-yl ferrocenoate (*Z*-2.19)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with undec-10-en-1-yl ferrocenoate (19.1 mg, 0.050 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (21.5 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.19** in >98:2 *Z*:*E* ratio as yellow oil (11.7 mg, 0.0274 mmol, 55% yield). **IR (neat):** 3429 (br, m), 2923 (s), 2852 (s), 1711 (s), 1690 (m), 1459 (s), 1412 (m), 1274 (s), 1136(s), 821 (s), 722 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.30 (t, *J* = 7.5 Hz, 1H), 4.81–4.80 (m, 2H), 4.39–4.38 (m, 2H), 4.22–4.19 (m, 5H), 4.12 (s, 2H), 2.03 (q, *J* = 7.2 Hz, 2H), 1.79 (s, 3H), 1.74 1.69 (m, 2H), 1.63 (brs, 1H), 1.46–1.41 (m, 2H), 1.37–1.27 (m, 12H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 171.9, 134.3, 129.0, 71.3, 70.2, 69.8, 64.4, 61.8, 30.2, 29.7, 29.6, 29.4, 29.4, 29.1, 27.7, 26.2, 21.4; **HRMS[M+H]$^+$**: Calcd for $C_{24}H_{35}FeO_3$: 427.1936, Found: 427.1947.

(*Z*)-2-(7-Hydroxy-6-methylhept-5-en-1-yl)isoindoline-1,3-dione (*Z*-2.20)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 2-(hex-5-en-1-yl)isoindoline-1,3-dione (12.2 mg, 0.050 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (21.5 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.20** in >98:2 *Z*:*E* ratio as colorless oil (11.0 mg, 0.038 mmol, 77% yield). **IR (neat)**: 3463 (br, m), 2936 (m), 2858 (m), 1769 (m), 1700 (s), 1466 (m), 1436 (m), 1395 (s), 1368 (m), 1336 (m), 1187 (m), 1087 (m), 1038 (m), 1005 (m), 945 (m), 864 (m), 718 (s), 529 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.83 (dd, *J* = 5.4, 3.1 Hz, 2H), 7.70 (dd, *J* = 5.5, 3.0 Hz, 2H), 5.24 (t, *J* = 7.3 Hz, 1H), 4.14 (d, *J* = 3.9 Hz, 2H), 3.67 (t, *J* = 7.4 Hz, 2H), 2.12 (q, *J* = 7.3 Hz, 2H), 1.79 (s, 3H), 1.73–1.63 (m, 4H), 1.41 (p, *J* = 7.3 Hz, 2H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 168.6, 135.2, 134.1, 132.2, 127.9, 123.4, 61.6, 37.8, 27.9, 26.9, 26.9, 21.5; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{16}H_{18}NO_2$: 256.1338, found: 256.1351.

(*Z*)-2-Methyl-9-(oxiran-2-yl)non-2-en-1-ol (*Z*-2.21)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 2-(oct-7-en-1-yl)oxirane (15.4 mg, 0.10 mmol) and a thf solution of *Z*-butene (35 wt %, 80 mg, 0.50 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.7 mg, 0.001 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (43.0 mg, 0.50 mmol), a solution of **Ru-9** (3.7 mg, 0.005 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.21** in >98:2 *Z*:*E* ratio as colorless oil (13.1 mg, 0.066 mmol, 66% yield). **IR (neat):** 3396 (br, m), 3030 (m), 2923 (s), 2854 (m), 1702 (w), 1466 (m), 946 (m), 715 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.29 (t, *J* = 7.5 Hz, 1H), 4.12 (d, *J* = 4.1 Hz, 2H), 2.91-2.88 (m, 1H), 2.75–2.73 (m, 1H), 2.46–2.45 (m, 1H), 2.04 (q, *J* = 7.2 Hz, 2H), 1.79 (s, 3H), 1.55–1.29 (m, 11H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 134.4, 128.8, 61.8, 52.5, 47.3, 32.6, 30.0, 29.4, 29.3, 27.6, 26.1, 21.4; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{12}H_{21}O$: 181.15924, Found: 181.16010.

(*Z*)-12-Hydroxy-11-methyldodec-10-enal (*Z*-2.22)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with undec-10-enal (16.8 mg, 0.10 mmol) and a thf solution of *Z*-butene (13 wt %, 430 mg, 1.00 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.75 mg, 0.001 mmol). The vessel was then sealed. The mixture was

allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (43.0 mg, 0.50 mmol), a solution of **Ru-9** (3.7 mg, 0.005 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.22** in >98:2 *Z*:*E* ratio as colorless oil (14.8 mg, 0.070 mmol, 70% yield). **IR (neat):** 3402 (br, m), 2923 (s), 2853 (s), 1723 (s), 1455 (m), 1409 (m), 1391 (m), 1110 (m), 1007(s), 947 (m), 722 (w) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 9.76 (t, *J* = 1.9 Hz, 1H), 5.30 (t, *J* = 7.4 Hz, 1H), 4.13 (s, 2H), 2.42 (td, *J* = 7.4, 1.9 Hz, 2H), 2.08–2.00 (m, 2H), 1.80–1.78 (m, 3H), 1.68–1.58 (m, 2H), 1.37–1.24 (m, 11H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 203.1, 134.3, 128.9, 61.7, 44.0, 30.1, 29.4, 29.4, 29.3, 29.3, 27.7, 22.2, 21.4; **HRMS[M+NH_4]$^+$**: Calcd for $C_{13}H_{28}NO_2$: 230.21200, Found: 230.21274.

(*Z*)-2-Methyl-5-phenylpent-2-en-1-ol (*Z*-2.23)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with but-3-en-1-ylbenzene (13.2 mg, 0.10 mmol) and a thf solution of *Z*-butene (35 wt %, 80 mg, 0.50 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.7 mg, 0.001 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (43.0 mg, 0.50 mmol), a solution of **Ru-9** (3.7 mg, 0.005 mmol in 200 μL thf) and

subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.23** in >98:2 *Z*:*E* ratio as colorless oil (11.5 mg, 0.0625 mmol, 65% yield). **IR (neat):** 3328 (br, w), 2921 (m), 1453 (s), 1030 (m), 1002 (s), 747 (m), 698 (s) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 7.31–7.29 (m, 2H), 7.21–7.17 (m, 3H), 5.50 (t, *J* = 7.7 Hz, 1H), 3.94 (s, 2H), 2.66 (t, *J* = 7.4 Hz, 2H), 2.37 (q, *J* = 7.5 Hz, 2H), 1.77 (s, 3H), 0.69 (brs, 1H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 141.9, 135.5, 128.8, 128.4, 127.3, 126.1, 61.6, 36.2, 29.7, 21.4; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{12}H_{15}$: 159.1174, Found: 159.1168.

(*Z*)-5-((Benzyloxy)methoxy)-2-methyl-5-phenylpent-2-en-1-ol (*Z*-2.24)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with (1-((benzyloxy)methoxy)but-3-en-1-yl)benzene (13.4 mg, 0.050 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (21.5 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel

chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.24** in >98:2 *Z*:*E* ratio as colorless oil (6.3 mg, 0.020 mmol, 40% yield). The product contain inseperable impurities and the yield was calculated based on impure material. **IR (neat)**: 3414 (br, m), 3030 (w), 2920 (m), 2885 (m), 1493 (m), 1380 (m), 1289 (m), 1204 (m), 1097 (m), 1077 (m), 1056 (s),1020 (m), 873 (m), 801 (m), 698 (s), 558 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.38–7.27 (m, 10H), 5.38 (t, *J* = 8.1 Hz, 1H), 4.72–4.67 (m, 3H), 4.62 (d, *J* = 7.0 Hz, 1H), 4.48 (d, *J* = 11.6 Hz, 1H), 4.11 (dd, *J* = 11.8, 3.6 Hz, 1H), 3.88 (dd, *J* = 11.8, 6.4 Hz, 1H), 2.64 (dt, *J* = 14.7, 8.6 Hz, 1H), 2.43–2.38 (m, 1H), 1.82 (s, 3H), 1.52 (brs, 1H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 141.5, 138.6, 137.8, 128.6, 128.6, 128.1, 128.0, 127.9, 127.0, 124.0, 92.2, 69.9, 61.6, 36.7, 31.1, 22.4; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{20}H_{23}O_2$: 295.1698, found: 295.1696.

(*Z*)-4-(4-Hydroxy-3-methylbut-2-en-1-yl)phenol (*Z*-2.25)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 4-allylphenol (6.7 mg, 0.050 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (43.0 mg, 0.50 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl acetate in hexanes) and

filtered through a small plug of activated charcoal to afford *Z*-**2.25** in 98:2 *Z*:*E* ratio as colorless oil (4.9 mg, 0.028 mmol, 55% yield). **M.p.:** 60–61 °C; **IR (neat)**: 3289 (br, m), 3020 (m), 2970 (m), 2918 (m), 1613 (m), 1597 (m), 1513(s), 1449 (m), 1238 (m), 1172 (m), 996 (m), 824 (m); **^{1}H NMR (600 MHz, CDCl$_3$)**: δ 7.03 (d, *J* = 8.3 Hz, 2H), 6.75 (d, *J* = 8.4 Hz, 2H), 5.49 (t, *J* = 7.6 Hz, 1H), 4.92 (brs, 1H), 4.24 (s, 2H), 3.34 (d, *J* = 7.6 Hz, 2H), 1.85 (s, 3H), 1.30 (brs, 1H); **^{13}C NMR (150 MHz, CDCl$_3$)**: δ 154.0, 135.0, 133.2, 129.5, 127.5, 115.5, 61.8, 33.0, 21.5; **HRMS[M+H-H$_2$O]$^+$**: Calcd for $C_{11}H_{13}O_2$: 161.0966, found: 161.097.

(*Z*)-4-(3,4-Dimethoxyphenyl)-2-methylbut-2-en-1-ol (*Z*-2.26)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 4-allyl-1,2-dimethoxybenzene (8.9 mg, 0.050 mmol) and a thf solution of *Z*-butene (35 wt %, 40 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (21.5 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.26** in >98:2 *Z*:*E* ratio as colorless oil (9.0 mg, 0.0405 mmol, 81% yield). **IR (neat):** 2998 (w), 2934 (w), 2834 (w), 1514 (s), 1464 (m), 1260 (m), 1234 (m), 1028 (m), 850 (w), 763 (s) cm^{-1};

^{1}H NMR (600 MHz, $CDCl_3$): δ 6.80 (d, *J* = 8.6 Hz, 1H), 6.71 (m, 2H), 5.50 (t, *J* = 7.7 Hz, 1H), 4.25 (brs, 2H), 3.87 (s, 3H), 3.85 (s, 3H), 3.37 (d, *J* = 7.6 Hz, 2H), 1.86 (s, 3H), 1.25 (brs, 1H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 149.1, 147.5, 135.3, 133.7, 127.2, 120.1, 111.8, 111.5, 61.8, 56.1, 56.0, 33.5, 21.5; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{13}H_{17}O_2$: 205.1229, Found: 205.1238.

(2*Z*,4*E*)-2-Methyl-5-phenylpenta-2,4-dien-1-ol (*Z*-2.27)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with (*E*)-buta-1,3-dien-1-ylbenzene (13.0 mg, 0.10 mmol) and a thf solution of *Z*-butene (13 wt %, 215 mg, 0.50 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.76 mg, 0.001 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (43.0 mg, 0.50 mmol), a solution of **Ru-9** (3.8 mg, 0.005 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.27** in 98:2 *Z*:*E* ratio as colorless oil (10.1 mg, 0.058 mmol, 58% yield). **IR (neat)**: 3321 (br, m), 2998 (m), 2966 (m), 2876 (m), 1488 (m), 1449 (m), 1347 (m), 1308 (m), 1251 (w), 1074 (m), 1034 (m), 1003 (s), 963 (s), 749 (s), 693 (s), 508 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)**: δ 7.40 (d, *J* = 7.3 Hz, 2H), 7.31 (t, *J* = 7.7 Hz, 2H), 7.22 (t, *J* = 7.3 Hz, 1H), 7.06 (dd, *J* = 15.4, 11.2 Hz, 1H), 6.50 (d, *J* = 15.4 Hz, 1H), 6.12 (d, *J* = 11.2 Hz, 1H), 4.37 (s, 2H), 1.95

(s, 3H), 1.33 (brs, 1H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 137.8, 137.6, 132.2, 128.7, 128.5, 127.6, 126.4, 124.1, 62.1, 21.9; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{12}H_{13}$: 157.1017, found: 157.102.

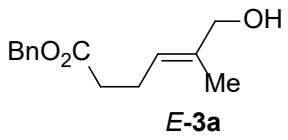
(*Z*)-4-(2-(Benzyloxy)phenyl)-2-methylbut-2-en-1-ol (*Z*-2.3)

In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 1-allyl-2-(benzyloxy)benzene (22.4 mg, 0.1000 mmol, 1.00 equiv.) and a thf solution of *Z*-2-butene (35 wt%, 160 mg, 0. 1000 mmol, 10.0 equiv.), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.7 mg, 0.0010 mmol, 1.00 mol %). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr for 2 mins). The vessel was then charged with (in this precise order) (*Z*)-2-methylbut-2-en-1-ol (172.0 mg, 0.2000 mmol, 20.0 equiv.) and a solution of **Ru-9** (2.2 mg, 0.0003 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. The vessel was then charged with a second batch of a solution of **Ru-9** (2.2 mg, 0.0003 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo*. The resulting black oil was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford product ***Z*-2.3** in >98:2 *Z*:*E* ratio as colorless oil (16.6 mg, 0.062 mmol, 62% yield). **IR (neat):** 3377 (br, m), 3062 (w), 1599 (w), 1492 (s), 1451 (s), 1239 (s), 751(s) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 7.44–7.39 (m, 4H), 7.36–7.33 (m, 1H), 7.19–7.15 (m, 2H), 6.93–6.91 (m, 2H), 5.46 (t, *J* = 7.8 Hz, 1H), 5.09 (s, 2H), 4.14 (s, 2H), 3.44 (d, *J* = 7.7 Hz, 2H), 1.81 (s, 3H), 1.18 (brs, 1H); **^{13}C**

NMR (150 MHz, $CDCl_3$): δ 156.5, 137.2, 135.2, 129.9, 129.8, 128.8, 128.2, 127.6, 127.4, 126.5, 121.1, 112.0, 70.3, 61.8, 28.9, 21.6; **HRMS[M+H]$^+$**: Calcd for $C_{18}H_{21}O_2$: 269.1542, Found: 269.1539.

Scope II: *E*-Trisubstituted allylic alcohols

Benzyl (*E*)-6-hydroxy-5-methylhex-4-enoate (*E*-2.14)



E-**3a**

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with benzyl pent-4-enoate (9.5 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*E*)-2-methylbut-2-en-1-ol (21.5 mg, 0.250 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *E*-**2.14** in >98:2 *E*:*Z* ratio as colorless oil (8.5 mg, 0.035 mmol, 75% yield). **IR (neat)**: 3372 (br, m), 3030 (w), 2918 (m), 2855 (m), 1731 (s), 1497 (m), 1454 (m), 1417 (m), 1381 (m), 1260 (m), 1212 (m), 1146 (s), 1065 (m), 1004 (m), 804 (m), 750 (m), 697 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.38−7.32 (m, 5H), 5.38 (t, *J* = 6.4 Hz, 1H), 5.12 (s, 2H), 3.97 (s, 2H), 2.47–2.33 (m, 4H), 1.62 (br, 4H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 173.2, 136.5, 136.2, 128.7, 128.4, 128.4, 123.7, 68.7,

66.4, 34.2, 23.3, 13.8; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{14}H_{17}O_2$: 217.1229, found: 217.1231.

(*E*)-9-Bromo-2-methylnon-2-en-1-ol (*E*-2.18)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 8-bromoct-1-ene (19.1 mg, 0.10 mmol) and a thf solution of *Z*-butene (35 wt %, 80 mg, 0.50 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.70 mg, 0.0010 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*E*)-2-methylbut-2-en-1-ol (43.0 mg, 0.50 mmol), a solution of **Ru-9** (3.7 mg, 0.005 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford *E*-**2.18** in >98:2 *E*:*Z* ratio as colorless oil (14.8 mg, 0.063 mmol, 63% yield). **IR (neat):** 3327 (br, m), 2927 (s), 2855 (m), 1460 (w), 1258 (w), 1009 (m), 908 (w), 730 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.40 (tq, *J* = 7.2, 1.3 Hz, 1H), 4.00 (d, *J* = 4.4 Hz, 2H), 3.41 (t, *J* = 6.8 Hz, 2H), 2.06–2.01 (m, 2H), 1.85 (dq, *J* = 7.9, 6.9 Hz, 2H), 1.66 (m, 3H), 1.47–1.28 (m, 7H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 134.9, 126.4, 69.2, 34.1, 32.9, 29.4, 28.6, 28.2, 27.6, 13.8; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{10}H_{18}Br$: 217.0592, Found: 217.0588.

(*E*)-2-Methyl-9-(oxiran-2-yl)non-2-en-1-ol (*E*-2.21)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 2-(oct-7-en-1-yl)oxirane (15.4 mg, 0.10 mmol) and a thf solution of *Z*-butene (35 wt %, 80 mg, 0.50 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.70 mg, 0.0010 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*E*)-2-methylbut-2-en-1-ol (43.0 mg, 0.50 mmol), a solution of **Ru-9** (3.7 mg, 0.005 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford *E*-**2.21** in >98:2 *E*:*Z* ratio as colorless oil (14.8 mg, 0.075 mmol, 75% yield). **IR (neat):** 3409 (br, m), 2924 (s), 2854 (m), 1459 (w), 1410 (w), 1011 (m), 834 (m), 724 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 5.39 (t, *J* = 7.2 Hz, 1H), 3.98 (s, 2H), 2.90-2.88 (m, 1H), 2.73 (t, *J* = 4.5 Hz, 1H), 2.46–2.45 (m, 1H), 2.02 (q, *J* = 7.1 Hz, 2H), 1.65 (s, 3H), 1.54–1.40 (m, 5H), 1.38–1.28 (m, 6H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 156.5, 137.2, 135.2, 129.9, 129.8, 128.8, 128.2, 127.6, 127.4, 126.5, 121.1, 112.0, 70.3, 61.8, 28.9, 21.6; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{12}H_{21}O$: 181.1592, Found: 181.1597.

(*E*)-12-Hydroxy-11-methyldodec-10-enal (*E*-2.22)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with undec-10-enal (16.8 mg, 0.10 mmol) and a thf solution of *Z*-butene (35 wt %, 80 mg, 0.50 mmol), this was followed by addition of a thf solution

(200 μL) of **Ru-9** (0.70 mg, 0.0010 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*E*)-2-methylbut-2-en-1-ol (43.0 mg, 0.50 mmol), a solution of **Ru-9** (3.7 mg, 0.005 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (10~20% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford *E*-**2.22** in >98:2 *E*:*Z* ratio as colorless oil (12.8 mg, 0.060 mmol, 60% yield). **IR (neat):** 3400 (br, m), 2924 (s), 2854 (m), 1724 (m), 1459 (m), 1001(w) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 9.76 (s, 1H), 5.42–5.38 (m, 1H), 4.00 (s, 2H), 2.44-2.39 (m, 2H), 2.02 (q, *J* = 7.1 Hz, 2H), 1.66 (s, 3H), 1.64–1.59 (m, 2H), 1.38–1.25 (m, 11H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 203.1, 134.7, 126.7, 69.2, 44.0, 29.6, 29.4, 29.3, 29.3, 27.7, 22.2, 13.8; **HRMS[M+NH_4]$^+$**: Calcd for $C_{13}H_{28}O_2N$: 230.2120, Found: 230.2120.

(2*E*,4*E*)-2-methyl-5-phenylpenta-2,4-dien-1-ol (*E*-2.27)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with (*E*)-buta-1,3-dien-1-ylbenzene (13.0 mg, 0.10 mmol) and a thf solution of *Z*-butene (13 wt %, 215 mg, 0.50 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.76 mg, 0.0010 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*E*)-2-methylbut-2-en-1-ol (86.0 mg, 1.00 mmol), a solution of **Ru-9** (3.8 mg, 0.005 mmol in 200

μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo*. The resulting black oil was purified by silica gel chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *E*-**2.27** in 98:2 *E*:*Z* ratio as colorless oil (9.6 mg, 0.052 mmol, 52% yield). **IR (neat)**: 3332 (br, m), 3056 (m), 3030 (m), 2915 (m), 2855 (m), 1667 (w), 1596 (w), 1489 (m), 1448 (m), 1385 (m), 1071 (m), 1001 (m), 966 (s), 748 (s), 692 (s) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.42 (d, *J* = 7.7 Hz, 2H), 7.32 (t, *J* = 7.6 Hz, 2H), 7.22 (t, *J* = 7.3 Hz, 1H), 7.02 (dd, *J* = 15.5, 11.0 Hz, 1H), 6.56 (d, *J* = 15.5 Hz, 1H), 6.25 (d, *J* = 11.4 Hz, 1H), 4.14 (d, *J* = 4.2 Hz, 2H), 1.90 (s, 3H), 1.44 (t, *J* = 4.5 Hz, 1H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 138.2, 137.8, 132.4, 128.7, 127.5, 126.5, 125.3, 124.8, 68.7, 14.6; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{12}H_{13}$: 157.1017, found: 157.1017.

Scope III: Trisubstituted allylic ethers

Benzyl (*Z*)-6-(benzyloxy)-5-methylhex-4-enoate (*Z*-2.29)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with benzyl pent-4-enoate (9.5 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-(((2-methylbut-2-en-1-yl)oxy)methyl)benzene (44.0 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting

solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (1~5% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford ***Z*-2.29** in >98:2 *Z*:*E* ratio as colorless oil (11.6 mg, 0.036 mmol, 72% yield). **IR (neat)**: 3030 (w), 2941 (m), 2917 (m), 2855 (m), 1735 (s), 1496 (w), 1454 (m), 1378 (m), 1352 (m), 1147 (m), 1090 (m), 1071 (m), 1028 (m), 998 (m), 736 (m), 697 (m); **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.39–7.27 (m, 10H), 5.35 (t, *J* = 6.7 Hz, 1H), 5.11 (s, 2H), 4.45 (s, 2H), 4.00 (s, 2H), 2.41−2.36 (m, 4H), 1.78 (s, 3H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 173.0, 138.6, 136.1, 134.0, 128.7, 128.5, 128.4, 127.8, 127.7, 127.3, 72.0, 68.5, 66.4, 34.6, 23.4, 21.8; **HRMS[M+H]$^+$**: Calcd for $C_{21}H_{25}O_3$: 325.1804, found: 325.1815.

(*Z*)-10-((4-Methoxybenzyl)oxy)-9-methyldec-8-en-1-ol (*Z*-2.30)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 8-nonen-1-ol (7.1 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-1-methoxy-4-(((2-methylbut-2-en-1-yl)oxy)methyl)benzene (51.6 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (1~5%

ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.30** in >98:2 *Z*:*E* ratio as colorless oil (7.6 mg, 0.026 mmol, 50% yield). **IR (neat)**: 3403 (br, m), 2926 (s), 2854 (m), 1612 (m), 1513 (s), 1463 (m), 1375 (m), 1301 (m), 1247 (s), 1173 (m), 1067 (m), 1036 (m), 819 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 7.29–7.25 (m, 2H), 6.90–6.85 (m, 2H), 5.36 (d, *J* = 8.1 Hz, 1H), 4.38 (s, 2H), 3.98 (s, 2H), 3.81 (s, 3H), 3.63 (t, *J* = 6.6 Hz, 2H), 2.00 (q, *J* = 7.0 Hz, 2H), 1.77 (q, *J* = 1.2 Hz, 3H), 1.55 (p, *J* = 6.8 Hz, 3H), 1.41–1.22 (m, 8H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 159.2, 132.1, 130.9, 130.0, 129.4, 113.9, 71.4, 68.3, 63.2, 55.4, 32.9, 30.1, 29.4, 29.4, 27.8, 25.8, 21.8; **HRMS[M+H]$^+$**: Calcd for $C_{19}H_{29}O_2$: 289.2168, found: 289.2176.

(*Z*)-2-(7-((4-Methoxybenzyl)oxy)-6-methylhept-5-en-1-yl)isoindoline-1,3-dione (*Z*-2.31)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 2-(hex-5-en-1-yl)isoindoline-1,3-dione (12.2 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-1-methoxy-4-(((2-methylbut-2-en-1-yl)oxy)methyl)benzene (51.6 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (5~20% ethyl ether in hexanes) and filtered through a small plug of

activated charcoal to afford *Z*-**2.31** in >98:2 *Z*:*E* ratio as colorless oil (10.4 mg, 0.026 mmol, 51% yield). **IR (neat)**: 2935 (m), 2855 (m), 1770 (m), 1708 (s), 1612 (m), 1512 (m), 1466 (m), 1437 (m), 1396 (m), 1337 (m), 1301 (m), 1246 (m), 1172 (m), 1071 (m), 1035 (m), 819 (m), 719 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.83 (dd, *J* = 5.4, 3.1 Hz, 2H), 7.70 (dd, *J* = 5.4, 3.0 Hz, 2H), 7.25 (d, *J* = 8.7 Hz, 2H), 6.86 (d, *J* = 8.6 Hz, 2H), 5.34 (t, *J* = 7.2 Hz, 1H), 4.37 (s, 2H), 3.96 (s, 2H), 3.79 (s, 3H), 3.66 (t, *J* = 7.3 Hz, 2H), 2.05 (q, *J* = 7.3 Hz, 2H), 1.76 (s, 3H), 1.66 (p, *J* = 7.4 Hz, 2H), 1.38 (p, *J* = 7.5 Hz, 2H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 168.6, 159.2, 134.0, 132.7, 132.3, 130.8, 129.4, 129.1, 123.3, 113.9, 71.5, 68.3, 55.4, 38.0, 28.3, 27.4, 27.3, 21.8; **HRMS[M+NH_4]$^+$**: Calcd for $C_{24}H_{31}N_2O_4$:411.2284, found: 411.2273.

(*Z*)-4-(4-(Benzyloxy)-3-methylbut-2-en-1-yl)-1,2-dimethoxybenzene (*Z*-2.32)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 4-allyl-1,2-dimethoxybenzene (8.9 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-(((2-methylbut-2-en-1-yl)oxy)methyl)benzene (44.0 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (5~20% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to

afford *Z*-**2.32** in 98:2 *Z*:*E* ratio as colorless oil (8.5 mg, 0.027 mmol, 55% yield). **IR (neat)**: 3464 (w), 2934 (m), 2836 (m), 1722 (m), 1592 (m), 1514 (s), 1453 (m), 1418 (m), 1261 (s), 1235 (m), 1153 (m), 1139 (m), 1093 (m), 1071 (m), 1027 (w), 852 (m), 808 (m), 740 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)**: δ 7.37–7.27 (m, 5H), 6.79−6.78 (s, 1H), 6.69 (d, *J* = 5.5 Hz, 2H), 5.57 (t, *J* = 7.6 Hz, 1H), 4.51 (s, 2H), 4.12 (s, 2H), 3.84 (d, *J* = 10.0 Hz, 6H), 3.34 (d, *J* = 7.5 Hz, 2H), 1.86 (s, 3H); **^{13}C NMR (125 MHz, $CDCl_3$)**: δ 149.1, 147.5, 138.6, 133.8, 133.1, 128.5, 128.3, 127.8, 127.7, 120.2, 111.9, 111.5, 72.2, 68.7, 56.1, 56.0, 33.7, 22.0; **HRMS[M+NH_4]$^+$**: Calcd for $C_{20}H_{28}O_3N$:330.2069, found: 330.206.

***tert*-Butyl (*Z*)-(5-((4-methoxybenzyl)oxy)-4-methylpent-3-en-1-yl)carbamate (*Z*-2.33)**

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with *tert*-butyl but-3-en-1-ylcarbamate (8.6 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-1-methoxy-4-(((2-methylbut-2-en-1-yl)oxy)methyl)benzene (51.6 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (5~20% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.33** in >98:2 *Z*:*E* ratio as colorless oil (6.7 mg, 0.020 mmol, 40% yield). **IR (neat)**: 3351 (br, m), 2971 (m), 2932 (m), 2859 (m), 1697 (m), 1612 (m),

1512 (s), 1454 (m), 1390 (m), 1365 (m), 1246 (s), 1170 (s), 1065 (m), 1034 (m), 819 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.27 (d, *J* = 8.3 Hz, 2H), 6.88 (d, *J* = 8.7 Hz, 2H), 5.33 (t, *J* = 7.5 Hz, 1H), 4.73 (s, 1H), 4.40 (s, 2H), 3.94 (s, 2H), 3.81 (s, 3H), 3.20–3.09 (m, 2H), 2.20 (q, *J* = 6.5 Hz, 2H), 1.79 (s, 3H), 1.43 (s, 9H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 159.3, 156.1, 135.2, 130.6, 129.5, 126.1, 113.9, 71.8, 68.2, 55.4, 55.4, 40.4, 28.6, 28.4, 22.2; **HRMS[M+H]$^+$**: Calcd for $C_{19}H_{30}O_4N$:336.2175, found: 336.2189.

(*Z*)-7-(Benzyloxy)-6-methylhept-5-enoic acid (*Z*-2.34)

In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with hex-5-enoic acid (5.7 mg, 0.050 mmol) and a thf solution of *Z*-2-butene (13 wt%, 108 mg, 0. 25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 mins). The vessel was then charged with (in this precise order) (*Z*)-(((2-methylbut-2-en-1-yl)oxy)methyl)benzene (88.0 mg, 0.50 mmol, 10.0 equiv.) and a solution of **Ru-9** (1.1 mg, 0.0015 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. The vessel was then charged with a second batch of a solution of **Ru-9** (1.1 mg, 0.0015 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo*. The resulting black oil was purified by silica gel chromatography (10~50% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford product ***Z*-2.34** in >98:2 *Z*:*E* ratio as colorless oil (4.7mg, 0.019 mmol, 38% yield). The product contain inseperable impurities and the yield was calculated based on impure

material. **IR (neat):** 3062 (m), 3030 (m), 2925 (m), 2855 (m), 1707 (s), 1453 (m), 1437 (m), 1376 (m), 1246 (m), 1071 (m), 940 (m), 737 (m), 698 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.38–7.26 (m, 5H), 5.35 (t, *J* = 7.1 Hz, 1H), 4.46 (s, 2H), 4.00 (s, 2H), 2.32 (t, *J* = 7.5 Hz, 2H), 2.08 (q, *J* = 7.3 Hz, 2H), 1.81–1.79 (m, 3H), 1.68 (p, *J* = 7.5 Hz, 2H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 178.6, 138.6, 133.5, 128.5, 128.4, 127.9, 127.7, 72.0, 68.5, 33.3, 27.1, 25.0, 21.9; **HRMS[M+H]$^+$**: Calcd for $C_{15}H_{21}O_3$: 249.1491, Found: 249.1499.

(*Z*)-10-Hydroxy-2-methyldec-2-en-1-yl acetate (*Z*-2.35)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 8-nonen-1-ol (7.1 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (Z)-2-methylbut-2-en-1-yl acetate (128.0 mg, 0.5 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *Z*-**2.35** in >98:2 *Z*:*E* ratio as colorless oil (7.1 mg, 0.024 mmol, 48% yield). **IR (neat)**: 3395 (br, m), 2925 (m), 2854 (m), 1737 (s), 1455 (m), 1367 (m), 1229 (s), 1022 (s), 985 (m), 916 (m), 732 (m), 633 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 5.40 (t, *J* = 7.4 Hz, 1H), 4.58 (s, 2H), 3.64 (t, *J* = 6.5 Hz, 2H), 2.07−2.02 (m, 5H), 1.84–1.69 (m, 3H), 1.59−1.53 (m, 2H), 1.44–1.24 (m, 8H); **^{13}C NMR**

(100 MHz, $CDCl_3$): δ 171.4, 131.2, 129.8, 63.4, 63.2, 32.9, 29.8, 29.4, 29.3, 27.9, 25.8, 21.6, 21.1; **HRMS[M+H]$^+$**: Calcd for $C_{13}H_{25}O_3$: 299.1804, found: 299.1806.

(*E*)-10-((4-Methoxybenzyl)oxy)-9-methyldec-8-en-1-ol (*E*-2.36)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 8-nonen-1-ol (7.1 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*E*)-1-methoxy-4-(((2-methylbut-2-en-1-yl)oxy)methyl)benzene (51.6 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *E*-**2.36** in >98:2 *E*:*Z* ratio as colorless oil (7.7 mg, 0.025 mmol, 50% yield). **IR (neat)**: 3110 (w), 2975 (m), 2931 (m), 1700 (s), 1465 (m), 1401 (s), 1365 (s), 1325 (m), 1212 (m), 1141 (s), 1031 (m), 967 (m), 850 (m), 813 (w) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.26 (d, *J* = 8.4 Hz, 2H), 6.87 (d, *J* = 8.5 Hz, 2H), 5.41 (t, *J* = 7.1 Hz, 1H), 4.38 (s, 2H), 3.87 (s, 2H), 3.80 (s, 3H), 3.63 (t, *J* = 6.5 Hz, 2H), 2.04 (q, *J* = 7.0 Hz, 2H), 1.66 (s, 3H), 1.61 (s, 1H), 1.56 (p, *J* = 6.7 Hz, 2H), 1.43–1.23 (m, 8H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 159.2, 132.2, 130.9, 129.5, 128.8, 113.9, 76.2, 71.2, 63.2, 55.4, 32.9, 29.6, 29.4,

29.4, 27.8, 25.9, 14.1; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{19}H_{29}O_2$: 289.2168, found: 289.2175.

(*E*)-1-(((9-Bromo-2-methylnon-2-en-1-yl)oxy)methyl)-4-methoxybenzene (*E*-2.37)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 8-bromo-1-octene (9.6 mg, 0.05 mmol) and a thf solution of *Z*-butene (13 wt %, 107 mg, 0.25 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.38 mg, 0.0005 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*E*)-1-methoxy-4-(((2-methylbut-2-en-1-yl)oxy)methyl)benzene (51.6 mg, 0.25 mmol), a solution of **Ru-9** (1.9 mg, 0.0025 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *E*-**2.37** in >98:2 *E*:*Z* ratio as colorless oil (9.6 mg, 0.027 mmol, 54% yield). **IR (neat)**: 2929 (m), 2854 (m), 1612 (m), 1586 (w), 1513 (s), 1463 (m), 1441 (m), 1352 (m), 1301 (m), 1247 (s), 1172 (m), 1073 (m), 1036 (m), 820 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)**: δ 7.26 (d, *J* = 8.5 Hz, 2H), 6.88 (d, *J* = 8.6 Hz, 2H), 5.41 (t, *J* = 7.4 Hz, 1H), 4.38 (s, 2H), 3.87 (s, 2H), 3.81 (s, 3H), 3.40 (t, *J* = 6.8 Hz, 2H), 2.05 (q, *J* = 7.1 Hz, 2H), 1.86 (p, *J* = 6.9 Hz, 2H), 1.66 (s, 3H), 1.50–1.30 (m, 6H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 159.2, 132.4, 130.89, 129.5, 128.5, 113.9, 113.9, 76.2, 71.2, 55.4, 34.1, 32.9,

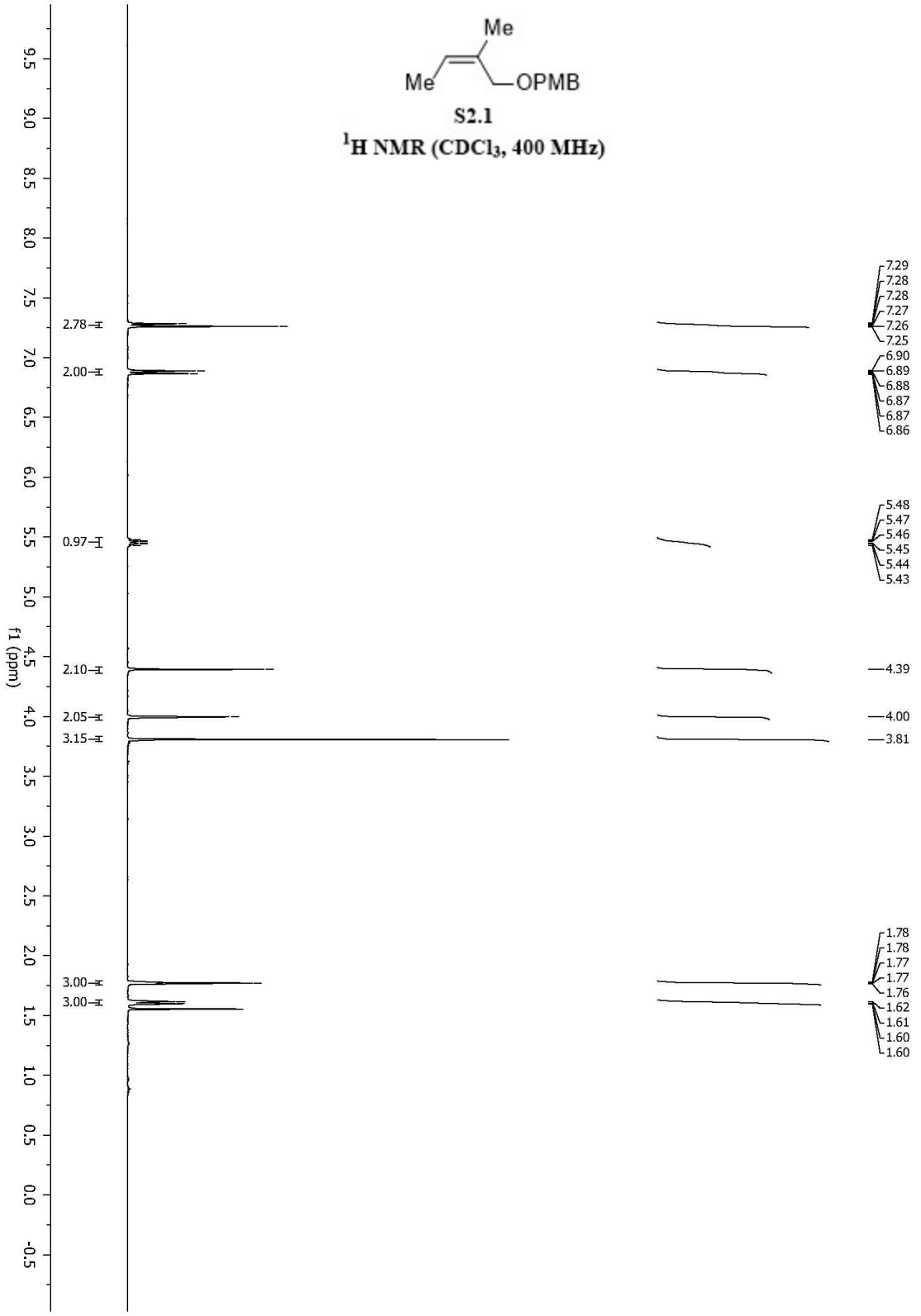
29.4, 28.6, 28.2, 27.7, 14.1; **HRMS[M+H]$^+$**: Calcd for $C_{18}H_{28}O_2Br$: 366.1273, found: 355.1267.

1-Methoxy-4-((((2*E*,4*E*)-2-methyl-5-phenylpenta-2,4-dien-1-yl)oxy)methyl)benzene (*E*-2.38)

Following the general procedure, in a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with (*E*)-buta-1,3-dien-1-ylbenzene (13.0 mg, 0.1 mmol) and a thf solution of *Z*-butene (13 wt %, 215 mg, 0.50 mmol), this was followed by addition of a thf solution (200 μL) of **Ru-9** (0.76 mg, 0.0010 mmol). The vessel was then sealed. The mixture was allowed to stir at 22 °C for 1 h, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*E*)-1-methoxy-4-(((2-methylbut-2-en-1-yl)oxy)methyl)benzene (51.6 mg, 0.25 mmol), a solution of **Ru-9** (3.8 mg, 0.0050 mmol in 200 μL thf) and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir at 22 °C for 15 h. At this point, the reaction was quenched by the addition of wet (undistilled) Et_2O while being exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (20~50% ethyl ether in hexanes) and filtered through a small plug of activated charcoal to afford *E*-**2.38** in >98:2 *E*:*Z* ratio as colorless oil (12.1 mg, 0.041 mmol, 41% yield). The product contain inseperable impurities and the yield was calculated based on impure material. **IR (neat)**: 3032 (w), 2997 (m), 2914 (m), 2851 (m), 1612 (m), 1586 (m), 1512 (s), 1449 (m), 1348 (m), 1301 (m), 1247 (s), 1173 (m), 1072 (m), 966 (m), 821 (m), 749 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.42 (d, *J* = 7.5 Hz, 2H), 7.32 (t, *J* = 7.7 Hz, 2H), 7.29 (d, *J* = 8.6 Hz, 2H), 7.22 (t, *J* = 7.3 Hz, 1H), 7.03 (dd, *J* = 15.5, 11.0 Hz, 1H), 6.90 (d, *J* = 8.6 Hz, 2H), 6.55 (d, *J* = 15.5 Hz, 1H), 6.24 (d, *J* = 10.9 Hz, 1H), 4.43

(s, 2H), 4.00 (s, 2H), 3.81 (s, 3H), 1.90 (s, 3H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 159.3, 137.8, 135.9, 132.4, 130.6, 129.5, 128.7, 127.5, 127.2, 126.5, 124.8, 113.9, 75.6, 71.6, 55.4, 14.8; **HRMS[M+H]$^+$**: Calcd for $C_{20}H_{23}O_2$: 295.1698, Found: 295.1714.

2.6.4 NMR spectra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Me
OPMB
S2.1
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2.00
0.97
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2.05
3.15
3.00
3.00
7.29
7.28
7.28
7.27
7.26
7.25
6.90
6.89
6.88
6.87
6.87
6.86
5.48
5.47
5.46
5.45
5.44
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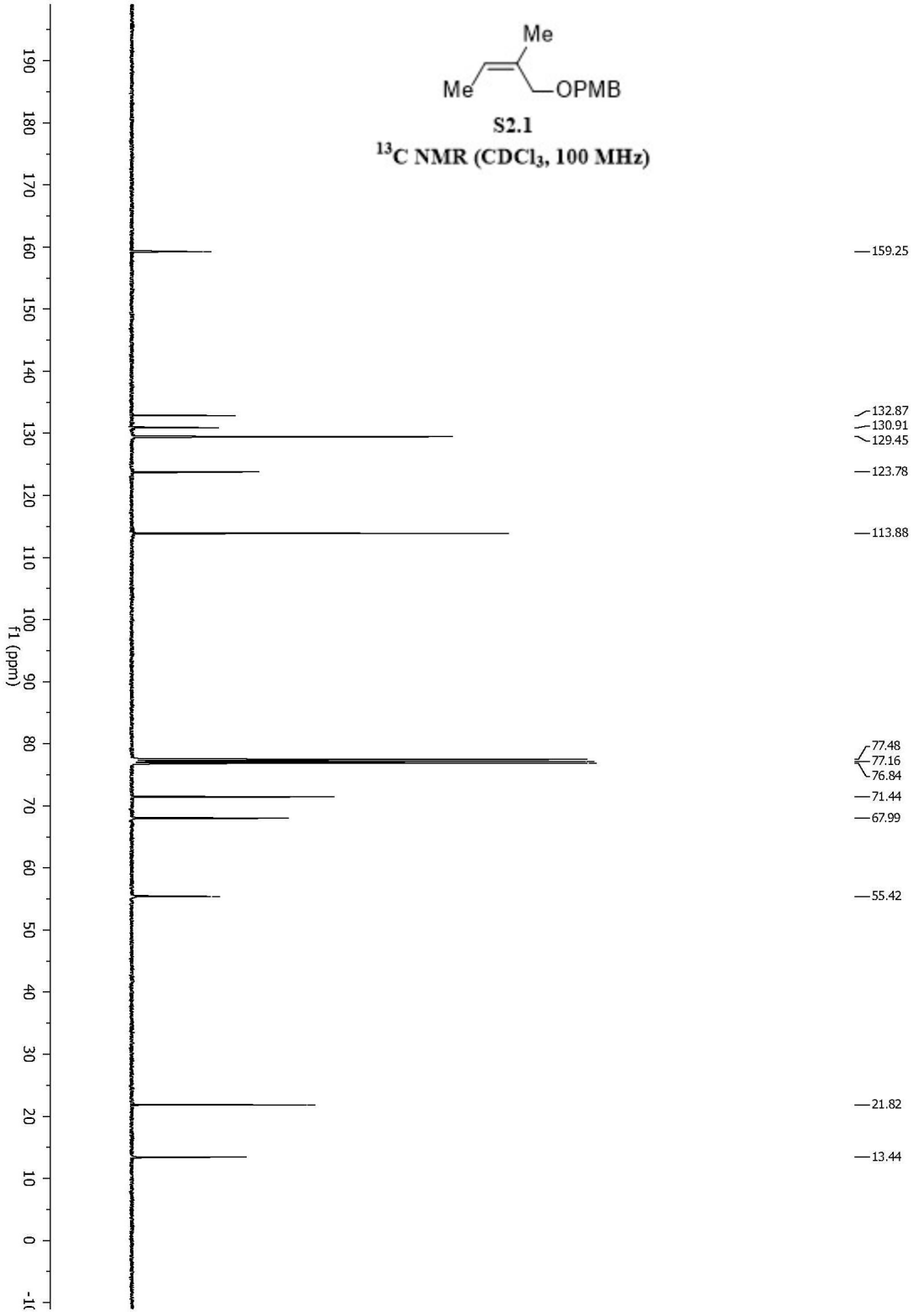
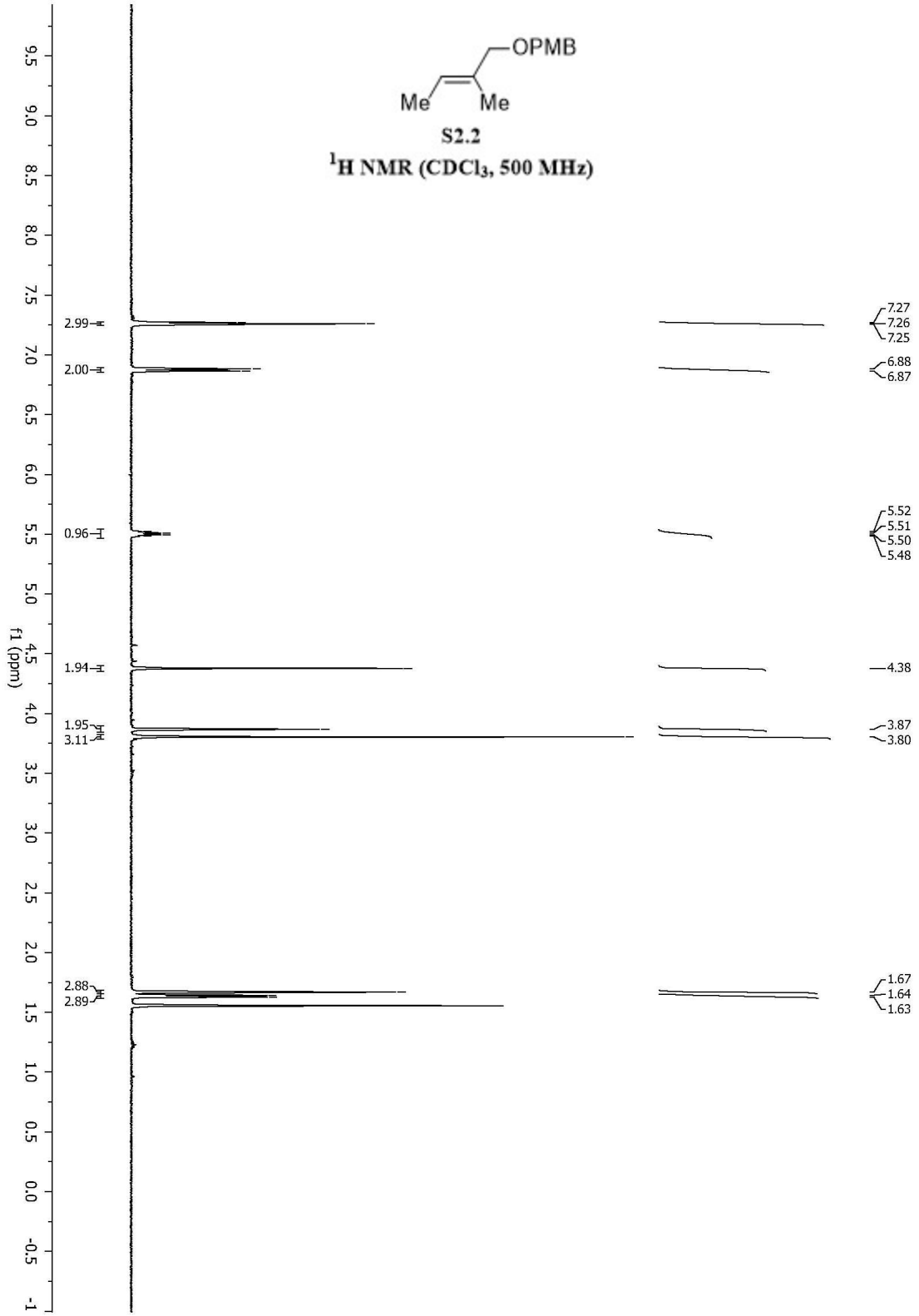
1.60
1.60



S2.1

^{13}C NMR ($CDCl_3$, 100 MHz)


OPMB
Me
Me
S2.2
^{1}H NMR (CDCl$_3$, 500 MHz)
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1.95
3.11
2.88
2.89
7.27
7.26
7.25
6.88
6.87
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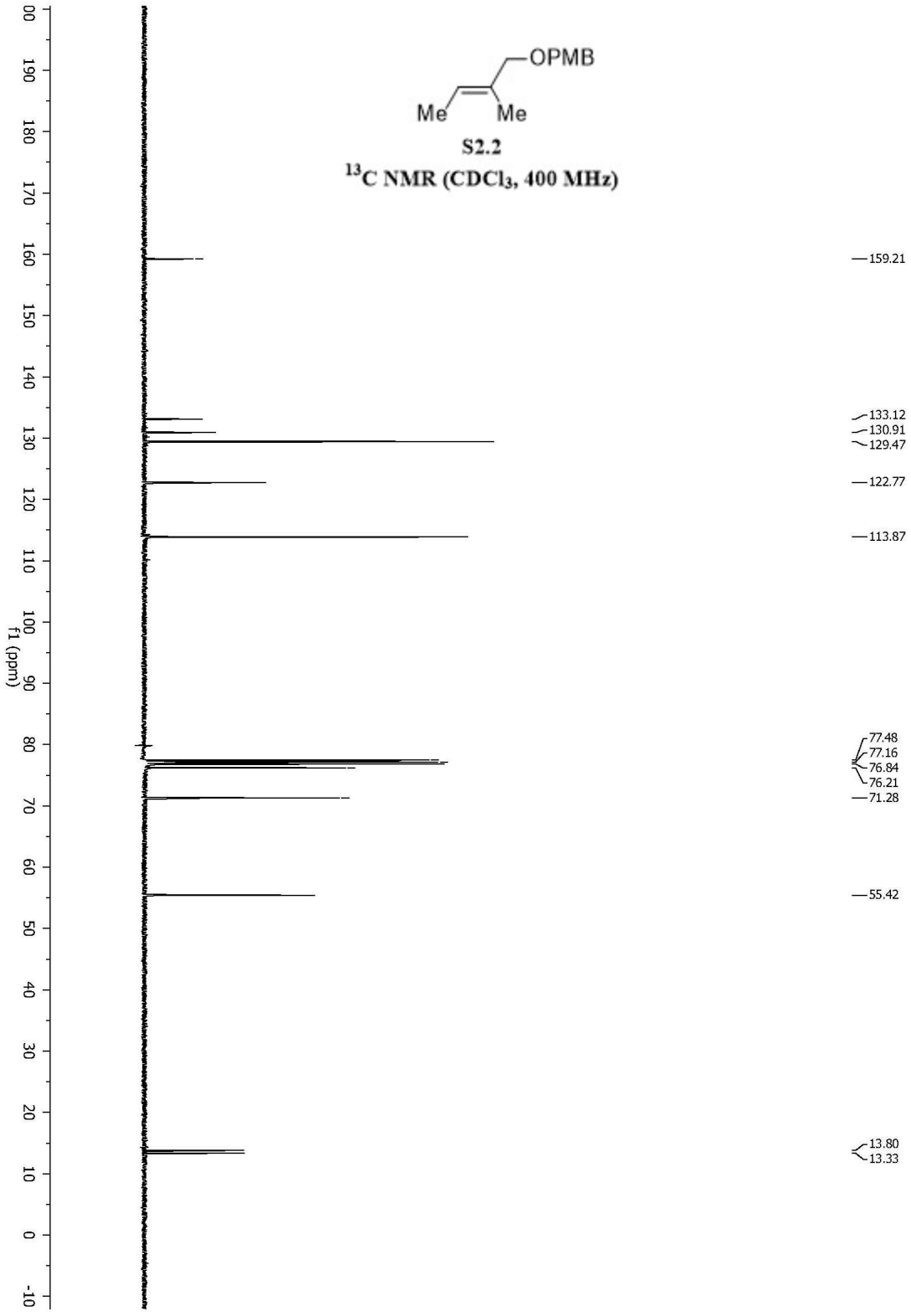
1.67
1.64
1.63


OPMB
Me
Me
S2.2
^{13}C NMR ($CDCl_3$, 400 MHz)
f1 (ppm)
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133.12
130.91
129.47
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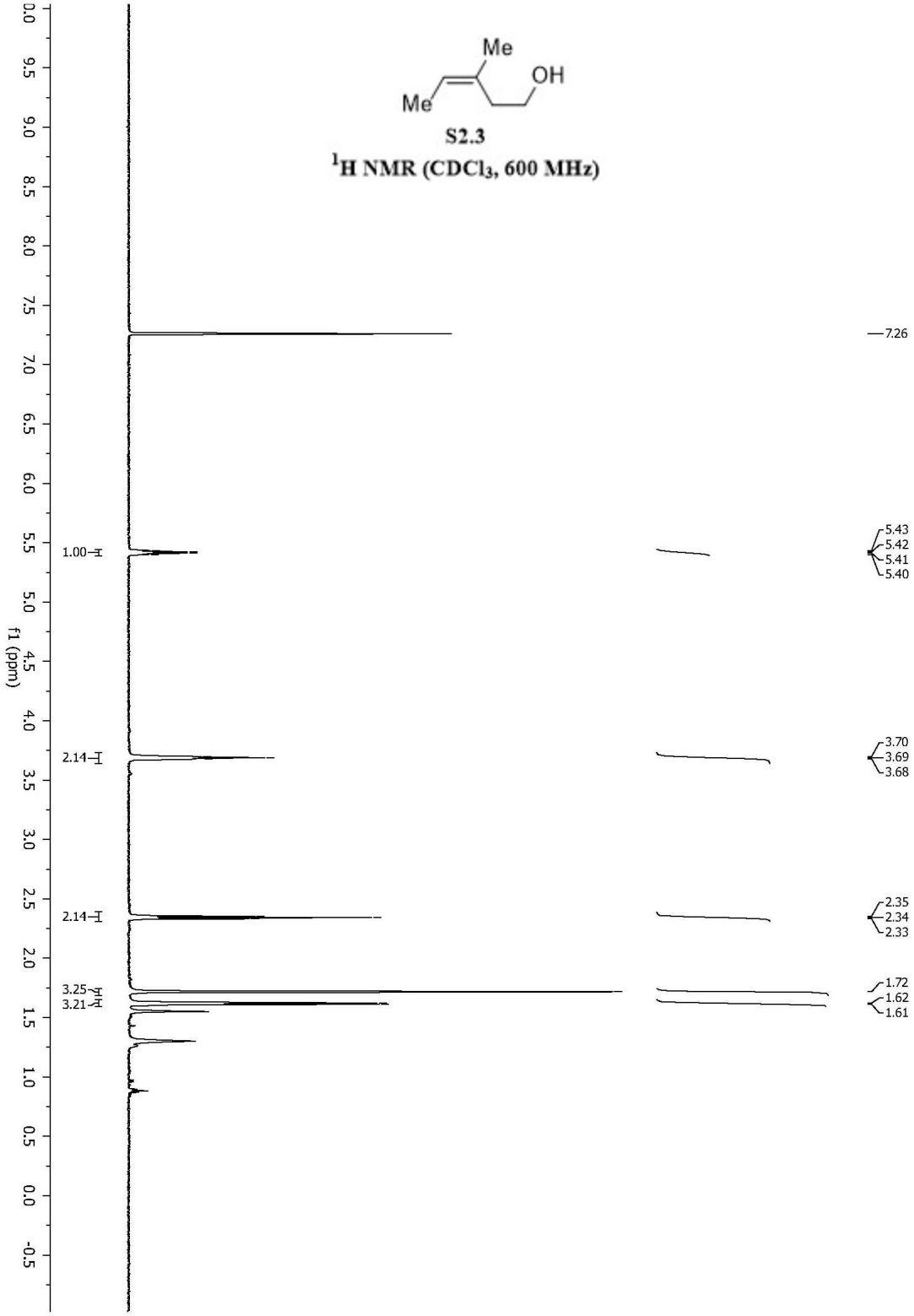
76.84
76.21
71.28
55.42
13.80
13.33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OH
Me
S2.3
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5.41
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3.69
3.68
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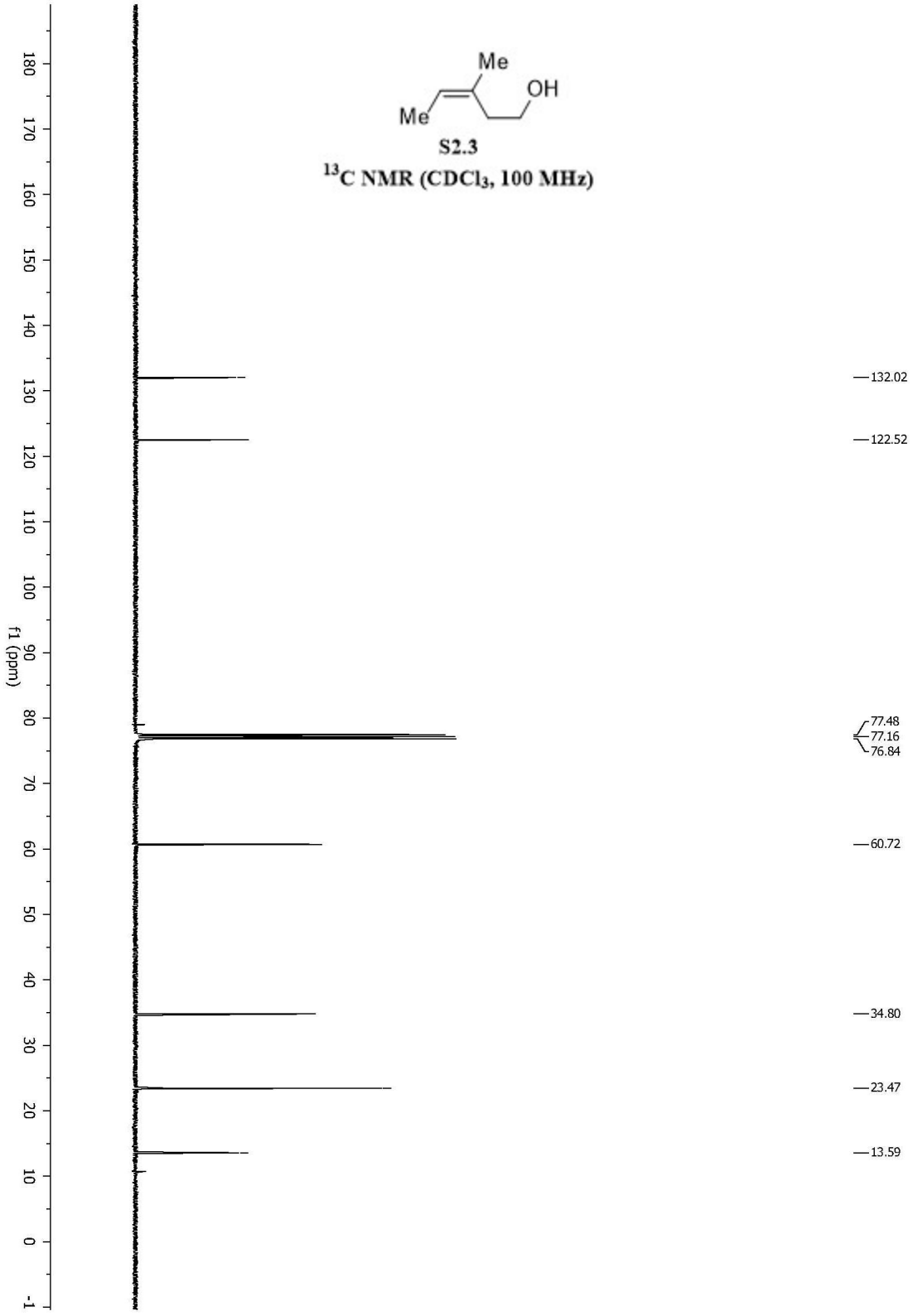
1.00
2.14
2.14
3.25
3.21
f1 (ppm)


Me
OH
Me
S2.3
^{13}C NMR ($CDCl_3$, 100 MHz)
f1 (ppm)
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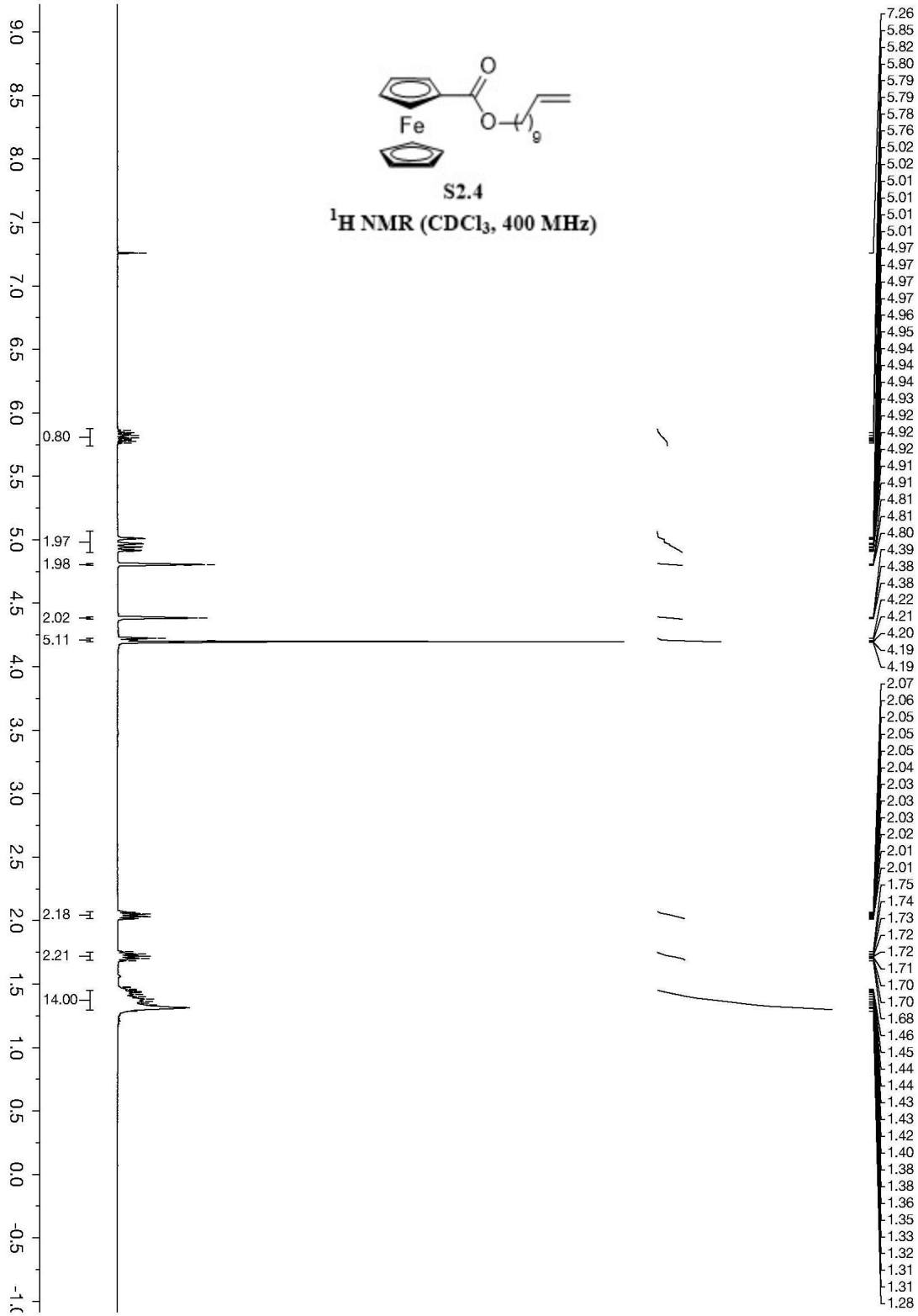
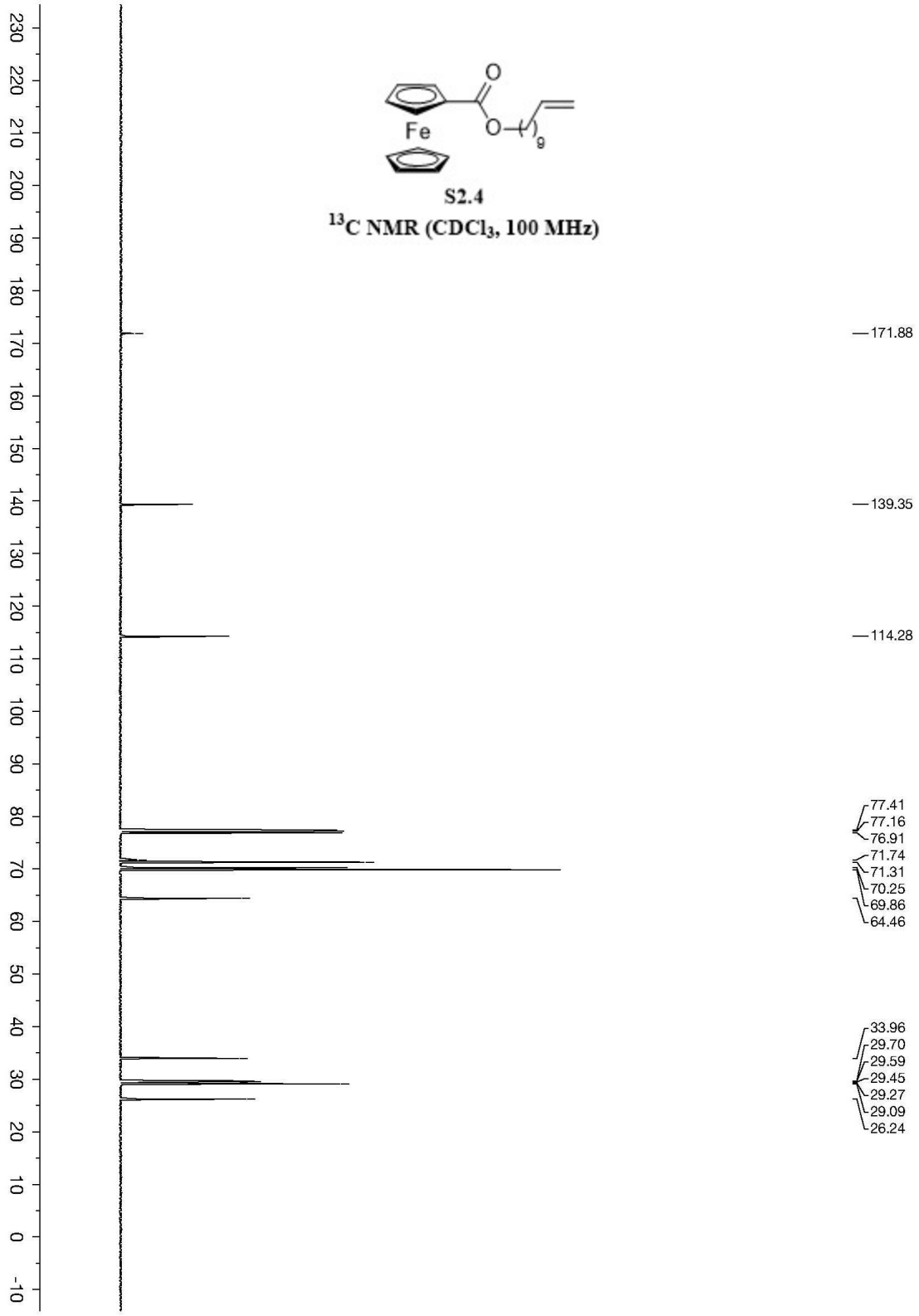
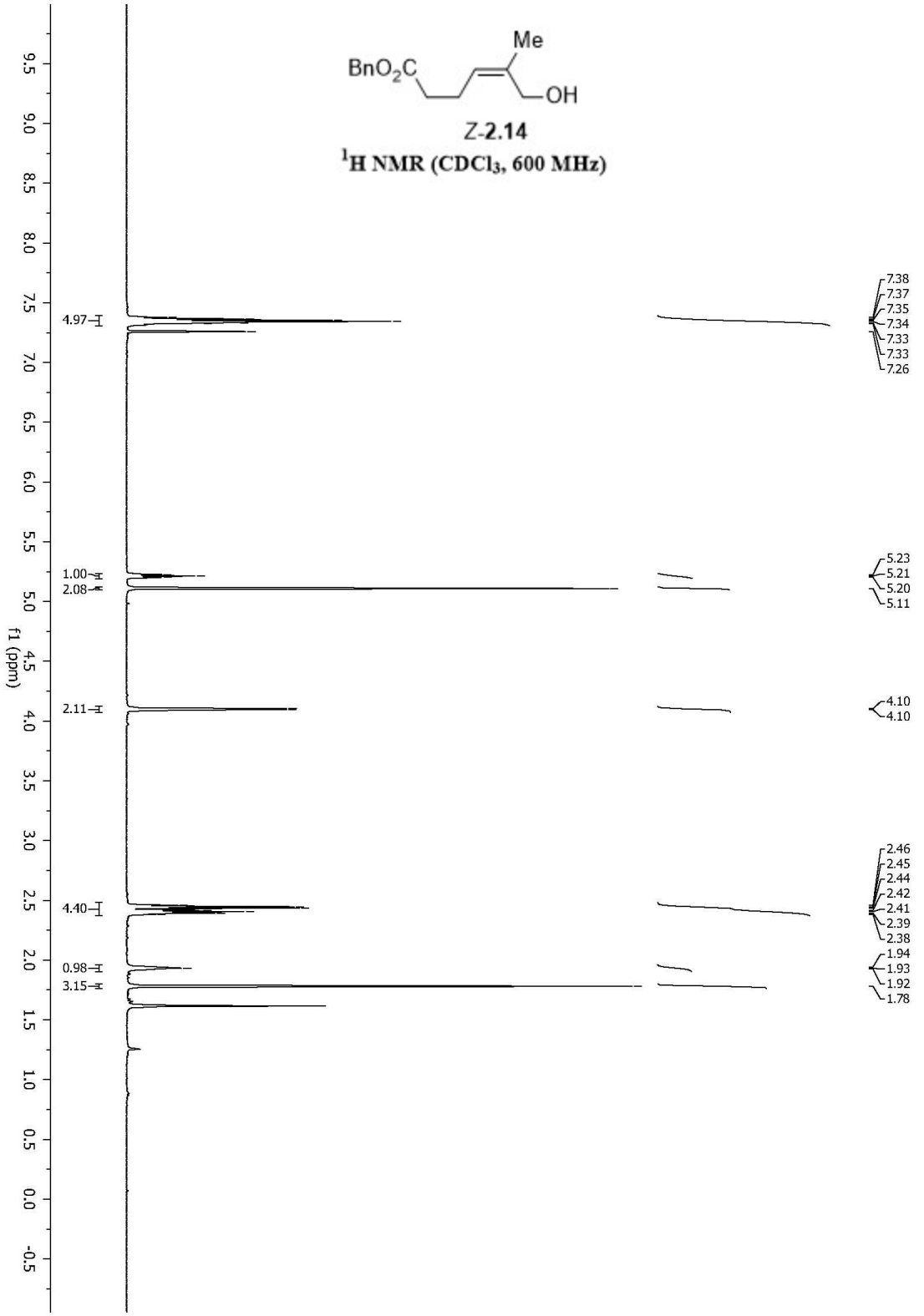
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-1
132.02
122.52
77.48
77.16
76.84
60.72
34.80
23.47
13.59

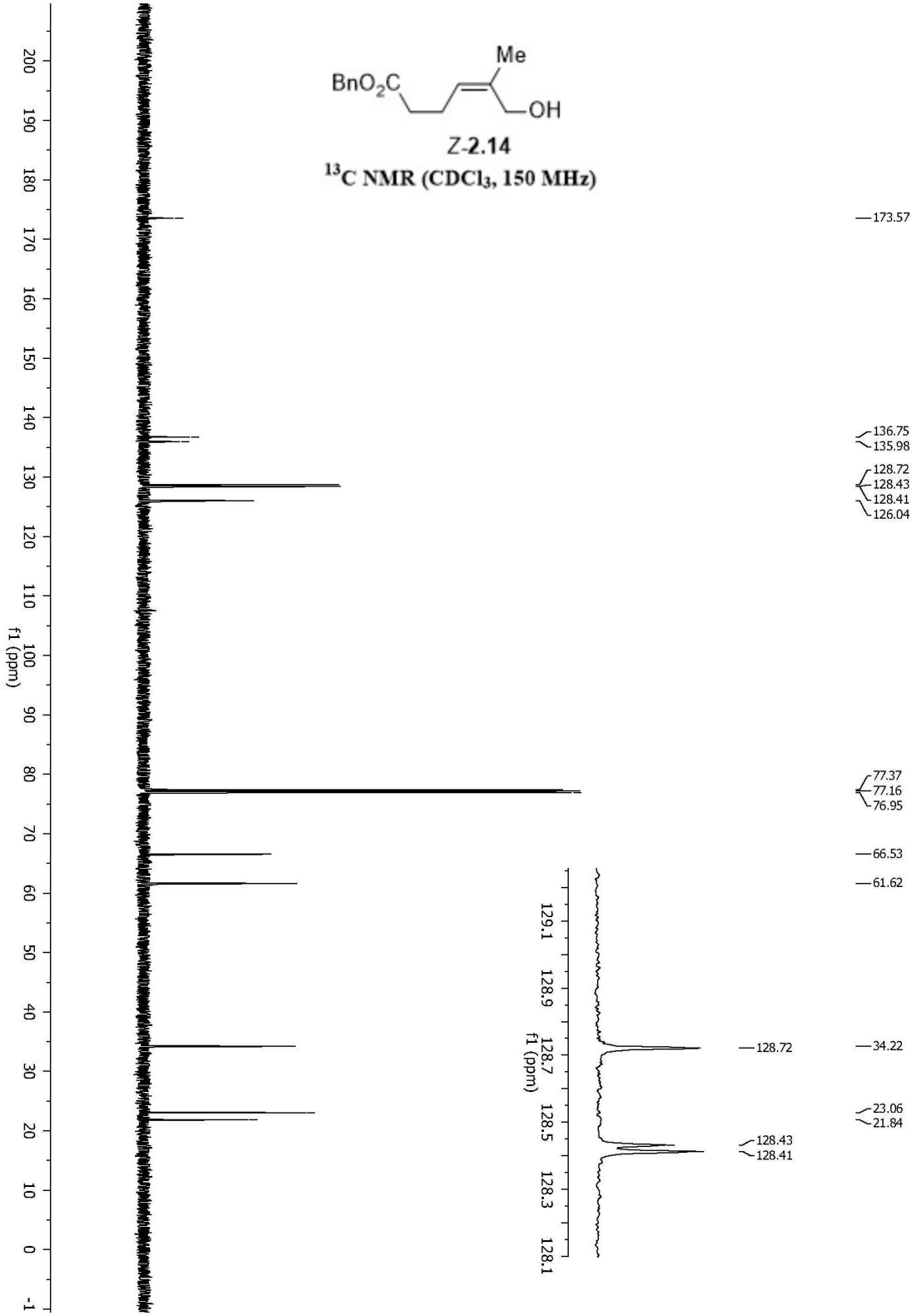

Fe
O
O
9
S2.4
^{1}H NMR (CDCl$_3$, 400 MHz)
0.80
1.97
1.98
2.02
5.11
2.18
2.21
14.00
7.26
5.85
5.82
5.80
5.79
5.79
5.78
5.76
5.02
5.02
5.01
5.01
5.01
5.01
4.97
4.97
4.97
4.97
4.96
4.95
4.94
4.94
4.94
4.93
4.92
4.92
4.92
4.91
4.91
4.81
4.81
4.80
4.39
4.38
4.38
4.22
4.21
4.20
4.19
4.19
2.07
2.06
2.05
2.05
2.05
2.04
2.03
2.03
2.03
2.02
2.01
2.01
1.75
1.74
1.73
1.72
1.72
1.71
1.70
1.70
1.68
1.46
1.45
1.44
1.44
1.43
1.43
1.42
1.40
1.38
1.38
1.36
1.35
1.33
1.32
1.31
1.31
1.28

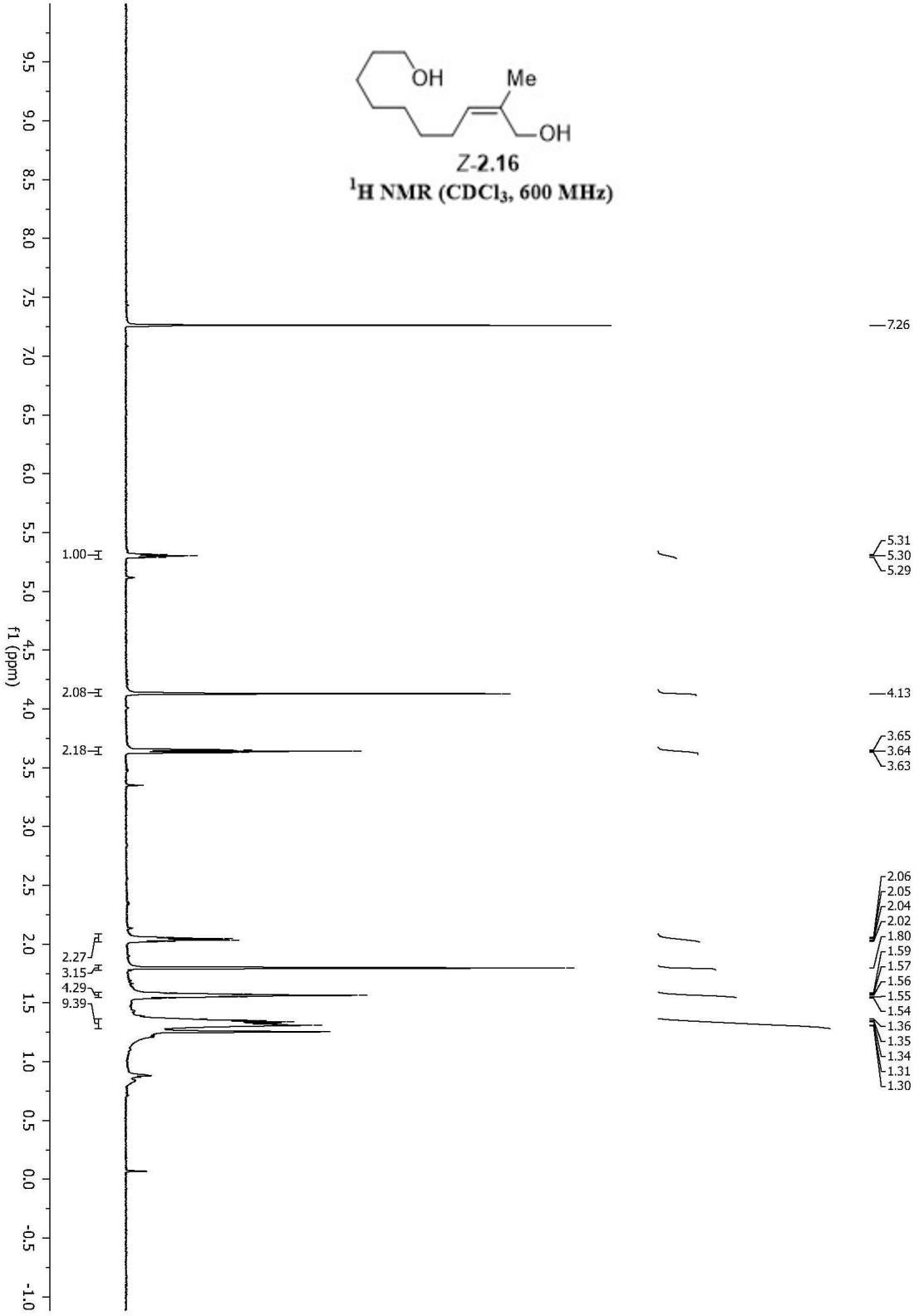


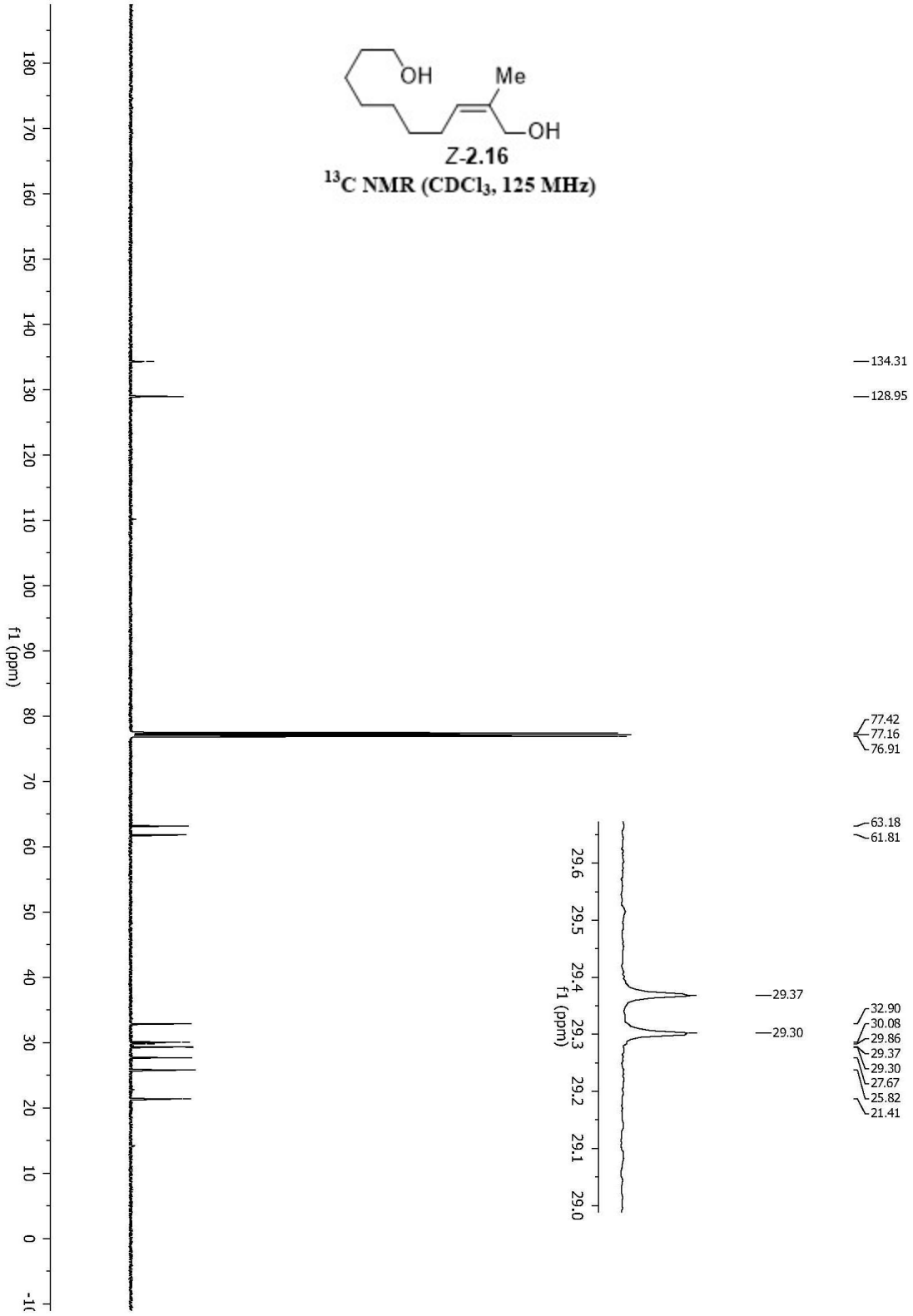
S2.4

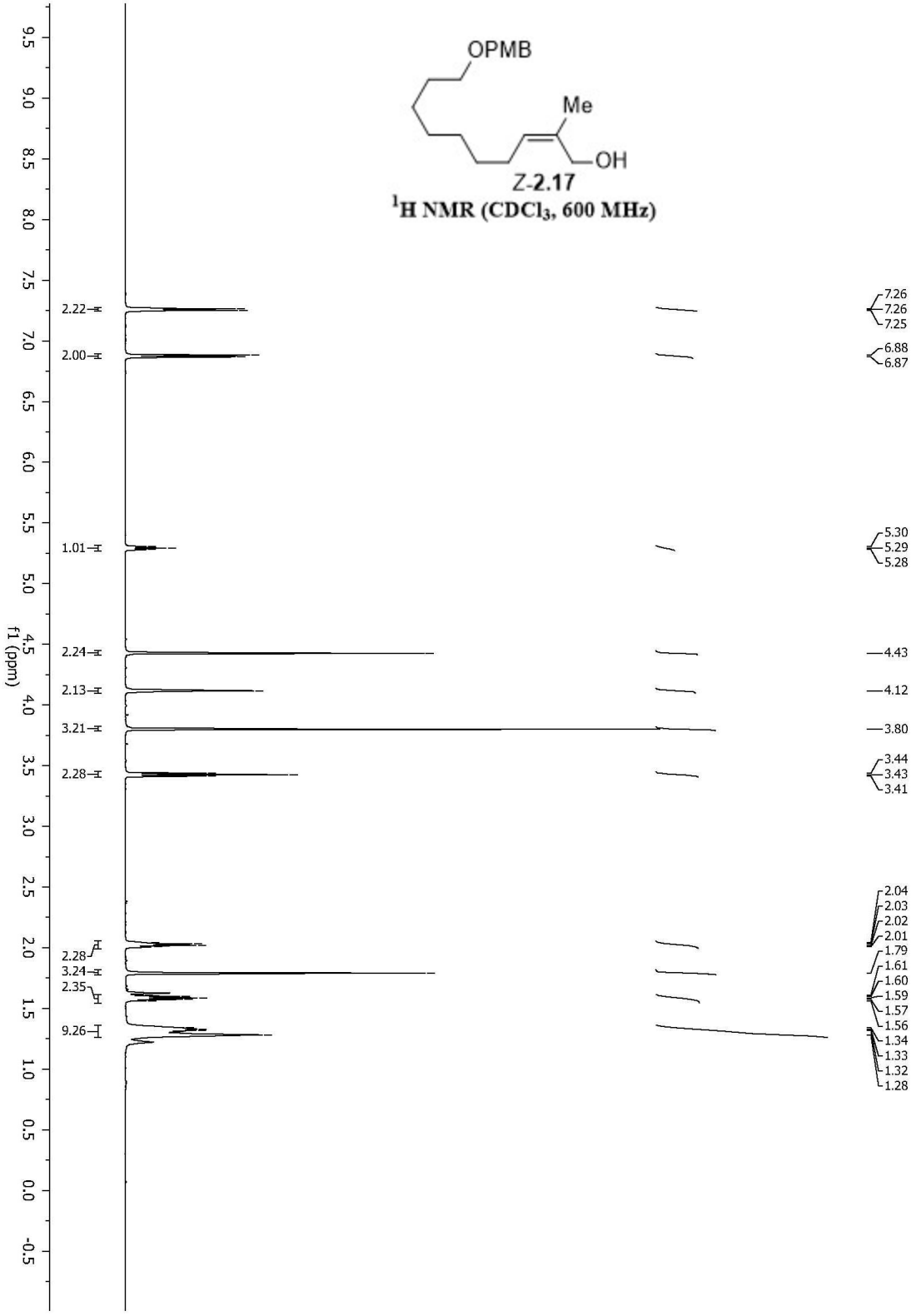
^{13}C NMR ($CDCl_3$, 100 MHz)

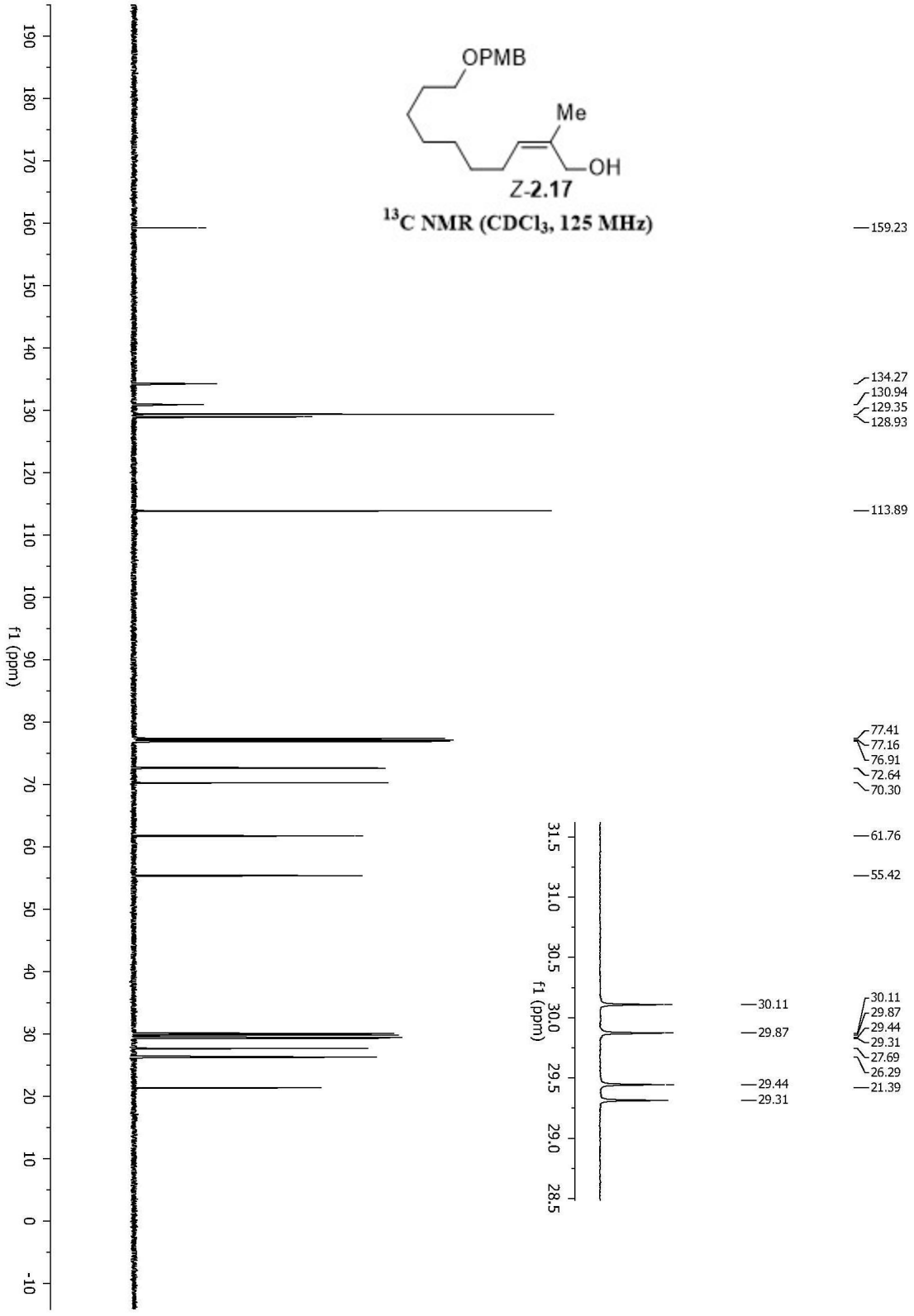

Me
BnO2C
OH
Z-2.14
1H NMR (CDCl3, 600 MHz)
f1 (ppm)
4.97
1.00
2.08
2.11
4.40
0.98
3.15
7.38
7.37
7.35
7.34
7.33
7.33
7.26
5.23
5.21
5.20
5.11
4.10
4.10
2.46
2.45
2.44
2.42
2.41
2.39
2.38
1.94
1.93
1.92
1.78

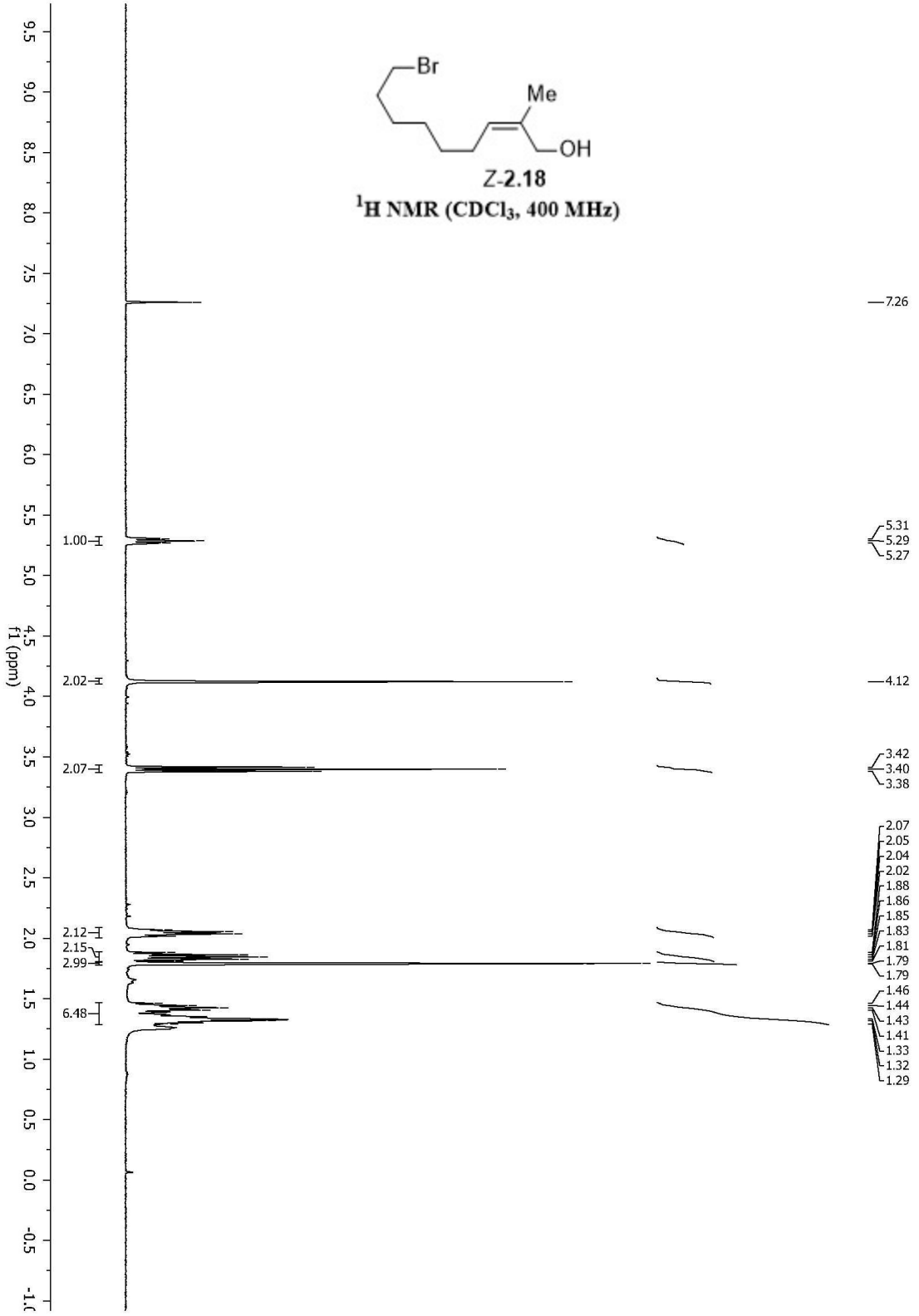

Me
BnO2C
OH
Z-2.14
13C NMR (CDCl3, 150 MHz)
173.57
136.75
135.98
128.72
128.43
128.41
126.04
77.37
77.16
76.95
66.53
61.62
34.22
23.06
21.84
f1 (ppm)

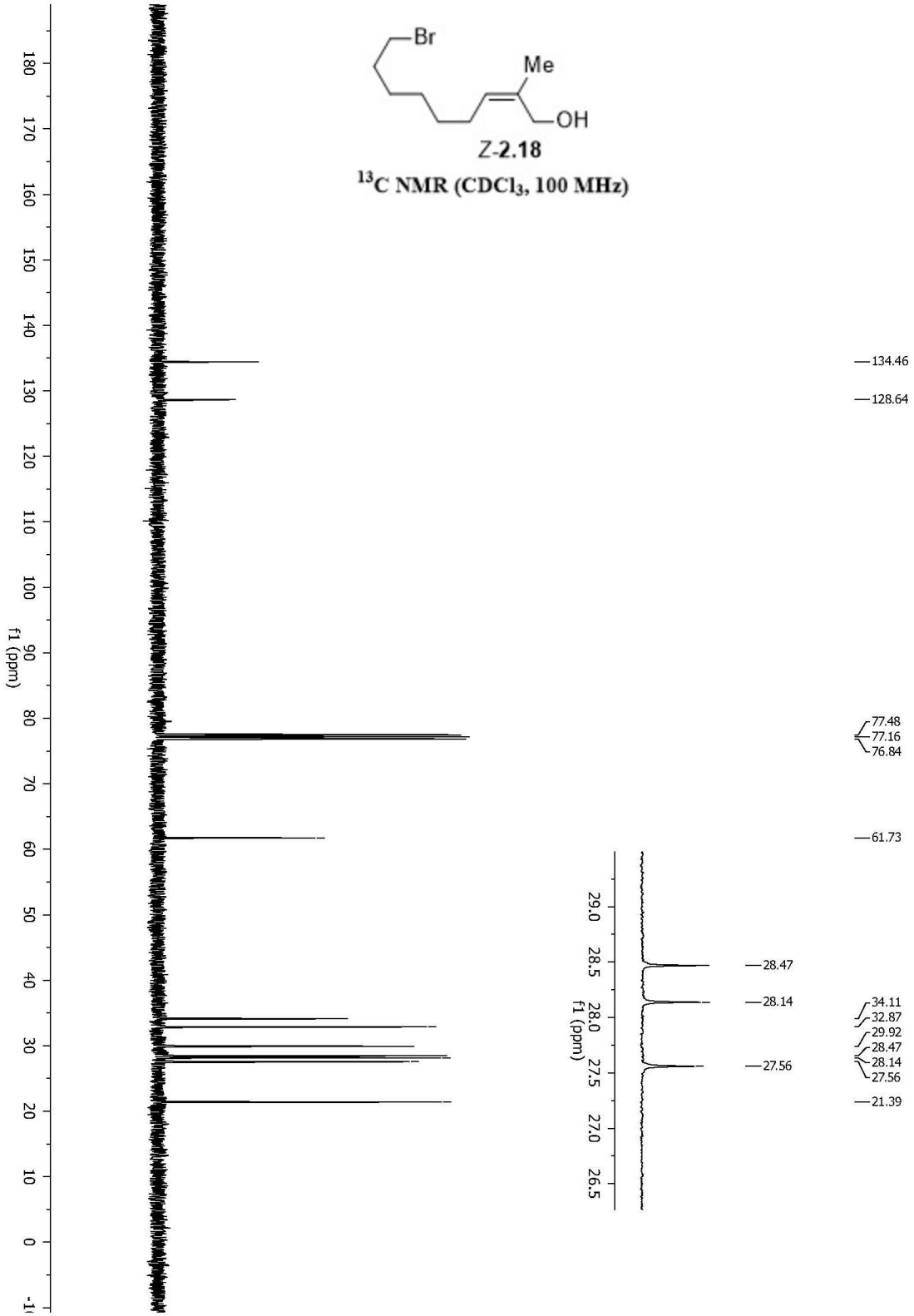

OH
Me
OH
Z-2.16
^{1}H NMR ($CDCl_3$, 600 MHz)
f1 (ppm)
1.00
2.08
2.18
2.27
3.15
4.29
9.39
7.26
5.31
5.30
5.29
4.13
3.65
3.64
3.63
2.06
2.05
2.04
2.02
1.80
1.59
1.57
1.56
1.55
1.54
1.36
1.35
1.34
1.31
1.30

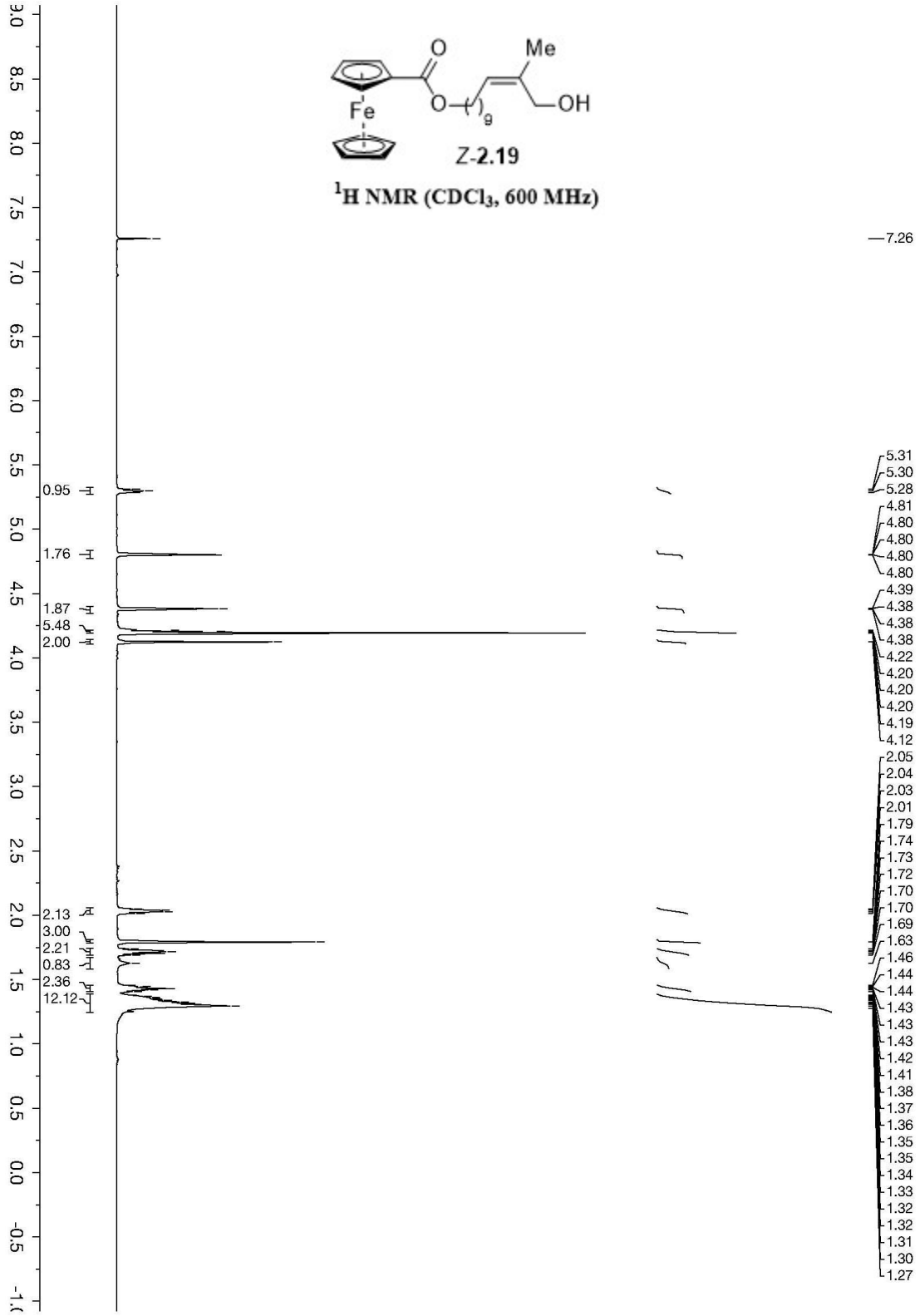

OH
Me
OH
Z-2.16
13C NMR (CDCl3, 125 MHz)
f1 (ppm)
134.31
128.95
77.42
77.16
76.91
63.18
61.81
29.37
29.30
32.90
30.08
29.86
29.37
29.30
27.67
25.82
21.41

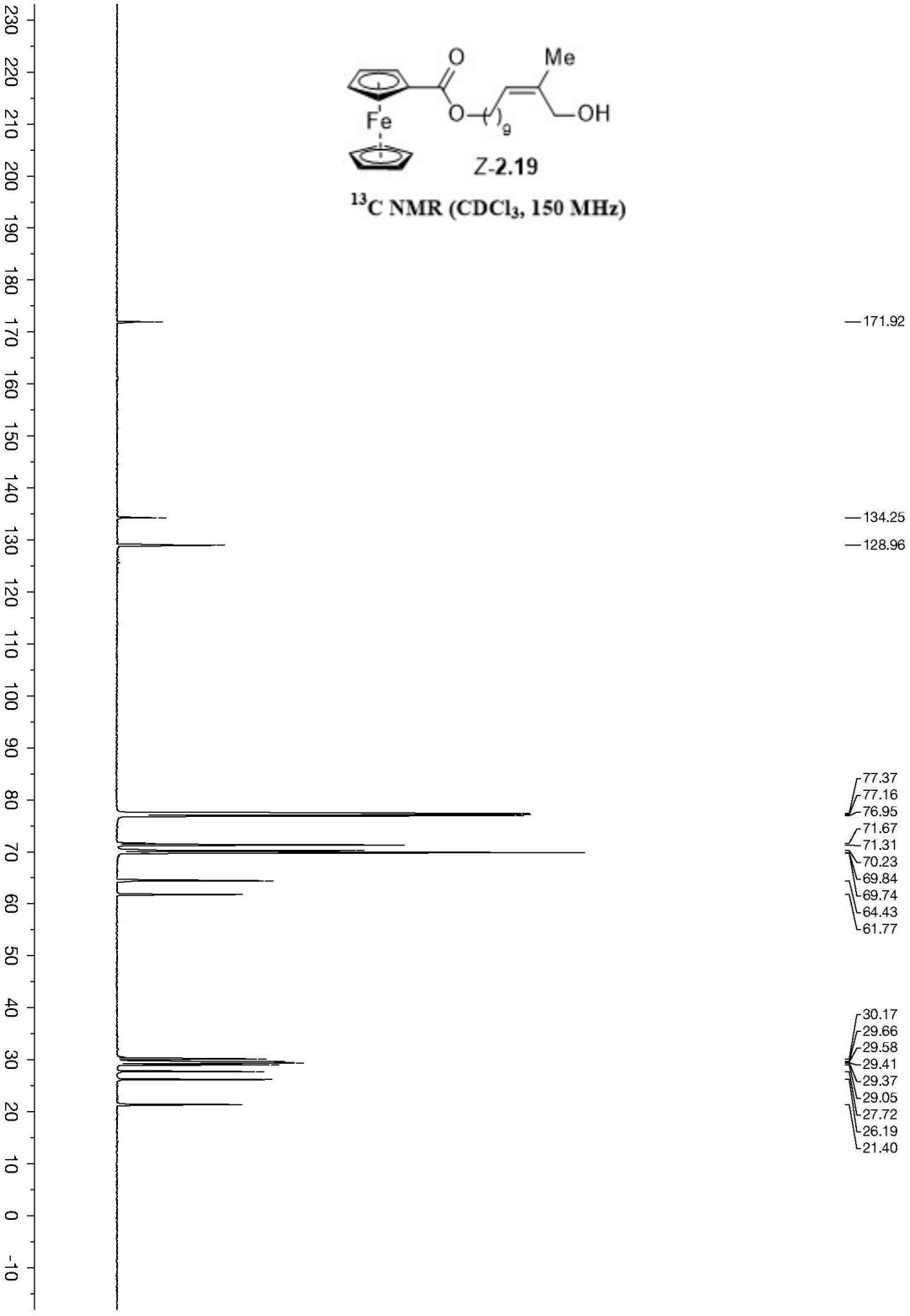

OPMB
Me
OH
Z-2.17
^{1}H NMR (CDCl$_3$, 600 MHz)
f1 (ppm)
2.22
2.00
1.01
2.24
2.13
3.21
2.28
2.28
3.24
2.35
9.26
7.26
7.26
7.25
6.88
6.87
5.30
5.29
5.28
4.43
4.12
3.80
3.44
3.43
3.41
2.04
2.03
2.02
2.01
1.79
1.61
1.60
1.59
1.57
1.56
1.34
1.33
1.32
1.28


OPMB
Me
OH
Z-2.17
^{13}C NMR ($CDCl_3$, 125 MHz)
f1 (ppm)
159.23
134.27
130.94
129.35
128.93
113.89
77.41
77.16
76.91
72.64
70.30
61.76
55.42
30.11
29.87
29.44
29.31
27.69
26.29
21.39


Br
Me
OH
Z-2.18
^{1}H NMR (CDCl$_3$, 400 MHz)
f1 (ppm)
1.00
2.02
2.07
2.12
2.15
2.99
6.48
7.26
5.31
5.29
5.27
4.12
3.42
3.40
3.38
2.07
2.05
2.04
2.02
1.88
1.86
1.85
1.83
1.81
1.79
1.79
1.46
1.44
1.43
1.41
1.33
1.32
1.29

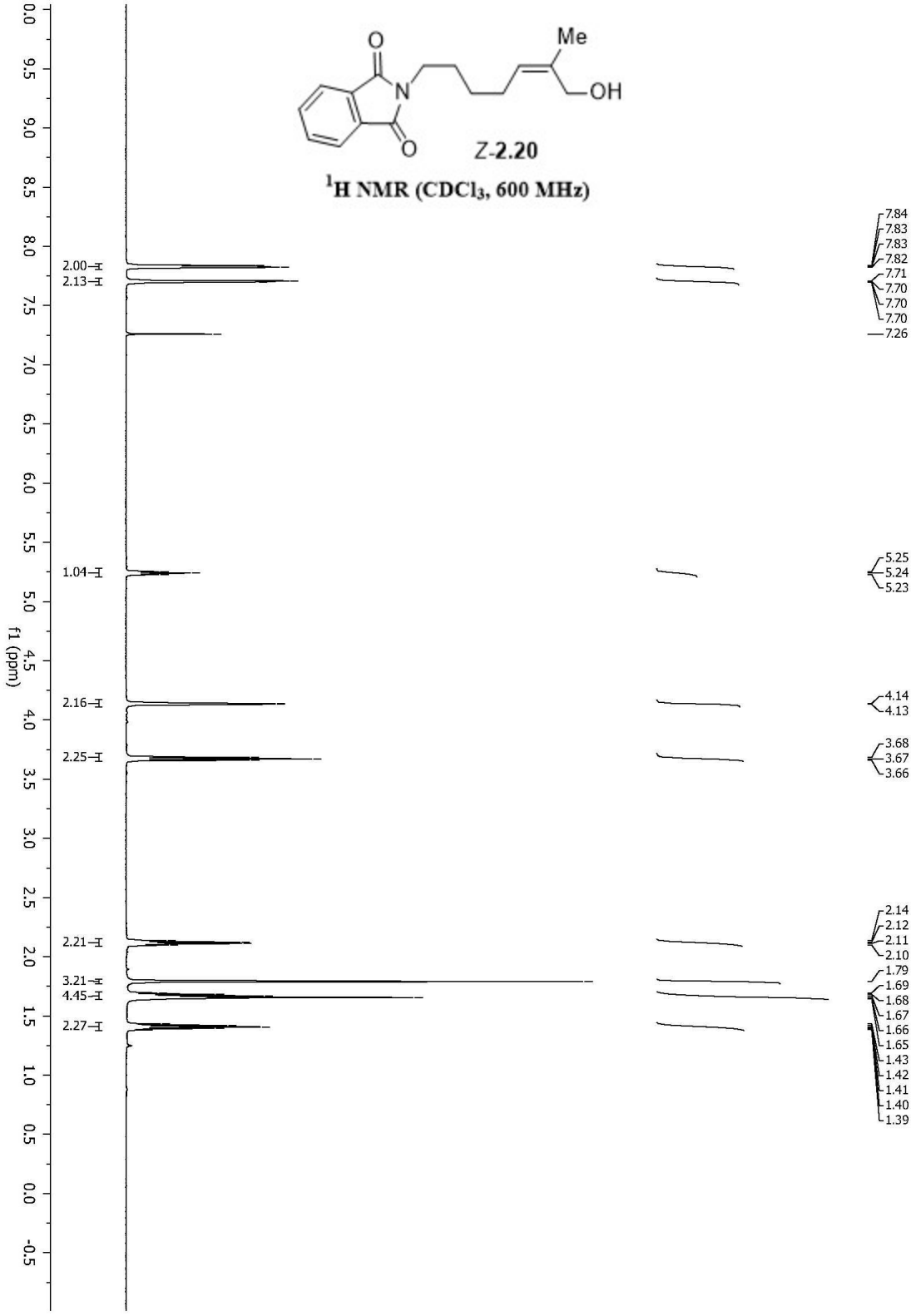

Br
Me
OH
Z-2.18
^{13}C NMR ($CDCl_3$, 100 MHz)
f1 (ppm)
134.46
128.64
77.48
77.16
76.84
61.73
28.47
28.14
27.56
34.11
32.87
29.92
28.47
28.14
27.56
21.39

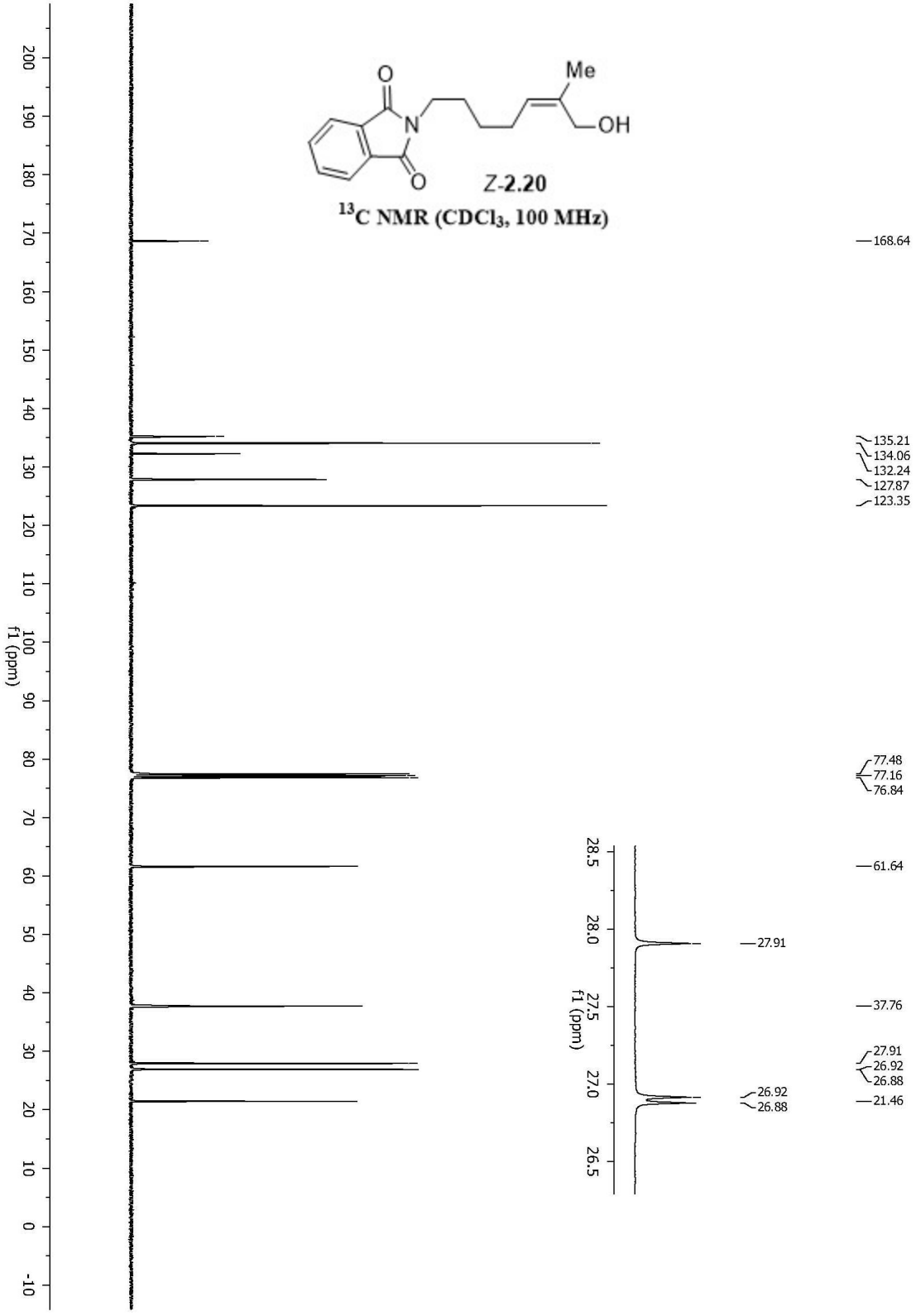

Me
O
Fe
O
OH
9
Z-2.19
^{1}H NMR (CDCl$_3$, 600 MHz)
7.26
0.95
1.76
1.87
5.48
2.00
2.13
3.00
2.21
0.83
2.36
12.12
5.31
5.30
5.28
4.81
4.80
4.80
4.80
4.80
4.39
4.38
4.38
4.38
4.22
4.20
4.20
4.20
4.19
4.12
2.05
2.04
2.03
2.01
1.79
1.74
1.73
1.72
1.70
1.70
1.69
1.63
1.46
1.44
1.44
1.43
1.43
1.43
1.42
1.41
1.38
1.37
1.36
1.35
1.35
1.34
1.33
1.32
1.32
1.31
1.30
1.27

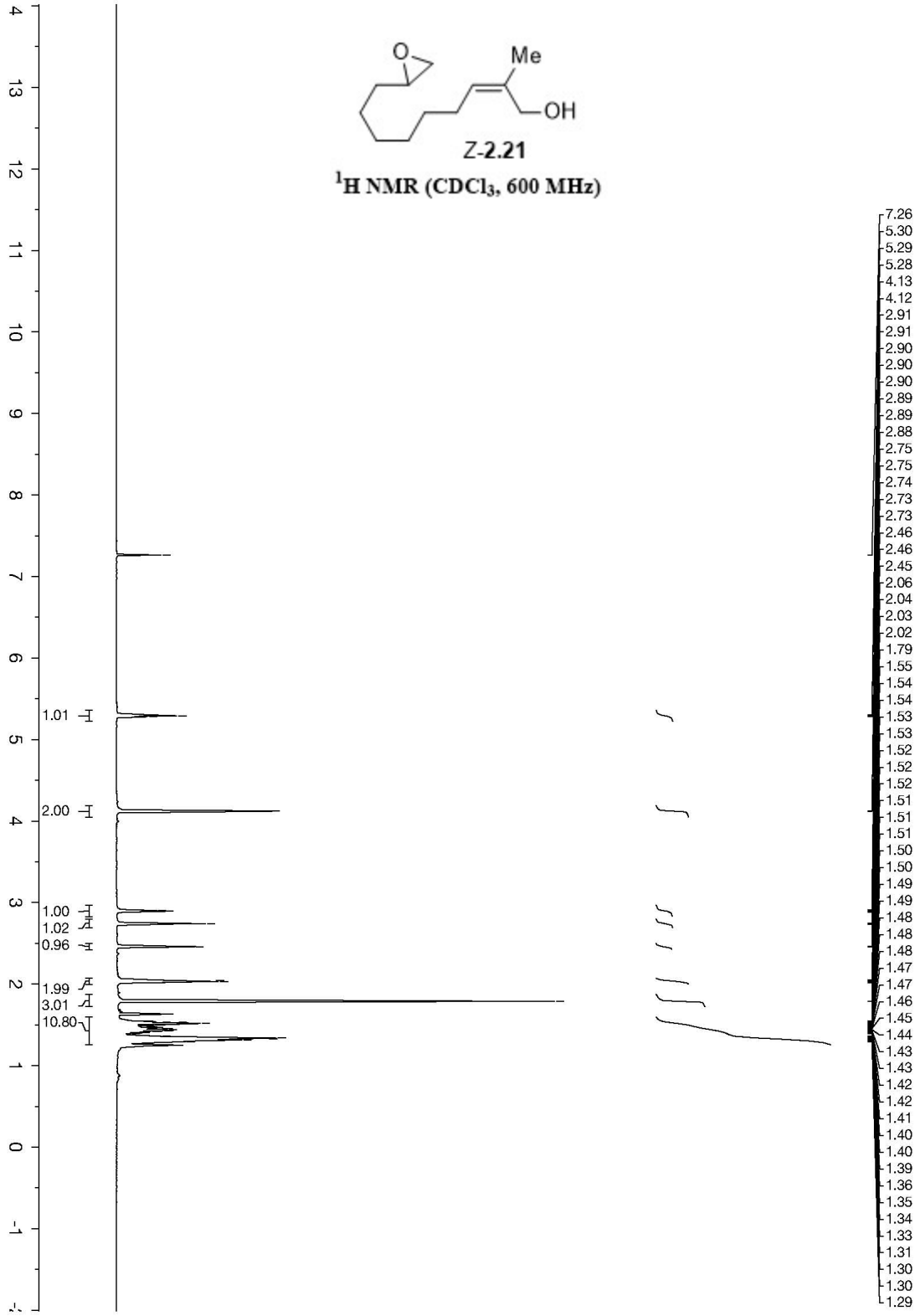


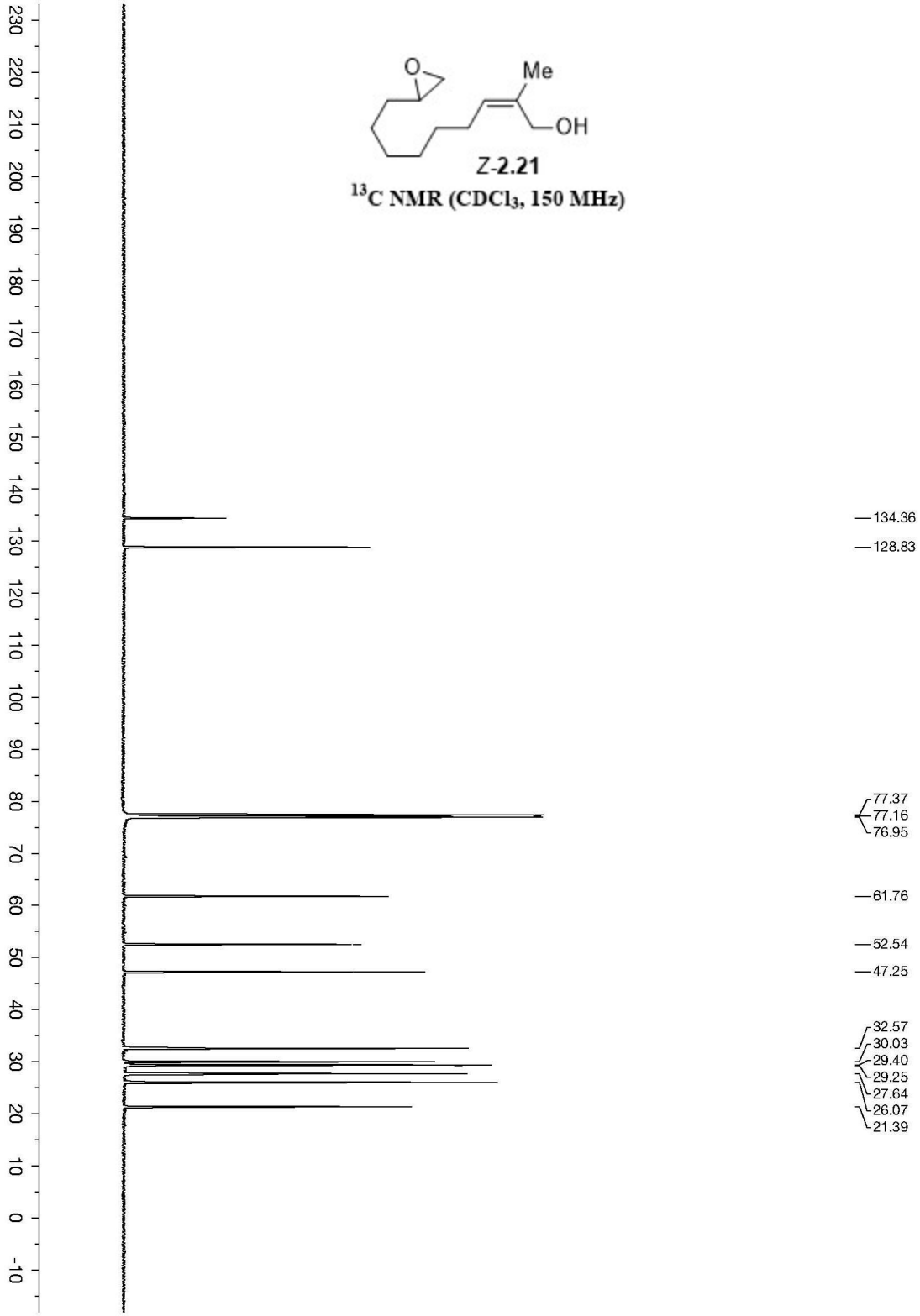
Z-**2.19**

^{13}C NMR ($CDCl_3$, 150 MHz)


Me
O
N
OH
O
Z-2.20
^{1}H NMR (CDCl$_3$, 600 MHz)
f1 (ppm)
2.00
2.13
1.04
2.16
2.25
2.21
3.21
4.45
2.27
7.84
7.83
7.83
7.82
7.71
7.70
7.70
7.70
7.26
5.25
5.24
5.23
4.14
4.13
3.68
3.67
3.66
2.14
2.12
2.11
2.10
1.79
1.69
1.68
1.67
1.66
1.65
1.43
1.42
1.41
1.40
1.39

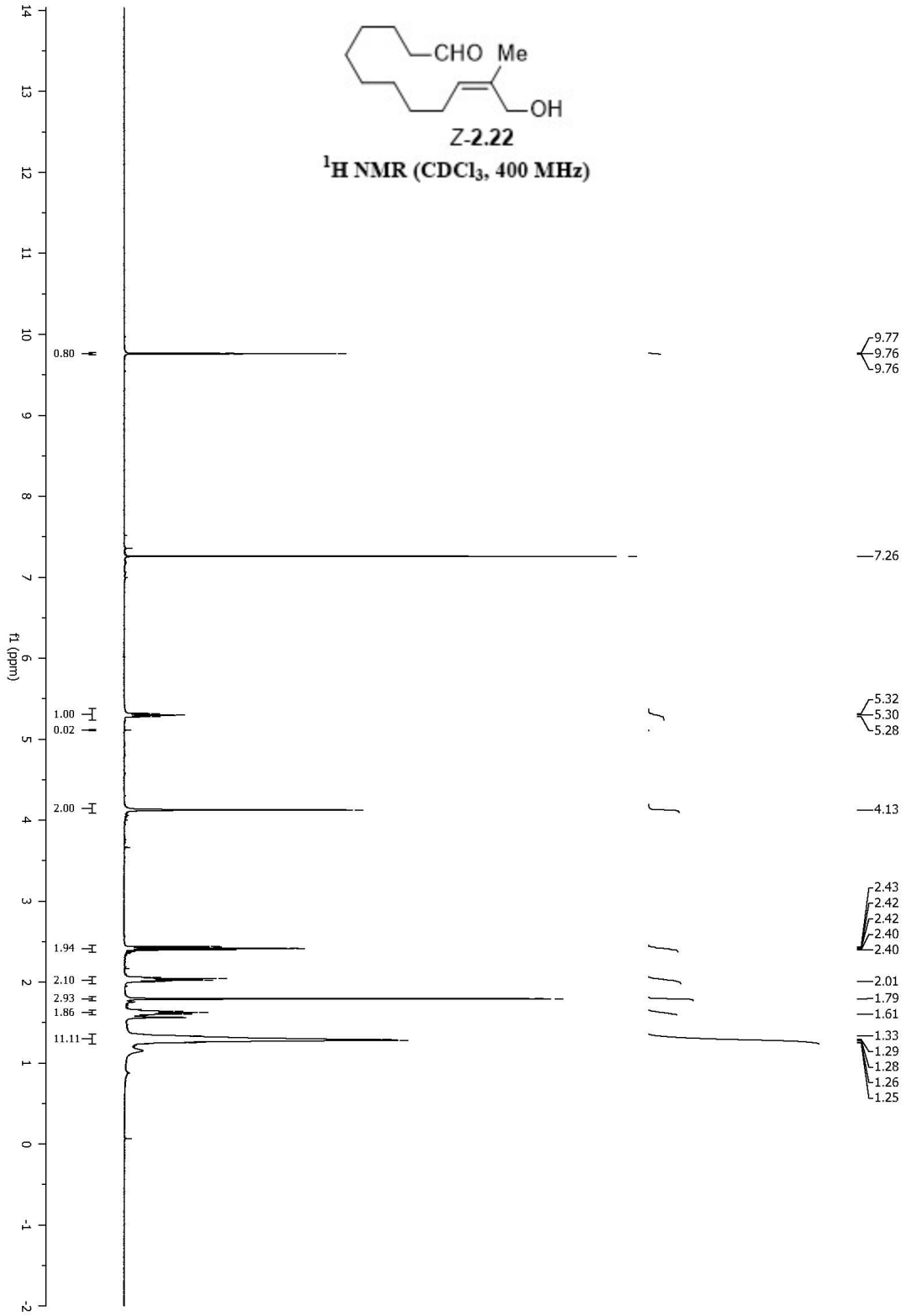

Me
OH
O
N
O
Z-2.20
^{13}C NMR ($CDCl_3$, 100 MHz)
f1 (ppm)
168.64
135.21
134.06
132.24
127.87
123.35
77.48
77.16
76.84
61.64
37.76
27.91
26.92
26.88
21.46

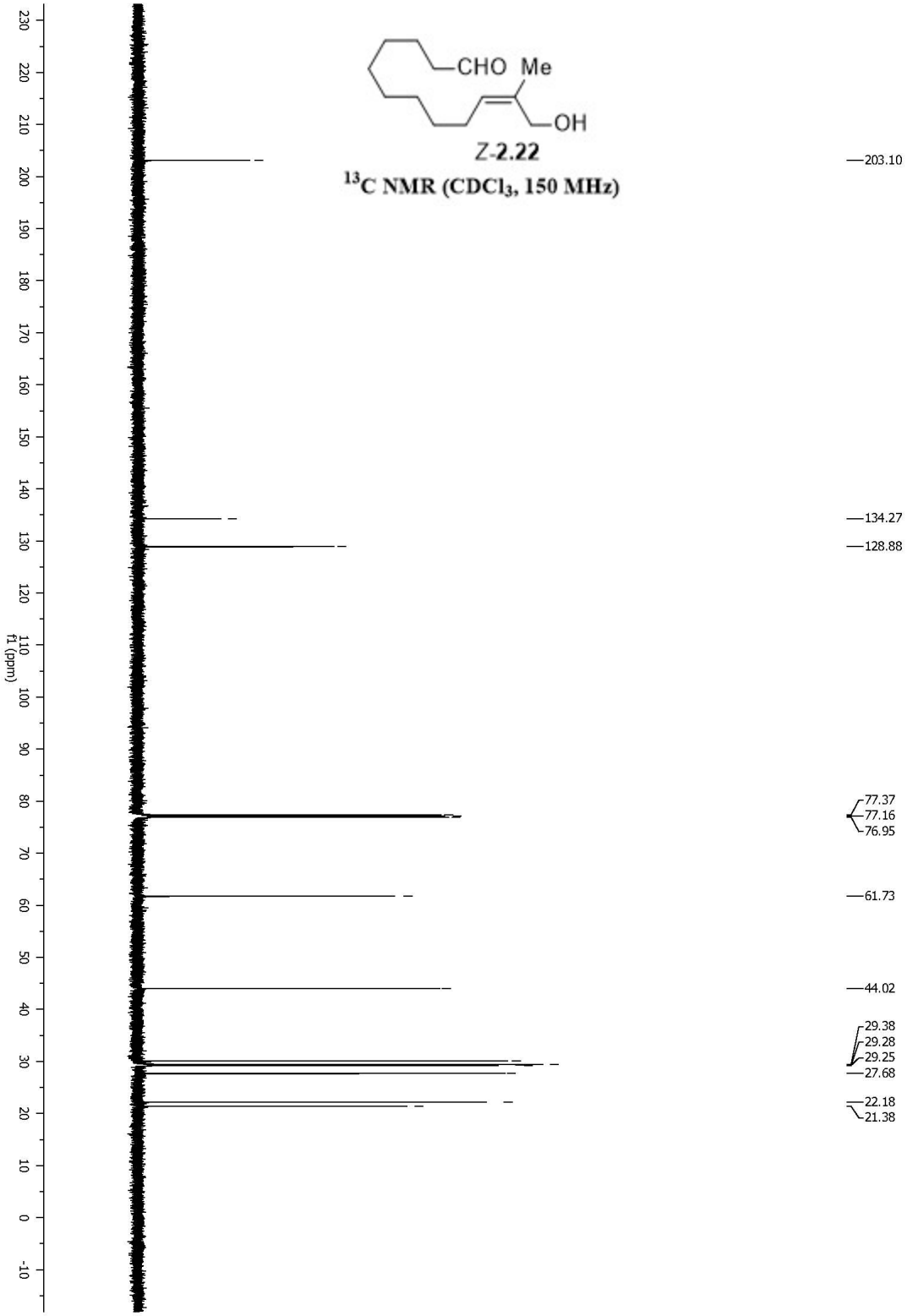

Me
OH
Z-2.21
1H NMR (CDCl3, 600 MHz)
1.01
2.00
1.00
1.02
0.96
1.99
3.01
10.80
7.26
5.30
5.29
5.28
4.13
4.12
2.91
2.91
2.90
2.90
2.90
2.89
2.89
2.88
2.75
2.75
2.74
2.73
2.73
2.46
2.46
2.45
2.06
2.04
2.03
2.02
1.79
1.55
1.54
1.54
1.53
1.53
1.52
1.52
1.52
1.51
1.51
1.51
1.51
1.50
1.50
1.49
1.49
1.48
1.48
1.48
1.48
1.47
1.47
1.46
1.45
1.44
1.43
1.43
1.42
1.42
1.41
1.40
1.40
1.39
1.36
1.35
1.34
1.33
1.31
1.30
1.30
1.29

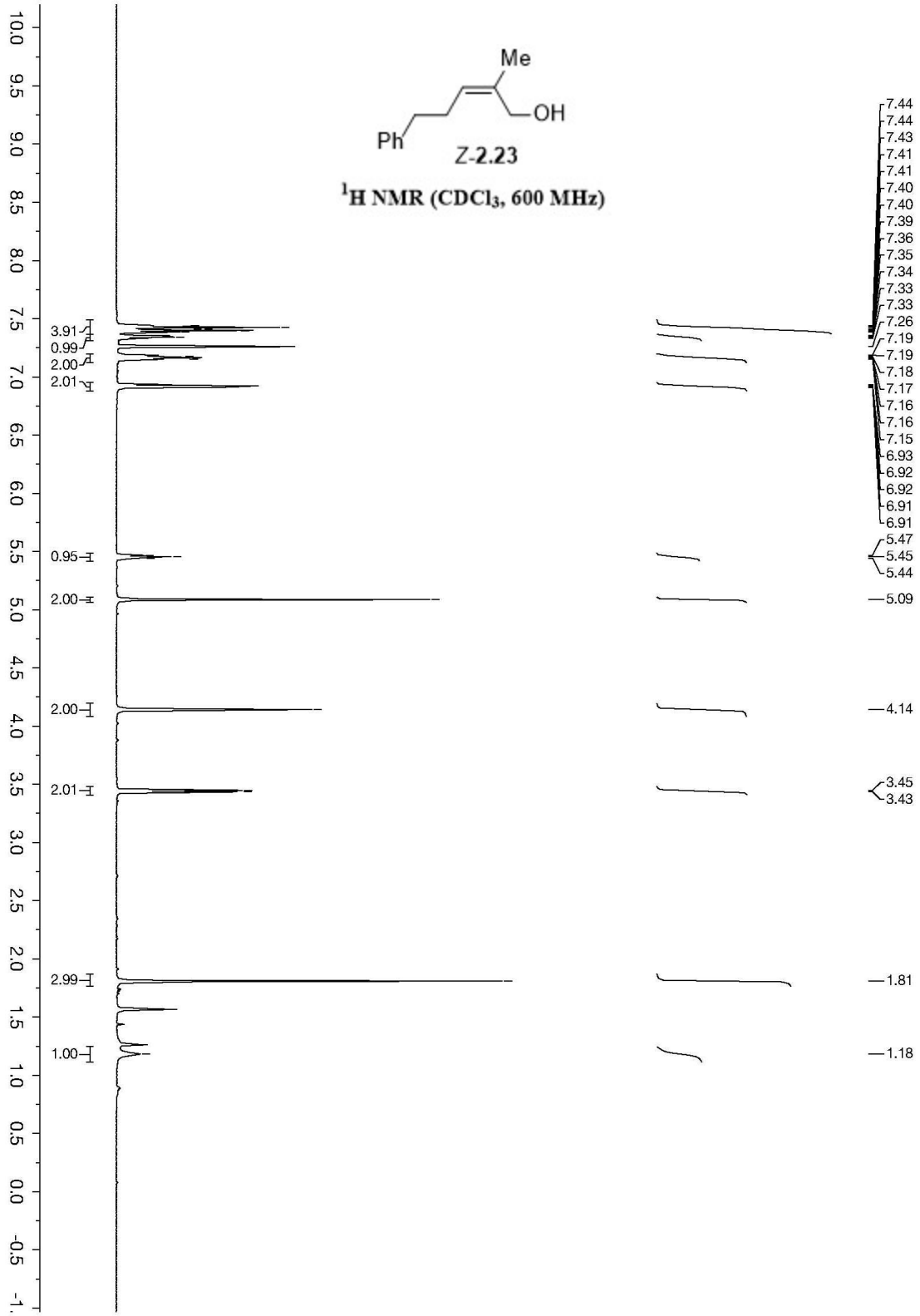


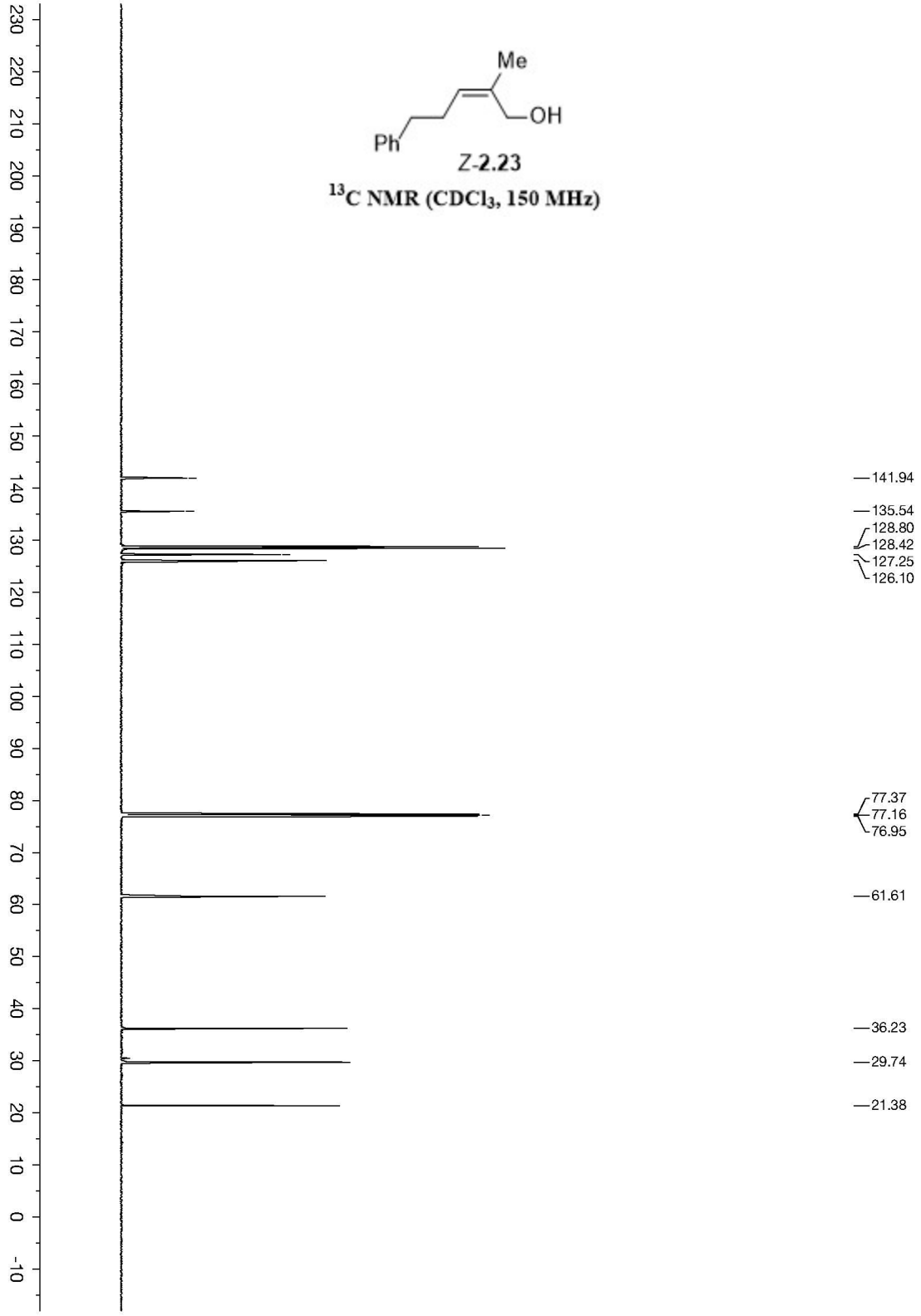
Z-2.21

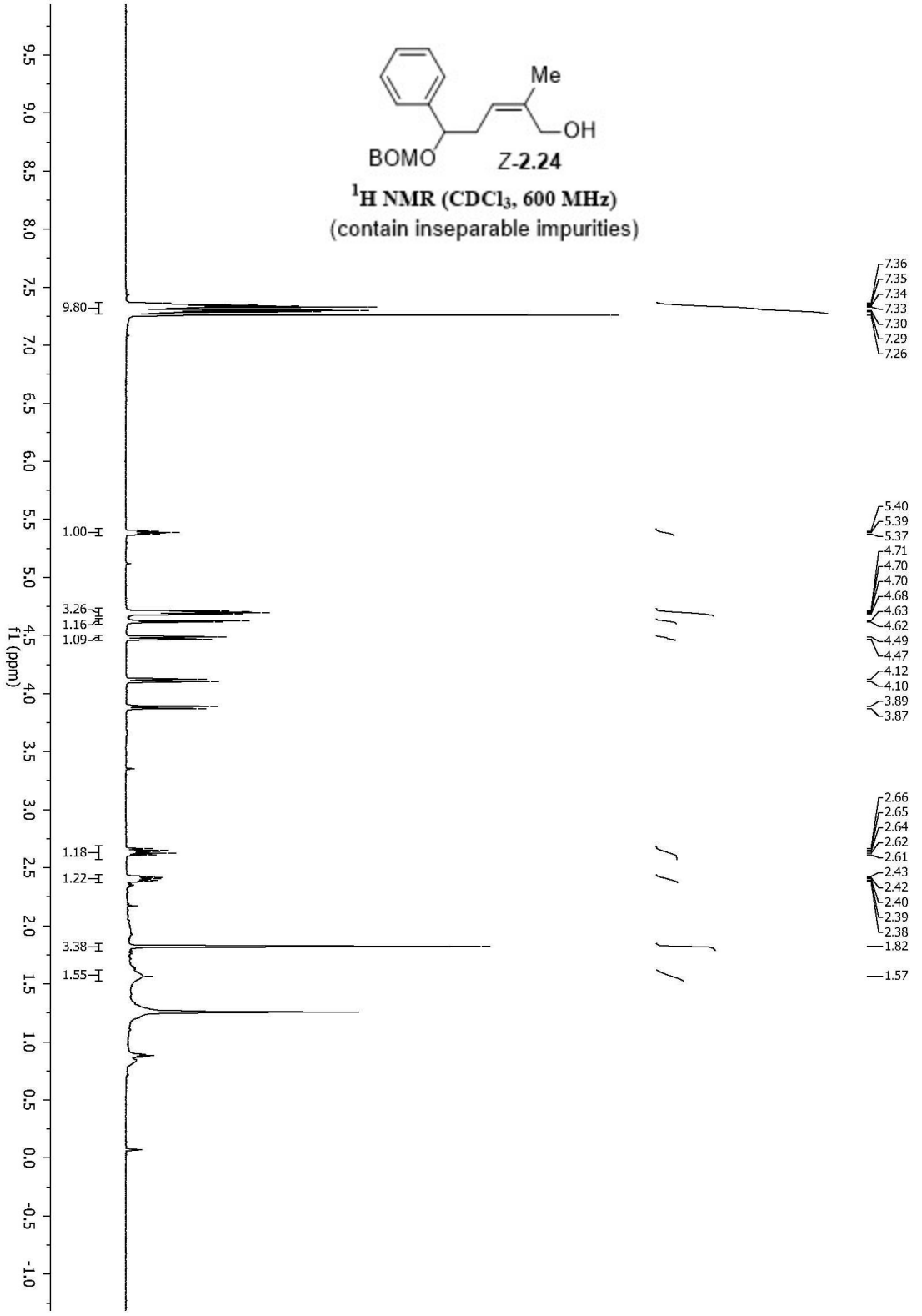
^{13}C NMR ($CDCl_3$, 150 MHz)

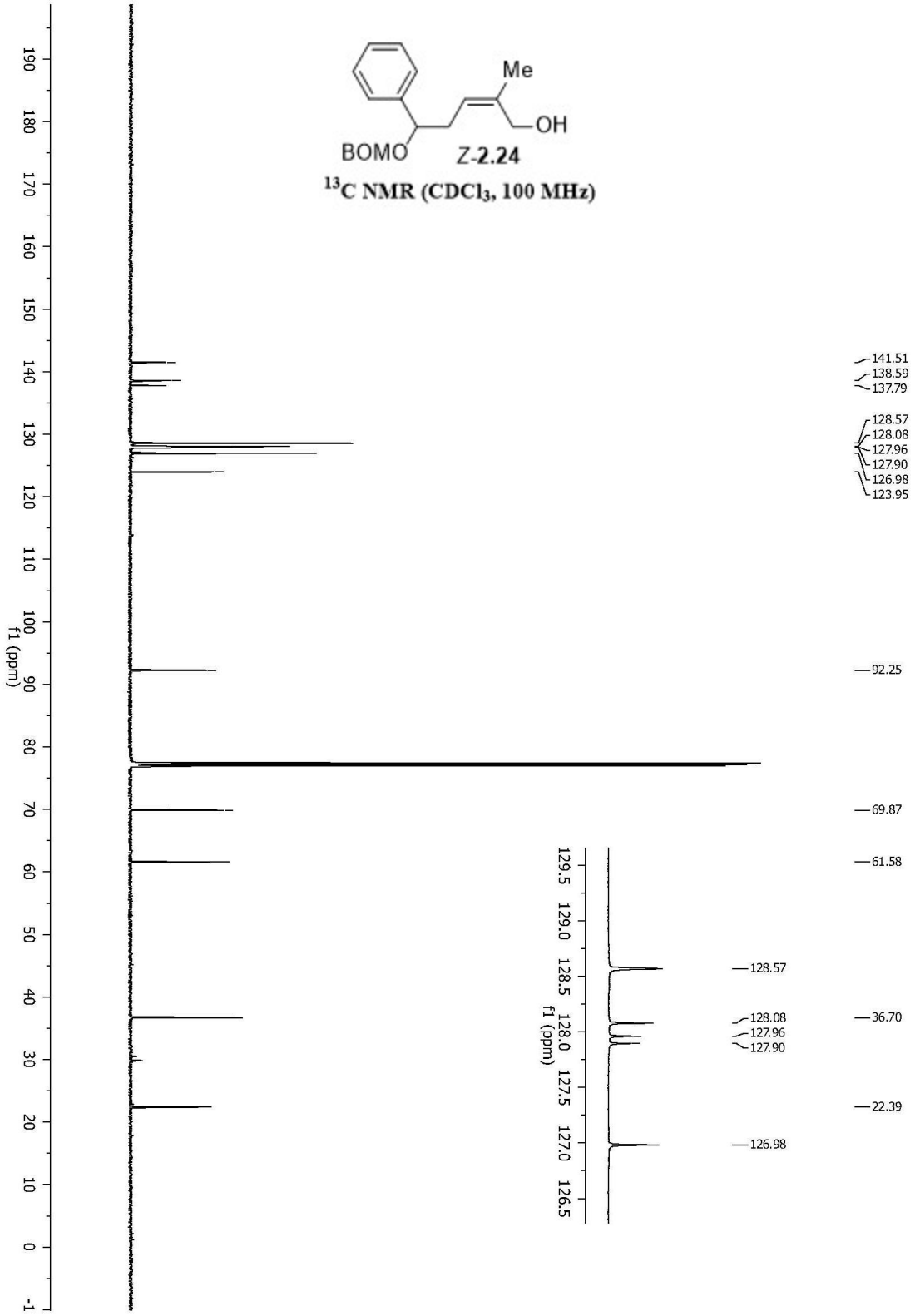

CHO
Me
OH
Z-2.22
^{1}H NMR (CDCl$_3$, 400 MHz)
f1 (ppm)
0.80
1.00
0.02
2.00
1.94
2.10
2.93
1.86
11.11
9.77
9.76
9.76
7.26
5.32
5.30
5.28
4.13
2.43
2.42
2.42
2.40
2.40
2.01
1.79
1.61
1.33
1.29
1.28
1.26
1.25

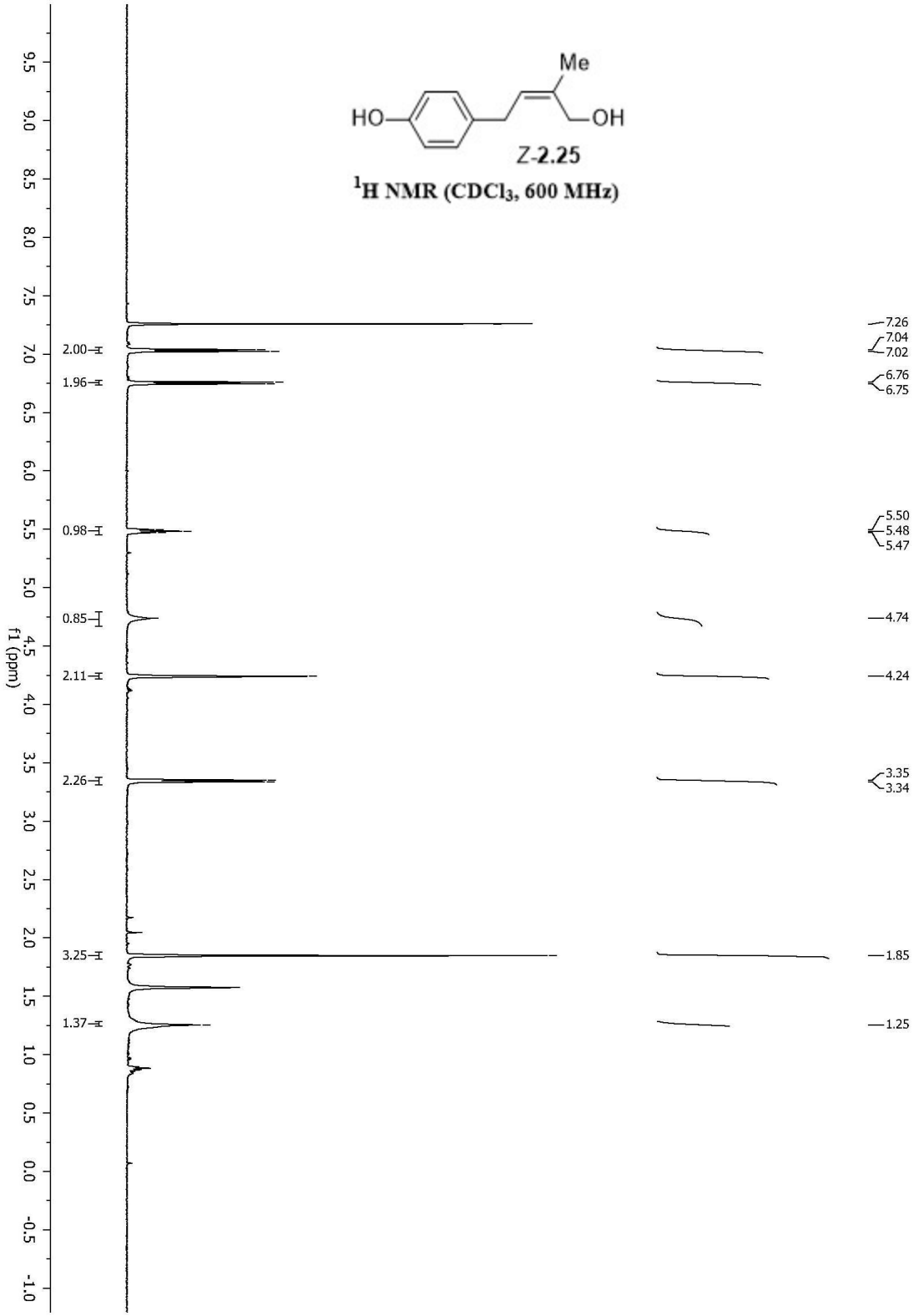

CHO
Me
OH
Z-2.22
^{13}C NMR ($CDCl_3$, 150 MHz)
f1 (ppm)
203.10
134.27
128.88
77.37
77.16
76.95
61.73
44.02
29.38
29.28
29.25
27.68
22.18
21.38

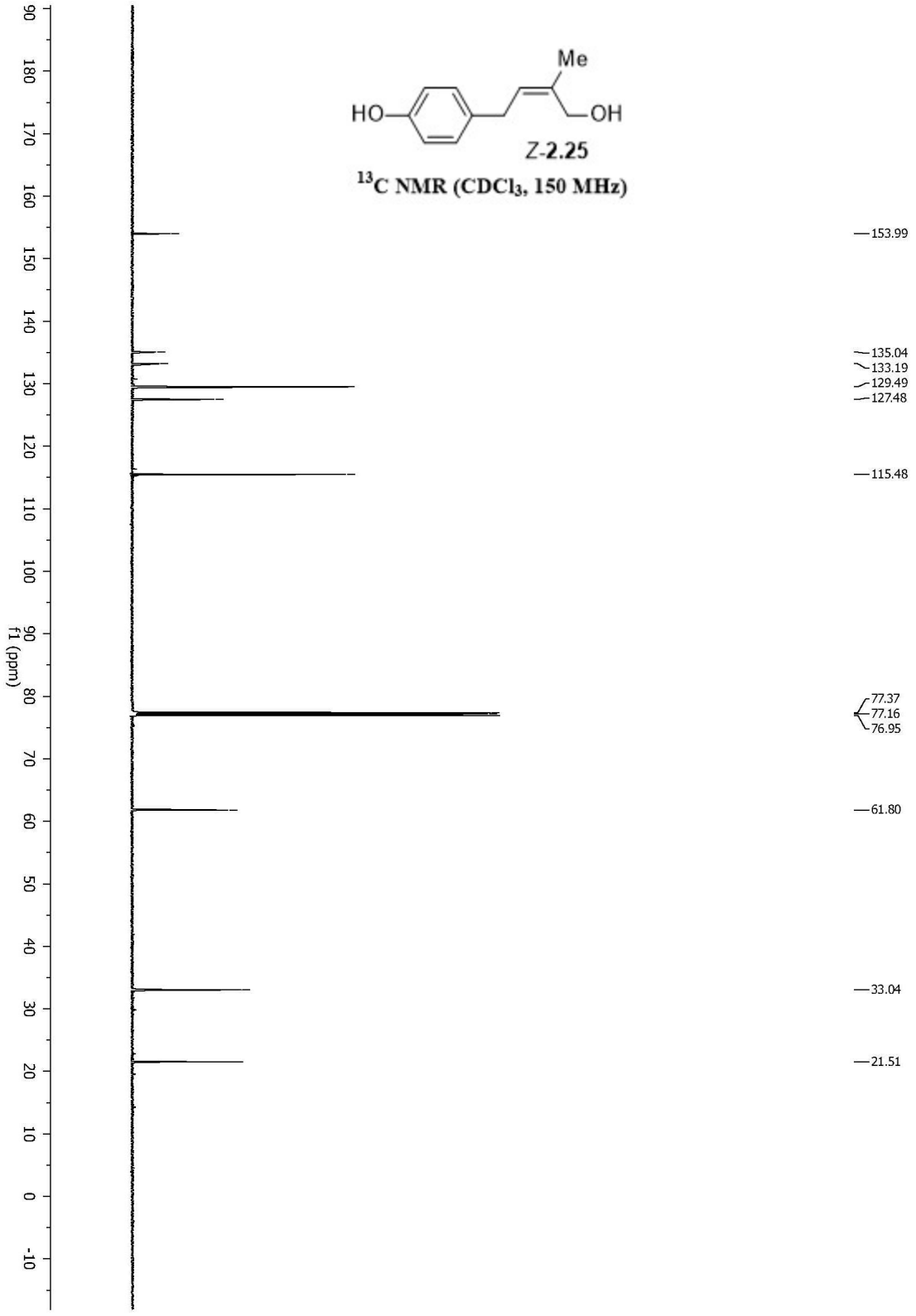

Me
OH
Ph
Z-2.23
^{1}H NMR (CDCl$_3$, 600 MHz)
7.44
7.44
7.43
7.41
7.41
7.40
7.40
7.39
7.36
7.35
7.34
7.33
7.33
7.26
7.19
7.19
7.18
7.17
7.16
7.16
7.15
6.93
6.92
6.92
6.91
6.91
5.47
5.45
5.44
5.09
4.14
3.45
3.43
1.81
1.18
3.91
0.99
2.00
2.01
0.95
2.00
2.00
2.01
2.99
1.00

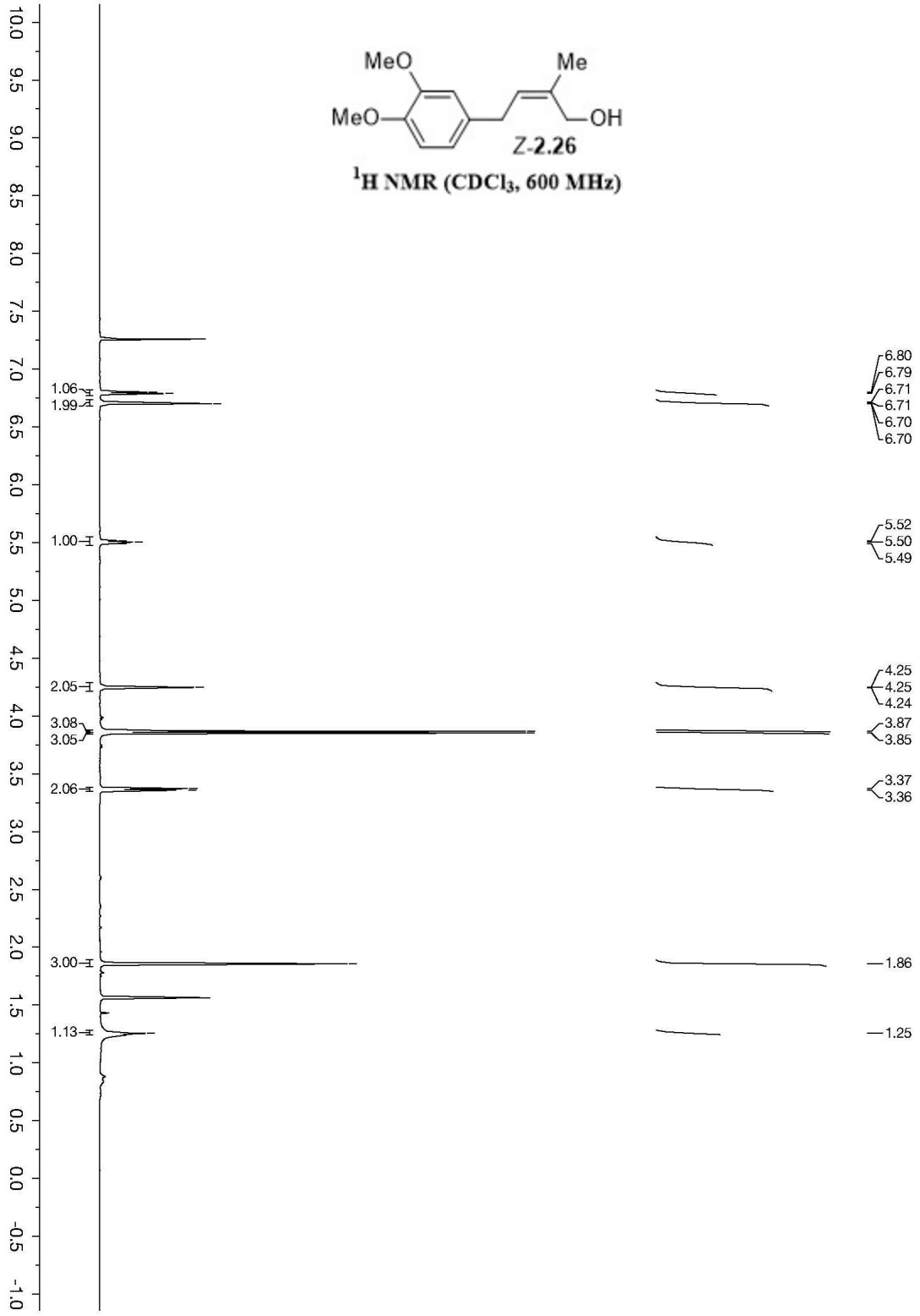

Me
OH
Ph
Z-2.23
^{13}C NMR ($CDCl_3$, 150 MHz)
141.94
135.54
128.80
128.42
127.25
126.10
77.37
77.16
76.95
61.61
36.23
29.74
21.38

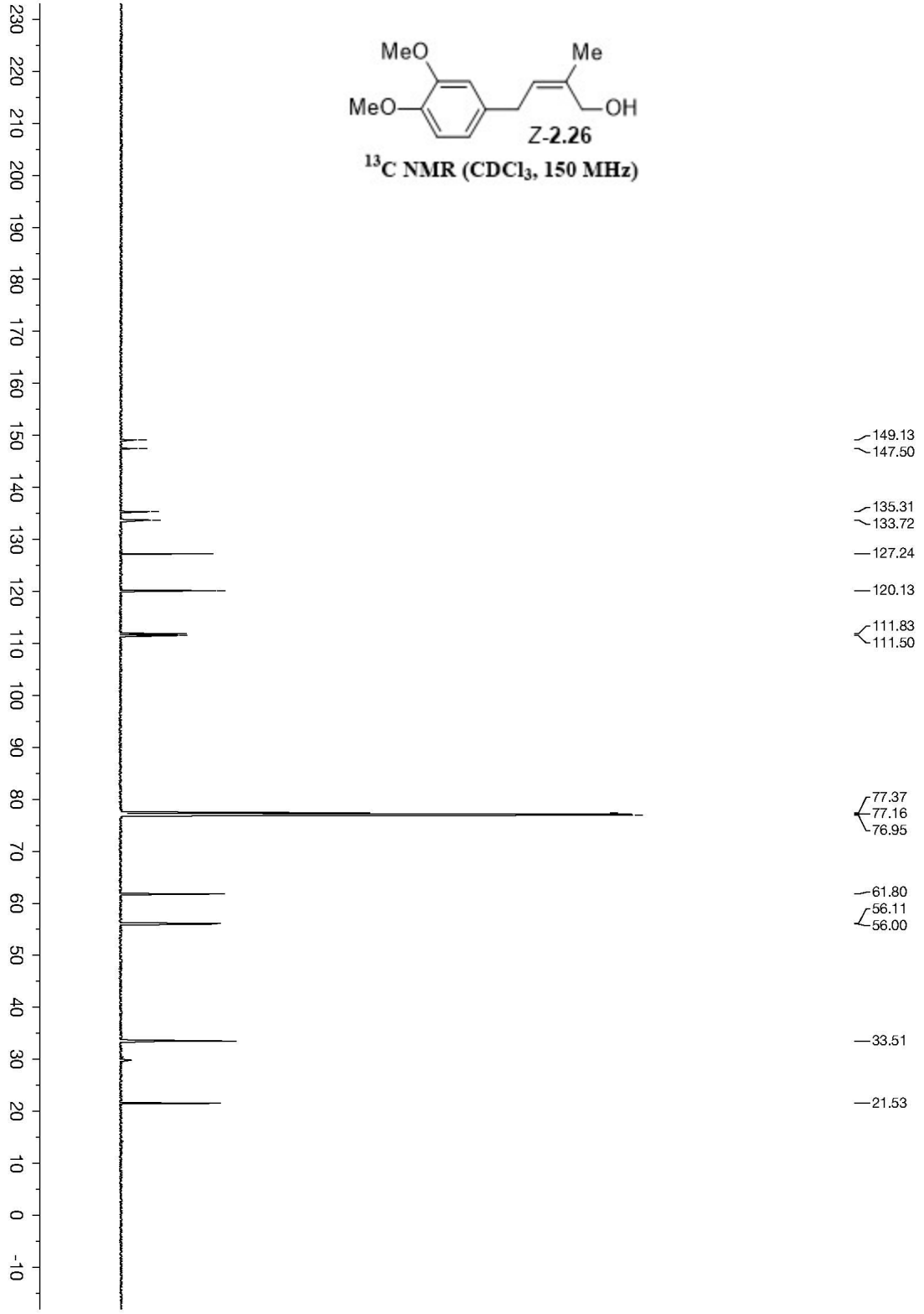

Me
OH
BOMO
Z-2.24
^{1}H NMR (CDCl$_3$, 600 MHz)
(contain inseparable impurities)
f1 (ppm)
9.80
1.00
3.26
1.16
1.09
1.18
1.22
3.38
1.55
7.36
7.35
7.34
7.33
7.30
7.29
7.26
5.40
5.39
5.37
4.71
4.70
4.70
4.68
4.63
4.62
4.49
4.47
4.12
4.10
3.89
3.87
2.66
2.65
2.64
2.62
2.61
2.43
2.42
2.40
2.39
2.38
1.82
1.57

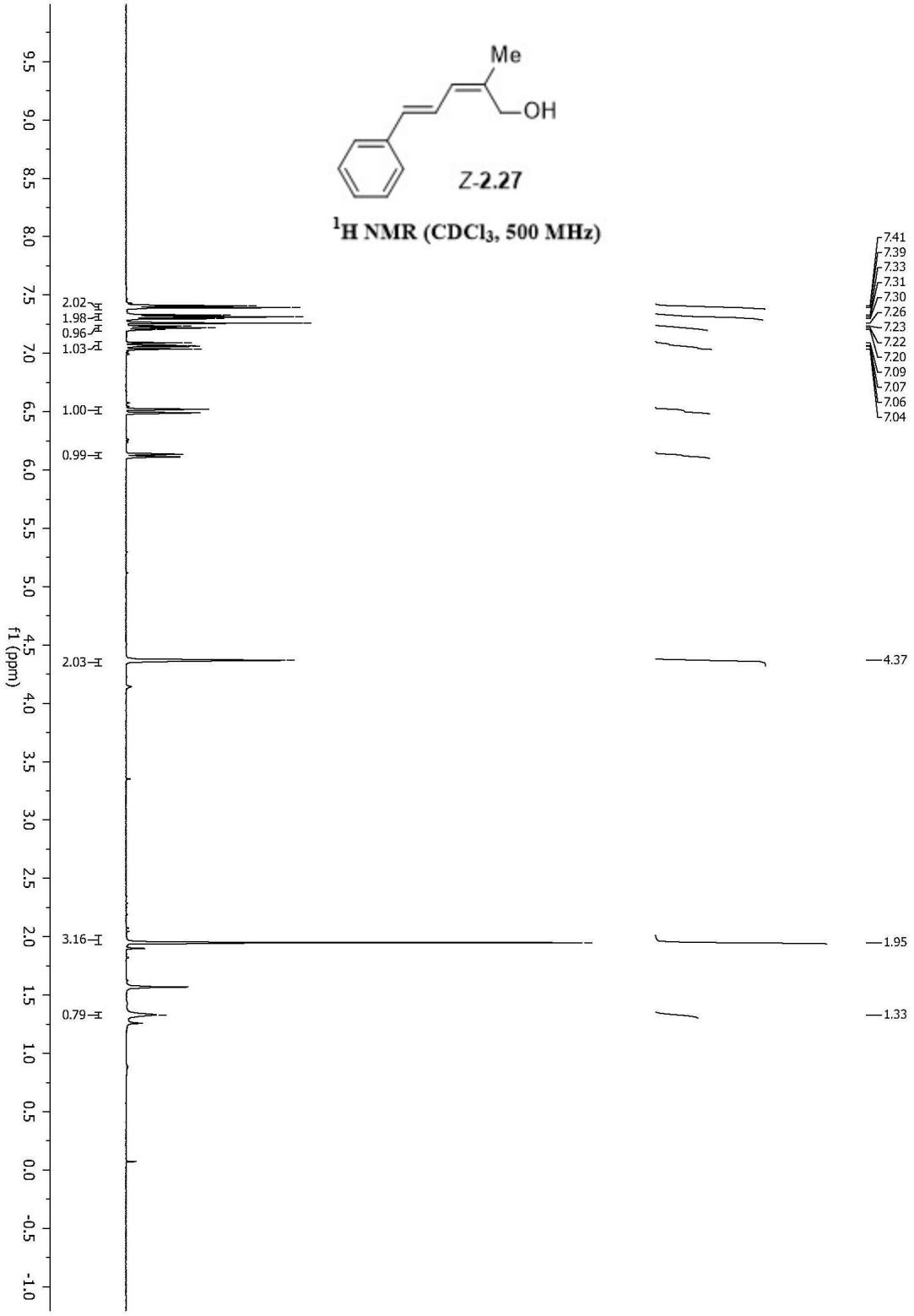

Me
OH
BOMO
Z-2.24
^{13}C NMR (CDCl$_3$, 100 MHz)
f1 (ppm)
141.51
138.59
137.79
128.57
128.08
127.96
127.90
126.98
123.95
92.25
69.87
61.58
36.70
22.39

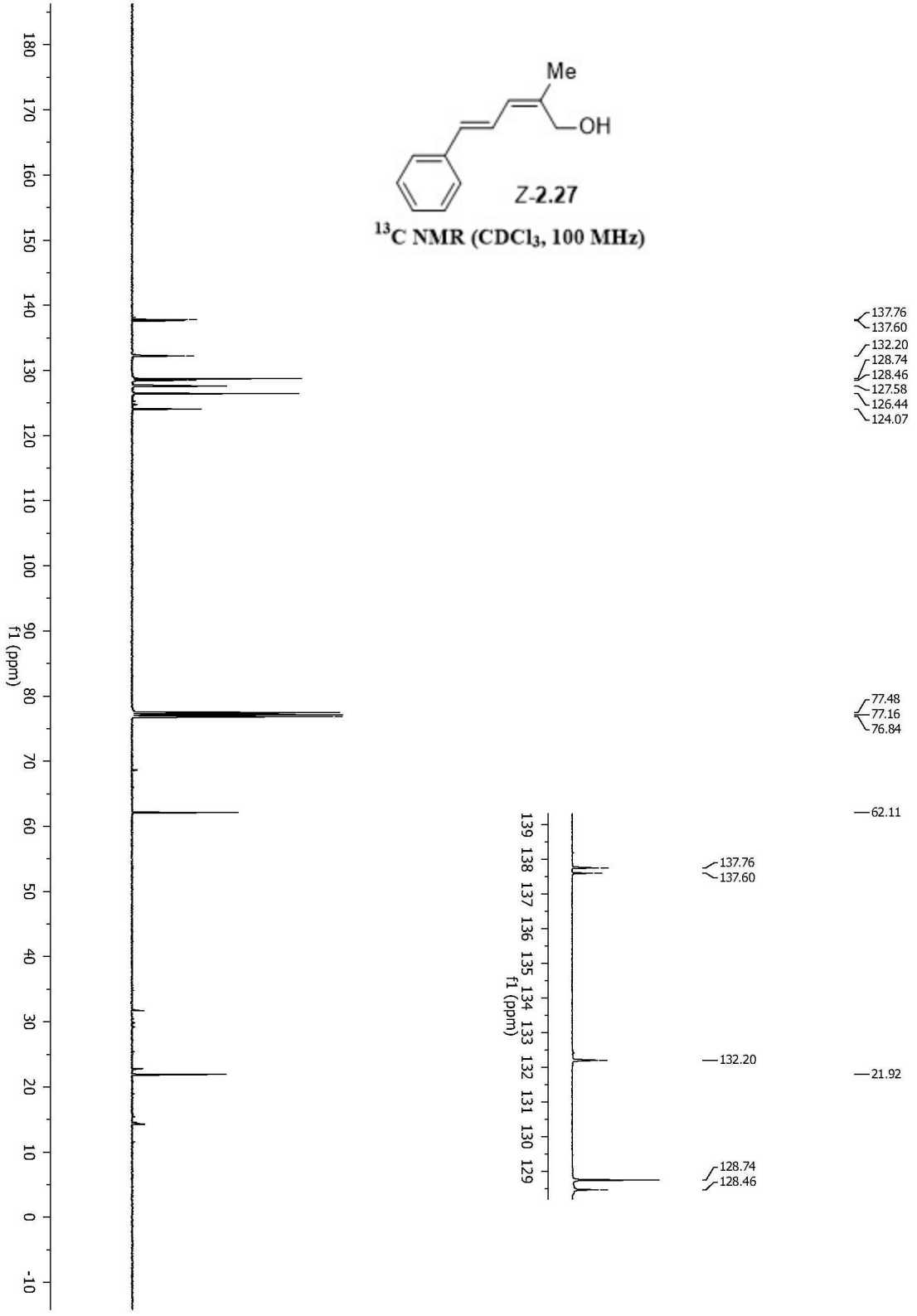

Me
HO
OH
Z-2.25
^{1}H NMR (CDCl$_3$, 600 MHz)
f1 (ppm)
2.00
1.96
0.98
0.85
2.11
2.26
3.25
1.37
7.26
7.04
7.02
6.76
6.75
5.50
5.48
5.47
4.74
4.24
3.35
3.34
1.85
1.25

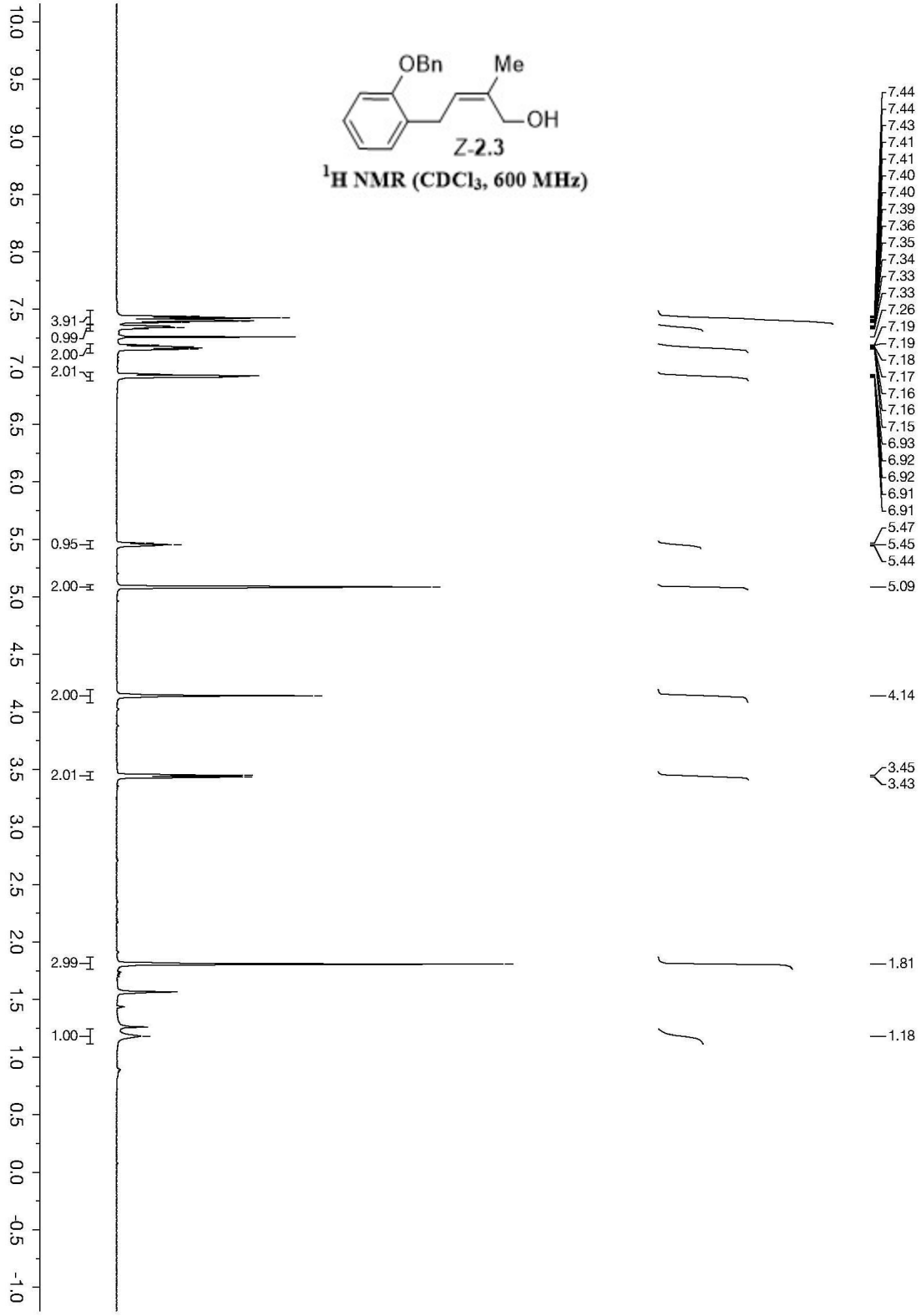

Me
HO
OH
Z-2.25
^{13}C NMR (CDCl$_3$, 150 MHz)
153.99
135.04
133.19
129.49
127.48
115.48
77.37
77.16
76.95
61.80
33.04
21.51
f1 (ppm)

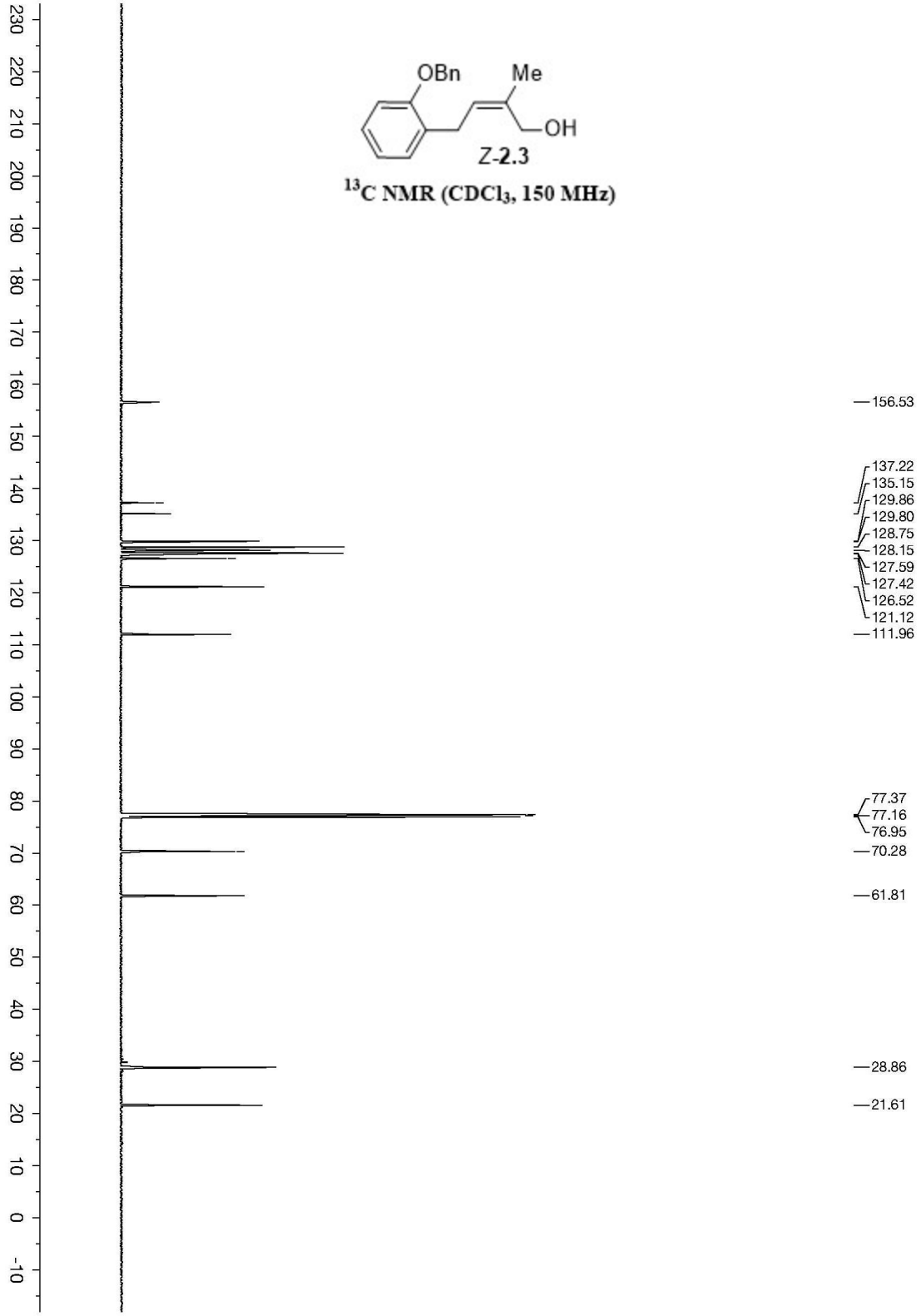

MeO
Me
MeO
OH
Z-2.26
^{1}H NMR (CDCl$_3$, 600 MHz)
1.06
1.99
1.00
2.05
3.08
3.05
2.06
3.00
1.13
6.80
6.79
6.71
6.71
6.70
6.70
5.52
5.50
5.49
4.25
4.25
4.24
3.87
3.85
3.37
3.36
1.86
1.25


MeO
Me
MeO
OH
Z-2.26
^{13}C NMR (CDCl$_3$, 150 MHz)
149.13
147.50
135.31
133.72
127.24
120.13
111.83
111.50
77.37
77.16
76.95
61.80
56.11
56.00
33.51
21.53

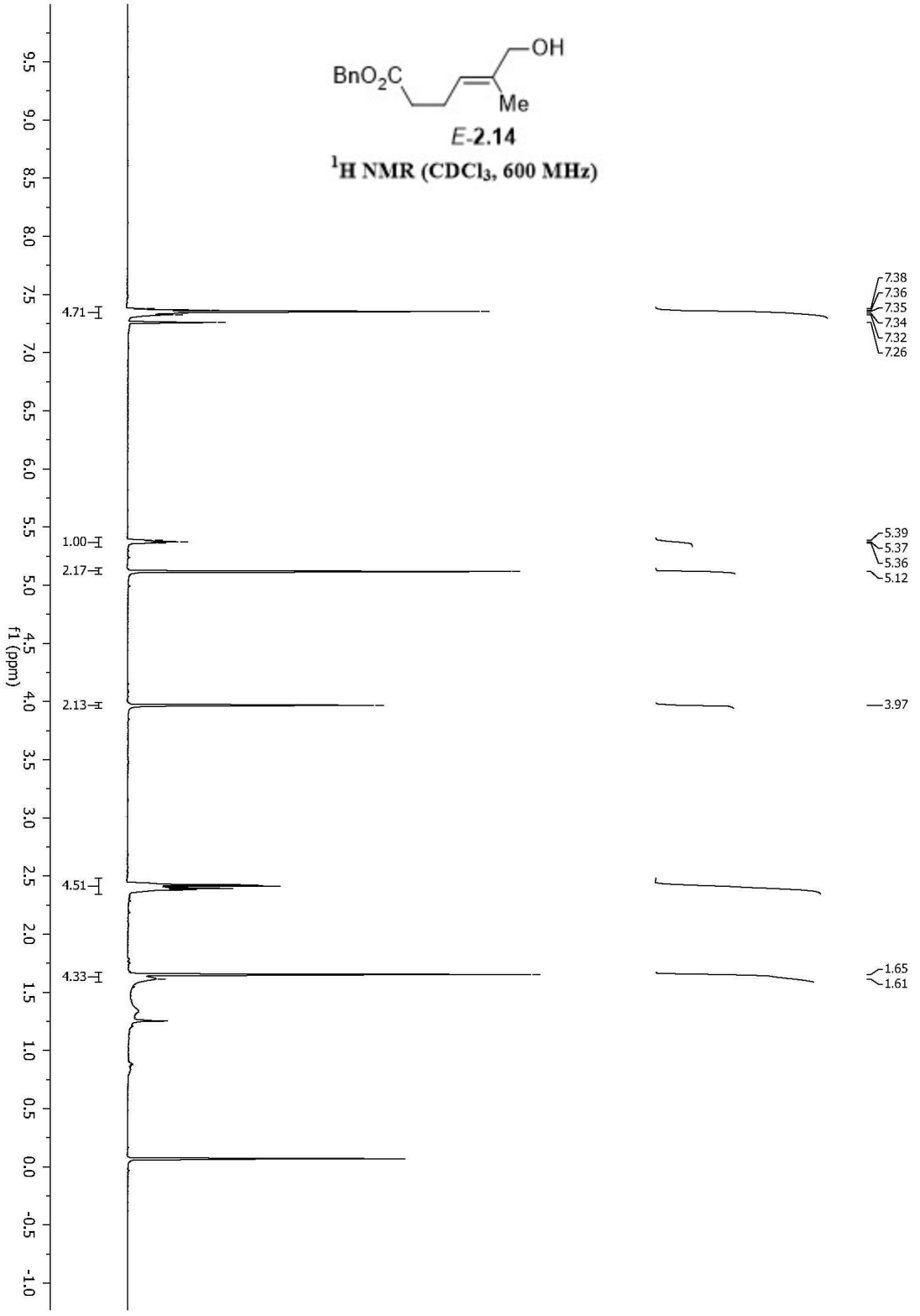

Me
OH
Z-2.27
^{1}H NMR (CDCl$_3$, 500 MHz)
2.02
1.98
0.96
1.03
1.00
0.99
2.03
3.16
0.79
7.41
7.39
7.33
7.31
7.30
7.26
7.23
7.22
7.20
7.09
7.07
7.06
7.04
4.37
1.95
1.33
f1 (ppm)

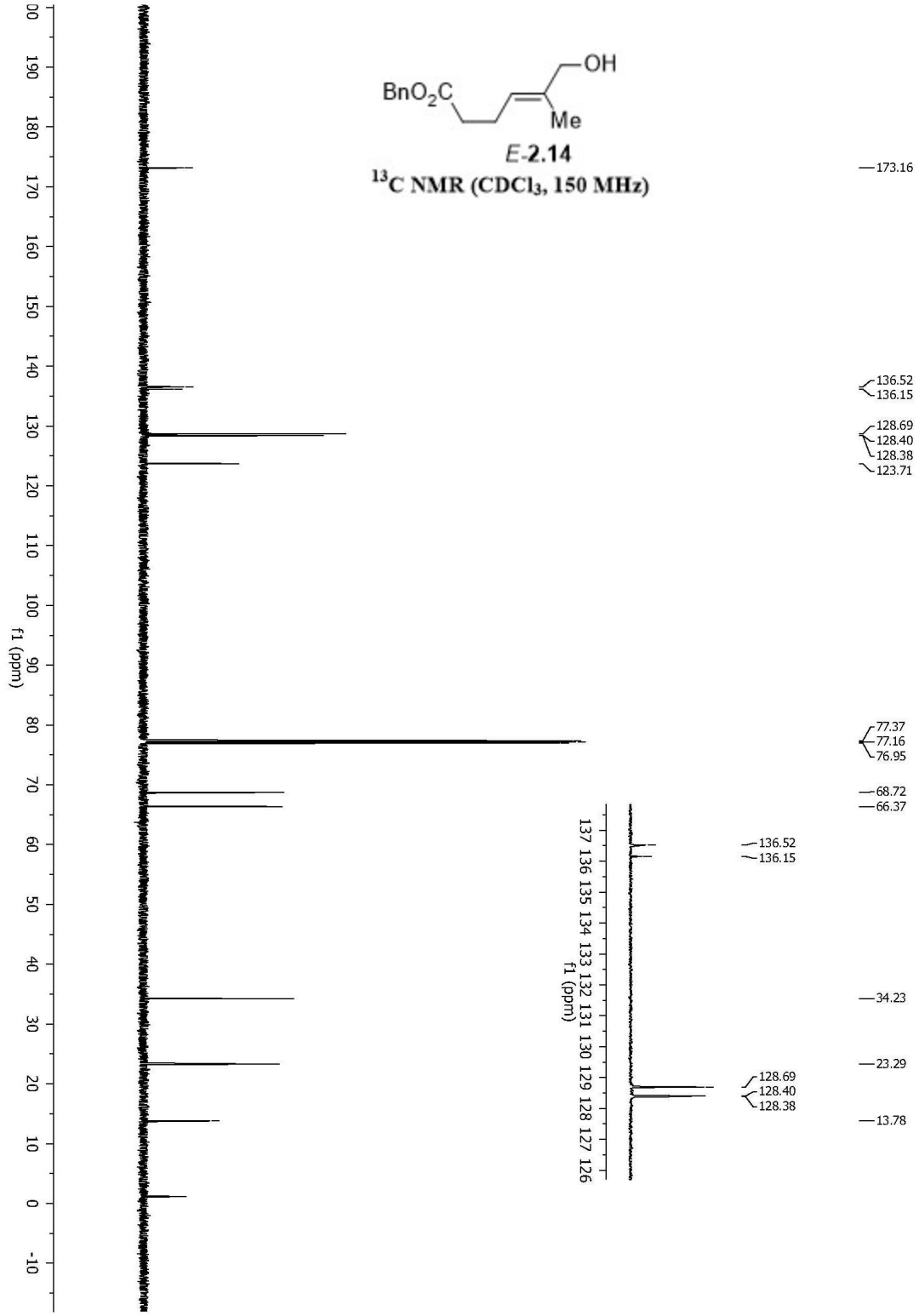

Me
OH
Z-2.27
^{13}C NMR ($CDCl_3$, 100 MHz)
f1 (ppm)
137.76
137.60
132.20
128.74
128.46
127.58
126.44
124.07
77.48
77.16
76.84
62.11
21.92

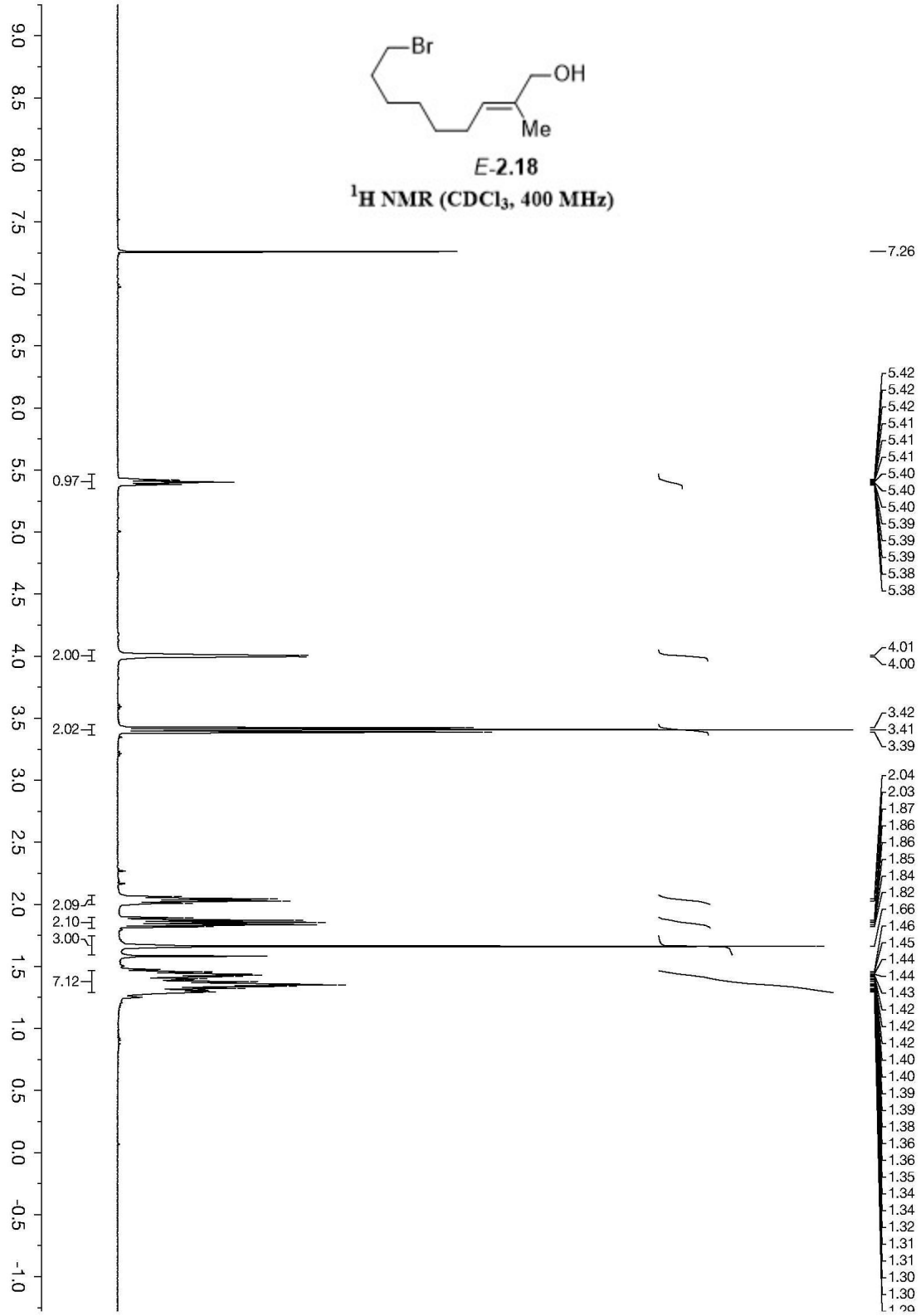

OBn
Me
OH
Z-2.3
^{1}H NMR (CDCl$_3$, 600 MHz)
7.44
7.44
7.43
7.41
7.41
7.40
7.40
7.39
7.36
7.35
7.34
7.33
7.33
7.26
7.19
7.19
7.18
7.17
7.16
7.16
7.15
6.93
6.92
6.92
6.91
6.91
5.47
5.45
5.44
5.09
4.14
3.45
3.43
1.81
1.18
3.91
0.99
2.00
2.01
0.95
2.00
2.00
2.01
2.99
1.00

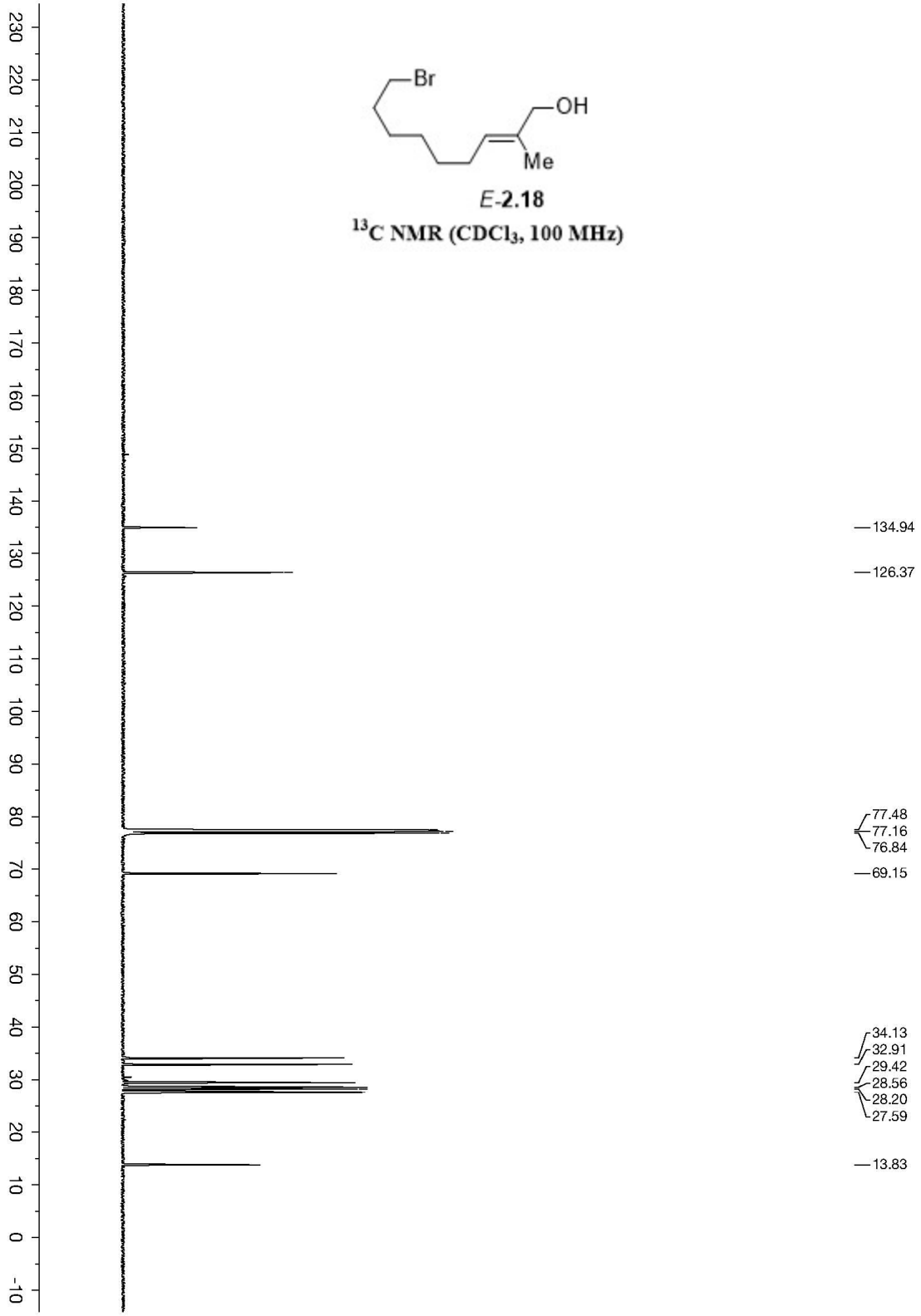


^{13}C NMR ($CDCl_3$, 150 MHz)


OH
BnO2C
Me
E-2.14
1H NMR (CDCl3, 600 MHz)
f1 (ppm)
4.71
1.00
2.17
2.13
4.51
4.33
7.38
7.36
7.35
7.34
7.32
7.26
5.39
5.37
5.36
5.12
3.97
1.65
1.61

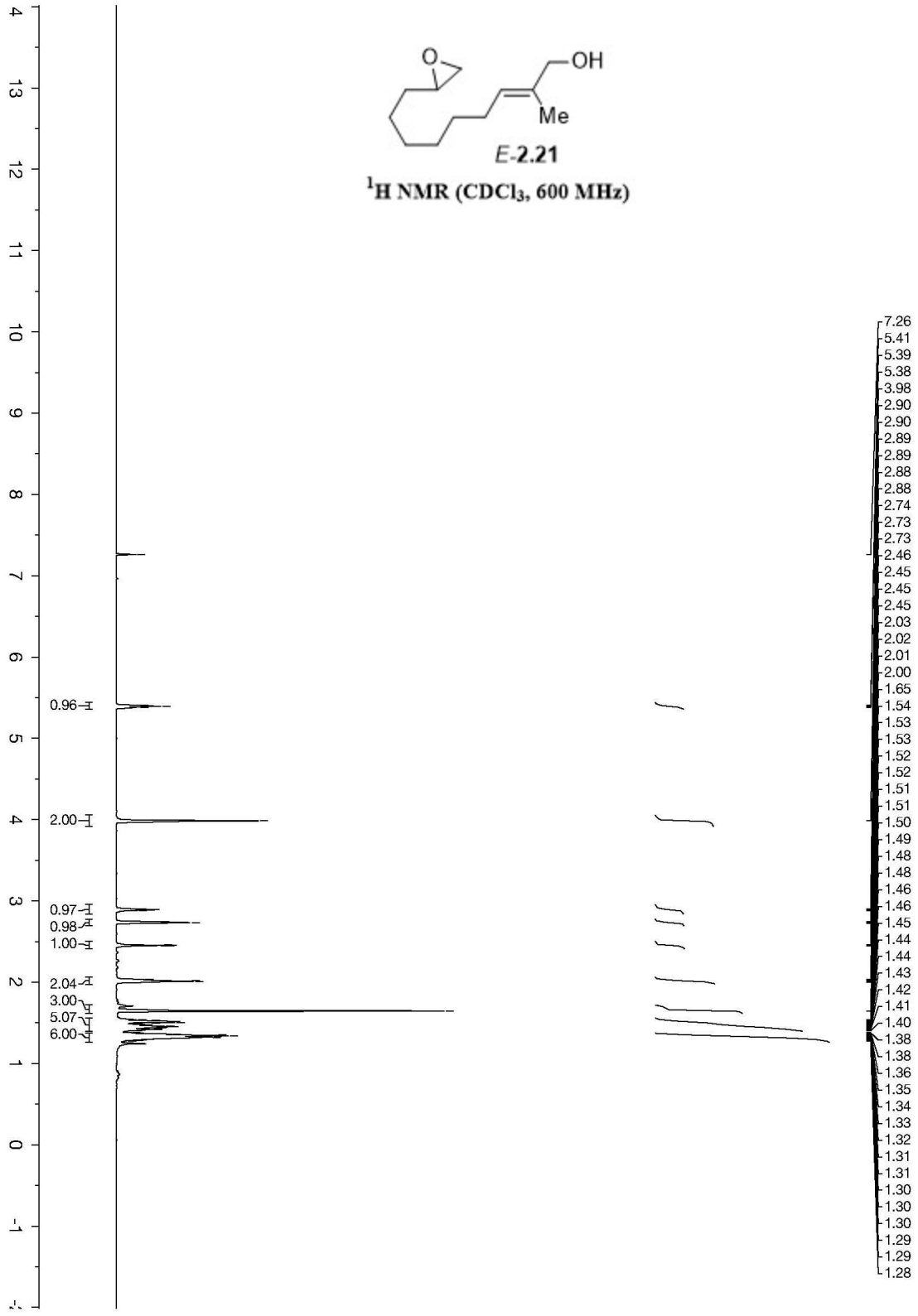

OH
BnO2C
Me
E-2.14
13C NMR (CDCl3, 150 MHz)
173.16
136.52
136.15
128.69
128.40
128.38
123.71
77.37
77.16
76.95
68.72
66.37
34.23
23.29
13.78
f1 (ppm)

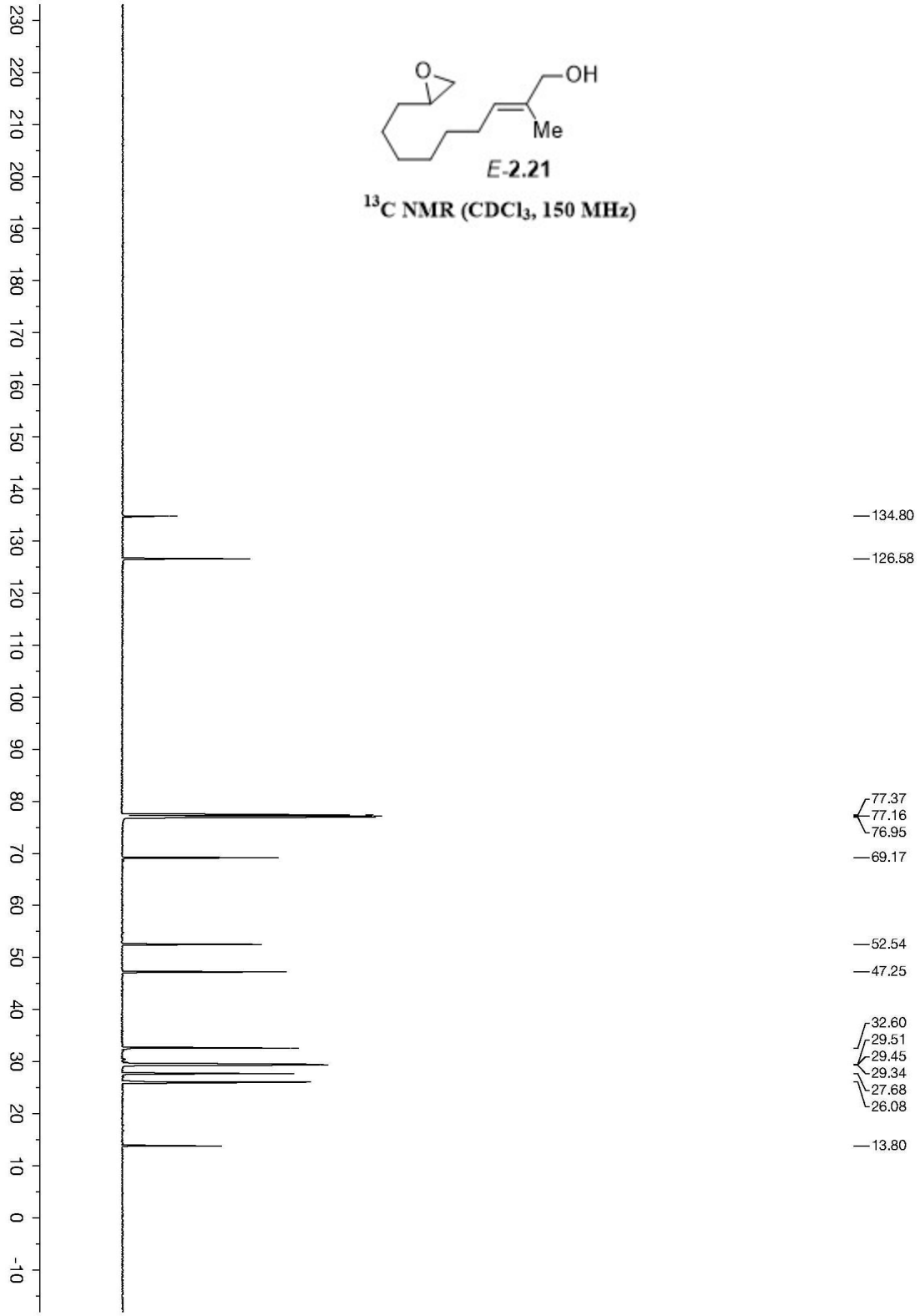

Br
OH
Me
E-2.18
1H NMR (CDCl3, 400 MHz)
7.26
5.42
5.42
5.42
5.41
5.41
5.41
5.40
5.40
5.40
5.39
5.39
5.39
5.38
5.38
4.01
4.00
3.42
3.41
3.39
2.04
2.03
1.87
1.86
1.86
1.85
1.84
1.82
1.66
1.46
1.45
1.44
1.44
1.43
1.42
1.42
1.42
1.40
1.40
1.39
1.39
1.38
1.36
1.36
1.35
1.34
1.34
1.32
1.31
1.31
1.30
1.30
0.97
2.00
2.02
2.09
2.10
3.00
7.12

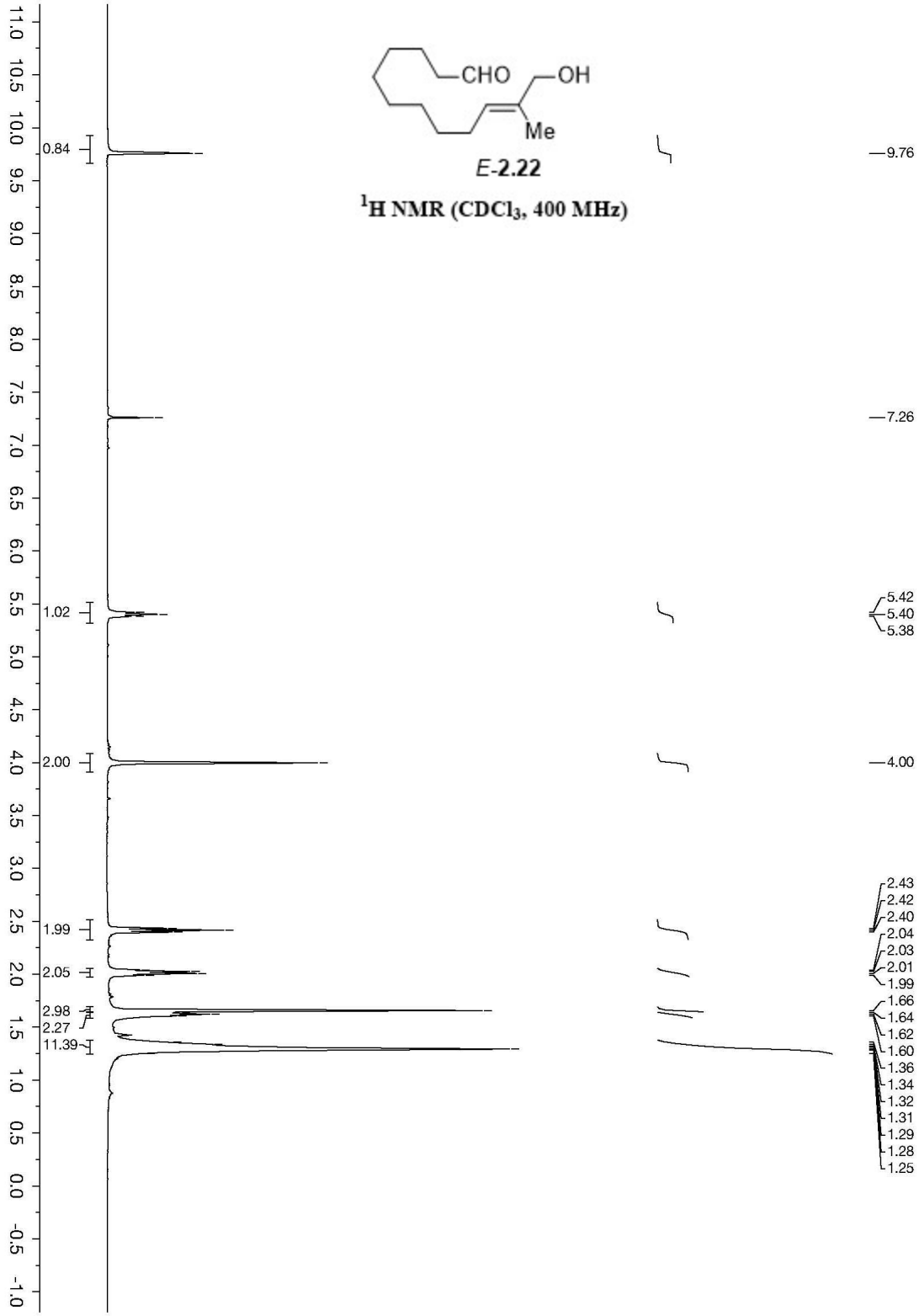


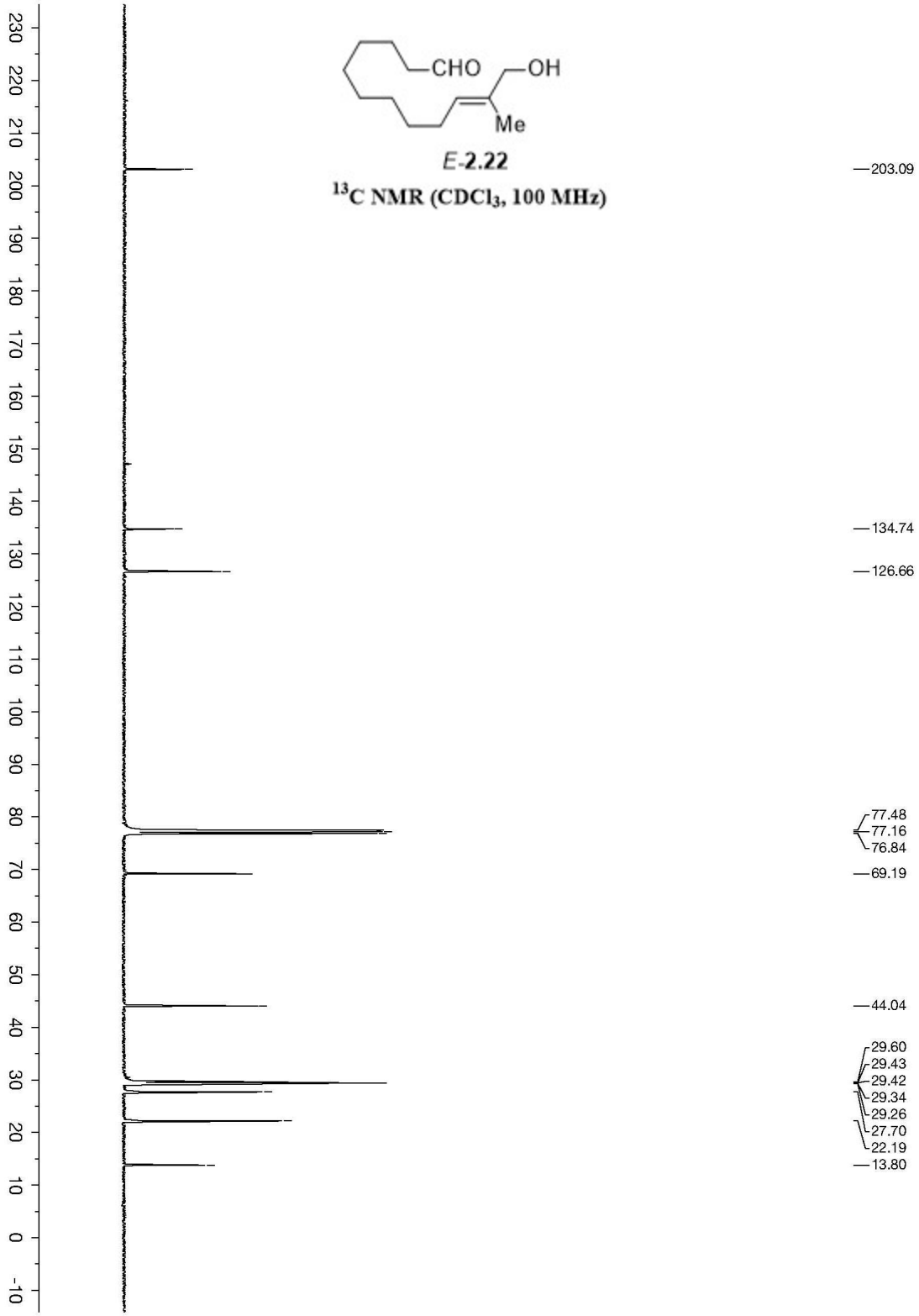
E-**2.18**

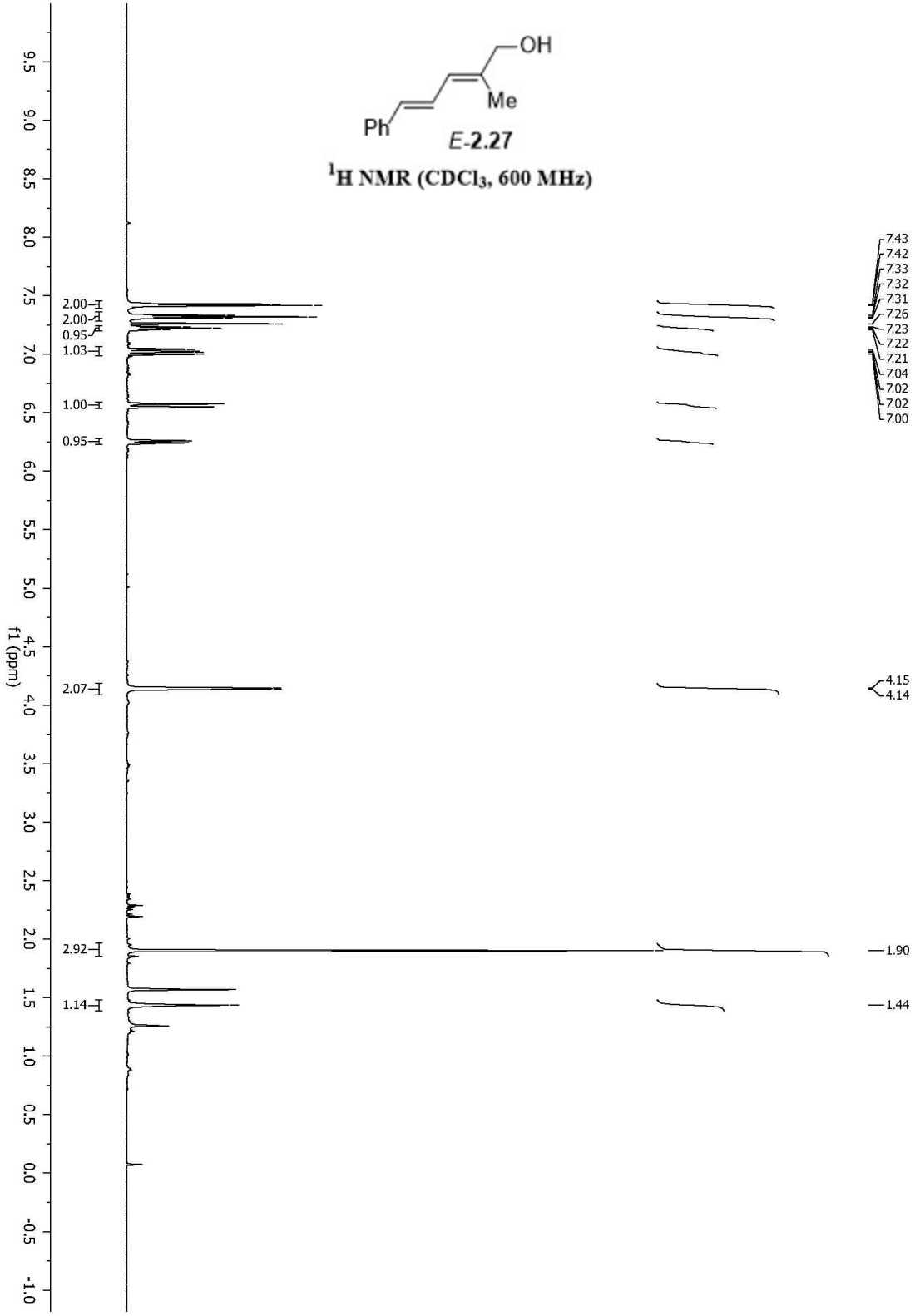
^{13}C NMR ($CDCl_3$, 100 MHz)

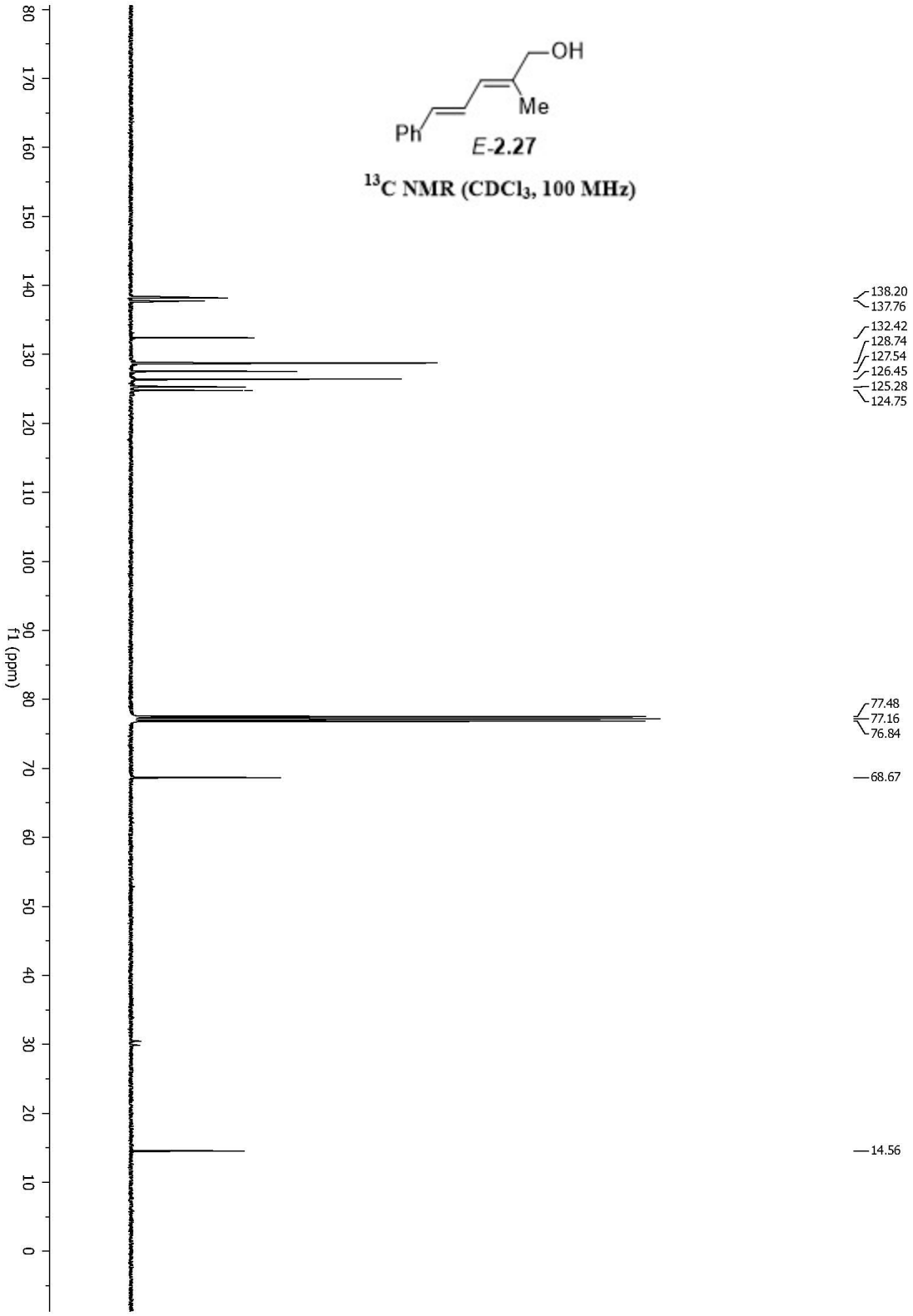

O
OH
Me
E-2.21
¹H NMR (CDCl₃, 600 MHz)
0.96
2.00
0.97
0.98
1.00
2.04
3.00
5.07
6.00
7.26
5.41
5.39
5.38
3.98
2.90
2.90
2.89
2.89
2.88
2.88
2.74
2.73
2.73
2.46
2.45
2.45
2.45
2.03
2.02
2.01
2.00
1.65
1.54
1.53
1.53
1.52
1.52
1.51
1.51
1.50
1.49
1.48
1.48
1.46
1.46
1.45
1.44
1.44
1.43
1.42
1.41
1.40
1.38
1.38
1.36
1.35
1.34
1.33
1.32
1.31
1.31
1.30
1.30
1.30
1.29
1.29
1.28

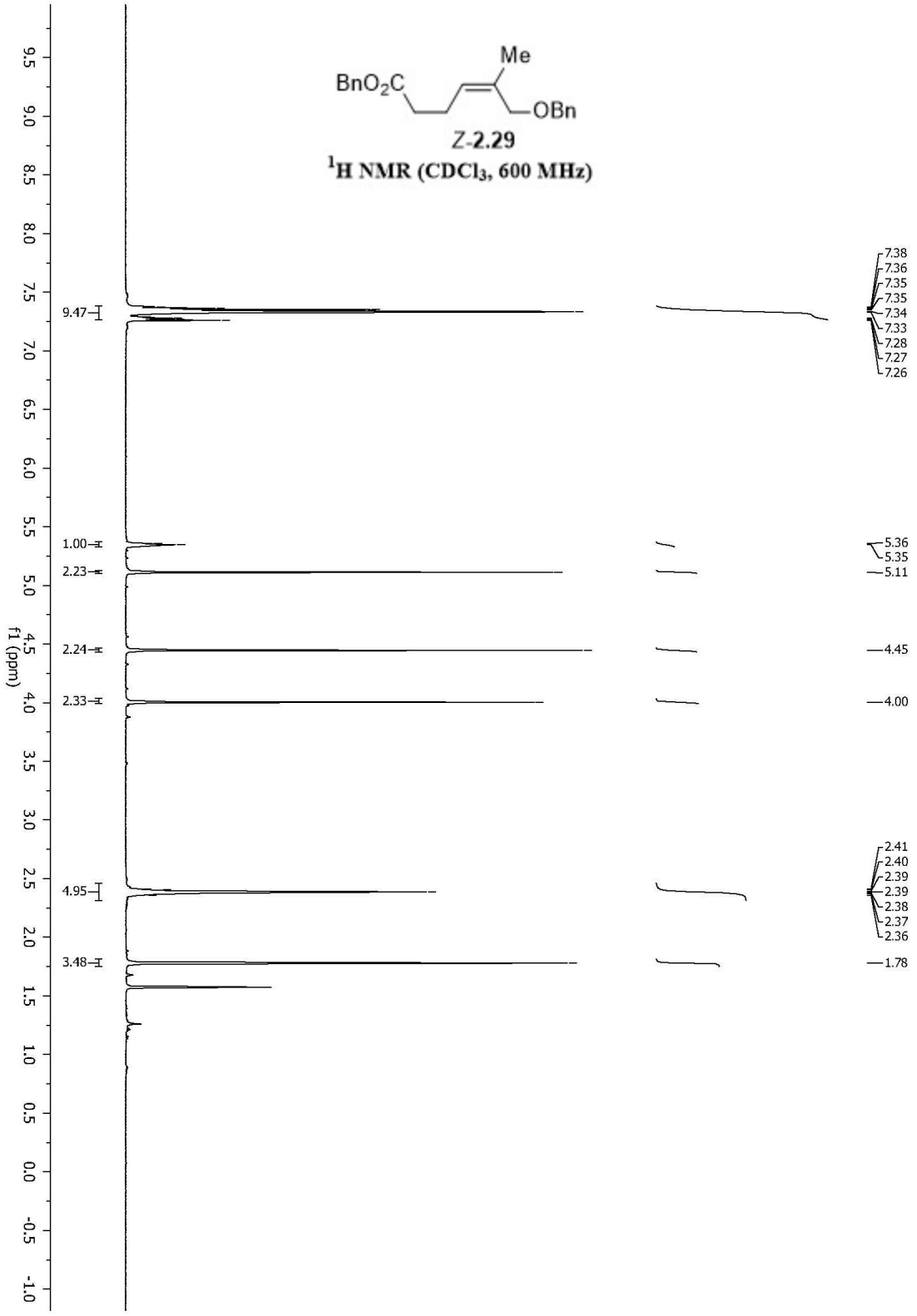

O
OH
Me
E-2.21
13C NMR (CDCl3, 150 MHz)
134.80
126.58
77.37
77.16
76.95
69.17
52.54
47.25
32.60
29.51
29.45
29.34
27.68
26.08
13.80

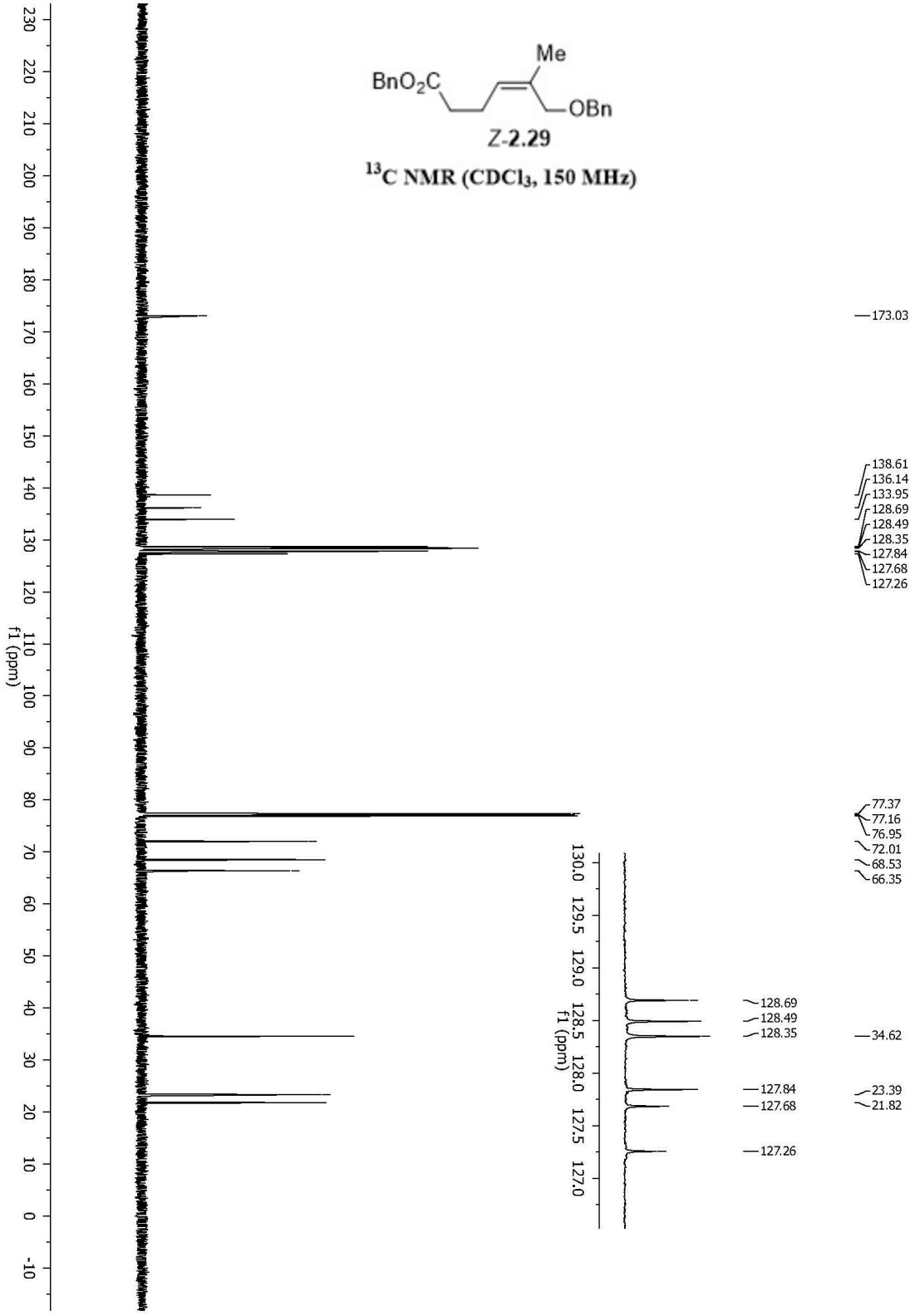

CHO
OH
Me
E-2.22
¹H NMR (CDCl₃, 400 MHz)
0.84
1.02
2.00
1.99
2.05
2.98
2.27
11.39
9.76
7.26
5.42
5.40
5.38
4.00
2.43
2.42
2.40
2.04
2.03
2.01
1.99
1.66
1.64
1.62
1.60
1.36
1.34
1.32
1.31
1.29
1.28
1.25

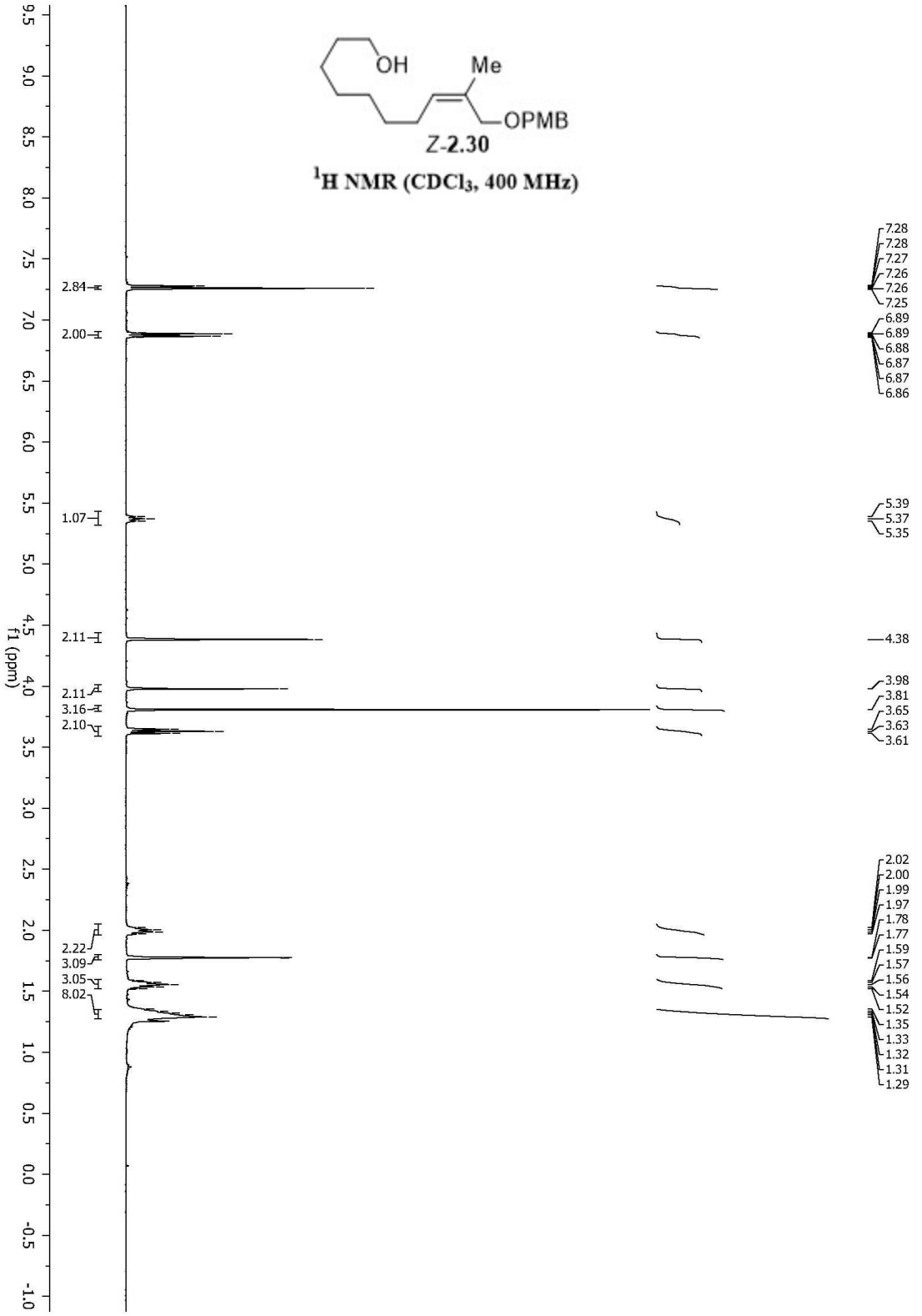

CHO
OH
Me
E-2.22
13C NMR (CDCl3, 100 MHz)
203.09
134.74
126.66
77.48
77.16
76.84
69.19
44.04
29.60
29.43
29.42
29.34
29.26
27.70
22.19
13.80

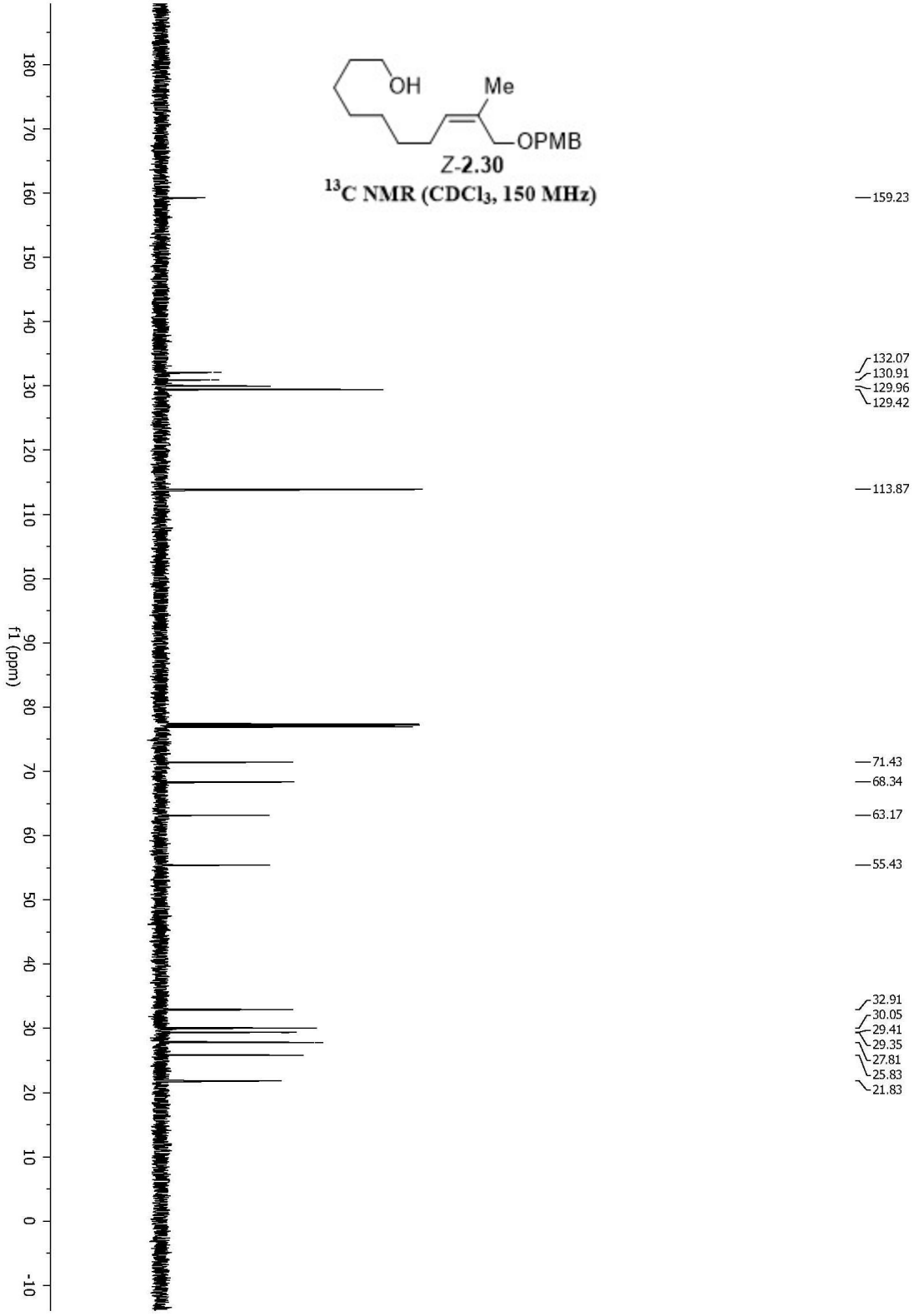

OH
Me
Ph
E-2.27
1H NMR (CDCl3, 600 MHz)
f1 (ppm)
2.00
2.00
0.95
1.03
1.00
0.95
2.07
2.92
1.14
7.43
7.42
7.33
7.32
7.31
7.26
7.23
7.22
7.21
7.04
7.02
7.02
7.00
4.15
4.14
1.90
1.44

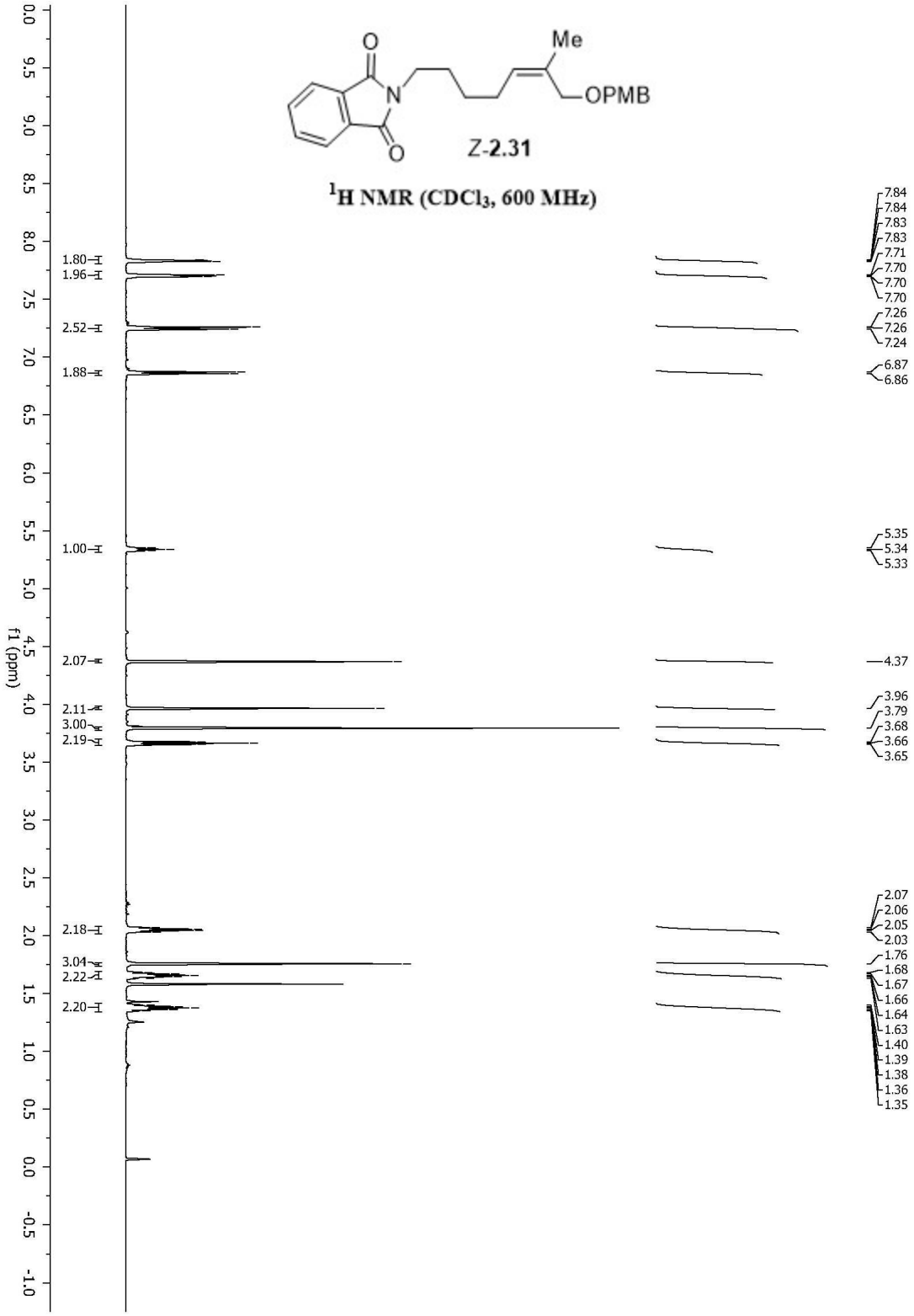

OH
Me
Ph
E-2.27
13C NMR (CDCl3, 100 MHz)
f1 (ppm)
138.20
137.76
132.42
128.74
127.54
126.45
125.28
124.75
77.48
77.16
76.84
68.67
14.56

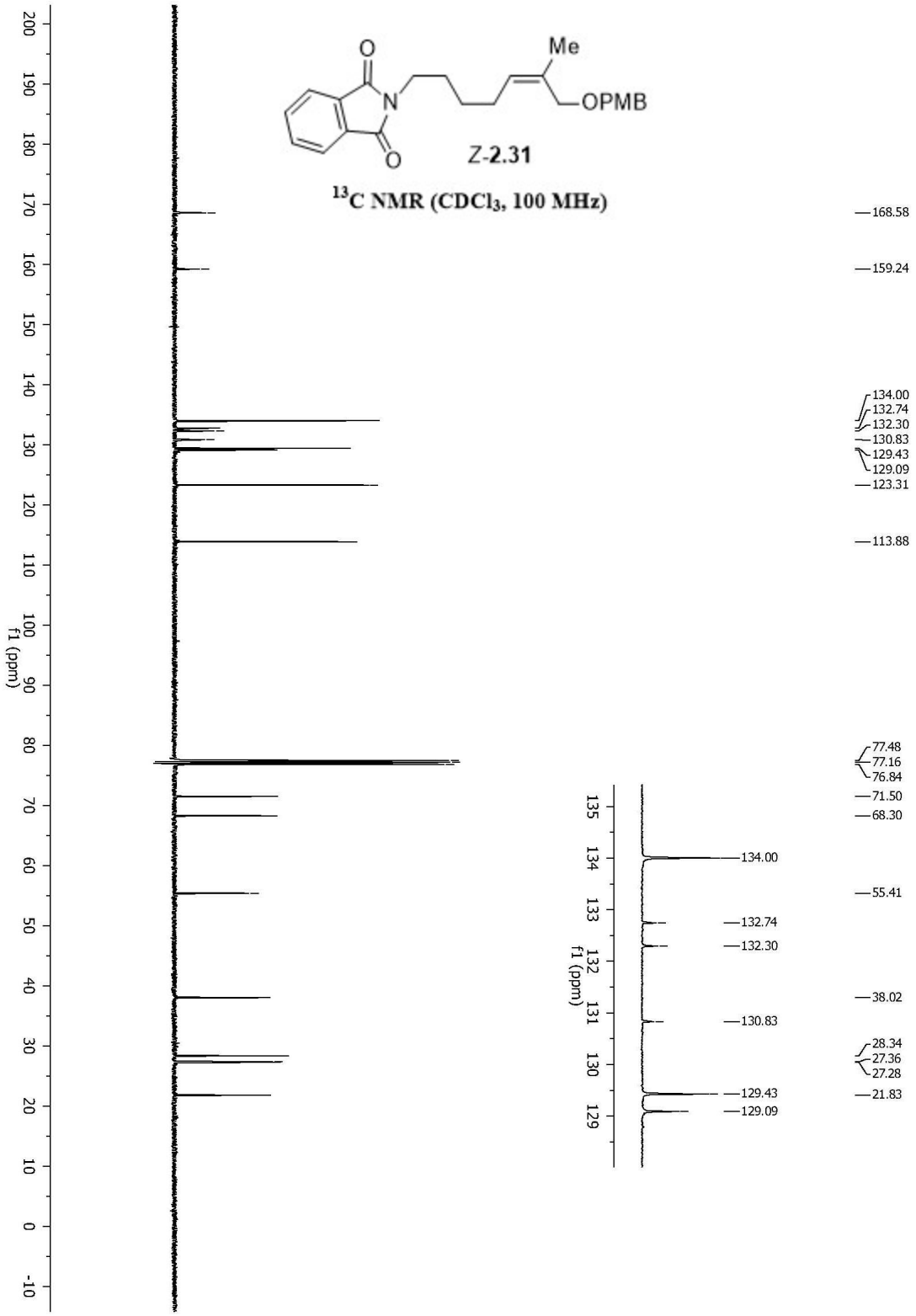

Me
BnO2C
OBn
Z-2.29
1H NMR (CDCl3, 600 MHz)
f1 (ppm)
9.47
1.00
2.23
2.24
2.33
4.95
3.48
7.38
7.36
7.35
7.35
7.34
7.33
7.28
7.27
7.26
5.36
5.35
5.11
4.45
4.00
2.41
2.40
2.39
2.39
2.38
2.37
2.36
1.78

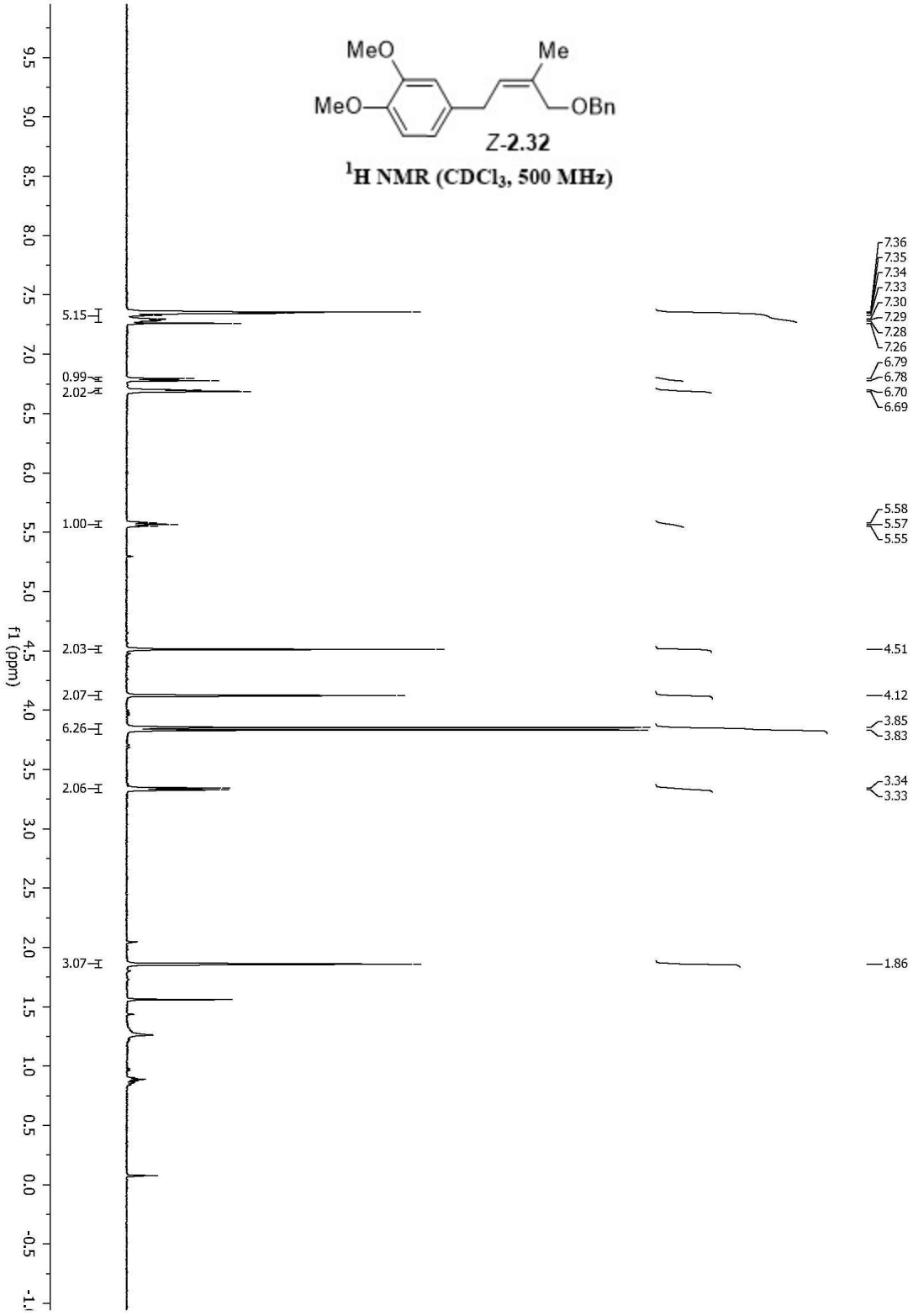

Me
BnO2C
OBn
Z-2.29
13C NMR (CDCl3, 150 MHz)
f1 (ppm)
173.03
138.61
136.14
133.95
128.69
128.49
128.35
127.84
127.68
127.26
77.37
77.16
76.95
72.01
68.53
66.35
34.62
23.39
21.82

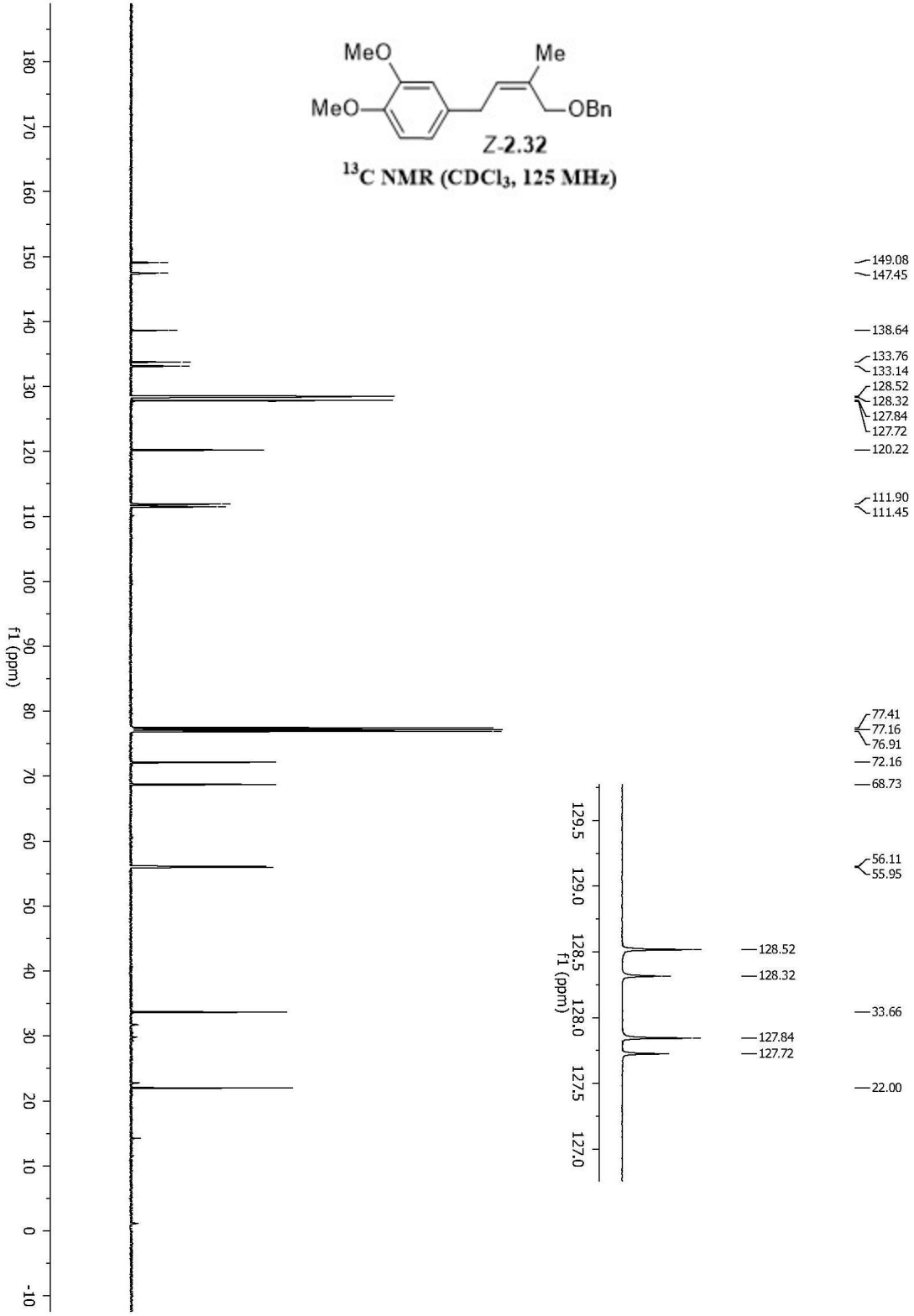

OH
Me
OPMB
Z-2.30
^{1}H NMR (CDCl$_3$, 400 MHz)
f1 (ppm)
2.84
2.00
1.07
2.11
2.11
3.16
2.10
2.22
3.09
3.05
8.02
7.28
7.28
7.27
7.26
7.26
7.25
6.89
6.89
6.88
6.87
6.87
6.86
5.39
5.37
5.35
4.38
3.98
3.81
3.65
3.63
3.61
2.02
2.00
1.99
1.97
1.78
1.77
1.59
1.57
1.56
1.54
1.52
1.35
1.33
1.32
1.31
1.29

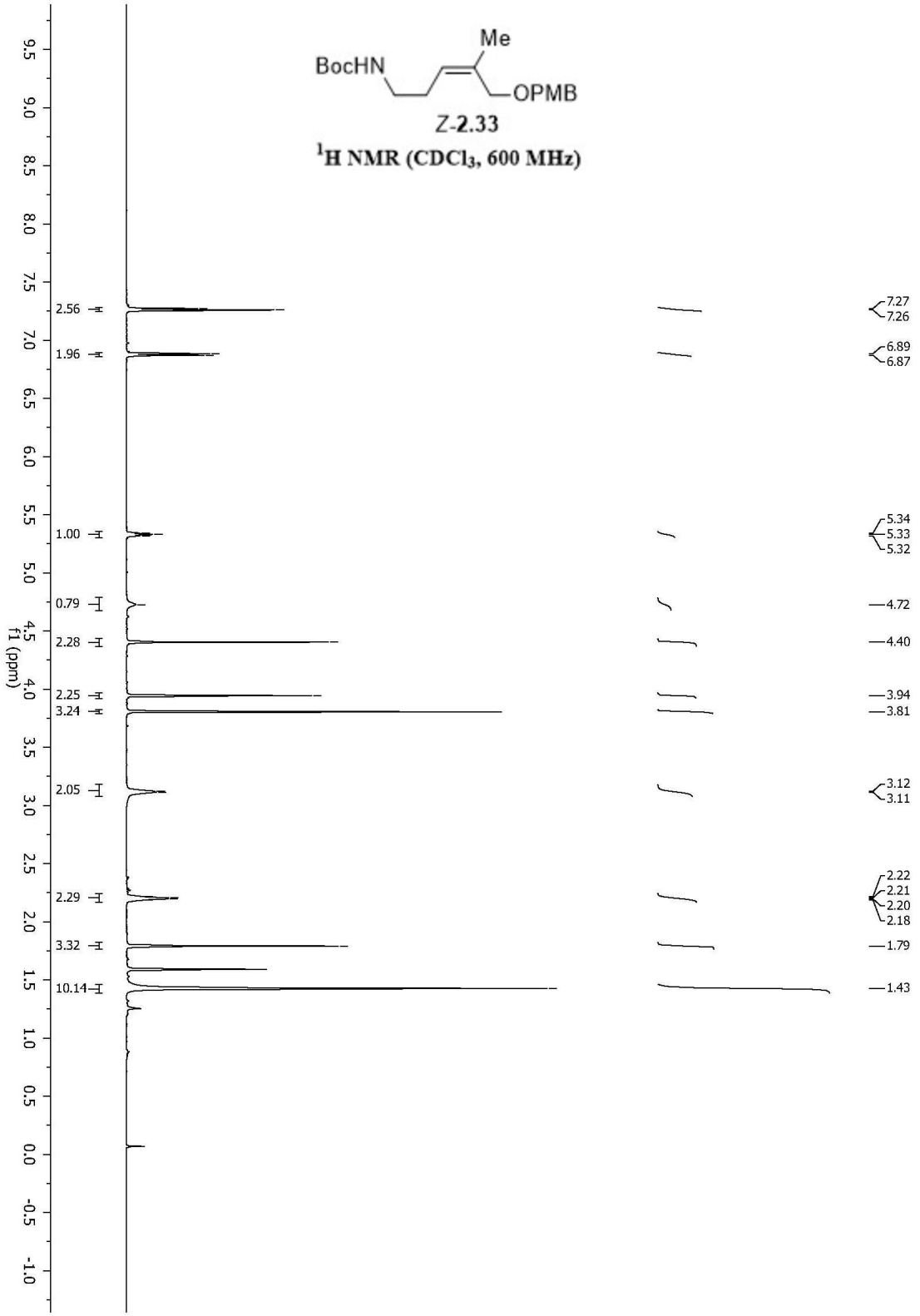

OH
Me
OPMB
Z-2.30
^{13}C NMR ($CDCl_3$, 150 MHz)
159.23
132.07
130.91
129.96
129.42
113.87
71.43
68.34
63.17
55.43
32.91
30.05
29.41
29.35
27.81
25.83
21.83
f1 (ppm)

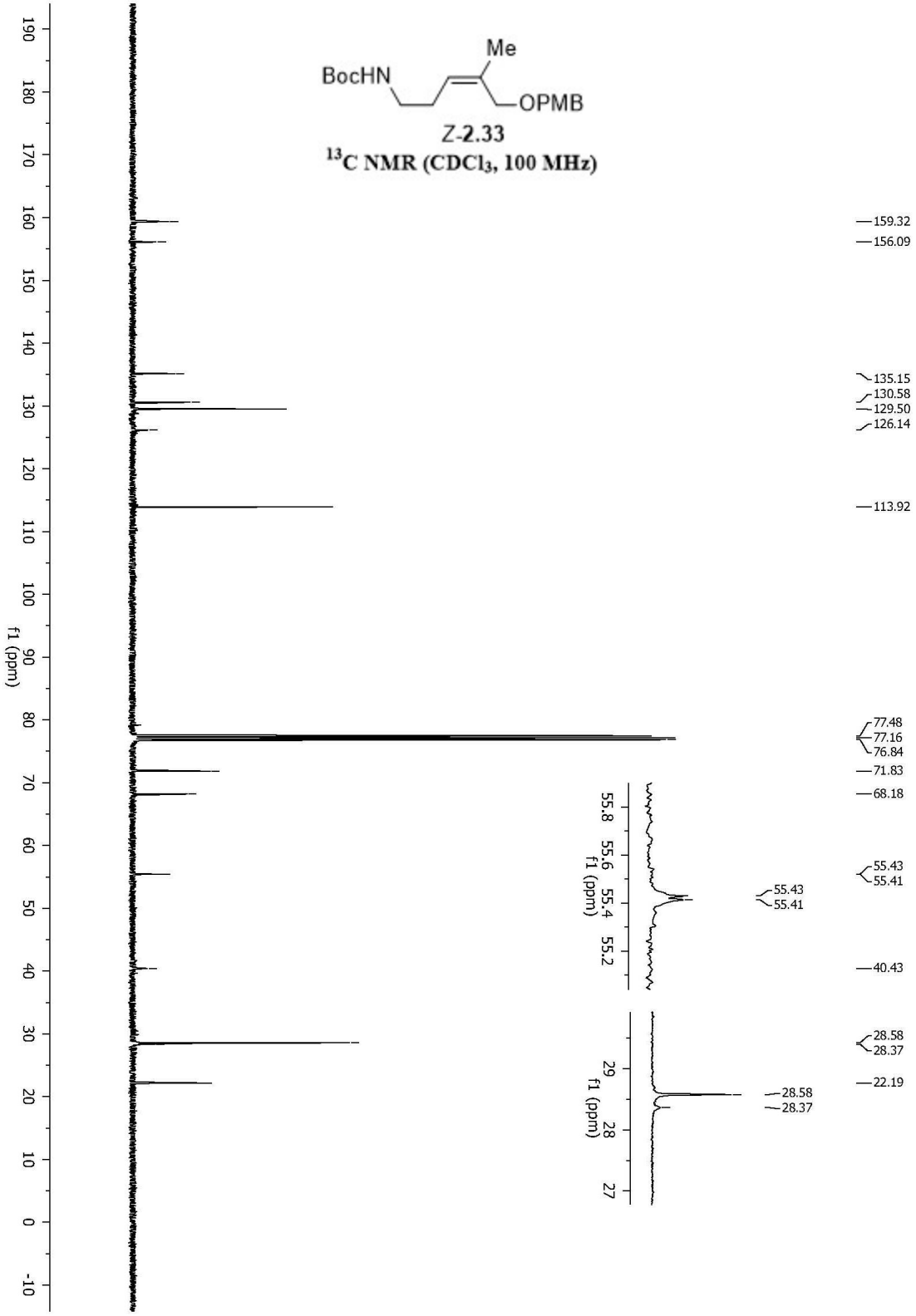

Me
O
N
OPMB
O
Z-2.31
^{1}H NMR ($CDCl_3$, 600 MHz)
f1 (ppm)
1.80
1.96
2.52
1.88
1.00
2.07
2.11
3.00
2.19
2.18
3.04
2.22
2.20
7.84
7.84
7.83
7.83
7.71
7.70
7.70
7.70
7.26
7.26
7.24
6.87
6.86
5.35
5.34
5.33
4.37
3.96
3.79
3.68
3.66
3.65
2.07
2.06
2.05
2.03
1.76
1.68
1.67
1.66
1.64
1.63
1.40
1.39
1.38
1.36
1.35

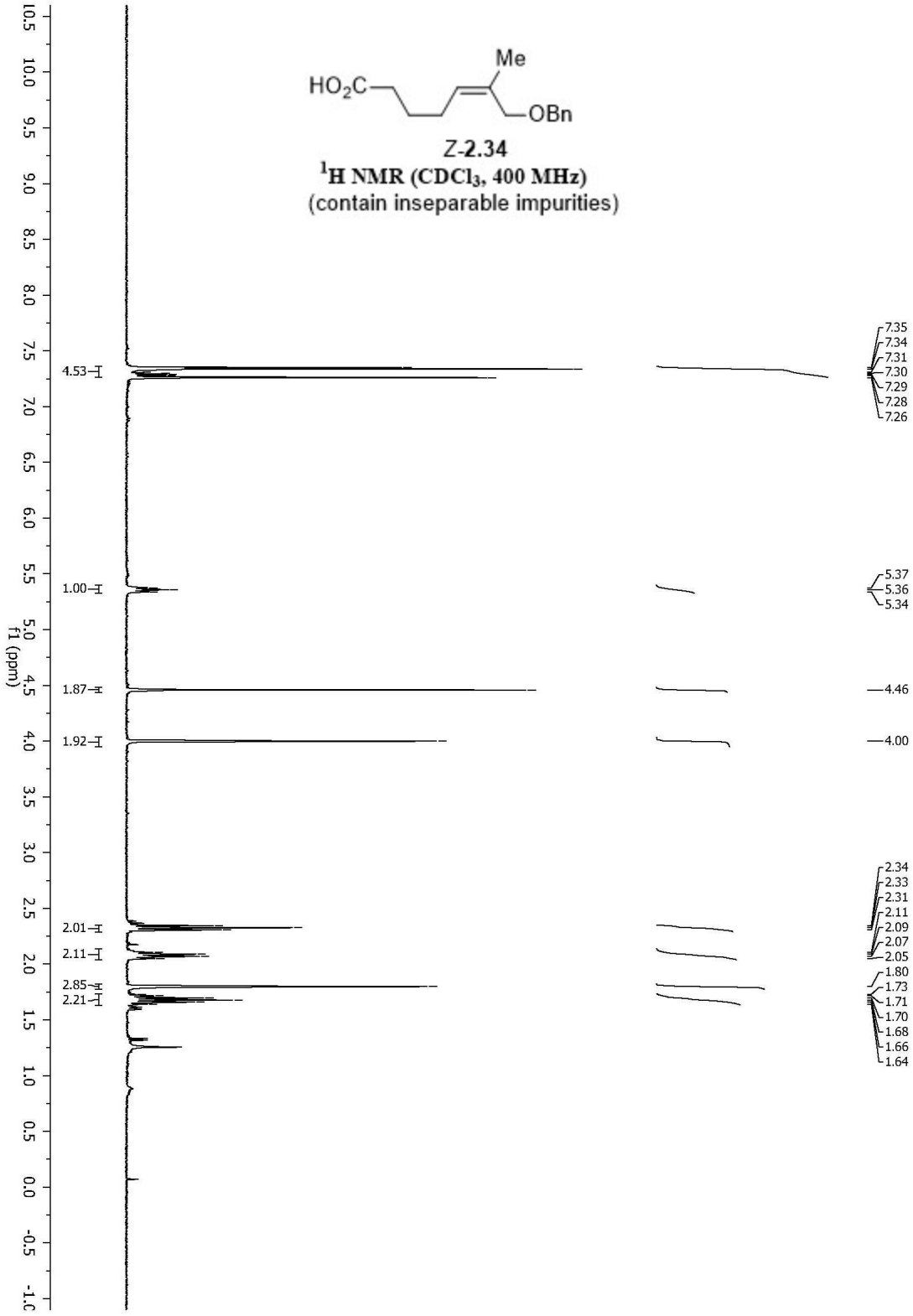

Me
O
N
OPMB
O
Z-2.31
^{13}C NMR ($CDCl_3$, 100 MHz)
168.58
159.24
134.00
132.74
132.30
130.83
129.43
129.09
123.31
113.88
77.48
77.16
76.84
71.50
68.30
55.41
38.02
28.34
27.36
27.28
21.83
f1 (ppm)

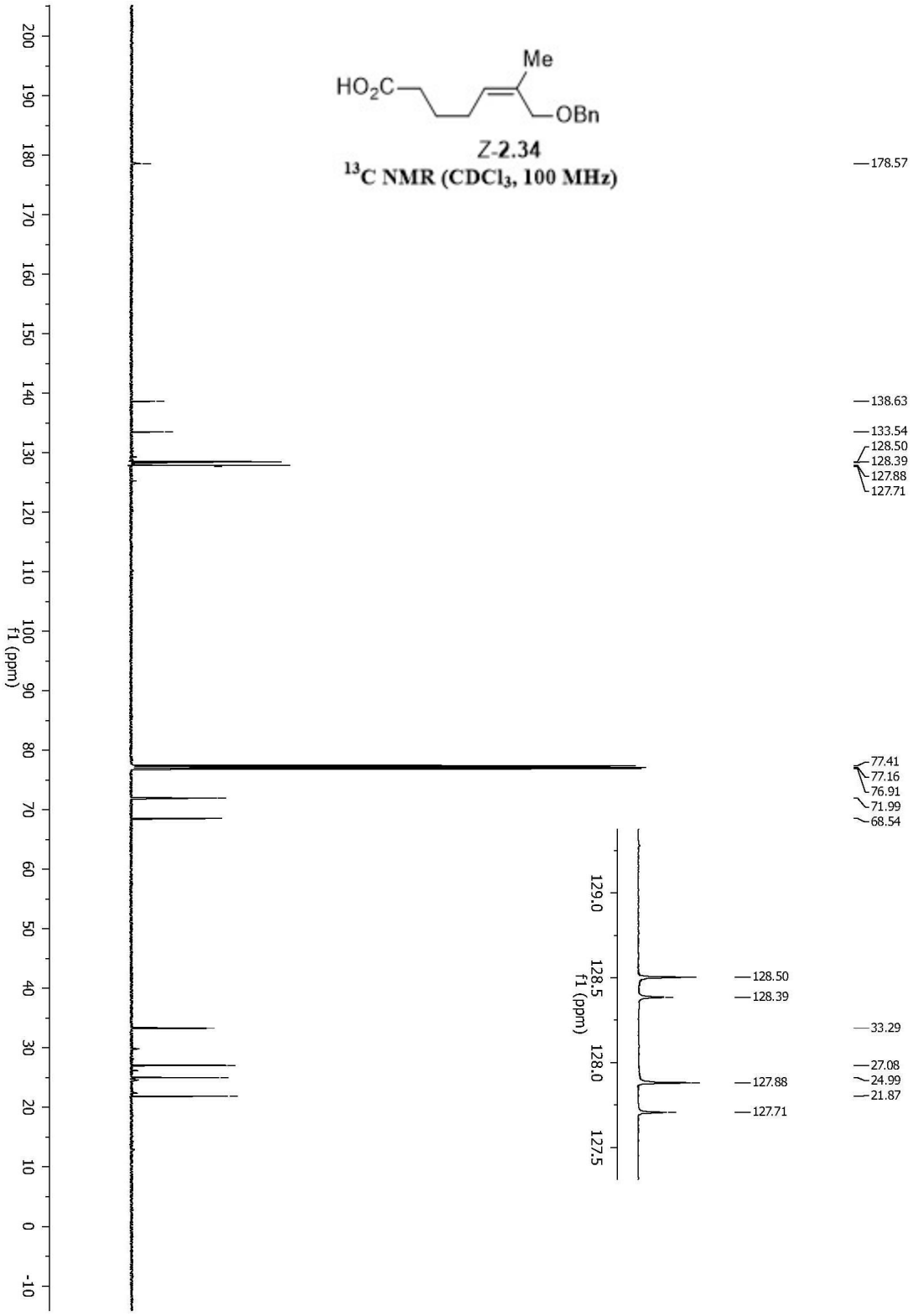

MeO
Me
MeO
OBn
Z-2.32
^{1}H NMR (CDCl$_3$, 500 MHz)
f1 (ppm)
5.15
0.99
2.02
1.00
2.03
2.07
6.26
2.06
3.07
7.36
7.35
7.34
7.33
7.30
7.29
7.28
7.26
6.79
6.78
6.70
6.69
5.58
5.57
5.55
4.51
4.12
3.85
3.83
3.34
3.33
1.86


MeO
Me
MeO
OBn
Z-2.32
^{13}C NMR ($CDCl_3$, 125 MHz)
f1 (ppm)
149.08
147.45
138.64
133.76
133.14
128.52
128.32
127.84
127.72
120.22
111.90
111.45
77.41
77.16
76.91
72.16
68.73
56.11
55.95
33.66
22.00


Me
BocHN
OPMB
Z-2.33
^{1}H NMR (CDCl$_3$, 600 MHz)
f1 (ppm)
2.56
1.96
1.00
0.79
2.28
2.25
3.24
2.05
2.29
3.32
10.14
7.27
7.26
6.89
6.87
5.34
5.33
5.32
4.72
4.40
3.94
3.81
3.12
3.11
2.22
2.21
2.20
2.18
1.79
1.43


Me
BocHN
OPMB
Z-2.33
13C NMR (CDCl3, 100 MHz)
159.32
156.09
135.15
130.58
129.50
126.14
113.92
77.48
77.16
76.84
71.83
68.18
55.43
55.41
40.43
28.58
28.37
22.19
f1 (ppm)


Me
HO2C
OBn
Z-2.34
1H NMR (CDCl3, 400 MHz)
(contain inseparable impurities)
f1 (ppm)
4.53
1.00
1.87
1.92
2.01
2.11
2.85
2.21
7.35
7.34
7.31
7.30
7.29
7.28
7.26
5.37
5.36
5.34
4.46
4.00
2.34
2.33
2.31
2.11
2.09
2.07
2.05
1.80
1.73
1.71
1.70
1.68
1.66
1.64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71.99
68.54
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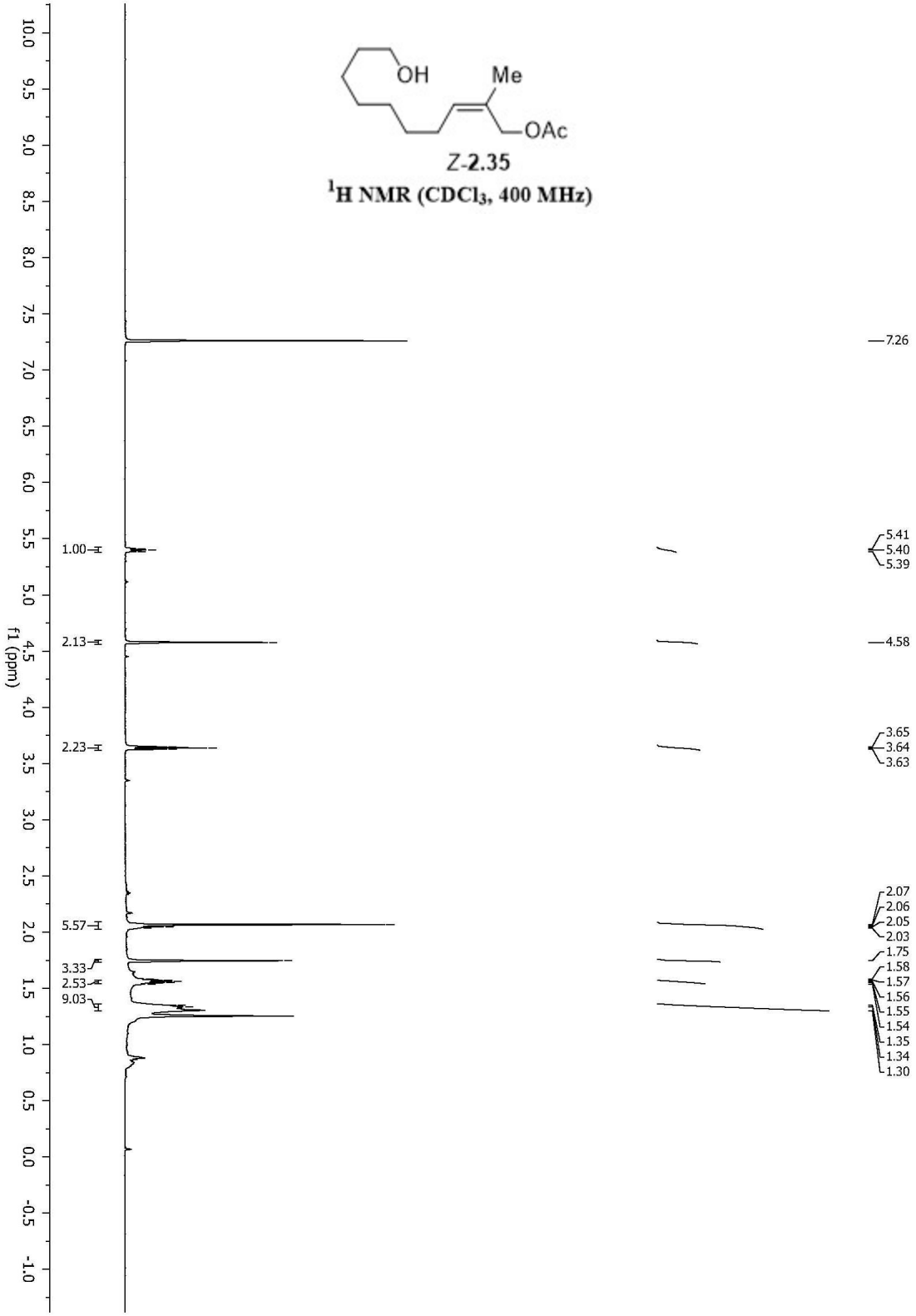
27.08
24.99
21.87
f1 (ppm)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f1 (ppm)
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2.23
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3.33
2.53
9.03
7.26
5.41
5.40
5.39
4.58
3.65
3.64
3.63
2.07
2.06
2.05
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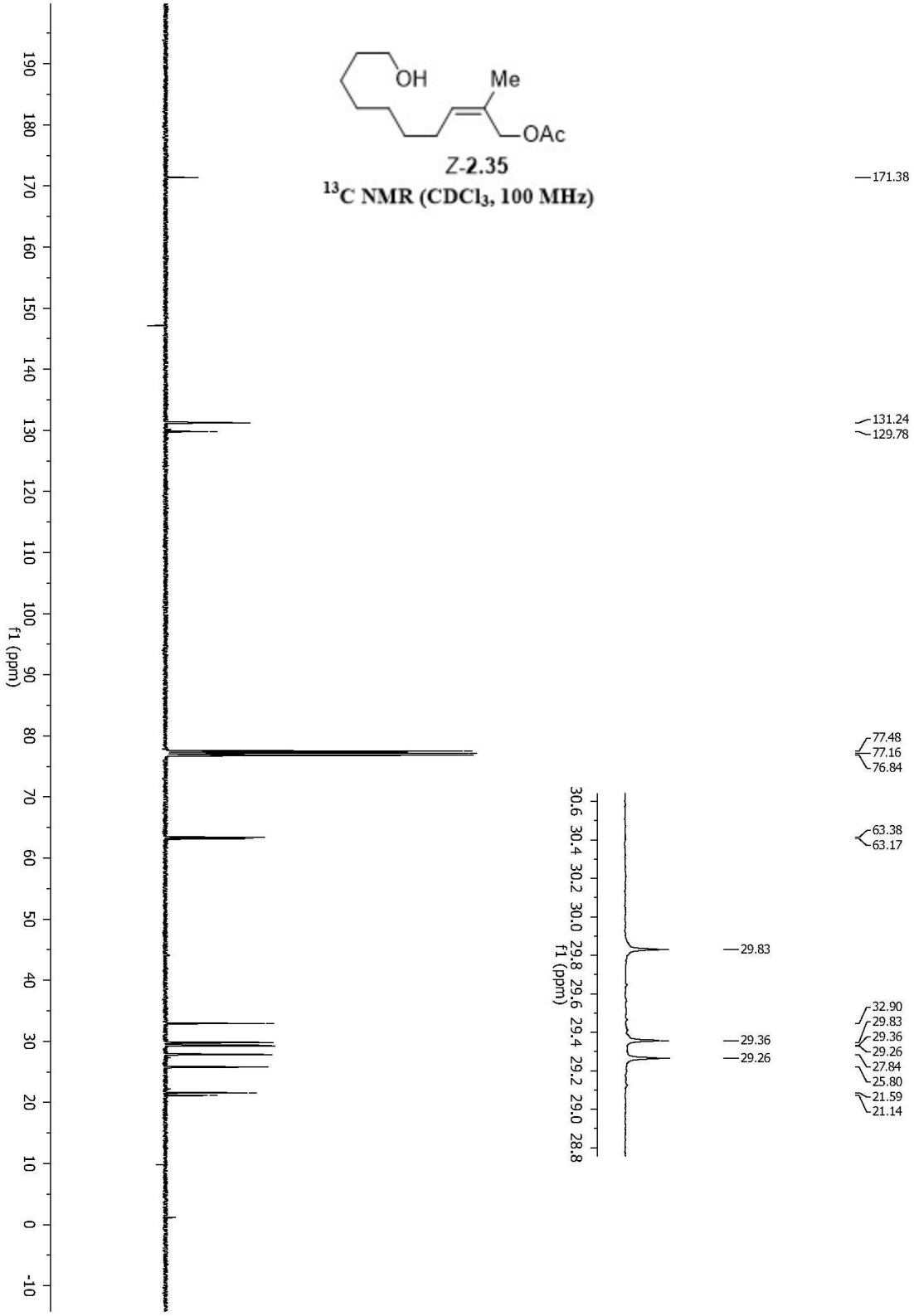
1.55
1.54
1.35
1.34
1.30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77.16
76.84
63.38
63.17
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29.26
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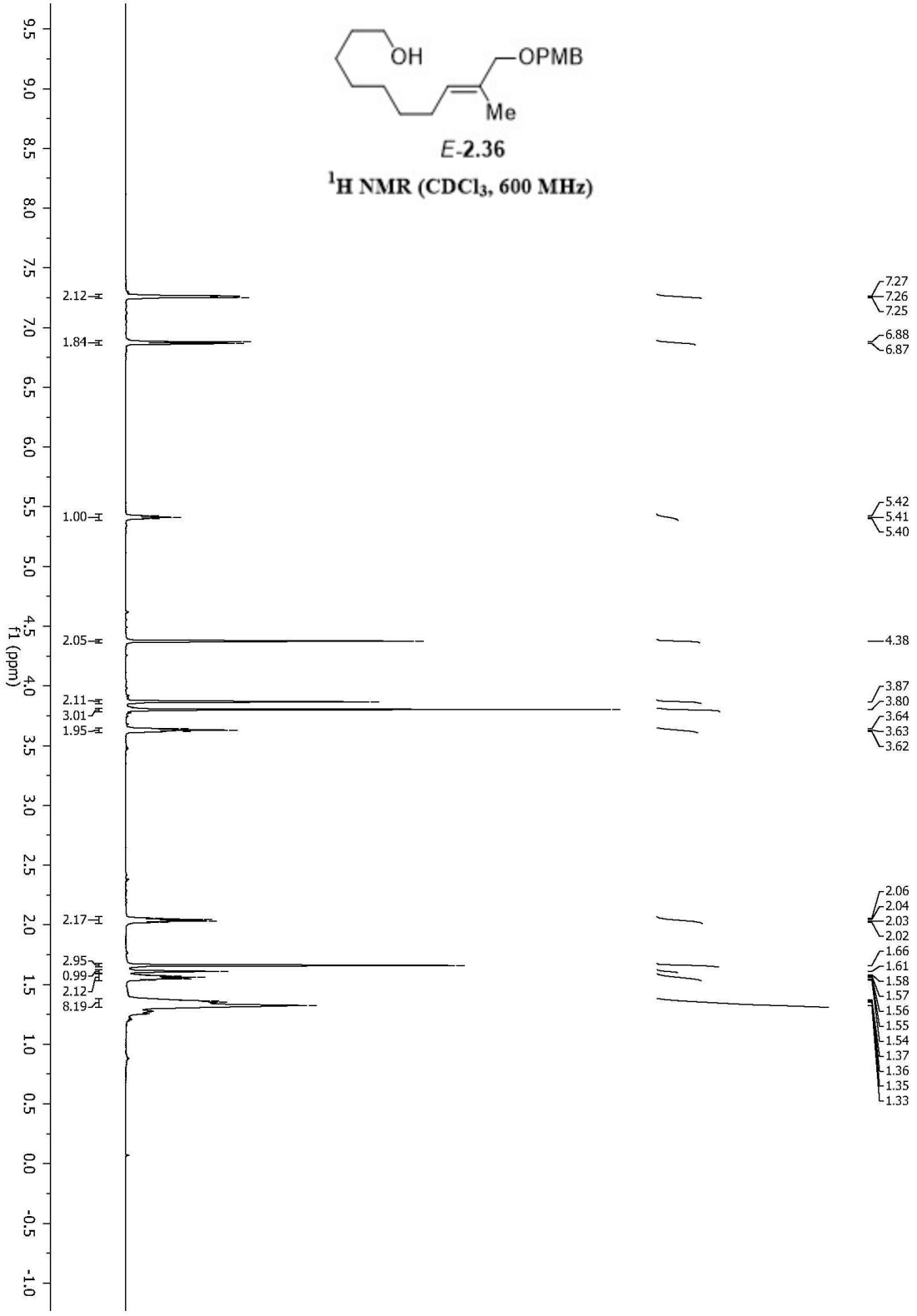
29.83
29.36
29.26
27.84
25.80
21.59
21.14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f1 (ppm)
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1.00
2.05
2.11
3.01
1.95
2.17
2.95
0.99
2.12
8.19
7.27
7.26
7.25
6.88
6.87
5.42
5.41
5.40
4.38
3.87
3.80
3.64
3.63
3.62
2.06
2.04
2.03
2.02
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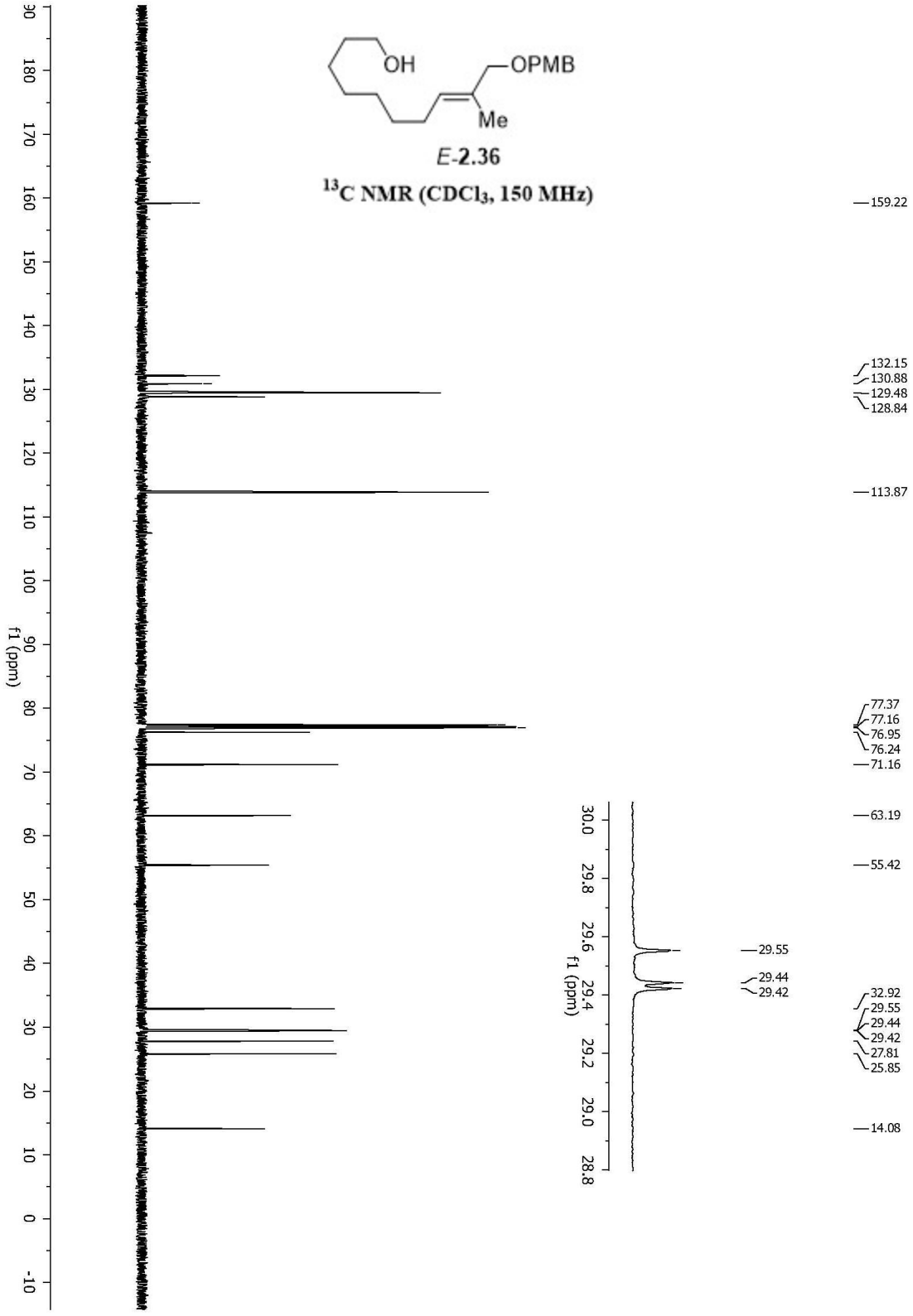
1.35
1.33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130.88
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113.87
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77.16
76.95
76.24
71.16
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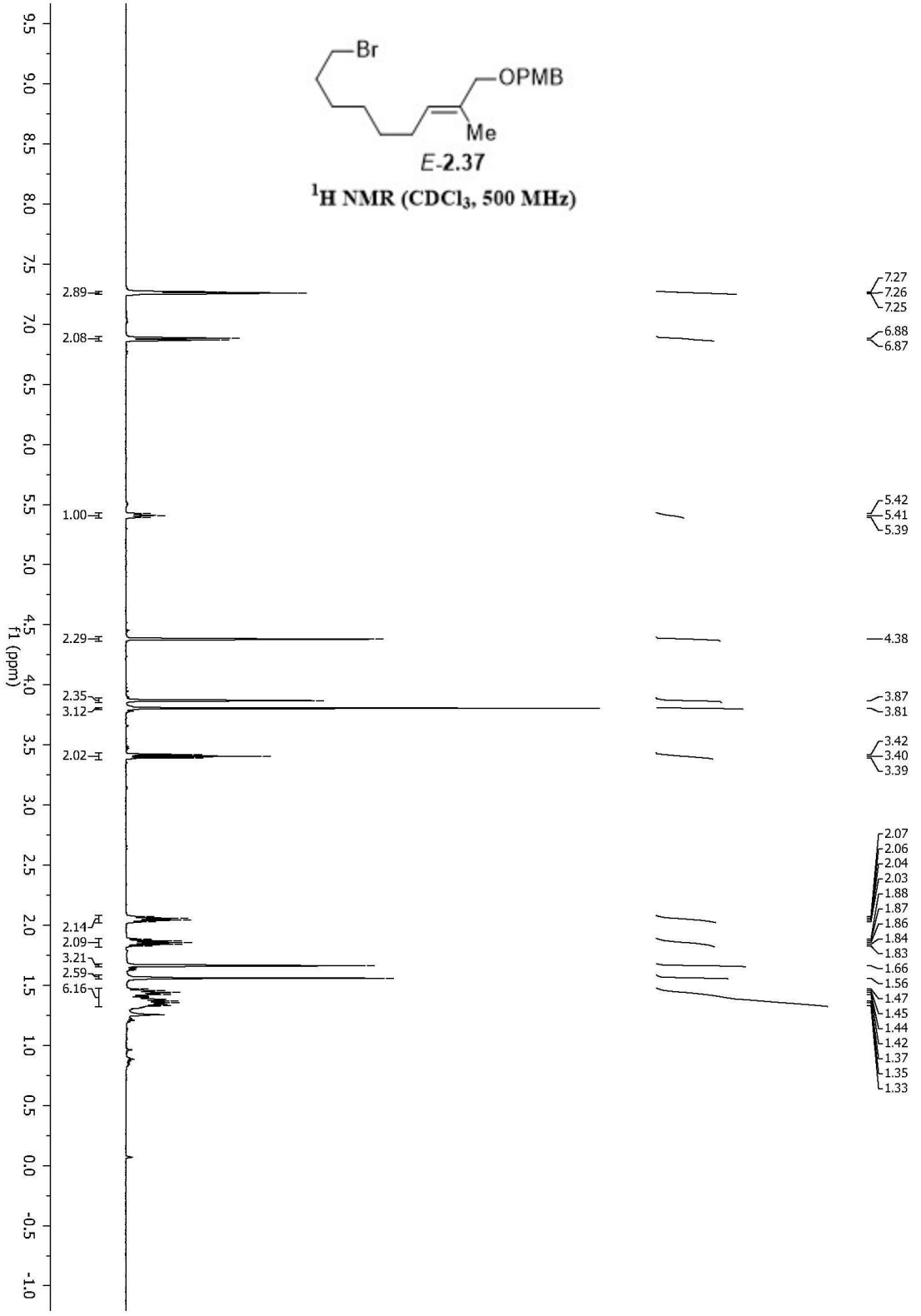
29.55
29.44
29.42
27.81
25.85
14.08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6.87
5.42
5.41
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3.87
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1.44
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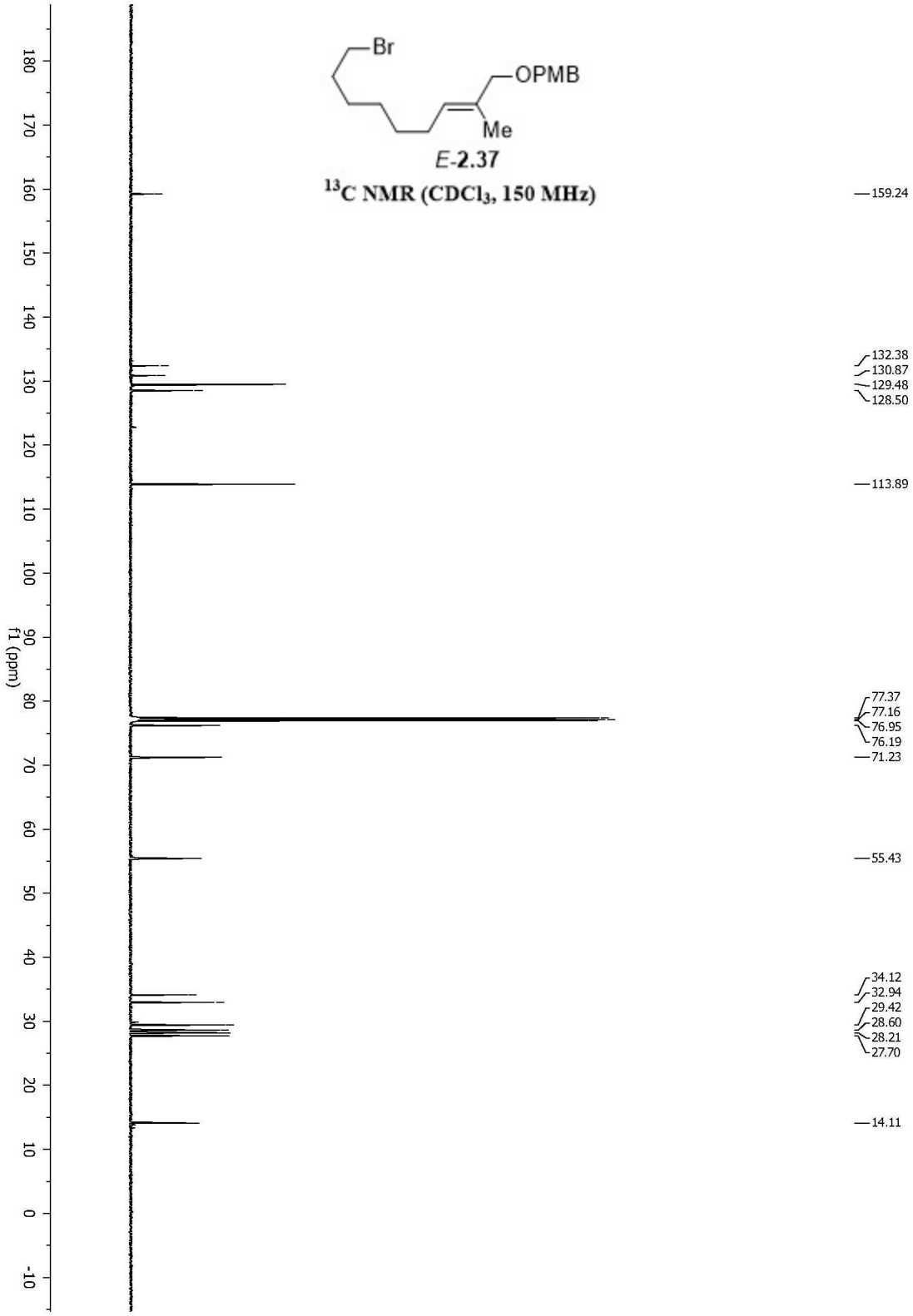
1.33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128.50
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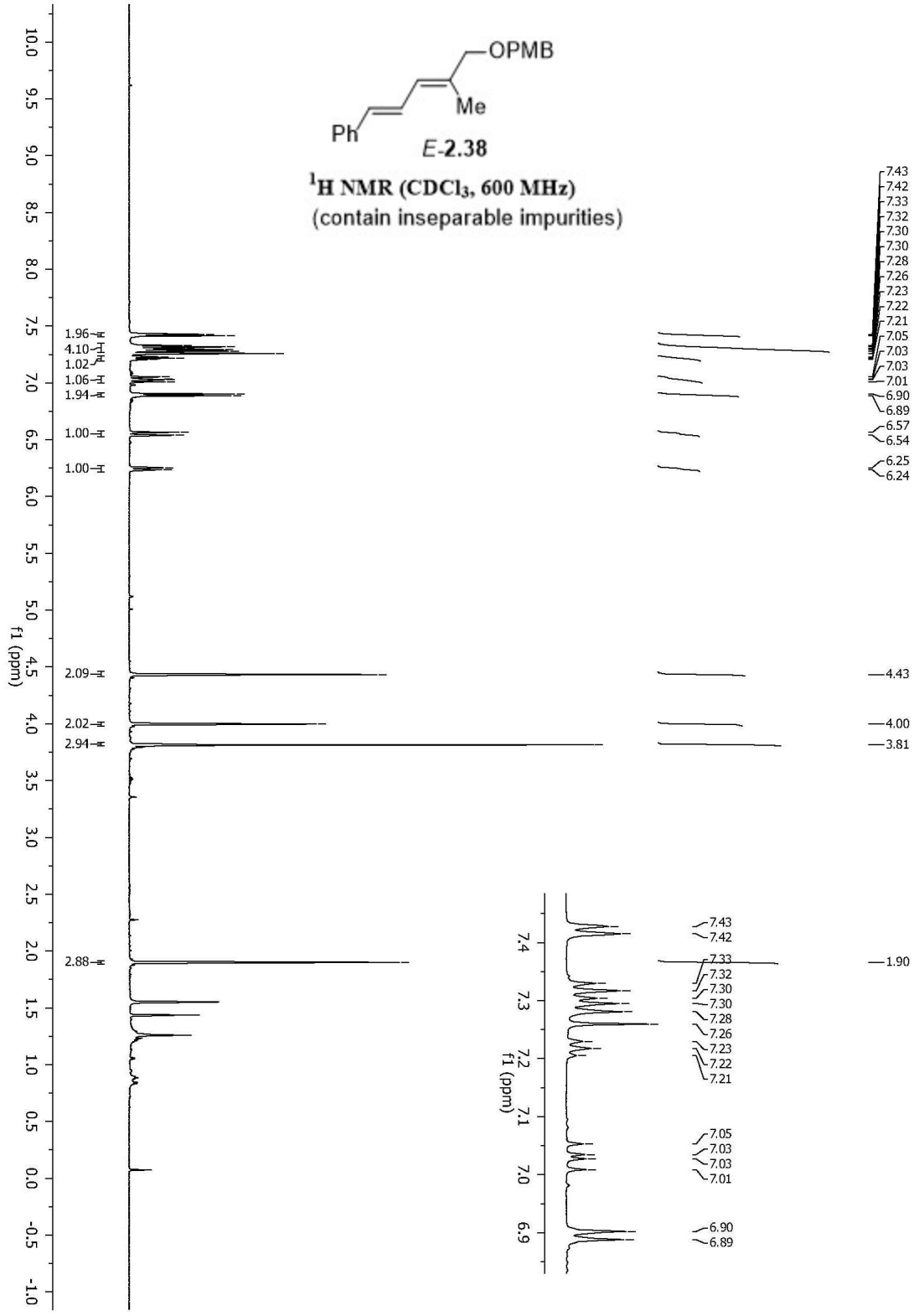
77.16
76.95
76.19
71.23
55.43
34.12
32.94
29.42
28.60
28.21
27.70
14.11
f1 (ppm)


OPMB
Me
Ph
E-2.38
1H NMR (CDCl3, 600 MHz)
(contain inseparable impurities)
f1 (ppm)
1.96
4.10
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2.02
2.94
2.88
4.43
4.00
3.81
1.90
7.43
7.42
7.33
7.32
7.30
7.30
7.28
7.26
7.23
7.22
7.21
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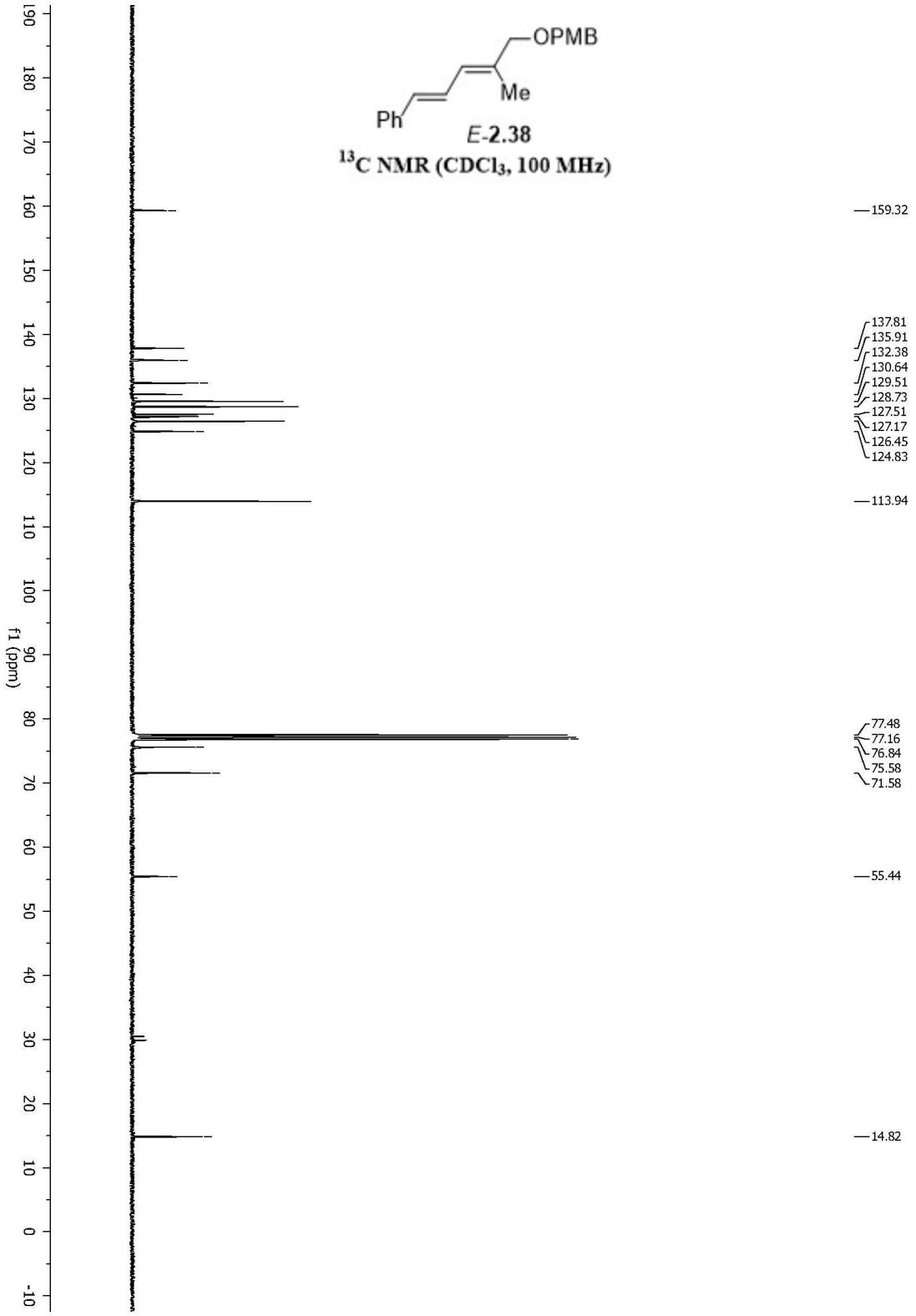
6.24


OPMB
Me
Ph
E-2.38
13C NMR (CDCl3, 100 MHz)
159.32
137.81
135.91
132.38
130.64
129.51
128.73
127.51
127.17
126.45
124.83
113.94
77.48
77.16
76.84
75.58
71.58
55.44
14.82
f1 (ppm)

2.6.5 Density Functional Theory (DFT) Calculations

DFT computations[44] were performed with the Gaussian 09 suite of programs.[45] Geometries were optimized with the ωB97XD[46] functional (recommended based on the accurate reproduction of x-ray geometries[51b]) and the Def2SVP basis set[47]. The effect of a polar reaction medium (tetrahydrofuran, thf) was approximated by means of an integral equation formalism variant of the polarizable continuum model (IEFPCM).[48] Stationary points were probed through vibrational analysis and Gibbs free energy corrections were performed under standard conditions (298.15 K, 1.0 atm). Transition states have been verified through Intrinsic Reaction Coordiante calculations (IRC) employing the L(ocal)

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(44) For reviews on the application of DFT calculations to transition metal chemistry, see: (a) Cramer, C. J.; Truhlar, D. G. *Phys. Chem. Chem. Phys.* **2009**, *11*, 10757−10816. (b) Grimme, S.; Ehrlich, S.; Goerigk, L. *J. Comp. Chem*. **2011**, *32*, 1456−1465. (c) Peverati, R.; Truhlar, D. G. *Phil. Trans. R. Soc. A* **2014**, *372*, 20120476. For recent comparisons of density funcionals in benchmark studies, see: (d) Mardirossian, N.; Head-Gordon, M. *J. Chem. Theory Comput.* **2016**, *12*, 4303−4325. (e) Mardirossian, N.; Head-Gordon, M. *J. Chem. Phys.* **2016**, *144*, 214110. (f) Brauer, B.; Kesharwani, M. K.; Kozuch, S.; Martin, J. M. *Phys. Chem. Chem. Phys.* **2016**, *18*, 20905−20925. (g) Weymuth, T.; Couzijn, E. P. A.; Chen, P.; Reiher, M. *J. Chem. Theory Comput.* **2014**, *10*, 3092−3103. (h) Zhang, W.; Truhlar, D. G.; Tang M. *J. Chem. Theory Comput.* **2013**, *9*, 3965−3977. (i) Yu, H. S.; He, X.; Li, S. L.; Truhlar, D. G. *Chem. Sci.* **2016**, *7*, 5032−5051. (j) Steinmetz, M.; Grimme S. *ChemistryOpen* **2013**, *2*, 115−124. (k) Goerigk, L.; Kruse H.; Grimme, S. *ChemPhysChem* **2011**, *12*, 3421−3433.

(45) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Mennucci, B.; Petersson, G. A.; Nakatsuji, H.; Caricato, M.; Li, X.; Hratchian, H. P.; Izmaylov, A. F.; Bloino, J.; Zheng, G.; Sonnenberg, J. L.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Vreven, T.; Montgomery, Jr., J. A.; Peralta, J. E.; Ogliaro, F.; Bearpark, M.; Heyd, J. J.; Brothers, E.; Kudin, K. N.; Staroverov, V. N.; Kobayashi, R.; Normand, J.; Raghavachari, K.; Rendell, A.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Rega, N.; Millam, J. M.; Klene, M.; Knox, J. E.; Cross, J. B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Martin, R. L.; Morokuma, K.; Zakrzewski, V. G.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Dapprich, S.; Daniels, A. D.; Farkas, Ö.; Foresman, J. B.; Ortiz, J. V.; Cioslowski, J.; Fox, D. J. *Gaussian 09, Revision **D.01**,* Gaussian, Inc., Wallingford CT, **2009**.

(46) Chai, J.-D.; Head-Gordon, M. *Phys. Chem. Chem. Phys.*, **2008**, *10*, 6615−6620.

(47) Weigend, F.; Ahlrichs, R. *Phys. Chem. Chem. Phys.* **2005**, *7*, 3297−3305.

(48) Scalmani, G.; Frisch, M. J. *J. Chem. Phys.* **2010**, *132*, 114110.

Q(uadratic) A(approximation) method,[49] followed by subsequent optimization of the end points with the above mentioned optimization method. We furthermore probed the performance of various density functionals through single point energy calculations at the geometries optimized at the levels described above by means of the SMD[50] solvation model with THF as solvent and the larger Def2TZVPP[47] basis set. Since the correct density functional is not known we tested several state of the art approaches that have been developed over the past decade:[44,51] MN15,[44i] M06,[52] ωB97XD,[46] PBE0-D3BJ[44b,53] and PBE0[44b] (see Figs. S2–1 to S2–5). In the manuscript we only report the PBE0-D3BJ/Def2TZVPP$_{thf(SMD)}$//ωB97XD/Def2SVP$_{THF(PCM)}$ energies. Images of the optimized transition states are shown in Figures S1–1 to S1–5. Electronic and Gibbs free energies are provided in Section 5 and a file for convenient viewing of computed geometries with the program Mercury 3.3 is appended as separate "coordinates.xyz" file in Section 6.[54]

Discussion of the results

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(49) (a) Page, M.; McIver Jr., J. W. *J. Chem. Phys.* **1988**, *88*, 922–935. (b) Page, M.; Doubleday Jr., C.; McIver Jr., J. W. *J. Chem. Phys.* **1990**, *93*, 5634–5642.

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(51) For selected examples highlighting the importance of including treatment of dispersion interactions in modeling olefin metathesis reactions promoted by Ru carbene complexes, see: (a) Torker, S.; Merki, D.; Chen. P. *J. Am. Chem. Soc.* **2008**, *130*, 4808−4814. (b) Minenkov, Y.; Occhipinti, G.; Singstad, A.; Jensen, V. R. *Dalton Trans.* **2012**, *41*, 5526−5541. (c) Minenkov, Y.; Occhipinti, G.; Jensen, V. R. *Organometallics* **2011**, *32*, 2099−2111. (d) Khan, R. K. M.; Torker, S.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2014**, *136*, 14337–14340. (e) Torker, S.; Koh, M. J.; Khan, R. K. M.; Hoveyda, A. H. *Organometallics* **2016**, *35*, 543−562. (f) Mikus, M. S.; Torker, S.; Hoveyda, A. H. *Angew. Chem., Int. Ed.* **2016**, *55*, 4997–5002.

(52) Zhao, Y.; Truhlar, D. G. *Acc. Chem. Res.* **2008**, *41*, 157−167.

(53) Adamo, C.; Barone, V. *J. Chem. Phys.* **1999***, 110*, 6158−6169.

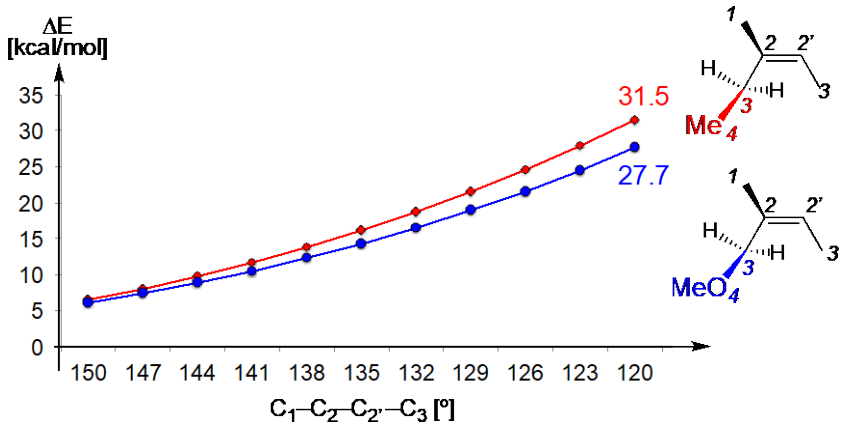
(54) Lichtenberger, D. L.; Gladysz, J. A. *Organometallics* **2014**, *33*, 835−835. The "coordinates.xyz" file can be generated by copying all the coordinates in Section 6 into a text file without empty lines and changing the extension to ".xyz".

There are a few structural features that explain why OM of trisubstituted olefins with an allylic heteroatom occurs more easily. (i) The first is an inherent substrate property and is related to the substrate's ability to undergo bending, which is determined by the degree of A(1,2) repulsion. (ii) The A(1,2) strain described in (i) will result in distinct energetic profiles, which will be discussed in Section 4.1.2.

Structural changes of the substrate during Olefin Metathesis

A key rationale for the experimentally observed reactivity trend between substrates containing or lacking an allylic heteroatom can be found in the ability of the olefin to undergo a change in hybridization at the C2 carbon from sp^2 (free olefin) to sp^3 (as part of the metallacyclobutane), see Figure S1. Contraction of the C1–C2–C2'–C3 dihedral angle, while keeping C3–C2–C2'–C3' at 0º, leads to a more rapid increase in electronic energy in case of the substrate that lacks the allylic heteroatom (31.5 vs 27.7 kcal/mol at 120º, respectively), which is mainly attributed to an increased A(1,2) strain between C1 and C4 (vs C1 and O4). In other words, trisubstituted olefins with an allylic heteroatom are predicted to undergo bending more easily, a necessary requirement for olefin metathesis. Apart from this inherent substrate property, a number of distinct structural and energetic nuances appear in the energetic profiles of 5 model reactions (see Schemes S1–S5).

Figure S1. Electronic energy of 2 model substrates as a function of dihedral angle[a]

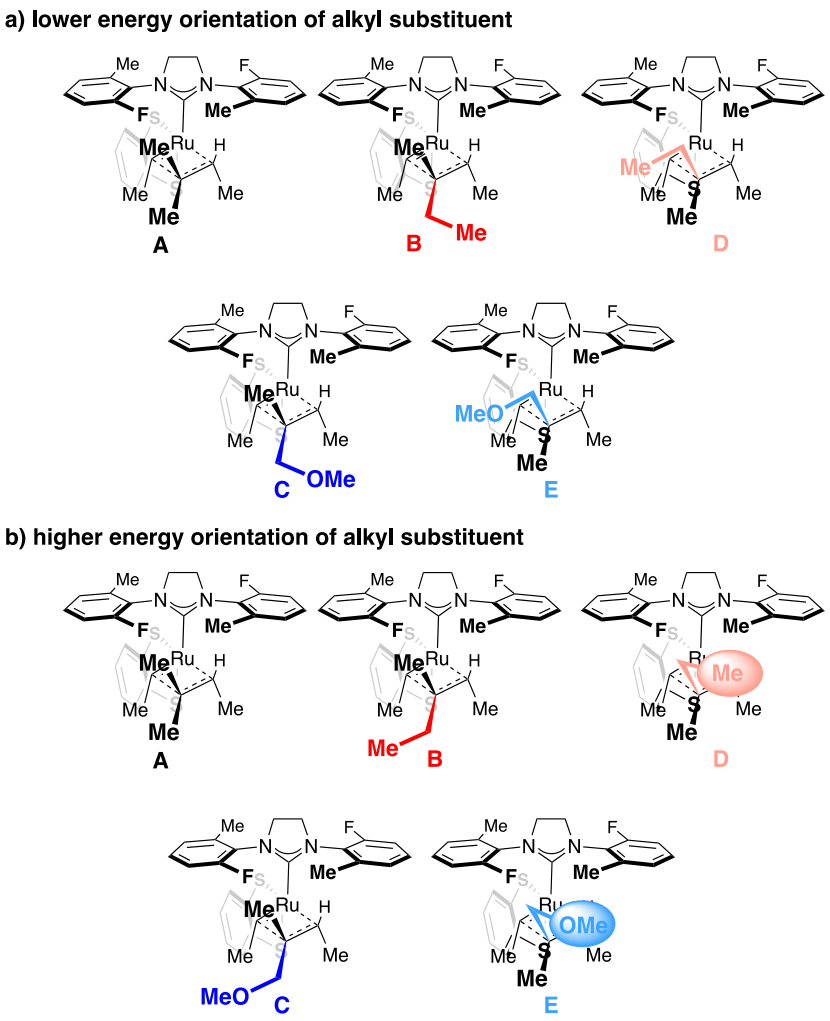


[a]C1–C2–C2'–C3 at the B97XD//Def2SVP$_{THF(PCM)}$ level (C3–C2–C2'–C3' is contrained to 0° during scan)

Investigation of 5 model reactions (A–E)

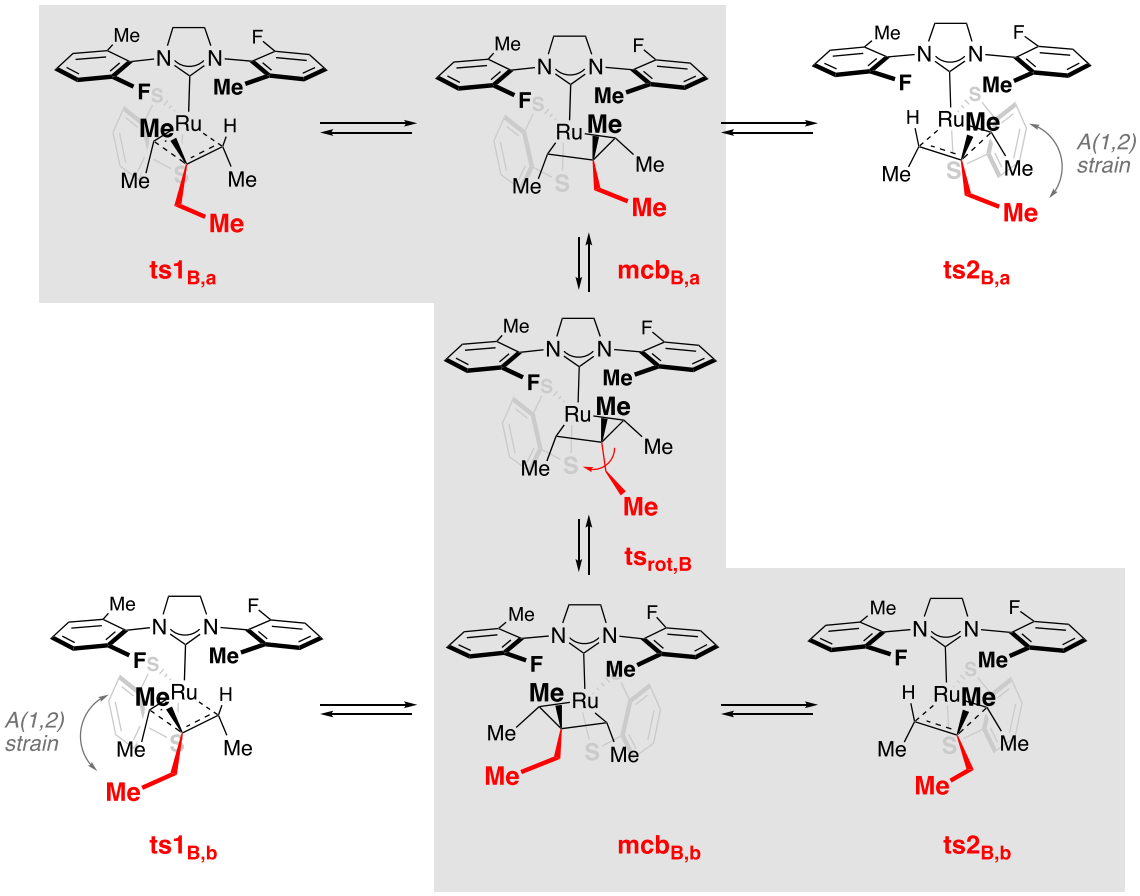
Degenerate model reactions of 5 different trisubstituted olefins [2-methyl-2-butene (**A**), (*Z*)-3-methyl-pent-2-ene (**B**), (*Z*)-1-methoxy-2-methylbut-2-ene (**C**), (*E*)-3-methyl-pent-2-ene (**D**) and (*E*)-1-methoxy-2-methylbut-2-ene (**E**)] with the Ru ethylidene derived from the nonchlorinated variant of **Ru-2** are compared (Scheme S1). Two orientations of the alkyl substituent are considered, giving rise to two energetically distinct OM sequences in absence of any conformational interchange: a lower energy process (index a) and a higher energy process (index b). In the following, reactions **B-E** are discussed in detail based on the free energy values obtained with PBE0-D3BJ/ Def2TZVPP$_{thf(SMD)}$//ωB97XD/Def2SVP$_{THF(PCM0}$ (for the corresponding energy profile see Figure S2-4). The corresponding free energy profiles with various other density functionals are shown in Figures S2–1 to S2–5, the computed structures can be found in Figures S1–1 to S1–5.

Scheme S1. Investigated cross-metathesis reactions



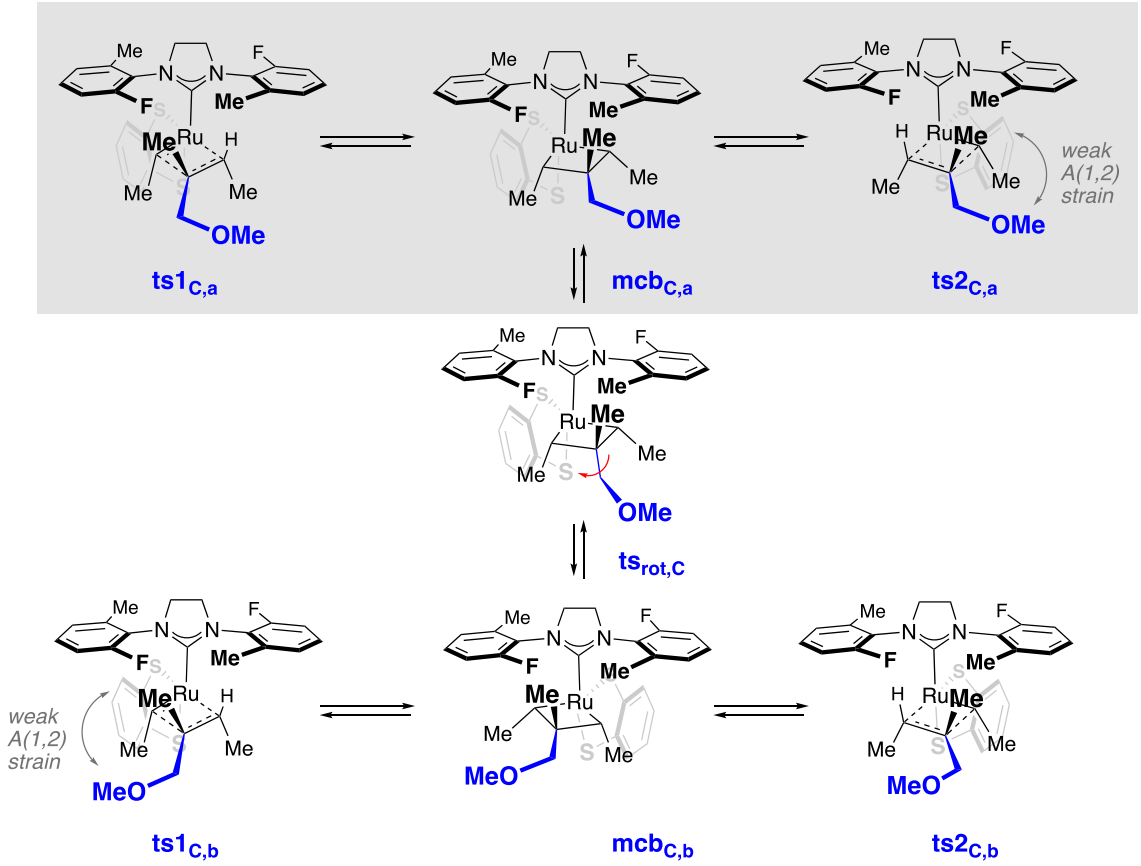
Reaction B: In reaction **B** (Scheme S2), $\mathbf{mcb}_{\mathbf{B,a}}$ is generated via $\mathbf{ts1}_{\mathbf{B,a}}$ (ΔG = 16.6 kcal/mol, Figure S2–4). Productive cleavage via $\mathbf{ts2}_{\mathbf{B,a}}$ (Scheme S2) is associated with a higher energy barrier (ΔG = 19.3 kcal/mol, Figure S2–4) as a result of A(1,2) repulsion (C2–C3–C4 = 116.8º, Figure S1–2). If the alkyl substituent were, however, allowed to rotate from $\mathbf{mcb}_{\mathbf{B,a}} \rightarrow \mathbf{mcb}_{\mathbf{B,b}}$ via $\mathbf{ts}_{\mathbf{rot,B}}$ (ΔG = 17.5 kcal/mol, Figure S2–4), cycloreversion could occur through the lower energy $\mathbf{ts2}_{\mathbf{B,b}}$ (ΔG = 17.9 kcal/mol, Fig. S2–4) in absence of significant A(1,2) repulsion (C2–C3–C4 = 112.5º, Figure S1–2).

Scheme S2. Reaction B



Reaction C: With the smaller OMe substituent in reaction **C** (vs a Me group in reaction **B**), OM can occur without rotation of the substituent at the β position of the mcb through the sequence **ts1**$_{C,a}$ → **mcb**$_{C,a}$ → **ts2**$_{C,a}$ (Scheme S3). That is, there is only weak A(1,2) strain in **ts2**$_{C,a}$ (C2–C3–O4 = 110.5º, Figure S1–3), resulting in a fairly low free energy (ΔG = 15.8 kcal/mol, Figure S2–4). Furthermore, rotation of the alkyl substituent through **ts**$_{rot,C}$ (ΔG = 17.5 kcal/mol, Figure S2–4) is energetically more demanding than productive cycloreversion through **ts2**$_{C,a}$.

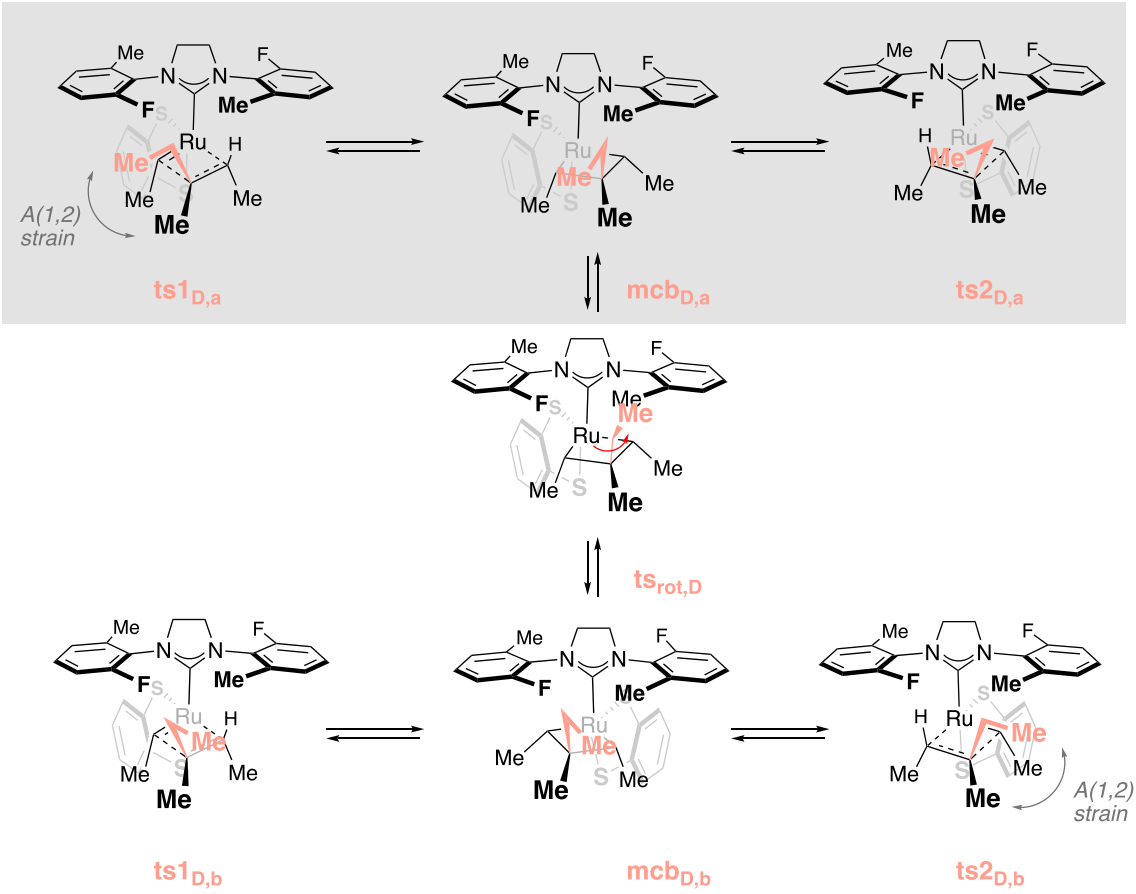
Scheme S3. Reaction C



Reaction D: Although rotation of the alkyl substituent via **ts$_{rot,B}$** seems to be relatively favored, it does not happen when the stereochemistry of the trisubstituted olefin is changed from *Z* to *E*. Rotation during reaction **D** via **ts$_{rot,D}$** (Scheme S4) is associated with a significant energy barrier (ΔG = 21.9 kcal/mol, Figure S2–4) and the reaction has to proceed through sequence **ts1$_{D,a}$** → **mcb$_{D,a}$** → **ts2$_{D,a}$** involving severe A(1,2) strain (Scheme S4). The high energy associated with **ts$_{rot,D}$** can be rationalized invoking severe steric clash between the two C–H bonds on the ethyl group in β position of the mcb and the hydrogen in α position (H···H = 1.87 Å; Figure S1–4). Additionally, the sulfur atom trans to the NHC is in close proximity to a C–H bond of the β methyl group (S···H = 2.61 Å and S···C3 = 3.44 Å; Figure S1–4). When the rotating alkyl group is at the bottom side as in **ts$_{rot,B}$**

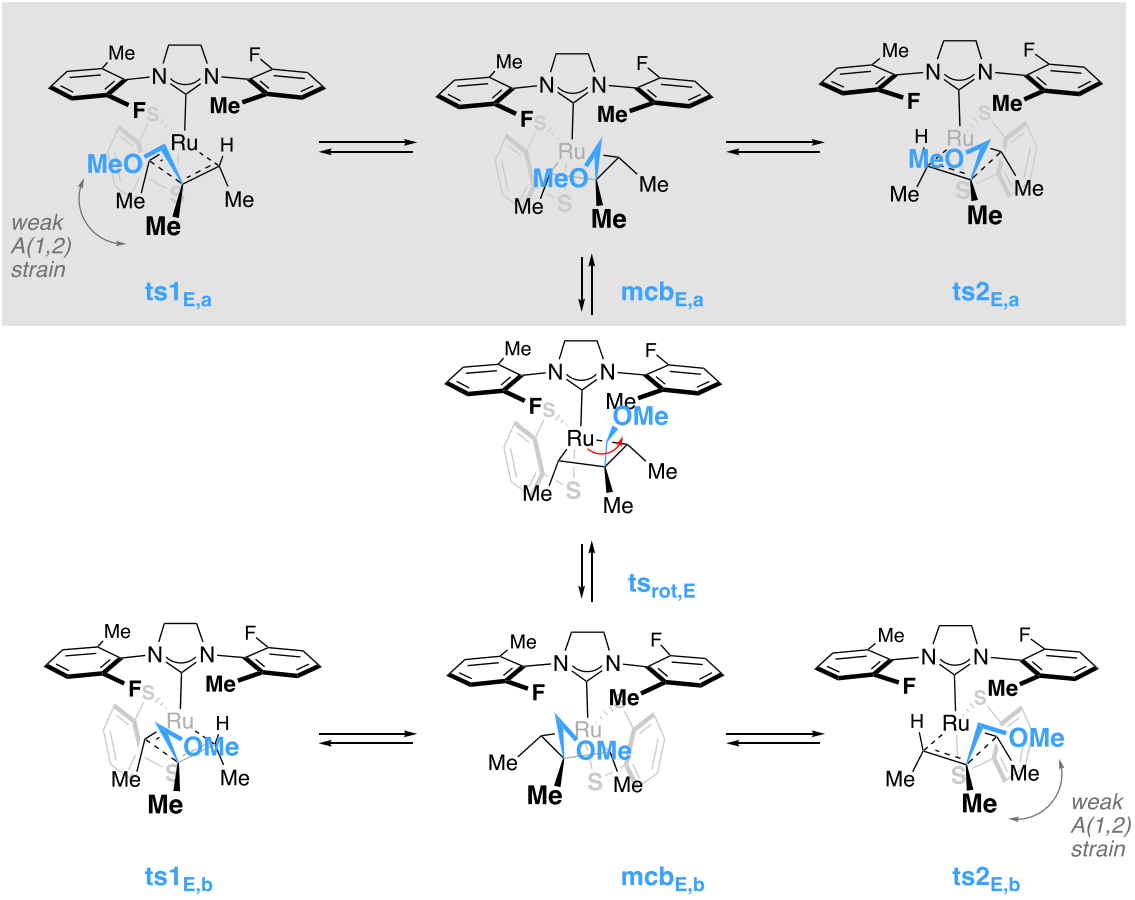
(Scheme S2), the disfavoring S···H interaction is relieved (S···C3 = 3.22 Å; Figure S1–2) and the mcb can adopt a slightly puckered conformation.

Scheme S4. Reaction D



Reactions E and A: For similar reasons, $\mathbf{ts_{rot,E}}$ (Scheme S5) is high in energy in reaction **E** (ΔG = 20.8 kcal/mol, Figure S2–4). Although rotation would be inconsequential in reaction **A**, the same trend in rotational barrier is also observed (Figure S1–1). Rotation of the bottom methyl group in β position ($\mathbf{ts_{rot,A\_1}}$) is associated with a barrier of 17.0 kcal/mol (Figure S2–4), whereas rotation of the methyl group on the top face of the mcb ($\mathbf{ts_{rot,A\_2}}$) is energetically significantly more demanding (ΔG = 19.3 kcal/mol, Figure S2–4).

Scheme S5. Reaction E



Discussion of the energetic trends with various density functionals

Regarding the energetic trends, all densitiy functionals predict reactions **B** and **D** to be less favored over the other three reactions, which is in agreement with the experimental results. The rate-limiting transition states with each functional for reactions **A-E** are summarized in Table S1. Nonetheless, the predicted energy differences are small and the preference for **A/C/E** over **B/D** is larger when dispersion is excluded (last row in Table S1). For example, without dispersion (PBE0, see also Figure S2–5), CM reactions **B** (29.3 kcal/mol for **ts2**$_{B,b}$) and **D** (28.2 kcal/mol for **ts1**$_{D,a}$) are predicted to be at least 1.1 kcal/mol less favored relative to the other three reactions (27.1 kcal/mol for **ts2**$_{C,a}$). The preference for reactions **A/C/E** is reduced (0.3 kcal/mol) when dispersion is included (PBE0-D3BJ,

see also Figure S2–4), presumably due to the weaker binding of the smaller 2-methyl-2-butene (16.3 kcal/mol for **ts1$_{A,a}$**) and the overestimation of dispersion interactions in solution.[55,56] Across the density functionals, reactions **C** and **E** with the larger substitutent in position pointing up are predicted to be energetically less demanding than than reactions **B** and **C** (larger substitutent in β position pointing down). This might be attributed to uncertainties in the estimation of entropic contributions. That is, the β substituent likely has little flexibility when pointing down and suffers from additional A(1,3) repulsion with the methyl groups in β position of the mcb. When pointing up, the steric interaction will likely be associated with a larger entropic contribution, i.e. it is subject to the rotation of the NHC ligand.

(55) Yang, L.; Adam, C.; Nichol, G. S.: Cockroft, S. L. *Nat. Chem.* **2013**, *5*, 1006−1010.

(56) Pollice, R.; Bot, M.; Kobylianskii, I. J.; Shenderovich, I.; Chen, P. *J. Am. Chem. Soc.* **2017**, *139*, 13126–13140.

Table S1. Rate limiting barrier with each density functional and the Def2TZVPP basis set in thf (SMD solvation model) after geometry optimization with □B97XD/Def2SVP$_{thf(PCM)}$. Free energy values are given in kcal/mol.

	MN15	**M06**	**ωB97XD**	**PBE0-D3BJ**	**PBE0**
Reaction A	**ts2$_a$/ts2$_b$** (11.5)	**ts2$_a$/ts2$_b$** (17.9)	**ts2$_a$/ts2$_b$** (17.7)	**ts1$_a$/ts1$_b$** (16.3)	**ts2$_a$/ts2$_b$** (26.7)
Reaction B	**ts2$_b$** (14.2)	**ts2$_b$** (19.8)	**ts2$_b$** (18.9)	**ts2$_b$** (17.9)	**ts2$_b$** (29.3)
Reaction C	**ts2$_a$** (11.5)	**ts2$_a$** (18.1)	**ts2$_a$** (17.7)	**ts2$_a$** (15.8)	**ts2$_a$** (27.1)
Reaction D	**ts1$_a$** (11.6)	**ts1$_a$** (18.1)	**ts1$_a$** (17.9)	**ts1$_a$** (16.6)	**ts1$_a$** (28.2)
Reaction E	**ts2$_a$** (10.0)	**ts2$_a$** (16.2)	**ts2$_a$** (15.8)	**ts2$_a$** (14.0)	**ts2$_a$** (25.2)
Preference for A/C/E over B/D	0.1	0.0	0.2	0.3	1.1

Computed structures and free energy diagrams

Computed structures for mode of reaction A (cf. Fig. 1, B97XD/Def2SVP$_{thf(PCM)}$)

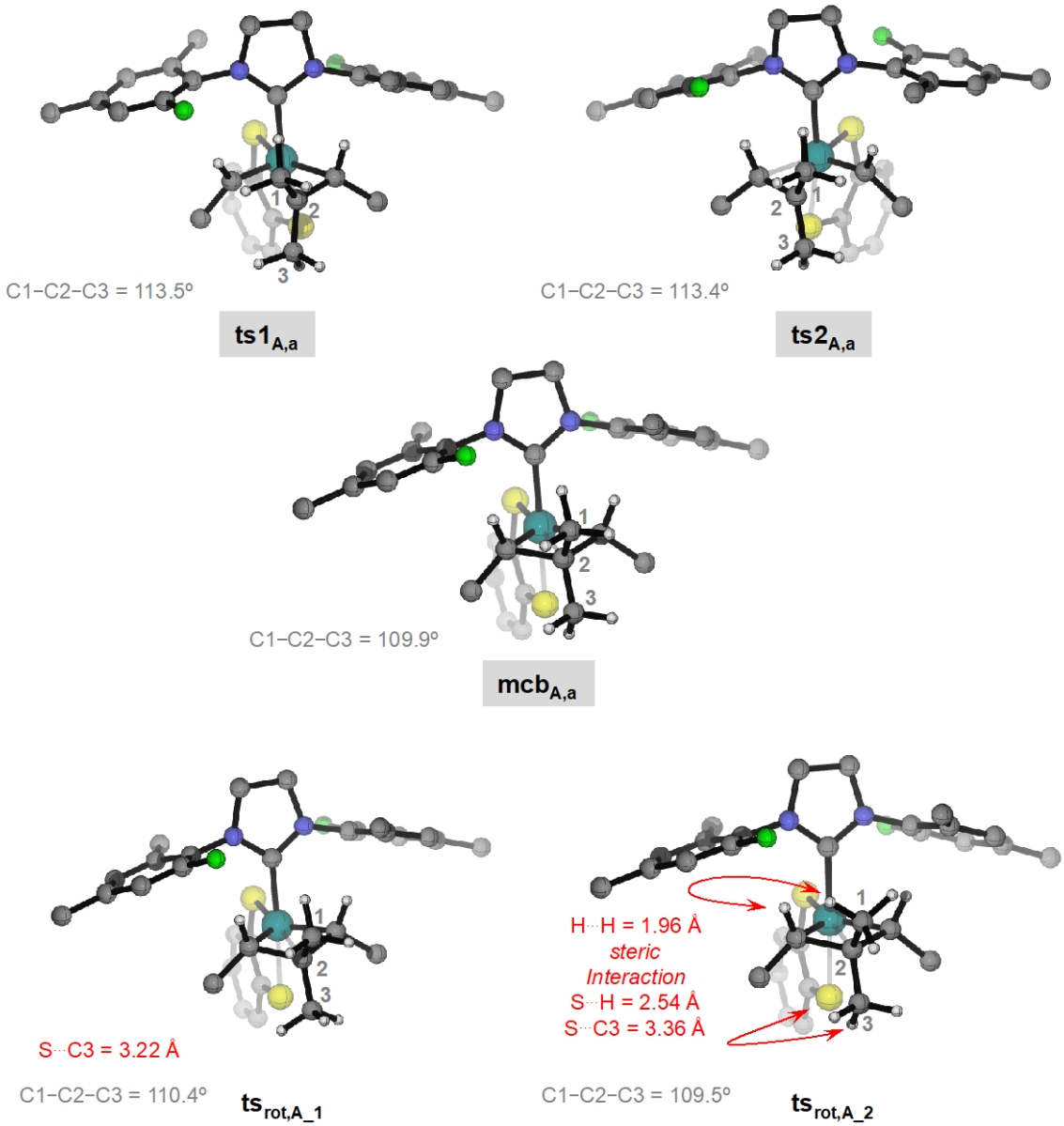


Fig. S1-1. Computed structures for mode of reaction A (cf. Fig. 1) at the B97XD/Def2SVP$_{thf(PCM)}$ level.

Computed structures for mode of reaction B (cf. Fig. 1, ωB97XD/Def2SVP$_{thf(PCM)}$)

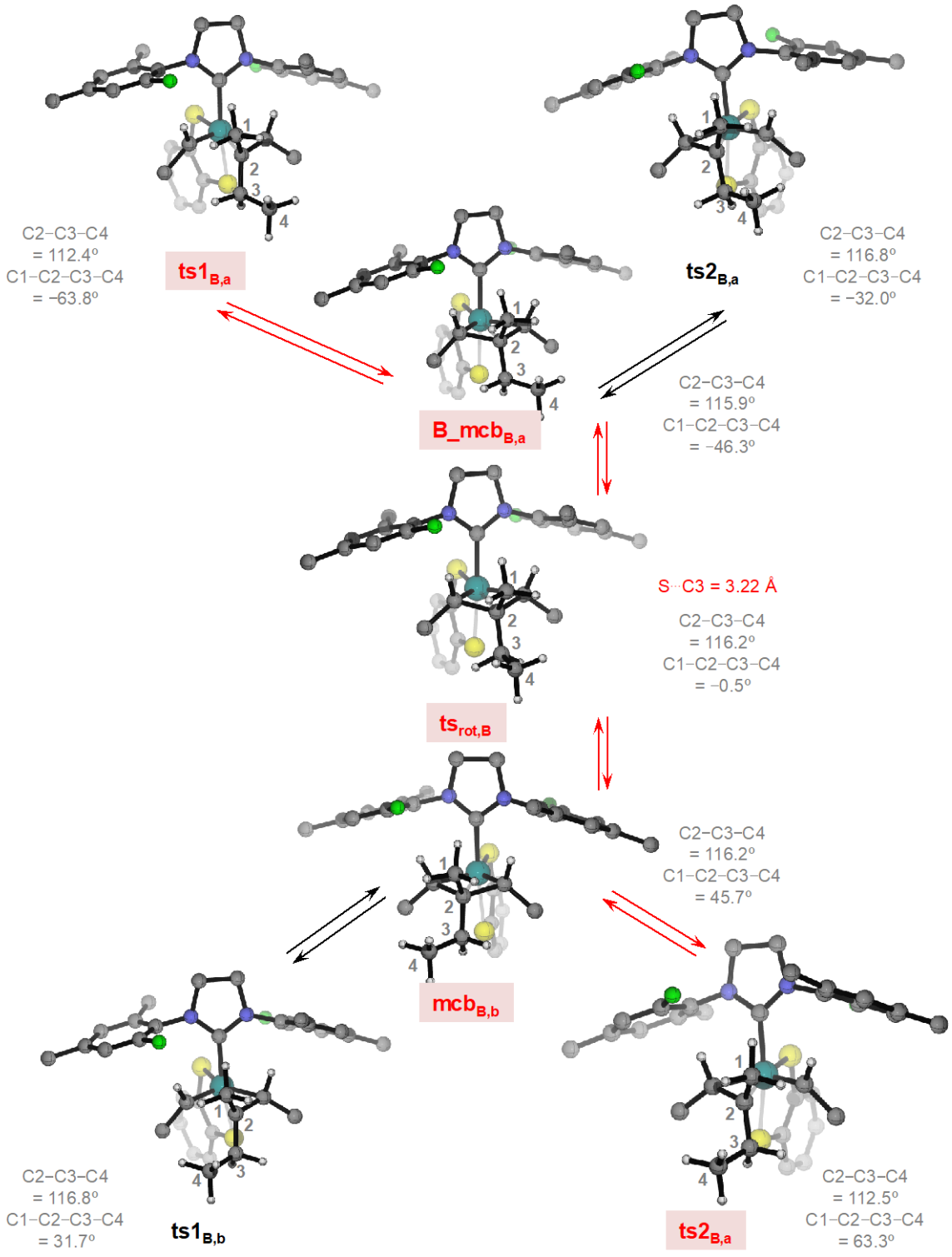


Fig. S1-2. Computed structures for mode of reaction B (cf. Fig. 1) at the B97XD/Def2SVP$_{THF(PCM)}$ level.

Computed structures for mode of reaction C (cf. Fig. 1, ωB97XD/Def2SVP$_{thf(PCM)}$)

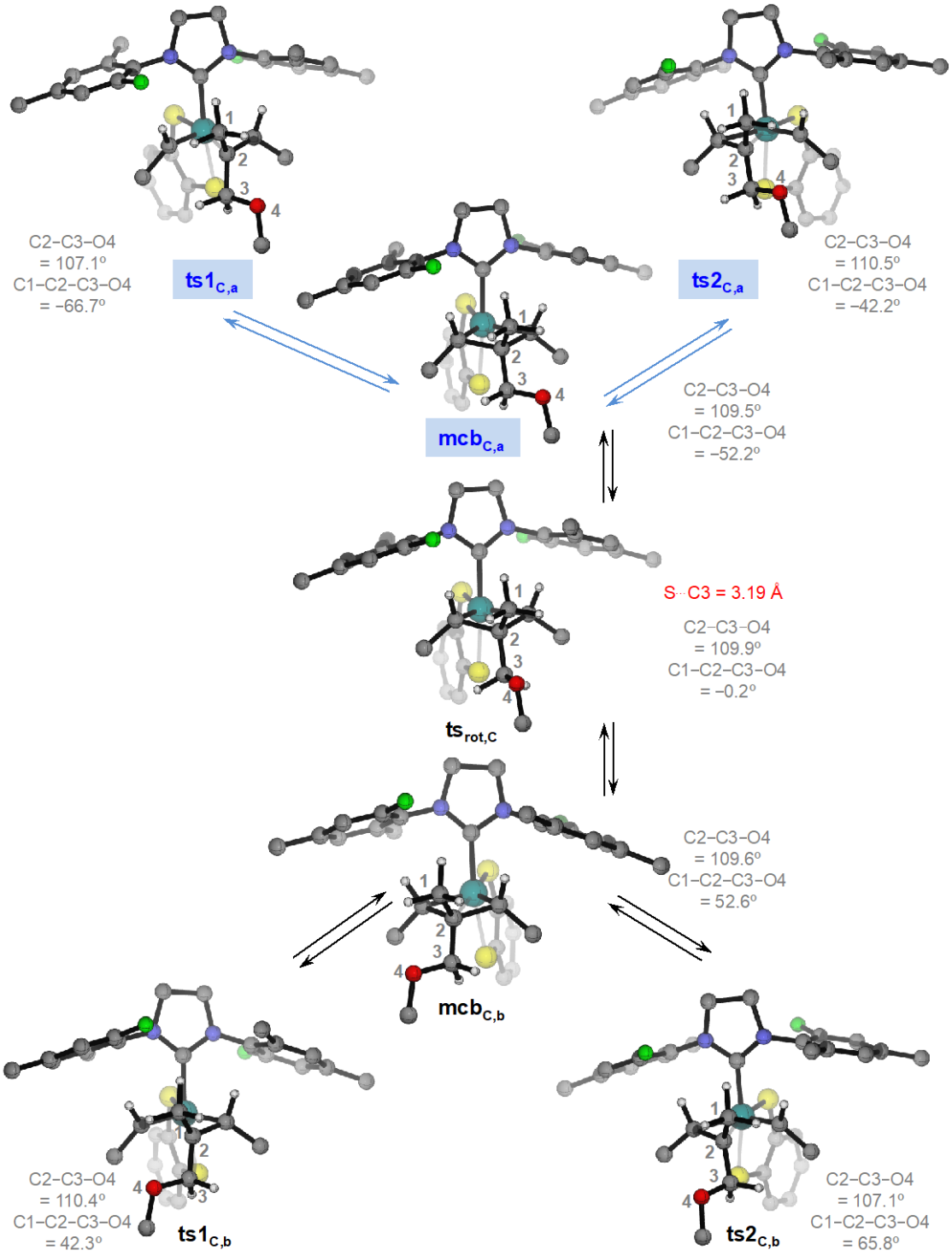


Fig. S1-3. Computed structures for mode of reaction C (cf. Fig. 1) at the B97XD/Def2SVP$_{THF(PCM)}$ level.

Computed structures for mode of reaction D (cf. Fig. 1, ωB97XD/Def2SVP$_{THF(PCM)}$)

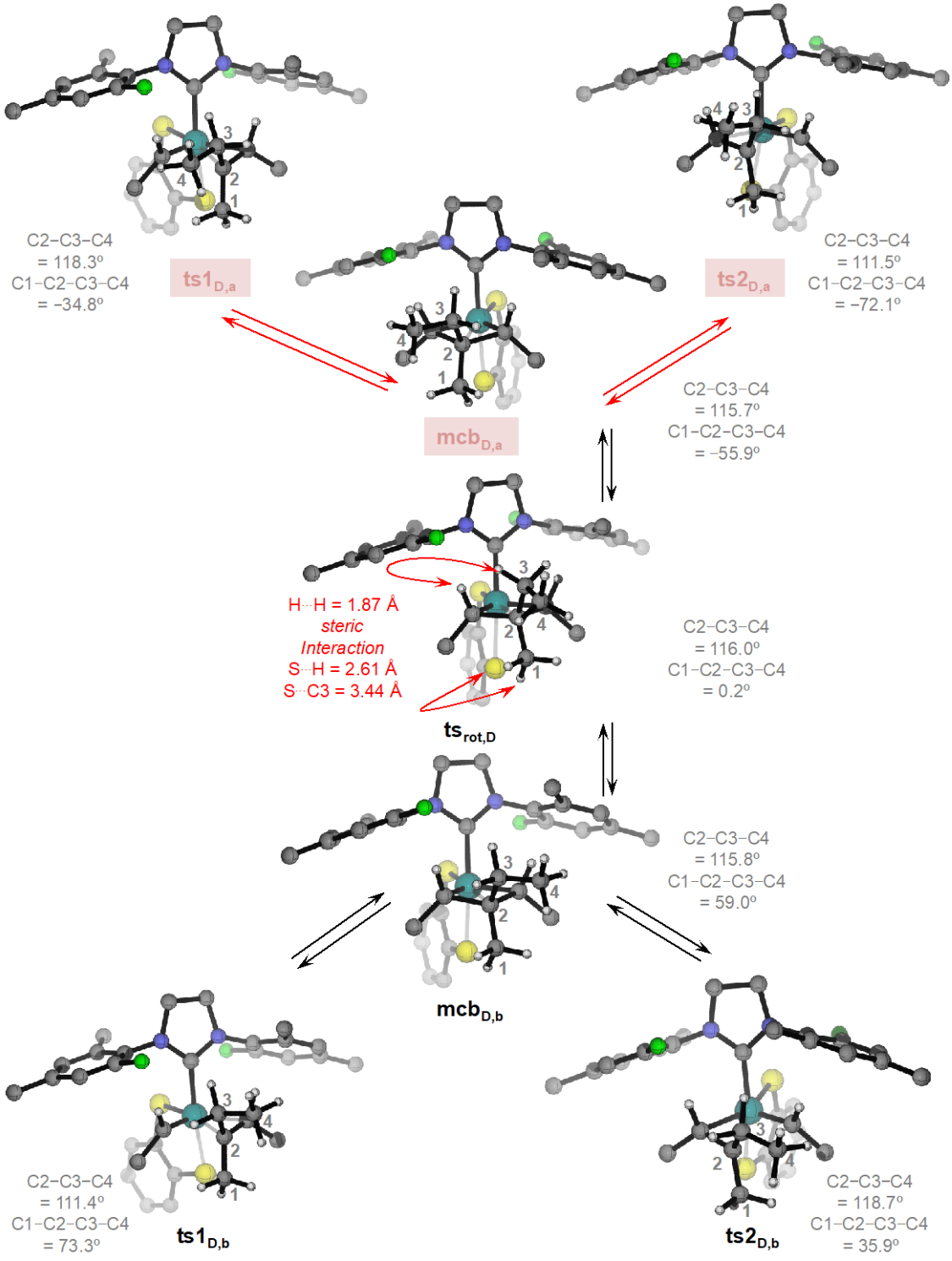


Fig. S1-4. Computed structures for mode of reaction D (cf. Fig. 1) at the B97XD/Def2SVP$_{THF(PCM)}$ level.

Computed structures for mode of reaction E (cf. Fig. 1, ωB97XD/Def2SVP$_{thf(PCM)}$)

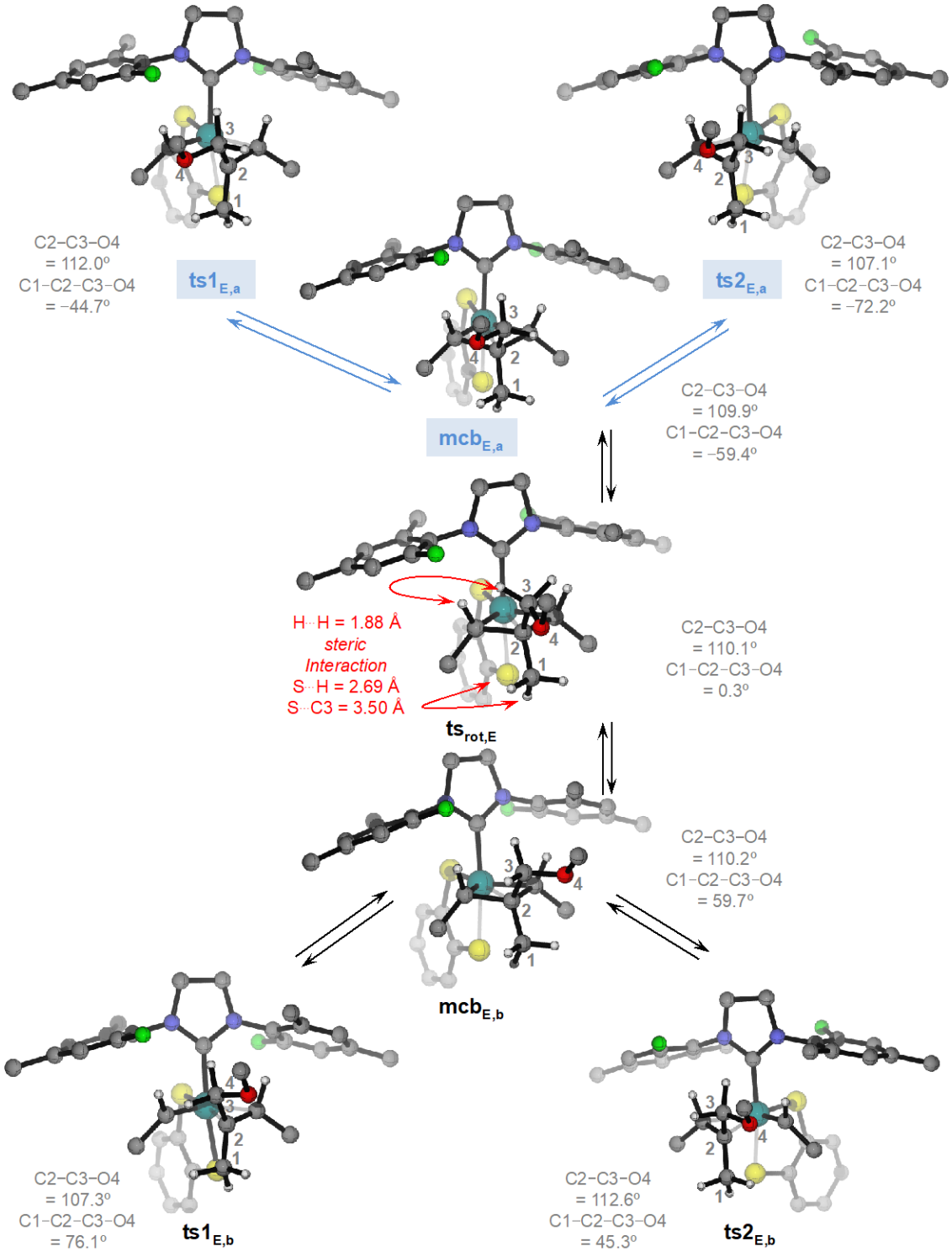


Fig. S1-5. Computed structures for mode of reaction E (cf. Fig. 1) at the B97XD/Def2SVP$_{THF(PCM)}$ level.

Free energies with MN15/Def2TZVPP$_{thf(SMD)}$//ωB97XD/Def2SVP$_{thf(PCM)}$

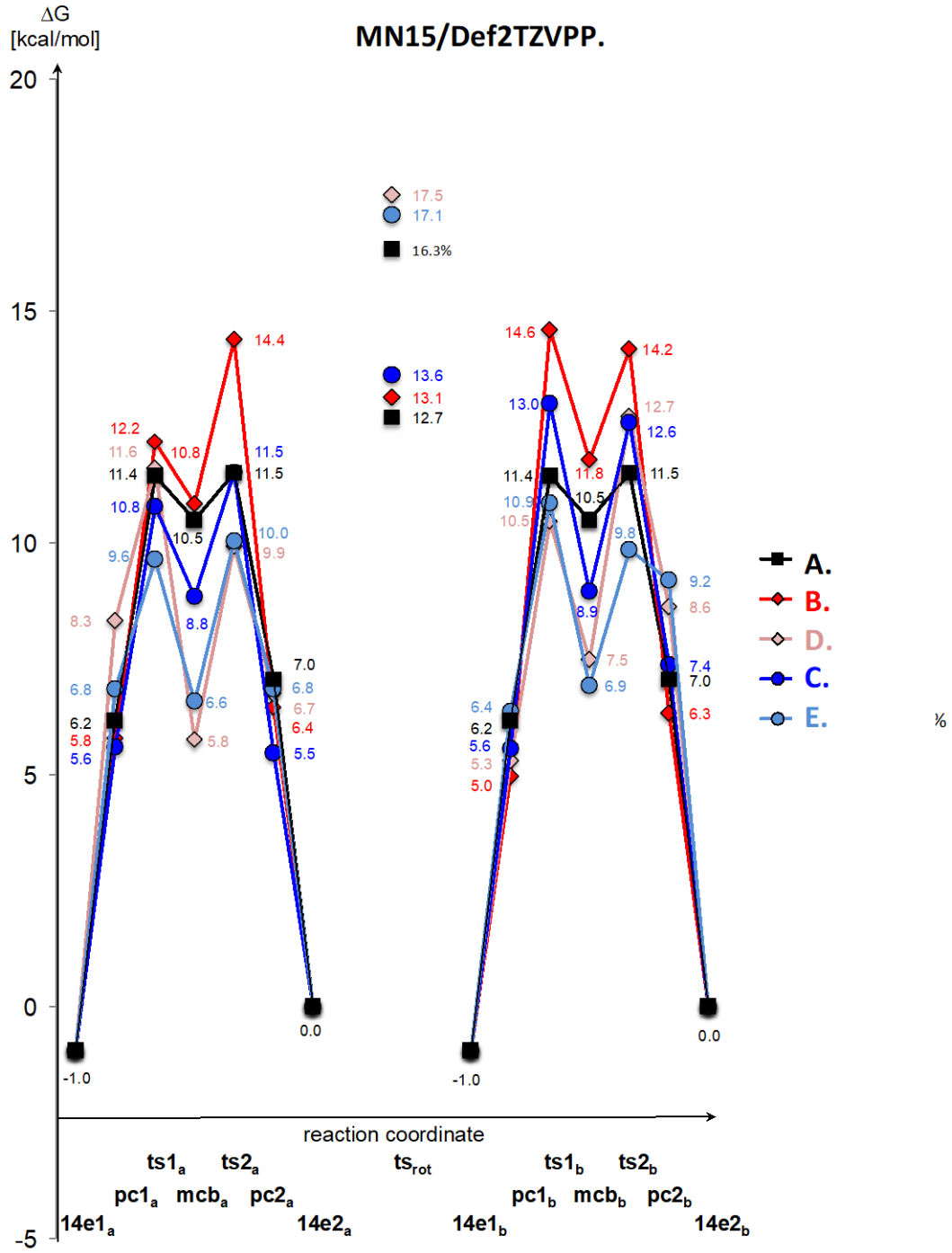


Fig. S2-1. Free energy barriers (G) for two the orientations of the alkyl substituent (a and b) with MN15//Def2TZVPP and THF as solvent (SMD model) after optimization with B97XD/Def2SVP$_{THF(PCM)}$. 14e = 14-electron complex, pc = π complex, ts = transition state, mcb = metallacylcobutane.

Free energies with M06/Def2TZVPP$_{thf(SMD)}$//ωB97XD/Def2SVP$_{thf(PCM)}$

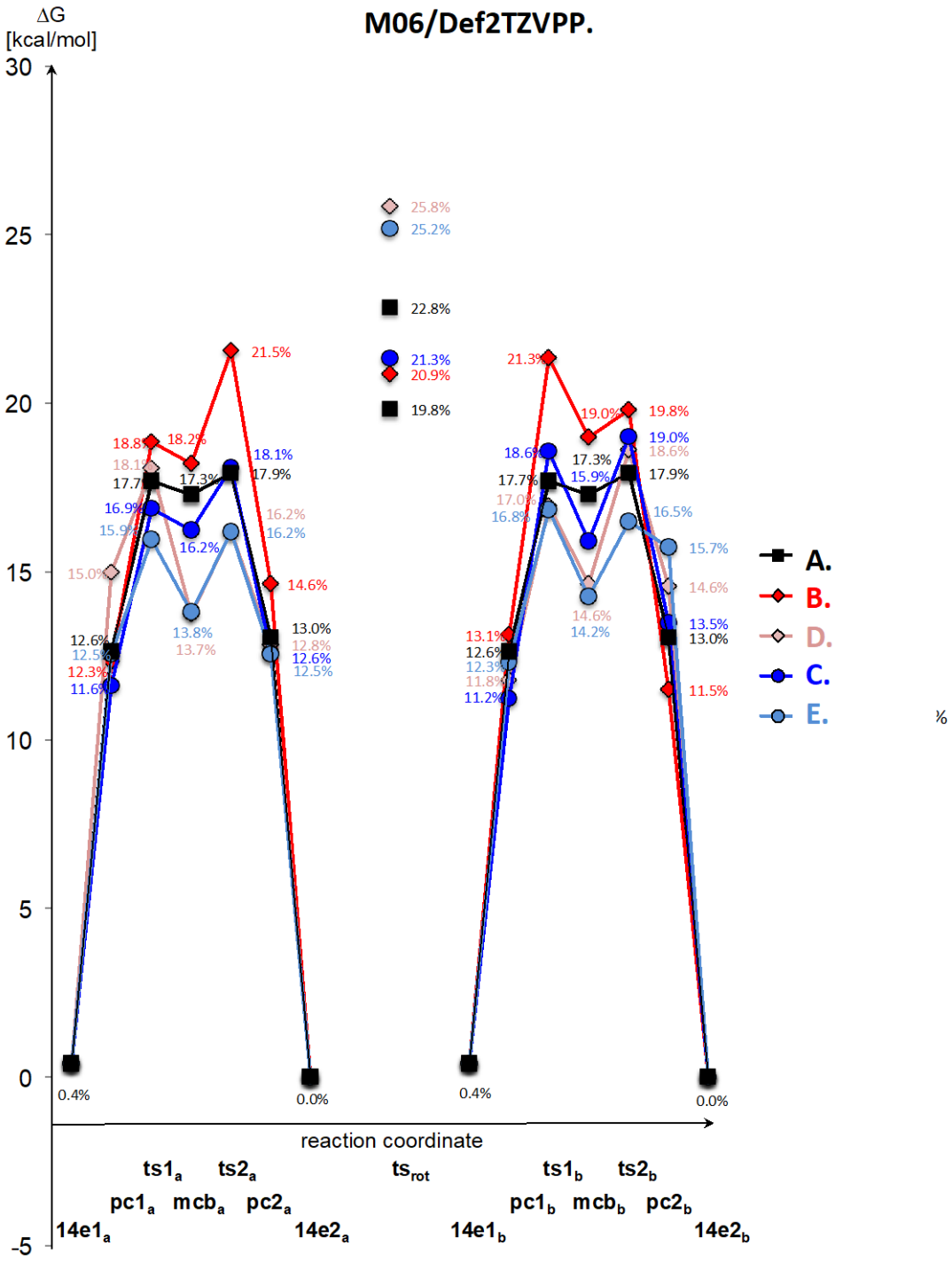


Fig. S2-2. Free energy barriers (G) for two the orientations of the alkyl substituent (a and b) with M06//Def2TZVPP and THF as solvent (SMD model) after optimization with B97XD/Def2SVP$_{THF(PCM)}$. 14e = 14-electron complex, pc = π complex, ts = transition state, mcb = metallacylcobutane.

Free energies with □B97XD/Def2TZVPP$_{thf(SMD)}$//ωB97XD/Def2SVP$_{thf(PCM)}$

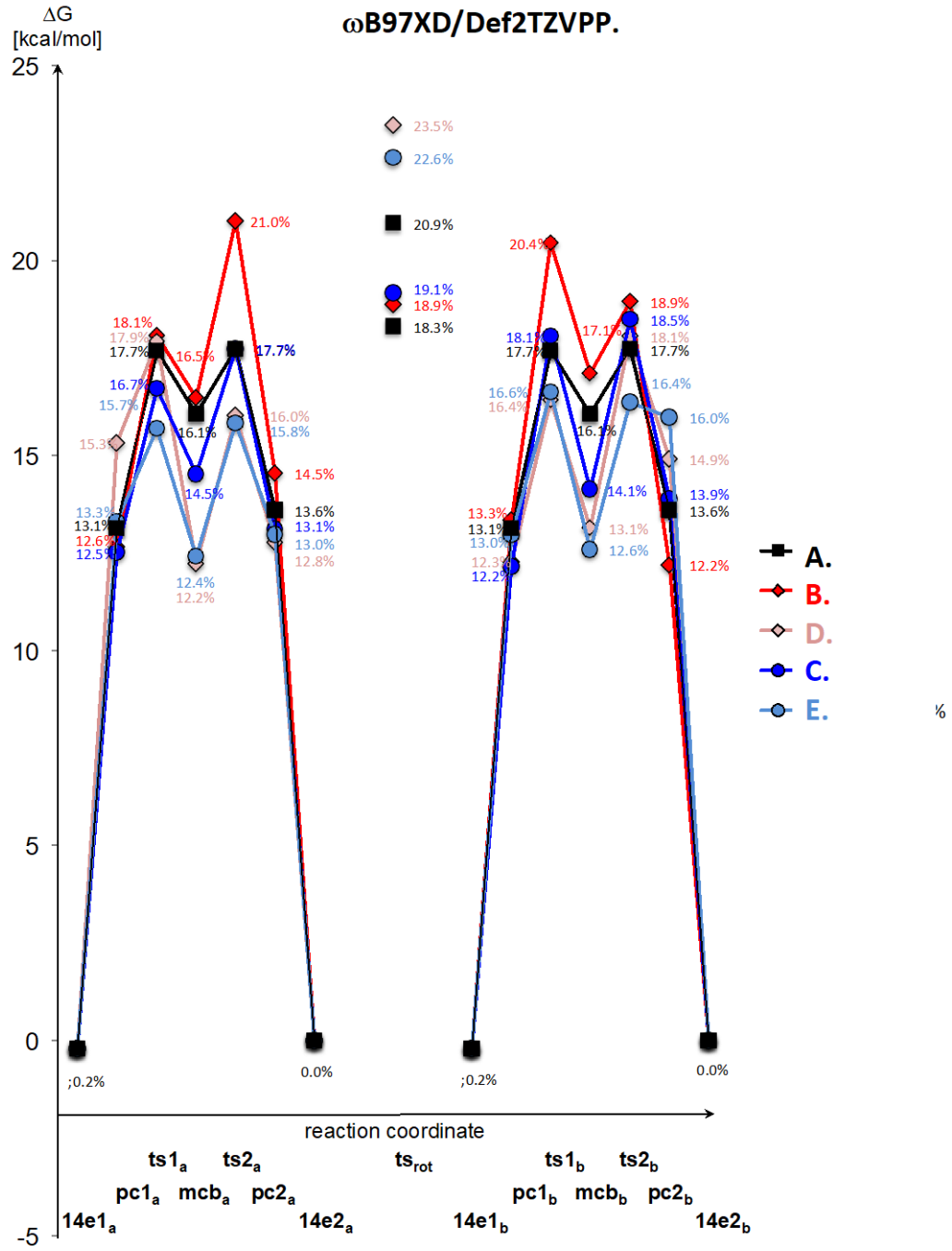


Fig. S2-3. Free energy barriers (G) for two the orientations of the alkyl substituent (a and b) withB97XD//Def2TZVPP and THF as solvent (SMD model) after optimization with B97XD/Def2SVP$_{THF(PCM)}$. 14e = 14-electron complex, pc = π complex, ts = transition state, mcb = metallacylcobutane.

Free energies with PBE0-D3BJ/Def2TZVPP$_{thf(SMD)}$//ωB97XD/Def2SVP$_{thf(PCM)}$

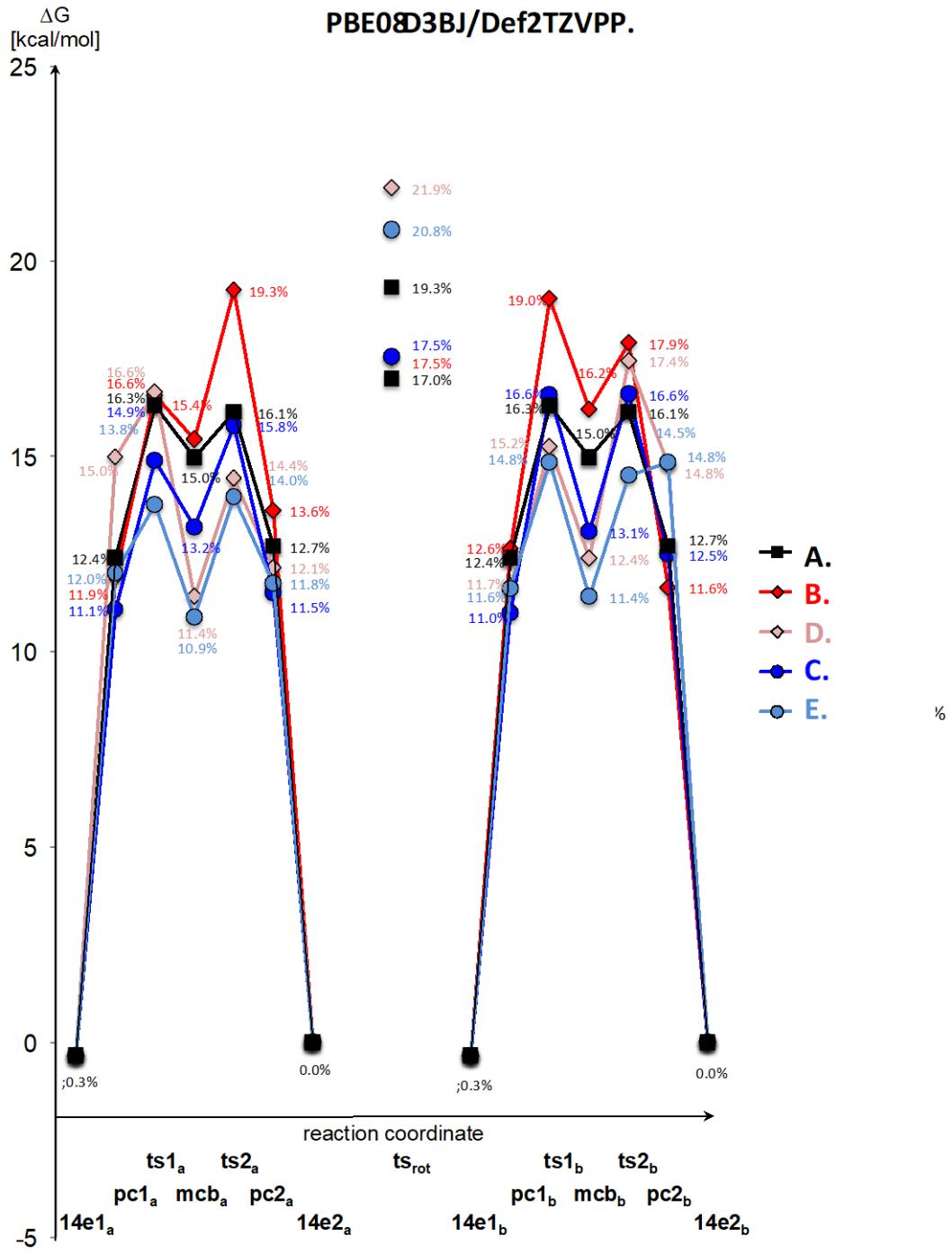


Fig. S2-4. Free energy barriers (G) for two the orientations of the alkyl substituent (a and b) with PBE0D3BJ//Def2TZVPP and THF as solvent (SMD model) after optimization with B97XD/Def2SVP$_{THF(PCM)}$. 14e = 14-electron complex, pc = π complex, ts = transition state, mcb = metallacylcobutane.

Free energies with PBE0/Def2TZVPP$_{thf(SMD)}$//ωB97XD/Def2SVP$_{thf(PCM)}$

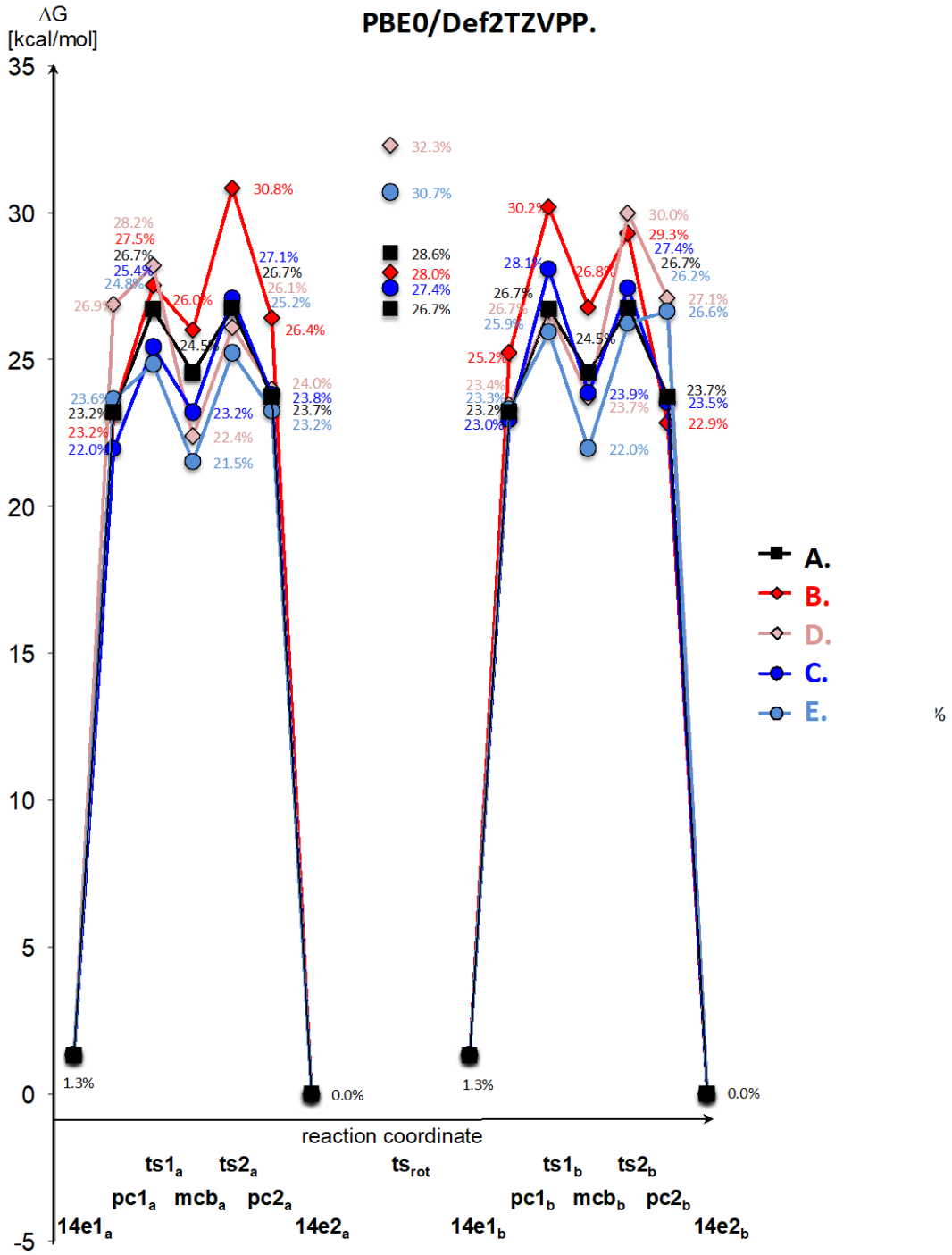


Fig. S2-5. Free energy barriers (G) for two the orientations of the alkyl substituent (a and b) with PBE0//Def2TZVPP and THF as solvent (SMD model) after optimization with B97XD/Def2SVP$_{THF(PCM)}$. 14e = 14-electron complex, pc = π complex, ts = transition state, mcb = metallacylcobutane.

Energies and Gibbs free energies

Optimization in Fig. 1 with ωB97XD/Def2SVP$_{THF(PCM)}$

	ωB97XD/Def2SVP in thf(PCM)					
structure	E(sum) [hartree]	□ΔE [kcal/mol]	G(sum) [hartree]	□ΔG [kcal/mol]	□ΔG$_{Corr}$ [kcal/mol]	Freq [cm^{-1}]
Z-2-Me-2-butene						86.0
Figure_1A:_14e1	-2441.00166994	-0.1	-2440.470469	-0.8	-0.8	11.0
Figure_1A:_pc1a	-2441.02296988	-13.4	-2440.461851	4.6	18.0	20.8
Figure_1A:_ts1a	-2441.01679971	-9.5	-2440.455093	8.8	18.4	-107.8
Figure_1A:_mcba	-2441.02682580	-15.8	-2440.459038	6.4	22.2	-30.9
Figure_1A:_ts2a	-2441.01681448	-9.6	-2440.456079	8.2	17.8	-119.3
Figure_1A:_pc2a	-2441.02256558	-13.2	-2440.462625	4.1	17.3	10.9
Figure_1A:_14e2	-2441.00158500	0.0	-2440.469178	0.0	0.0	18.6
Figure_1A:_ts_rot1	-2441.01978878	-11.4	-2440.455507	8.6	20.0	-319.4
Figure_1A:_14e1	-2441.00166994	-0.1	-2440.470469	-0.8	-0.8	11.0
Figure_1A:_pc1a	-2441.02296988	-13.4	-2440.461851	4.6	18.0	20.8
Figure_1A:_ts1a	-2441.01679971	-9.5	-2440.455093	8.8	18.4	-107.8
Figure_1A:_mcba	-2441.02682580	-15.8	-2440.459038	6.4	22.2	-30.9
Figure_1A:_ts2a	-2441.01681448	-9.6	-2440.456079	8.2	17.8	-119.3
Figure_1A:_pc2a	-2441.02256558	-13.2	-2440.462625	4.1	17.3	10.9
Figure_1A:_14e2	-2441.00158500	0.0	-2440.469178	0.0	0.0	18.6
Z-2-Me-2-butene						86.0
Figure_1A:_14e1	-2441.00166994	-0.1	-2440.470469	-0.8	-0.8	11.0
Figure_1A:_pc1a	-2441.02296988	-13.4	-2440.461851	4.6	18.0	20.8
Figure_1A:_ts1a	-2441.01679971	-9.5	-2440.455093	8.8	18.4	-107.8
Figure_1A:_mcba	-2441.02682580	-15.8	-2440.459038	6.4	22.2	-30.9
Figure_1A:_ts2a	-2441.01681448	-9.6	-2440.456079	8.2	17.8	-119.3

Figure_1A:_pc2a	-2441.02256558	-13.2	-2440.462625	4.1	17.3	10.9
Figure_1A:_14e2	-2441.00158500	0.0	-2440.469178	0.0	0.0	18.6
Figure_1A:_ts_rot2	-2441.01670882	-9.5	-2440.451129	11.3	20.8	-319.4
Figure_1A:_14e1	-2441.00166994	-0.1	-2440.470469	-0.8	-0.8	11.0
Figure_1A:_pc1b	-2441.02296988	-13.4	-2440.461851	4.6	18.0	20.8
Figure_1A:_ts1b	-2441.01679971	-9.5	-2440.455093	8.8	18.4	-107.8
Figure_1A:_mcbb	-2441.02682580	-15.8	-2440.459038	6.4	22.2	-30.9
Figure_1A:_ts2b	-2441.01681448	-9.6	-2440.456079	8.2	17.8	-119.3
Figure_1A:_pc2b	-2441.02256558	-13.2	-2440.462625	4.1	17.3	10.9
Figure_1A:_14e2	-2441.00158500	0.0	-2440.469178	0.0	0.0	18.6
Z-3-Me-pent-2-ene						62.9
Figure_1B:_14e1	-2480.27613550	-0.1	-2479.717623	-0.8	-0.8	11.0
Figure_1B:_pc1a	-2480.29824226	-13.9	-2479.709998	4.0	17.9	19.5
Figure_1B:_ts1a	-2480.29158860	-9.8	-2479.701988	9.0	18.8	-119.0
Figure_1B:_mcba	-2480.29757701	-13.5	-2479.705849	6.6	20.1	14.0
Figure_1B:_ts2a	-2480.28879050	-8.0	-2479.698493	11.2	19.2	-163.7
Figure_1B:_pc2a	-2480.29933950	-14.6	-2479.709590	4.2	18.8	22.3
Figure_1B:_14e2	-2480.27605056	0.0	-2479.716332	0.0	0.0	18.6
Figure_1B:_ts_rot	-2480.29252087	-10.3	-2479.702279	8.8	19.2	-111.5
Figure_1B:_14e1	-2480.27613550	-0.1	-2479.717623	-0.8	-0.8	11.0
Figure_1B:_pc1b	-2480.29962133	-14.8	-2479.710045	3.9	18.7	18.6
Figure_1B:_ts1b	-2480.28854729	-7.8	-2479.698406	11.2	19.1	-160.8
Figure_1B:_mcbb	-2480.29744658	-13.4	-2479.704602	7.4	20.8	18.3
Figure_1B:_ts2b	-2480.29077148	-9.2	-2479.700919	9.7	18.9	-102.1
Figure_1B:_pc2b	-2480.29642363	-12.8	-2479.711282	3.2	16.0	1.9
Figure_1B:_14e2	-2480.27605056	0.0	-2479.716332	0.0	0.0	18.6

E-3-Me-pent-2-ene						79.8
Figure_1D:_14e1	-2480.27609469	-0.1	-2479.716796	-0.8	-0.8	11.0
Figure_1D:_pc1a	-2480.29539921	-12.2	-2479.705812	6.1	18.2	22.1
Figure_1D:_ts1a	-2480.29104861	-9.4	-2479.701961	8.5	17.9	-106.4
Figure_1D:_mcba	-2480.30339663	-17.2	-2479.712562	1.8	19.0	13.6
Figure_1D:_ts2a	-2480.29374246	-11.1	-2479.705521	6.3	17.4	-105.7
Figure_1D:_pc2a	-2480.29900427	-14.4	-2479.710700	3.0	17.4	24.3
Figure_1D:_14e2	-2480.27600975	0.0	-2479.715505	0.0	0.0	18.6
Figure_1D:_ts_rot	-2480.28989582	-8.7	-2479.694691	13.1	21.8	-154.9
Figure_1D:_14e1	-2480.27609469	-0.1	-2479.716796	-0.8	-0.8	11.0
Figure_1D:_pc1b	-2480.29892456	-14.4	-2479.710294	3.3	17.6	20.2
Figure_1D:_ts1b	-2480.29373439	-11.1	-2479.704129	7.1	18.3	-104.9
Figure_1D:_mcbb	-2480.30318155	-17.1	-2479.711104	2.8	19.8	12.8
Figure_1D:_ts2b	-2480.29074189	-9.2	-2479.701892	8.5	17.8	-108.2
Figure_1D:_pc2b	-2480.29454693	-11.6	-2479.706690	5.5	17.2	22.2
Figure_1D:_14e2	-2480.27600975	0.0	-2479.715505	0.0	0.0	18.6
Z-1-OMe-2-Me-2-butene						43.1
Figure_1C:_14e1	-2555.39720385	-0.1	-2554.835301	-0.8	-0.8	11.0
Figure_1C:_pc1a	-2555.41949149	-14.0	-2554.828008	3.8	17.8	15.4
Figure_1C:_ts1a	-2555.41282736	-9.9	-2554.821613	7.8	17.6	-116.4
Figure_1C:_mcba	-2555.42345401	-16.5	-2554.827791	3.9	20.4	14.4
Figure_1C:_ts2a	-2555.41466450	-11.0	-2554.822602	7.2	18.2	-128.1
Figure_1C:_pc2a	-2555.42235225	-15.8	-2554.831270	1.7	17.6	16.9
Figure_1C:_14e2	-2555.39711891	0.0	-2554.834010	0.0	0.0	18.6
Figure_1C:_ts_rot	-2555.41491956	-11.2	-2554.819492	9.1	20.3	-123.8
Figure_1C:_14e1	-2555.39720385	-0.1	-2554.835301	-0.8	-0.8	11.0
Figure_1C:_pc1b	-2555.42245101	-15.9	-2554.831741	1.4	17.3	11.3
Figure_1C:_ts1b	-2555.41406366	-10.6	-2554.822156	7.4	18.1	-105.3

Figure_1C:_mcbb	-2555.42288927	-16.2	-2554.828914	3.2	19.4	20.1
Figure_1C:_ts2b	-2555.41279751	-9.8	-2554.819981	8.8	18.6	-125.6
Figure_1C:_pc2b	-2555.41914903	-13.8	-2554.827203	4.3	18.1	22.6
Figure_1C:_14e2	-2555.39711891	0.0	-2554.834010	0.0	0.0	18.6
E-1-OMe-2-Me-2-butene						64.5
Figure_1E:_14e1	-2555.39839334	-0.1	-2554.835920	-0.8	-0.8	11.0
Figure_1E:_pc1a	-2555.42134202	-14.5	-2554.830645	2.5	17.0	21.8
Figure_1E:_ts1a	-2555.41671996	-11.6	-2554.826465	5.1	16.7	-112.8
Figure_1E:_mcba	-2555.42775261	-18.5	-2554.832178	1.5	20.0	-38.9
Figure_1E:_ts2a	-2555.41432520	-10.1	-2554.824903	6.1	16.2	-116.4
Figure_1E:_pc2a	-2555.41918809	-13.1	-2554.829250	3.4	16.5	13.8
Figure_1E:_14e2	-2555.39830840	0.0	-2554.834629	0.0	0.0	18.6
Figure_1E:_ts_rot	-2555.41086636	-7.9	-2554.814956	12.3	20.2	-168.3
Figure_1E:_14e1	-2555.39839334	-0.1	-2554.835920	-0.8	-0.8	11.0
Figure_1E:_pc1b	-2555.42053133	-13.9	-2554.829351	3.3	17.3	17.3
Figure_1E:_ts1b	-2555.41526318	-10.6	-2554.823718	6.8	17.5	-109.7
Figure_1E:_mcbb	-2555.42880752	-19.1	-2554.832579	1.3	20.4	14.3
Figure_1E:_ts2b	-2555.41702938	-11.7	-2554.825621	5.7	17.4	-93.4
Figure_1E:_pc2b	-2555.42056204	-14.0	-2554.827237	4.6	18.6	21.7
Figure_1E:_14e2	-2555.39830840	0.0	-2554.834629	0.0	0.0	18.6

E(sum) . electronic energy in hartree with MN12SX/Def2SVP:UFF in THF(PCM) after mass balance
G(sum) .sum of electronic and thermal free energies with MN12SX/Def2SVP:UFF in THF(PCM) after mass balance
ΔE … relative electronic energy in kcal/mol with MN12SX/Def2SVP:UFF in THF(PCM)
ΔG … relative free energy in kcal/mol with MN12SX/Def2SVP:UFF in THF(PCM)
ΔG_{corr} thermal correction to free energy in kcal/mol obtained with MN12SX/Def2SVP:UFF in THF(PCM)
$\Delta G = \Delta E + \Delta G_{corr}$)
Freq … lowest frequency

Single point energies in Figure 1 with MN15, M06 and □B97XD (Def2TZVPP)

MN15/Def2TZVPP thf(SMD)		M06/Def2TZVPP thf(SMD)		ωB97XD/Def2TZVPP thf(SMD)	
ΔE_{sp} [kcal/mol]	ΔG_{sp} [kcal/mol]	ΔE_{sp} [kcal/mol]	ΔG_{sp} [kcal/mol]	ΔE_{sp} [kcal/mol]	ΔG_{sp} [kcal/mol]
-0.2	-1.0	1.1	0.4	0.5	-0.2
-11.9	6.2	-5.4	12.6	-4.9	13.1
-6.9	11.4	-0.7	17.7	-0.7	17.7
-11.7	10.5	-4.9	17.3	-6.1	16.1
-6.3	11.5	0.1	17.9	-0.1	17.7
-10.2	7.0	-4.2	13.0	-3.7	13.6
0.0	0.0	0.0	0.0	0.0	0.0
-7.3	12.7	-0.2	19.8	-1.7	18.3
-0.2	-1.0	1.1	0.4	0.5	-0.2
-11.9	6.2	-5.4	12.6	-4.9	13.1
-6.9	11.4	-0.7	17.7	-0.7	17.7
-11.7	10.5	-4.9	17.3	-6.1	16.1
-6.3	11.5	0.1	17.9	-0.1	17.7
-10.2	7.0	-4.2	13.0	-3.7	13.6
0.0	0.0	0.0	0.0	0.0	0.0
-0.2	-1.0	1.1	0.4	0.5	-0.2
-11.9	6.2	-5.4	12.6	-4.9	13.1
-6.9	11.4	-0.7	17.7	-0.7	17.7
-11.7	10.5	-4.9	17.3	-6.1	16.1
-6.3	11.5	0.1	17.9	-0.1	17.7
-10.2	7.0	-4.2	13.0	-3.7	13.6
0.0	0.0	0.0	0.0	0.0	0.0
-4.5	16.3	2.0	22.8	0.1	20.9
-0.2	-1.0	1.1	0.4	0.5	-0.2
-11.9	6.2	-5.4	12.6	-4.9	13.1
-6.9	11.4	-0.7	17.7	-0.7	17.7
-11.7	10.5	-4.9	17.3	-6.1	16.1
-6.3	11.5	0.1	17.9	-0.1	17.7
-10.2	7.0	-4.2	13.0	-3.7	13.6
0.0	0.0	0.0	0.0	0.0	0.0
-0.2	-1.0	1.1	0.4	0.5	-0.2
-12.1	5.8	-5.6	12.3	-5.3	12.6
-6.6	12.2	0.1	18.8	-0.7	18.1
-9.2	10.8	-1.9	18.2	-3.6	16.5
-4.8	14.4	2.4	21.5	1.8	21.0
-12.4	6.4	-4.2	14.6	-4.3	14.5
0.0	0.0	0.0	0.0	0.0	0.0
-6.0	13.1	1.7	20.9	-0.3	18.9
-0.2	-1.0	1.1	0.4	0.5	-0.2
-13.8	5.0	-5.6	13.1	-5.4	13.3
-4.5	14.6	2.2	21.3	1.4	20.4
-9.0	11.8	-1.8	19.0	-3.7	17.1
-4.7	14.2	0.9	19.8	0.0	18.9
-9.6	6.3	-4.5	11.5	-3.8	12.2
0.0	0.0	0.0	0.0	0.0	0.0

-0.2	-1.0	1.1	0.4	0.5	-0.2
-9.9	8.3	-3.3	15.0	-2.9	15.3
-6.3	11.6	0.1	18.1	0.0	17.9
-13.3	5.8	-5.3	13.7	-6.8	12.2
-7.5	9.9	-1.2	16.2	-1.4	16.0
-10.7	6.7	-4.6	12.8	-4.7	12.8
0.0	0.0	0.0	0.0	0.0	0.0
-4.3	17.5	4.1	25.8	1.7	23.5
-0.2	-1.0	1.1	0.4	0.5	-0.2
-12.4	5.3	-5.9	11.8	-5.4	12.3
-7.8	10.5	-1.3	17.0	-1.8	16.4
-12.3	7.5	-5.2	14.6	-6.7	13.1
-5.1	12.7	0.8	18.6	0.3	18.1
-8.5	8.6	-2.6	14.6	-2.3	14.9
0.0	0.0	0.0	0.0	0.0	0.0
-0.2	-1.0	1.1	0.4	0.5	-0.2
-12.2	5.6	-6.2	11.6	-5.3	12.5
-6.9	10.8	-0.8	16.9	-0.9	16.7
-11.6	8.8	-4.2	16.2	-5.9	14.5
-6.6	11.5	-0.1	18.1	-0.4	17.7
-12.1	5.5	-5.0	12.6	-4.4	13.1
0.0	0.0	0.0	0.0	0.0	0.0
-6.7	13.6	1.0	21.3	-1.1	19.1
-0.2	-1.0	1.1	0.4	0.5	-0.2
-11.8	5.6	-6.1	11.2	-5.2	12.2
-5.1	13.0	0.5	18.6	0.0	18.1
-10.4	8.9	-3.5	15.9	-5.2	14.1
-6.0	12.6	0.4	19.0	-0.2	18.5
-10.7	7.4	-4.6	13.5	-4.2	13.9
0.0	0.0	0.0	0.0	0.0	0.0
-0.2	-1.0	1.1	0.4	0.5	-0.2
-10.1	6.8	-4.4	12.5	-3.7	13.3
-7.0	9.6	-0.7	15.9	-1.0	15.7
-13.4	6.6	-6.2	13.8	-7.6	12.4
-6.1	10.0	0.0	16.2	-0.3	15.8
-9.6	6.8	-3.9	12.5	-3.5	13.0
0.0	0.0	0.0	0.0	0.0	0.0
-3.2	17.1	5.0	25.2	2.4	22.6
-0.2	-1.0	1.1	0.4	0.5	-0.2
-10.9	6.4	-4.9	12.3	-4.3	13.0
-6.6	10.9	-0.7	16.8	-0.9	16.6
-13.5	6.9	-6.2	14.2	-7.8	12.6
-7.6	9.8	-0.9	16.5	-1.0	16.4
-9.4	9.2	-2.9	15.7	-2.6	16.0
0.0	0.0	0.0	0.0	0.0	0.0

ΔE_{sp} … relative single point electronic energy in thf(PCM) in kcal/mol with Def2TZVPP
ΔG_{sp} … relative single point free energy in thf(PCM) in kcal/mol $\Delta G_{sp} = \Delta E_{sp}$/Def2TZVPP + ΔG_{corr}[level of optimization])

Single point energies in Figure 1 with PBE0-D3BJ and PBE0 (Def2TZVPP)

PBE0-D3BJ/Def2TZVPP thf(SMD)		PBE0/Def2TZVPP thf(SMD)	
ΔE_{sp} [kcal/mol]	ΔG_{sp} [kcal/mol]	ΔE_{sp} [kcal/mol]	ΔG_{sp} [kcal/mol]
0.4	-0.3	2.1	1.3
-5.6	12.4	5.2	23.2
-2.1	16.3	8.3	26.7
-7.2	15.0	2.3	24.5
-1.6	16.1	9.0	26.7
-4.6	12.7	6.5	23.7
0.0	0.0	0.0	0.0
-3.0	17.0	6.7	26.7
0.4	-0.3	2.1	1.3
-5.6	12.4	5.2	23.2
-2.1	16.3	8.3	26.7
-7.2	15.0	2.3	24.5
-1.6	16.1	9.0	26.7
-4.6	12.7	6.5	23.7
0.0	0.0	0.0	0.0
0.4	-0.3	2.1	1.3
-5.6	12.4	5.2	23.2
-2.1	16.3	8.3	26.7
-7.2	15.0	2.3	24.5
-1.6	16.1	9.0	26.7
-4.6	12.7	6.5	23.7
0.0	0.0	0.0	0.0
-1.5	19.3	7.8	28.6
0.4	-0.3	2.1	1.3
-5.6	12.4	5.2	23.2
-2.1	16.3	8.3	26.7
-7.2	15.0	2.3	24.5
-1.6	16.1	9.0	26.7
-4.6	12.7	6.5	23.7
0.0	0.0	0.0	0.0
0.4	-0.3	2.1	1.3
-6.0	11.9	5.3	23.2
-2.2	16.6	8.8	27.5
-4.6	15.4	5.9	26.0
0.1	19.3	11.6	30.8
-5.2	13.6	7.6	26.4
0.0	0.0	0.0	0.0
-1.6	17.5	8.8	28.0
0.4	-0.3	2.1	1.3
-6.1	12.6	6.5	25.2
-0.1	19.0	11.1	30.2
-4.6	16.2	6.0	26.8
-1.0	17.9	10.4	29.3
-4.3	11.6	6.9	22.9

0.0	0.0	0.0	0.0
0.4	-0.3	2.1	1.3
-3.3	15.0	8.6	26.9
-1.3	16.6	10.3	28.2
-7.6	11.4	3.4	22.4
-3.0	14.4	8.7	26.1
-5.3	12.1	6.5	24.0
0.0	0.0	0.0	0.0
0.1	21.9	10.5	32.3
0.4	-0.3	2.1	1.3
-6.0	11.7	5.8	23.4
-3.0	15.2	8.4	26.7
-7.4	12.4	3.9	23.7
-0.3	17.4	12.2	30.0
-2.4	14.8	9.9	27.1
0.0	0.0	0.0	0.0
0.4	-0.3	2.1	1.3
-6.7	11.1	4.2	22.0
-2.7	14.9	7.8	25.4
-7.2	13.2	2.8	23.2
-2.4	15.8	8.9	27.1
-6.0	11.5	6.2	23.8
0.0	0.0	0.0	0.0
-2.7	17.5	7.1	27.4
0.4	-0.3	2.1	1.3
-6.3	11.0	5.6	23.0
-1.5	16.6	10.0	28.1
-6.3	13.1	4.5	23.9
-2.1	16.6	8.8	27.4
-5.6	12.5	5.5	23.5
0.0	0.0	0.0	0.0
0.4	-0.3	2.1	1.3
-4.9	12.0	6.7	23.6
-2.9	13.8	8.2	24.8
-9.1	10.9	1.5	21.5
-2.2	14.0	9.1	25.2
-4.7	11.8	6.8	23.2
0.0	0.0	0.0	0.0
0.6	20.8	10.5	30.7
0.4	-0.3	2.1	1.3
-5.6	11.6	6.1	23.3
-2.6	14.8	8.5	25.9
-9.0	11.4	1.5	22.0
-2.9	14.5	8.8	26.2
-3.8	14.8	8.0	26.6
0.0	0.0	0.0	0.0

ΔE_{sp} … relative single point electronic energy in thf(PCM) in kcal/mol with Def2TZVPP
ΔG_{sp} … relative single point free energy in thf(PCM) in kcal/mol $\Delta G_{sp} = \Delta E_{sp}$/Def2TZVPP + ΔG_{corr}[level of optimization])

Chapter Three

A Ru-Based Catechothiolate Catalyst Bearing an Unsaturated NHC Ligand for Synthesis of Z-α,β-Unsaturated Carbonyl Compounds by Cross Metathesis

3.1 Introduction

Z-α,β-Unsaturated carbonyl moieties are found in many biologically active molecules (e.g., neopeltolide,[1] motualevic acid B,[2] and 6-nor-absicic acid;[3] Scheme 3.1) and can be used as precursors to many more bioactive entities (e.g., dihydrocompactin,[4] Scheme 3.1). Among the methods commonly used for synthesis of *Z-α,β*-unsaturated carbonyl compounds are Wittig-type processes[5] or partial hydrogenation reactions of internal ynonates (Scheme 3.2).[6] The former set typically requires the use of strongly basic conditions (e.g., KO*t*-Bu[7] or KHMDS[8]), low reaction temperatures,[9] and/or stoichiometric amounts of toxic additives (e.g., 18-crown-6);[5b] an example is the conversion of aldehyde **3.1** to *Z*-enone **3.2** (Scheme 3.2a). An *α,β*-unsaturated carboxylic acid cannot be accessed

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(1) (a) Wright, A. E.; Botelho, J. C.; Guzman, E.; Harmody, D.; Linley, P.; McCarthy, P. J.; Pitts, T. P.; Pomponi, S. A.; Reed, J. K. *J. Nat. Prod.* **2007**, *70*, 412–416. (b) Yu, M.; Schrock, R. R.; Hoveyda, A. H. *Angew. Chem., Int. Ed*. **2014**, *54*, 215–220.

(2) Keffer, J. L.; Plaza, A.; Bewley, C. A. *Org. Lett*. **2009**, *11*, 1087−1090.

(3) Ueno, K.; Araki, Y.; Hirai, N.; Saito, S.; Mizutani, M.; Sakata, K.; Todoroki, Y. *Bioorg. Med. Chem*. **2005**, *13*, 3359−3370.

(4) Sammakia, T.; Johns, D. M.; Kim, G.; Berliner, M. A. *J. Am. Chem. Soc*. **2005**, *127*, 6504−6505.

(5) (a) Ando, K. *Synlett* **2001**, *2001*, 1272−1274. (b) Fortin, S.; Dupont, F.; Deslongchamps, P. *J. Org. Chem*. **2002**, *67*, 5437–5439.

(6) Hornberger, K. R.; Hamblett, C. L.; Leighton, J. L. *J. Am. Chem. Soc*. **2000**, *122*, 12894 – 12895.

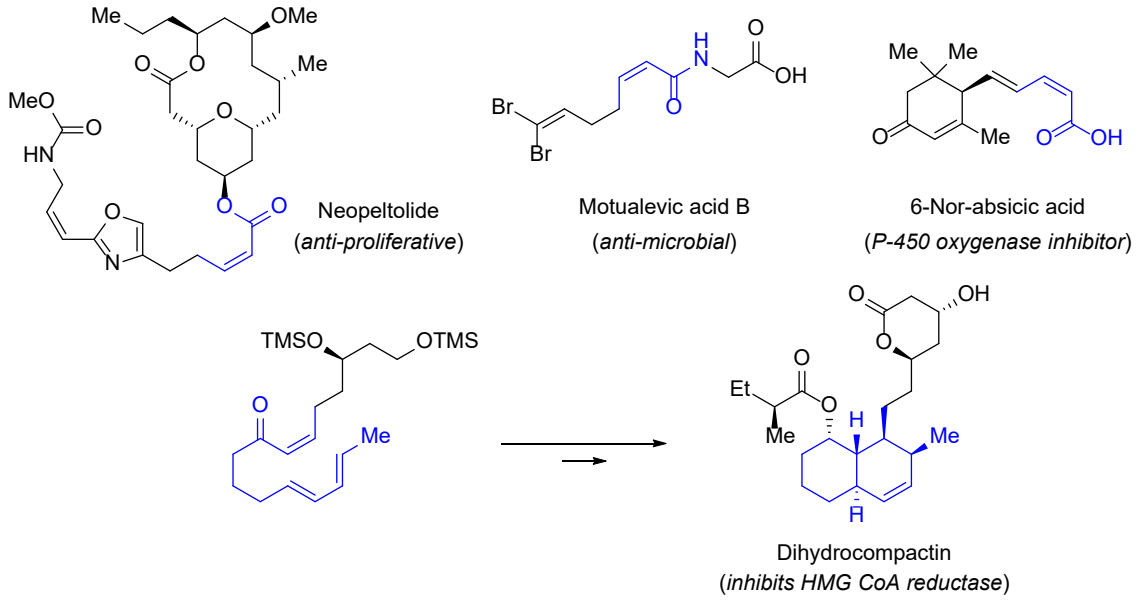
(7) Kojima, S.; Kawaguchi, K.; Matsukawa, S.; Uchida, K.; Akiba, K. *Chem. Lett*. **2002**, *31*, 170−171.

(8) Wang, Y.; Janjic, J.; Kozmin, S. A. *J. Am. Chem. Soc*. **2002**, *12*4, 13670−13671.

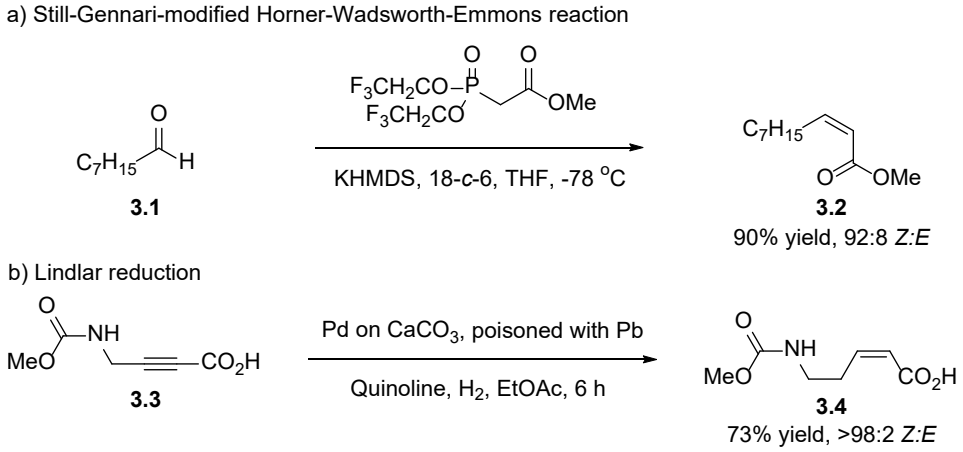
(9) Chatterjee, S.; Ghadigaonkar, S.; Sur, P.; Sharma, A.; Chattopadhyay, S. *J. Org. Chem*. **2014**, *79*, 8067−8076.

efficiently through a Wittig-type process, requiring hydrolysis of a corresponding carboxylic ester under conditions that might result in side reactions.[9] What is more, stereoselectivity of Wittig-type transformations is variable. An alternative strategy for synthesis of an *α,β*-unsaturated acid entails ynoate hydrogenation (e.g., **3.3** to **3.4**, Scheme 3.2b); however, over-reduction, lack of reproducibility, and/or moderate stereoselectivity detract from the utility of such methods.

Scheme 3.1. Representative *Z*-*α,β*-Unsaturated Carbonyl Moieties in Biologically Active Compounds and Synthesis Intermediates



Scheme 3.2. Representative Methods for Synthesizing *Z*-*α,β*-Unsaturated Carbonyl Compounds



In comparison, catalytic olefin metathesis provides a distinct and more direct disconnection for synthesis of *Z*-*α,β*-unsaturated carbonyl compounds. Hoveyda *et a.l* have disclosed two olefin metathesis-based strategies for synthesis of *Z*-*α,β*-unsaturated carbonyl compounds (Scheme 3.3).[10,11] One entails *Z*-selective macrocyclic ring-closing metathesis (MRCM) reactions that are catalyzed by a Mo-based complex to generate *Z*-enoates.[10] Thus 14- to 24-membered cyclic *Z*-enoates were accessed in 55–90% yield and 79:21–90:10 *Z:E* selectivity. Although stereoselectivity was not exceptional, pure *Z* enoate isomers could be obtained by silica gel chromatography. Another disclosure is in regards to catalytic *Z*-selective cross metathesis (CM) proceses, which are also catalyzed by a Mo-based complex, to generate linear *Z*-enoates (Scheme 3.3).[11] Accordingly, various *Z*-*α,β*-unsaturated *tert*-butyl esters were synthesized in 33–70% yield with 93:7 to >98:2 *Z:E* selectivity. Nonetheless, these latter approaches do not extend to preparation of unsaturated amides and reactions with less hindered acrylic esters were low yielding, perhaps owing to intramolecular C=O→Mo coordination.[12] We therefore wondered whether more broadly applicable strategies might be introduced through the use of less Lewis acidic Ru catechothiolate complexes.[13]

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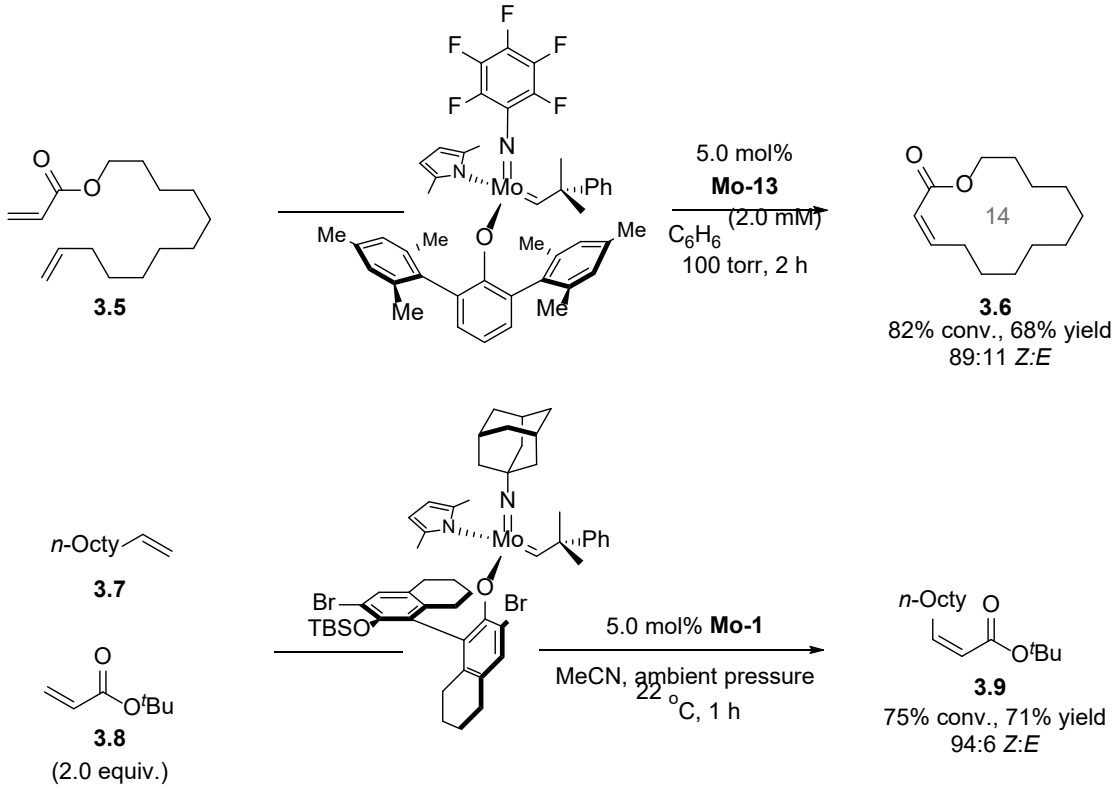
(10) Zhang, H.; Yu, E. C.; Torker, S.; Schrock, R. R.; Hoveyda, A. H. *J. Am. Chem. Soc*. **2014**, *136*, 16493–16496.

(11) Yu, E. C.; Johnson, B. M.; Townsend, E. M.; Schrock, R. R. Hoveyda. A. H. *Angew. Chem., Int. Ed.* **2016**, *55*, 13210–13214.

(12) Sattely, E. S.; Cortez, G. A.; Moebius, D. C.; Schrock, R. R.; Hoveyda, A. H. *J. Am. Chem. Soc*. **2005**, *127*, 4584–4585.

(13) (a) *Handbook of Metathesis;* Grubbs, R. H., Wenzel, A. G., O'Leary, D. J., Khosravi, E., Eds.; Wiley-VCH: Weinheim, 2014. (b) Hoveyda, A. H. *J. Org. Chem.* **2014**, *79*, 4763–4792.

Scheme 3.3. Synthesis of *Z*-*α,β*-Unsaturated Carbonyl Compounds with Mo-Based Complexes

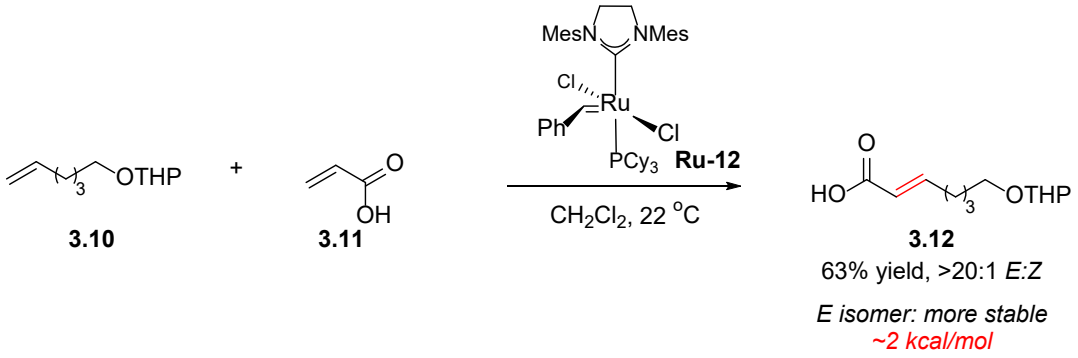


Under normal circumstances, an olefin metathesis reaction with a Ru-based complex generates *E*-*α,β*-unsaturated carbonyl compounds (Scheme 3.4).[14] The challenge associated with *Z*-selective metathesis of an enoate is that an *E* acrylate is usually approximately 2 kcal/mol more stable than its corresponding *Z* isomer. This makes it somewhat challenging to design a kinetically controlled approach that preferentially affords *Z*-*α,β*-unsaturated carbonyl compounds.[15]

(14) (a) Chatterjee, A. K.; Morgan, J. P.; Scholl, M.; Grubbs, R. H. *J. Am. Chem. Soc.* **2000**, *122*, 3783–3784. (b) Choi, T.-L.; Chatterjee, A. K.; Grubbs, R. H. *Angew. Chem., Int. Ed.* **2001**, *40*, 1277–1279.

(15) Smith, M. B., March, J. In *Advanced Organic Chemistry: Reactions, Mechanisms and structure,* 6th ed.; Wiley: New Jersey, 2006; pp 111.

Scheme 3.4. A Cross-Metathesis Reaction to Generate an *α,β*-Unsaturated Carbonyl Compound



3.2 Initial Investigations

3.2.1 Identification of Trisubstituted Alkene Byproducts in Cross-Metathesis (CM)

Preliminary studies indicated that Ru catechothiolate complexes, effective in the formation of a variety of *Z*-alkene products,[16] cannot be used to generate *Z*-*α,β*-unsaturated carbonyl compounds through CM reactions. For instance, in the presence of **Ru-10**, which is precursor to one of the more active forms of catechothiolate Ru carbenes, the reaction between *Z*-*β*-methyl-acrylate **3.13a** and *Z*-3-hexene (**3.14**) afforded enoate **3.15** in 28% yield (>98:2 *Z:E*; Scheme 3.5).[17] As a reminder, 1,2-disubstituted alkenes were used as substrates in a stereoretentive process because Ru catethothiolate complexes easily decompose when monosubstituted alkenes are involved.[18] A range of *Z*-disubstituted alkenes are commercially available and can be efficiently synthesized in one or two steps. A notable observation regarding the reaction between **3.13a** and **3.14** was that trisubstituted alkenes **3.16a** and **3.16b** were also formed as byproducts (GC-MS analysis).

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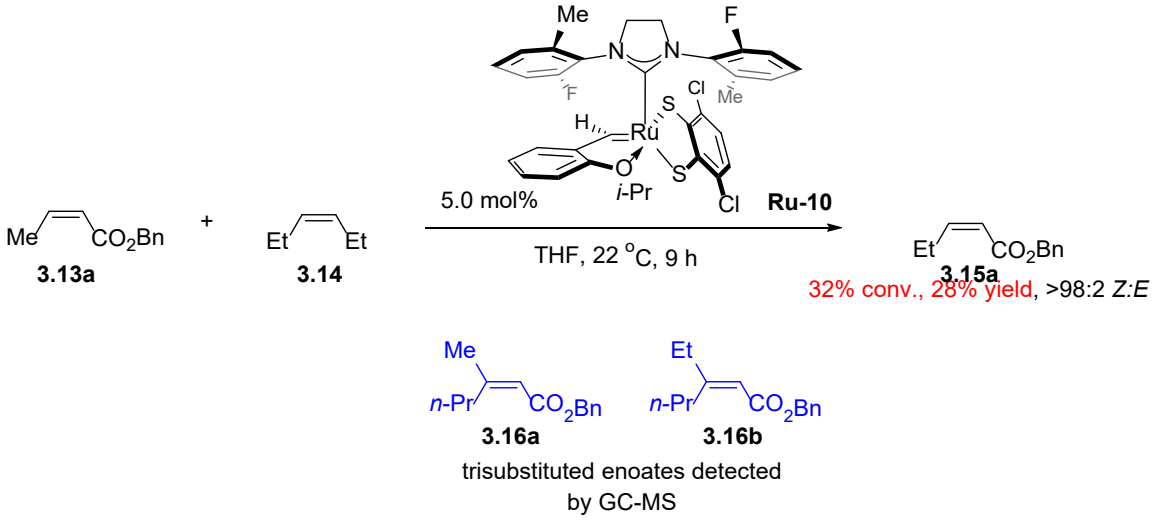
(16) (a) Koh, M. J.; Khan, R. K. M.; Torker, S.; Hoveyda, A. H. *Angew. Chem., Int. Ed*. **2014**, *53*, 1968–1972. (b) Koh, M. J.; Khan, R. K. M.; Torker, S.; Yu, M.; Mikus, M.; Hoveyda, A. H. *Nature* **2015**, *517*, 181–186. (c) Xu, C.; Shen, X.; Hoveyda, A. H. *J. Am. Chem. Soc*. **2017**, *139*, 10919–10928. (d) Xu, C.; Liu, Z.; Torker, S.; Shen, X.; Xu, D.; Hoveyda, A. H. *J. Am. Chem. Soc*. **2017**, *139*, 15640–15643.

(17) For additional details, see Chapter Two of this thesis.

(18) For additional details, see Chapter One of this thesis.

We were intrigued by this latter observation and surmised that it might offer clues as to why the CM reaction leading to the desired *Z*-enoate is inefficient.

Scheme 3.5. Initial Attempt to Synthesize an *α,β*-Unsaturated Enoate[a]

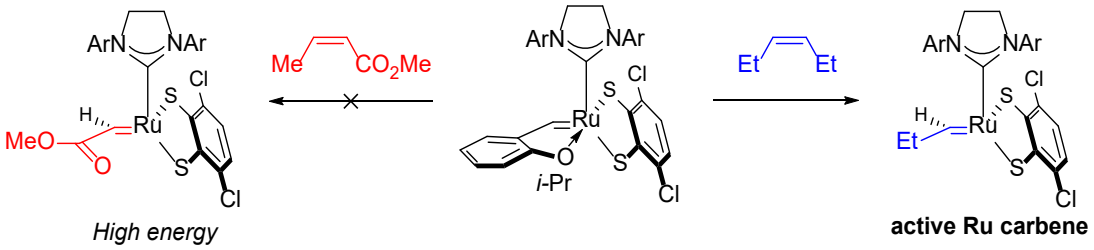


[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

3.2.2 DFT Studies

To gain insight regarding different competing reaction pathways and how trisubstituted alkene byproducts might be generated, DFT studies were carried out (complexes lacking the two Cl substituents were used for the sake of simplicity). These investigations suggested that a Ru catechothiolate complex probably first reacts with *cis*-3-hexene to generate a catalytically active species; reaction involving a less π-Lewis basic alkene of an enoate would be less favored. The resulting Ru carbene intermediate could then react with a *Z*-enoate in two ways (Scheme 3.7).

Scheme 3.6. Initiation of a Ru Catechothiolate Complex in CM of a *Z*-*α,β*-Unsaturated Enoate



One route would generate the desired product via **ts1**$_{\textbf{productive}}$, **mcb**$_{\textbf{productive}}$, and **ts2**$_{\textbf{productive}}$ (ts = transition state, mcb = metallacyclobutane). The other (nonproductive) pathway would occur if a *Z*-enoate approaches the Ru carbene such that the ester group is able to stabilize the accumulated electron density posited at C_α of **mcb**$_{\textbf{nonproductive}}$[19] ($\Delta G_{rel}$ = 7.9 kcal/mol for **mcb**$_{\textbf{nonproductive}}$ vs ΔG_{rel} = 13.4 kcal/mol for **mcb**$_{\textbf{productive}}$). Additionally, the presence of ester group at C_α lowers the barrier to distortion of metallacyclobutane ring, resulting in proper alignment of Ru-S_{cis} and Ru-C_α bonds (highlighted in red in **ts**$_{\textbf{distorted}}$). This would lead to diminution of destabilizing *trans* influence involving the Ru–S_{cis} bond and Ru–C_α bonds.[20] The **mcb**$_{\textbf{distorted}}$ can then undergo *β*-hydride elimination because of the availability of a coordination site.[21] Subsequent reductive elimination of the resulting Ru hydride species (***π*-allyl**) would then lead to the formation of a trisubstituted alkene along with an olefin metathesis-inactive Ru complex.

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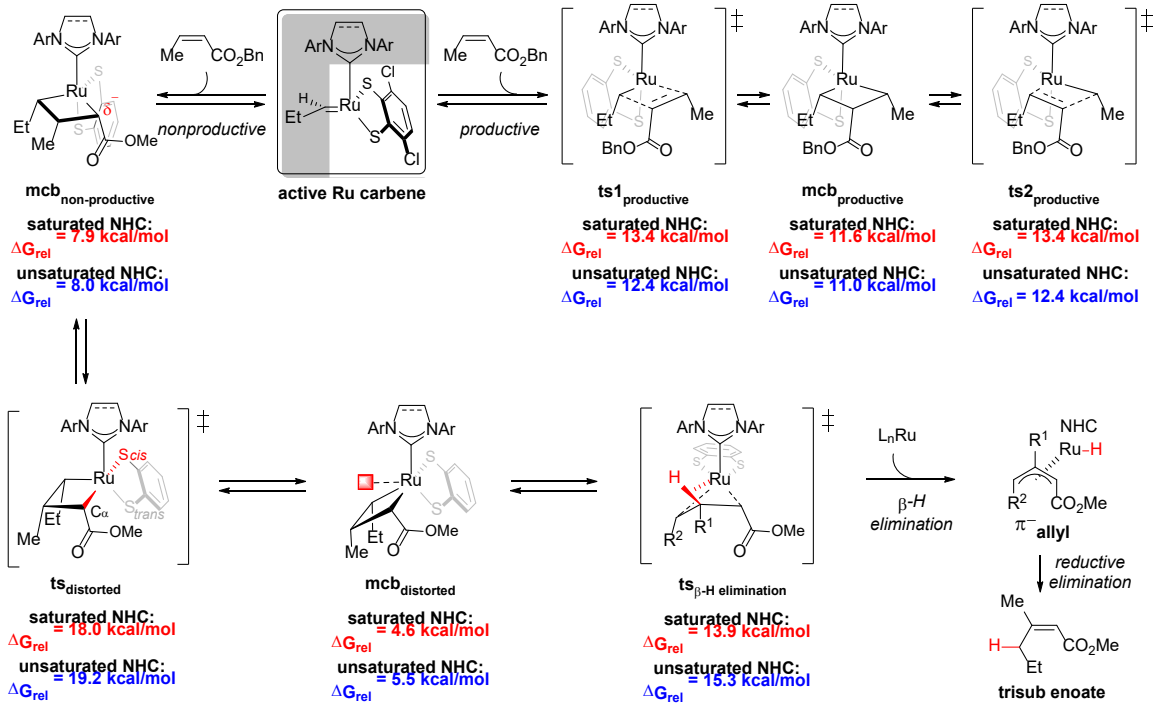
(19) Torker, S.; Koh, M. J.; Khan, R. K. M.; Hoveyda, A. H. *Organometallics* **2016**, *35*, 543−563.

(20) (a) Solans-Monfort, X.; Coperet, C.; Eisenstein, O. *J. Am. Chem. Soc*. **2010**, *132*, 7750−7757. (b) Pucino, M.; Inoue, M.; Gordon, C. P.; Schowner, R.; Stöhr, L.; Sen, S.; Hegedüs, C.; Robé, E.; Tóth, F.; Buchmeiser, M. R.; Copéret, C. *Angew. Chem., Int. Ed*. **2018**, *57*, 14566−14569.

(21) (a) Janse van Rensburg, W.; Steynberg, P. J.; Meyer, W. H.; Kirk, M. M.; Forman, G. S. *J. Am. Chem. Soc.* **2004**, *126*, 14332−14333. (b) Engel, J.; Smit, W.; Foscato, M.; Occhipinti, G.; Törnroos, K. W.; Jensen, V. R. *J. Am. Chem. Soc.* **2017**, *139*, 16609−16619.

Scheme 3.7. Various Pathways for CM Reactions Involving *Z*-*α*,*β*-Unsaturated Enoates[a]



[a]DFT studies were performed at the PBE0-D3BJ/Def2TZVPP// ωB97XD/Def2SVP$_{CH2Cl2(SMD)}$ level. For further detail, see the Experimental Section. ts = transition state; mcb = metallacylcobutane; NHC = *N*-heterocyclic carbene

3.3 Ru Catechothiolate Complexes Bearing an Unsaturated NHC Ligand

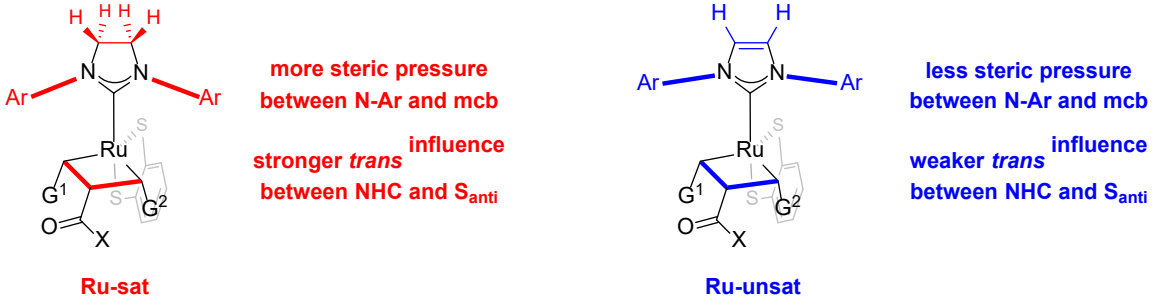
3.3.1 Comparisons of Complexes with Saturated and Unsaturated NHC Ligands

Based on the above mechanistic considerations, we reasoned that one possible way to improve efficiency of CM reactions that afford *Z*-enoates efficiently might be through the use of a Ru complex that contains an unsaturated NHC ligand (Scheme 3.8). Although it is generally considered that Ru dichloro complexes bearing a saturated NHC are more effective,[22] there is a fundamental difference between transformations catalyzed by a Ru dichloro and Ru catechothioalte complex. In the case of Ru dichloro complexes, reactions

(22) (a) Scholl, M.; Ding, S.; Lee, C. W.; Grubbs, R. H. *Org. Lett*. **1999**, *1*, 953−956. (b) Bielawski, C. W.; Grubbs, R. H. *Angew. Chem., Int. Ed*. **2000**, *39*, 2903−2906. (c) Lummiss, J. A. M.; Higman, C. S.; Fyson, D. L.; McDonald, R.; Fogg, D. E. *Chem. Sci*. **2015**, *6*, 6739−6746.

proceed via *anti*-to-NHC metallacyclobutanes whereas those catalyzed by Ru catechothiolates involve *syn*-to-NHC metallacyclobutanes.[23] This is a significant difference, which can cause an NHC ligand to impact a transformation entirely differently. Unsaturated NHC ligands are less σ-donating,[24] as indicated by the differences in acidity and the variations in chemical shifts of ^{31}P and ^{79}Se NMR spectra of the corresponding NHC-phosphinide and NHC-selenide adducts.[25,26] It therefore appears that there is less *trans* influence between an unsaturated NHC and an apical sulfide ligand in **mcb**$_{\textbf{productive}}$ and, as a result, the productive pathway should be more favored if the former ligand type is used. Furthermore, a smaller N-C-N angle in the backbone of an unsaturated NHC ligand should cause a "lift" of the N-aryl rings, decreasing steric pressure in **mcb**$_{\textbf{nonproductive}}$.[23] Hence, metallacylcobutane ring would be less distorted and the nonproductive pathway would be less dominant.

Scheme 3.8. Comparison of Ru Catechothiolates Bearing Saturated and Unsaturated NHC



(23) For additional details, see Chapter One of this thesis.

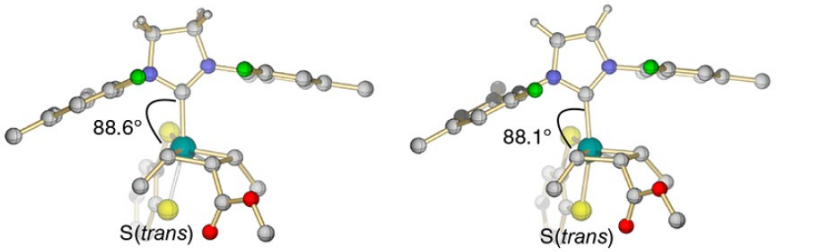
(24) Nelson, D. J.; Nolan, S. P. *Chem. Soc. Rev.* **2013**, *42*, 6723−6753.

(25) For acidity measurements, see: Magill, A. M.; Cavell, K. J.; Yates, B. F. *J. Am. Chem. Soc.* **2004**, *126*, 8717−8724.

(26) (a) Back, O.; Henry-Ellinger, M.; Martin, C. D.; Martin, D.; Bertrand, G. *Angew. Chem., Int. Ed.* **2013**, *52*, 2939−2943. (b) Liske, A.; Verlinden, K.; Buhl, H.; Schaper, K.; Ganter, C. *Organometallics* **2013**, *32*, 5269−5272.

Our proposal is supported by DFT calculations (Scheme 3.7), which indicated that an unsaturated NHC ligand indeed lowers the energy required to reach **mcb$_{productive}$** (ΔG_{rel} = 12.4 kcal/mol in **ts2$_{productive}$** vs 13.4 kcal/mol for the saturated complex) while enhancing the barrier to **mcb$_{distorted}$** (ΔG_{rel} = 19.2 kcal/mol in **ts$_{distorted}$** vs 18.0 kcal/mol for the saturated complex) and *β*-hydride elimination (ΔG_{rel} = 15.3 kcal/mol in **ts$_{\beta\text{-Helim}}$** vs 18.0 kcal/mol for the saturated complex).

Scheme 3.9. Calculated Models for **mcb$_{productive}$** with Saturated and Unsaturated NHC Ligands[a]



mcb$_{productive}$ (saturated NHC):
Ru- C(NHC) ..... 2.105 Å
Ru- S(*trans*) ..... 2.423 Å
C(NHC)- Ru–S(*trans*).... 163.5°
C(NHC)- Ru–Cα .... 88.6 & 97.9°

mcb$_{productive}$ (unsaturated NHC):
Ru- C(NHC) ..... 2.122 Å
Ru- S(*trans*) ..... 2.418 Å
C(NHC)- Ru–S(*trans*).... 166.4°
C(NHC)- Ru–Cα .... 88.1 & 96.5°

[a]DFT Calculations were performed at the PBE0-D3BJ/Def2TZVPP// ωB97XD/Def2SVP$_{CH2Cl2(SMD)}$ level. For full details, see the Experimental Section. mcb = metallacylcobutane; NHC = *N*-heterocyclic carbene

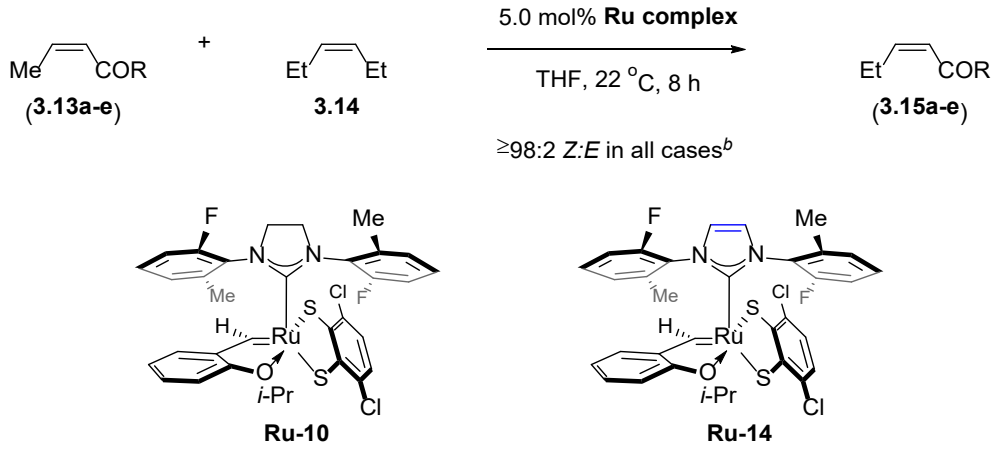
The bond lengths and angles obtained through DFT calculations are consistent with our proposal and the calculated energy values (Scheme 3.9). DFT studies reveal that Ru-S$_{(trans)}$ bond in **mcb$_{productive}$** derived from a Ru complex bearing a saturated NHC is longer than that containing an unsaturated derivative (2.423 vs 2.418 Å). Thus, **mcb$_{productive}$** with a saturated NHC possesses stronger *trans* influence and is higher in energy compared to that with an unsaturated ligand (ΔG_{rel} = 11.6 vs 11.0 kcal/mol). The angle between Ru–C$_{(NHC)}$ bond and Ru–Cα bond in **mcb$_{productive}$** with a saturated NHC is larger (88.6° vs 88.1°),

in line with the proposal that there is greater larger steric interaction between an unsaturated NHC and a metallacyclobutane ring.

3.3.2 Experimental Support Regarding the Differences Between Ru Catechothiolate Complexes Bearing Saturated and Unsaturated NHC Ligands

To probe our hypothesis further, we synthesized complex **Ru-14** and used it for reactions between *Z*-3-hexene and *Z*-butenoic acid derivatives (Scheme 3.10). While CM with **Ru-10** afforded ester **3.15a** in 28% yield, the transformation involving **Ru-14** generated **3.15a** in 78% yield. Similarly, reaction with **Ru-14** afforded *Z*-*α,β*-unsaturated acid **3.15b** and Weinreb amide **3.15c** in 68–70% yield, whereas reaction in the presence of **Ru-10** furnished these products in 25% yield. The catalysts derived from these two complexes showed comparable efficiency in CM of secondary and primary amides.

Scheme 3.10. Experimental Data regarding the Differences in Reactions with Ru Catechothiolate Complexes Bearing Saturated and Unsaturated NHC Ligands[a]



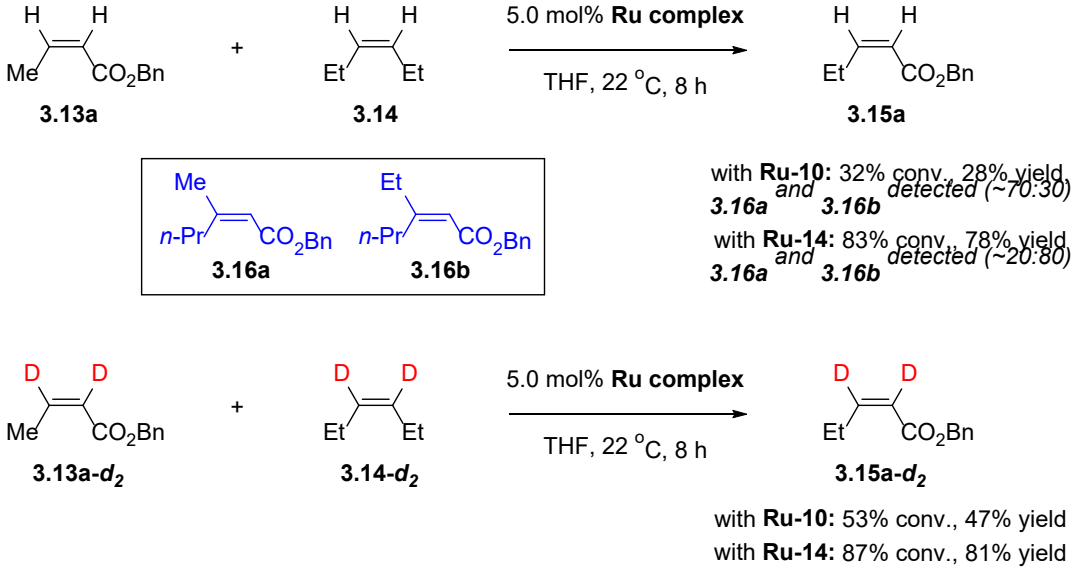
	conv.[b], yield[c]				
R =	OBn (**3.15a**)	OH (**3.15b**)	N(Me)OMe (**3.15c**)	NHBn (**3.15d**)	NH_2 (**3.15e**)
with **Ru-10**:	32%, 28%	32%, 25%	35%, 25%	98%, 88%	96%, 89%
with **Ru-14**:	83%, 78%	88%, 70%	75%, 68%	91%, 84%	97%, 93%

[a]Reactions were performed under N_2 atm. [b]Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). [c]Yields for purified products (±5%). For full details, see the Experimental Section.

To determine whether there is any relation between catalyst decomposition and low efficiency of reactions with Ru complex bearing a saturated NHC, we examined CM reactions involving deuterated alkenes (Scheme 3.11). All transformations involving deuterated or non-labeled alkenes furnished products in >98:2 *Z:E* selectivity. In the case of non-deuterated alkenes, trisbustituted alkene byproducts **3.16a** and **3.16b** were formed regardless of whether **Ru-10** and **Ru-14** were used (detected by GC-MS).[27] However, these byproducts were generated in different ratios (~70:30 for **Ru-10** and ~80:20 for **Ru-14**); this is probably because **3.16a** was generated from **3.13a** whereas **3.16b** was generated from **3.15a**. These findings pointed to higher reactivity and longer life time for complexes derived from **Ru-14**. We surmised that deuterated alkene substrates might generate products in higher yield because of a difference in the rate of β-hydride elimination. Indeed, as shown in Scheme 3.11, with **Ru-10** as catalyst precursor, CM between **3.13a-*d*$_2$** and **3.14a-*d*$_2$** afforded **3.15a-*d*$_2$** in 47% yield (vs 28% yield with unlabeled olefin). The reaction of deuterated alkenes with **Ru-14** afforded **3.15a** in a similar yield as that with a non-deuterated substrate. This is probably because β-hydride elimination is less facile when **Ru-14** involved and there is as a result a narrower gap in the rates of transformations involving non-deuterated and deuterated alkenes.

(27) See Supporting Information for details.

Scheme 3.11. The Proof of *β*-Hydride Elimination Pathway[a]



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

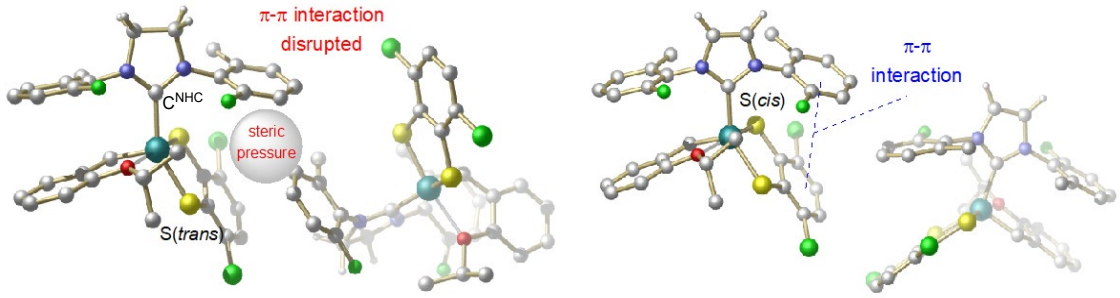
3.3.3 X-ray Structures of Ru Catechothiolate Complexes That Contain a Saturated or an Unsaturated NHC Ligand

For better understanding of the chemistry of the Ru complex with an unsaturated NHC ligand and how this might differ from those that contain a saturated variant, we obtained the x-ray crystal structures shown in Scheme 3.12. The more extended Ru-C^{NHC} bond and wider C^{NHC}-Ru-$S_{(trans)}$ angle in **Ru-10** compared to that in **Ru-14** are inconsistent with our original proposal that a saturated NHC is a stronger electron-donor and thus gives rise to stronger *trans* influence. We reasoned that this might be owing to crystal packing forces. Generally, there is π-π interactions between an NHC aryl group and the catechothiolate ligand in a Ru catechothiolate complex.[28] Such π-π interaction is disrupted in **Ru-10** because of either the benzylidene of a neighboring molecule or the positioning of

(28) Hunter, C. A.; Lawson, K. R.; Perkins, J.; Urch, C. J. *J. Chem. Soc., Perkin Trans*. **2001**, *2*, 651−669.

2-fluro-6-methyl phenyl and/or isopropoxy groups. The Ru-S_{trans} bond length is, on the other hand, longer in **Ru-10** than that in **Ru-14**, which is as we predicted. Another structural attribute that is not impacted by the aforementioned π-π interaction is the N-C^{NHC}-N angle, which is larger in **Ru-10** (vs **Ru-14**), implying that the aryl group of the saturated NHC ligand is more projected toward a catechothiolate ligand and can cause a greater degree of steric pressure in a metallacyclobutane ring.

Scheme 3.12. X-Ray Crystal Structures of **Ru-10** vs **Ru-14**



X-ray structure for Ru-10 (sat)
Ru-C^{NHC}.....2.072 Å
Ru-S(*trans*).....2.283 Å
C^{NHC}-Ru-S(*trans*).....149.0°
N-C^{NHC}-N.....106.5°

X-ray structure for Ru-14 (unsat)
Ru-C^{NHC}.....2.055 Å
Ru-S(*trans*).....2.265 Å
C^{NHC}-Ru-S(*trans*).....139.6°
N-C^{NHC}-N.....103.9°

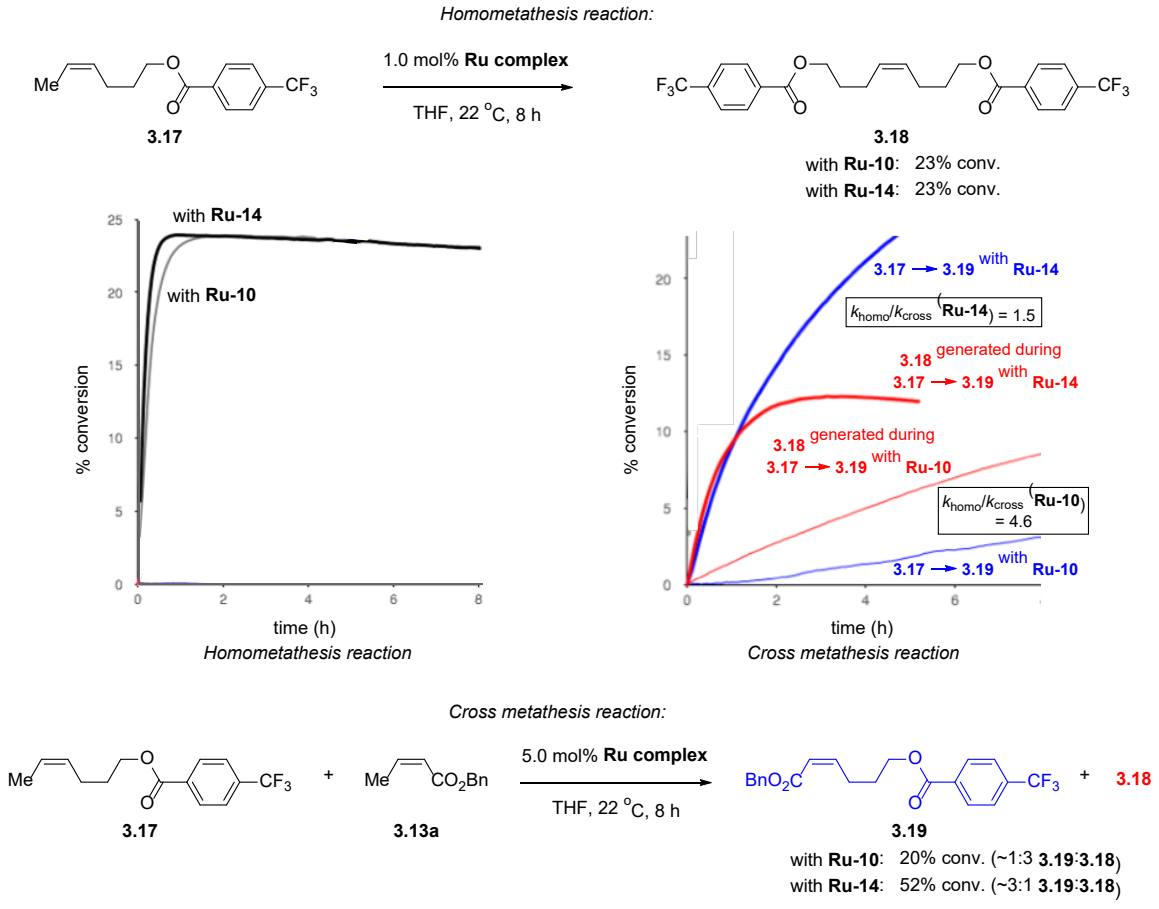
3.3.4 Kinetic Profiles for Reactions with Ru Catechothiolate Complexes

There was still the question as to why two complexes show similar reactivity in CM of primary and secondary amides while there is distinct efficiency levels in the case of involving esters, acids, and Weinreb amides. This might be because primary and secondary amides are less electron-withdrawing than esters, acids, and Weinreb amides. Thus, distortion of $\mathbf{mcb}_{\mathbf{nonproductive}}$ in reactions involving primary and secondary amides is less favored (Scheme 3.7) and there is less catalyst decompositions. The difference in the ability of Ru complexes that contain a saturated or unsaturated NHC ligand becomes less pronounced in reactions that involve relatively electron-rich alkenes. Coordination of the latter class of olefins to a Ru complex is probably more facile such that the energy barrier

to **mcb**$_{\textbf{productive}}$ is diminished and less of a distinctive feature of the type of complex used (Scheme 3.7).

To gain further insight, we monitored CM reactions of ^{19}F-containing substrates in the presence of **Ru-10** and **Ru-14** (Scheme 3.13). Comparable reactivity was observed (23% conv in both cases) for homo-metathesis of 1,2-dialkyl-substituted alkenes (**3.17**→**3.18**), which is similar to what we observed for transformations with primary and secondary enoic amides. Compared to *α,β*-unsaturated esters, acids, and Weinreb amides, 1,2-dialkyl-substituted alkene, *α,β*-unsaturated primary and secondary amides are more electron-rich. These findings support that aforementioned mechanistic scenario.

Scheme 3.13. Kinetic Profiles of CM with **Ru-10** vs **Ru-14**



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^1H NMR spectra of unpurified product mixtures (±2%). For full details, see the Experimental Section.

In the CM reaction of electron-deficient enoate **3.13a** with 1,2-dialkyl-substituted alkene **3.17**, catalysts derived from complexes **Ru-10** and **Ru-14** showed distinct reactivity (52% conv to ~3:1 **3.19**:**3.18** with **Ru-14** vs 20% conv to ~1:3 **3.19**:**3.18** with **Ru-10**). Control experiments indicated that a Lewis base, such as an ester group, might coordinate to the Ru complex to diminish its catalytic activity,[29] an effect that is likely more detrimental for **Ru-14** because of its more Lewis acidic metal center.

We also investigated the relative rates of homo-metathesis and CM reactions by ^{19}F NMR spectroscopy. The rates for homo-metathesis of 1,2-dialkyl-substituted alkenes **3.17** with **Ru-10** and **Ru-14** were found to be similar. However, while homo-metathesis of **3.17** was slightly more facile with performed in the presence of **Ru-10** (k_{homo}/k_{cross} = 1.5), there was a larger rate differential with **Ru-14** (k_{homo}/k_{cross} = 4.6). These findings are in line with our proposal that Ru complex bearing an unsaturated NHC is more effective in promoting reactions involving electron-deficient alkenes.

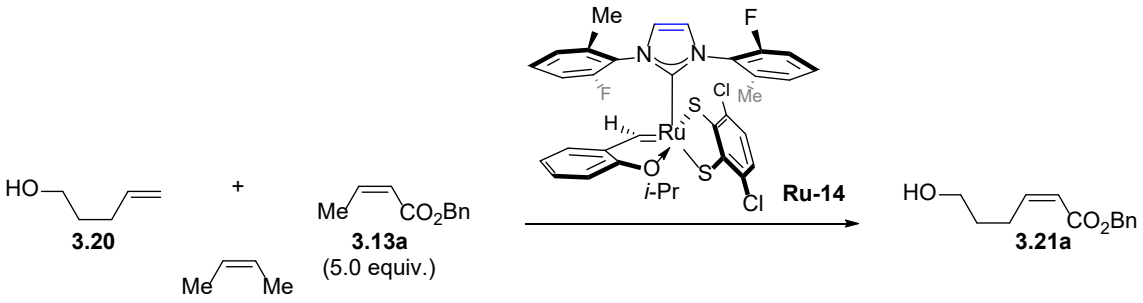
3.4 CM with *Z*-*α*,*β*-unsaturated Carbonyl Compounds

Establishing Conditions. To maximize applicability, we developed different sets of conditions. For relatively unhindered alkene substrates, such as **3.20**, capping of monosubstituted alkene is necessary (Scheme 3.14). After the capping step, with addition of 5.0 mol% catalyst and evacuation under 100 torr vacuum (Condition A), the desired product was isolated in 43% yield. When two batches of catalyst, each corresponding to 4.0 mol% loading was added (Condition B), the transformation was more efficient (63%

(29) Jung, K.; Kim, K.; Sung, J.-C.; Ahmed, T. S.; Hong, S. H.; Grubbs, R. H.; Choi, T.-L. *Macromolecules* **2018**, *51*, 4564−4571.

yield). When the capping step was omitted (Condition C), the product was isolated in just 25% yield (likely due to methylidene decomposition; see Chapter 1). Only for CM of hindered alkenes, where homo-metathesis is less competitive, were we able to forego methylene capping.

Scheme 3.14. CM Conditions for Reactions with Complex **Ru-14**[a]



Condition A:	**Condition B:**	**Condition C:**
1.0 mol% **Ru-14**, 5.0 euqiv. *Z*-butene, THF, 22 °C, 1 h; 5.0 mol% **Ru-14**, THF, 100 torr, 22 °C, 1 h; ambient pressure, 7 h.	1.0 mol% **Ru-14**, 5.0 euqiv. *Z*-butene, THF, 22 °C, 1 h; 4.0 mol% **Ru-14**, 100 torr, THF, 22 °C, 1 h; ambient pressure, 7 h; 4.0 mol% **Ru-14**, 100 torr, THF, 22 °C, 1 h; ambient pressure, 11 h;	without capping *Only suitable for hindered alkenes*
89% conv., 43% yield, >98:2 Z:E	***88% conv., 63% yield, >98:2 Z:E***	*29% conv., 25% yield, >98:2 Z:E*

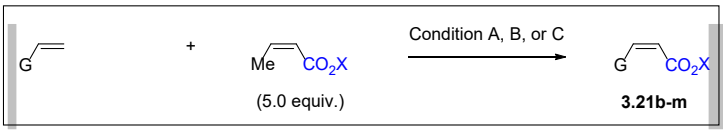
[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

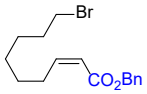
3.4.1 Synthesis of *Z*-*α,β*-Unsaturated Esters

We began with studying the CM reactions of *Z*-*α,β*-unsaturated esters. The desired products could be afforded in 57–76% yield with 96:4–>98:2 *Z:E* selectvity (Scheme 3.15). Substrates containing an aldehyde (**3.21f**), an acid (**3.21g**), an indole (**3.21i**), a conjugated diene (**3.21h**) and a phenol (**3.21k**) proved to be suitable. Other than unhindered benzyl esters, sterically demanding *Z*-*α,β*-unsaturated *tert*-butyl esters (**3.21l** & **3.21m**) were compatible starting materials. We were able to synthesize *α*-branched alkene **3.21m** in 76%

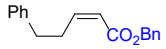
yield as a single stereoisomer. For certain substrates (**3.21a-c**, **3.21k**), reactions were conducted according to conditions A and B; the latter protocol typically proved to be more efficient.

Scheme 3.15. CM Reactions that Afford *Z*-*α*,*β*-Unsaturated Esters[a]

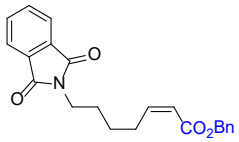




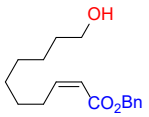
3.21b
Condition A:
78% conv., 55% yield, 98:2 *Z*:*E*
Condition B:
84% conv., 63% yield, 98:2 *Z*:*E*



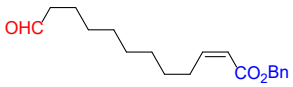
3.21c
Condition A:
80% conv., 53% yield, 98:2 *Z*:*E*
Condition B:
87% conv., 66% yield, 98:2 *Z*:*E*



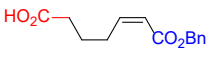
3.21d
Condition A:
66% conv., 45% yield, 97:3 *Z*:*E*
Condition B:
82% conv., 60% yield, 96:4 *Z*:*E*



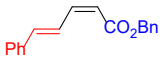
3.21e
Condition B:
88% conv., 64% yield, >98:2 *Z*:*E*



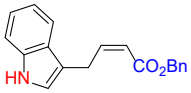
3.21f
Condition B:
86% conv., 69% yield, >98:2 *Z*:*E*



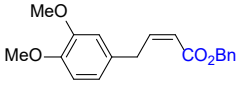
3.21g
Condition B:
81% conv., 57% yield, >98:2 *Z*:*E*



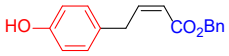
3.21h
Condition B:
78% conv., 61% yield, 98:2 *Z*:*E*



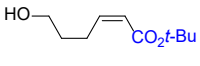
3.21i
Condition B:
81% conv., 57% yield, >98:2 *Z*:*E*



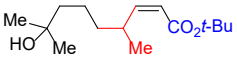
3.21j
Condition B:
92% conv., 67% yield, >98:2 *Z*:*E*



3.21k
Condition A:
73% conv., 46% yield, 98:2 *Z*:*E*
Condition B:
95% conv., 59% yield, 98:2 *Z*:*E*



3.21l
Condition B:
94% conv., 55% yield, >98:2 *Z*:*E*



3.21m
Condition C (no capping):
82% conv., 76% yield, >98:2 *Z*:*E*

[a]Reactions were performed under N_2 atm. Conversion and *Z*:*E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). Condition A, B, C same as in Scheme 3.14. For full details, see the Experimental Section.

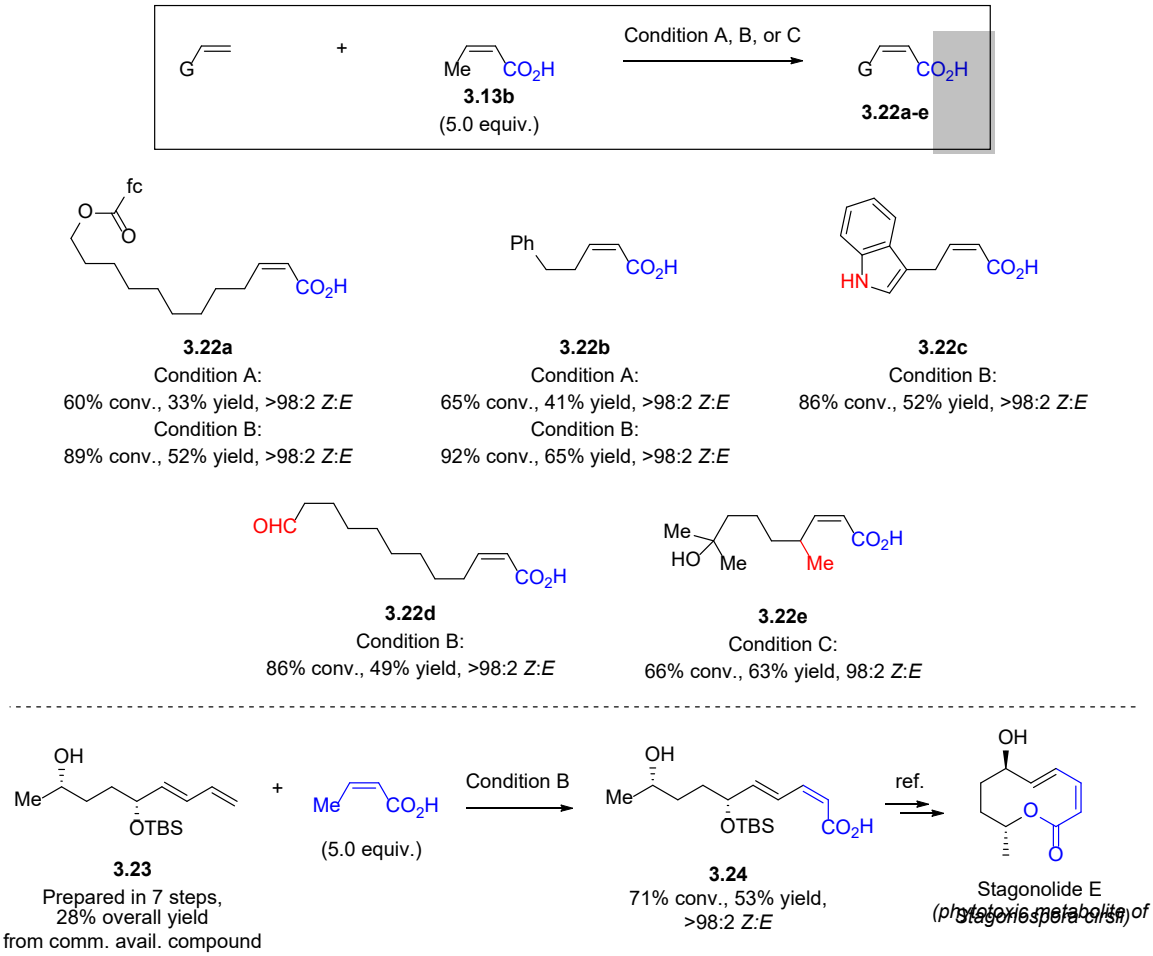
3.4.2 Synthesis of *Z*-*α*,*β*-Unsaturated Acids

Another important set of substrates are *Z*-*α*,*β*-unsaturated acids (Scheme 3.16). Compounds that contain an indole (**3.22c**), an aldehyde (**3.22d**), or an *α*-branched alkene (**3.22e**) readily underwent reaction to give the expected products in 49–65% yield and >98:2 *Z*:*E* selectivity. It merits note that such entities cannot be synthesized directly

by a Wittig-type process. What is more, synthesis pathways that involve the corresponding carboxylic esters require strongly basic or acidic conditions, which can limit applicability. To highlight the utility of the approach, we prepared **3.24**, which is a precursor to antifungal/cytotoxic agent stagonolide E (Scheme 3.16).[30] The previously reported synthesis of intermediate **3.24**, entailing the use of Still-Gennari method, demanded 11 steps and afforded the desired compound in 4% overall yield and as a 91:9 mixture of *Z* and *E* isomers.[9] The new route commenced with preparation of enantiomerically pure diene **3.23** in seven steps from commercially available starting materials. CM with *Z*-butenoic acid afforded **3.24** in 53% yield as a single isomer (>98% *Z*). By avoiding functional group conversions, an eight-step synthesis route to generate **3.24** was thus devised, significantly improving efficiency (15% vs 4% overall yield) and the stereochemical purity of the product (>98:2 vs 91:9 *Z:E*).

(30) Evidente, A.; Capasso, R.; Andolfi, A.; Vurro, M.; Chiara Zonno, M. *Nat. Toxins* **1999**, *6*, 183.

Scheme 3.16. CM Reactions that Afford *Z-α,β*-Unsaturated Acids[a]



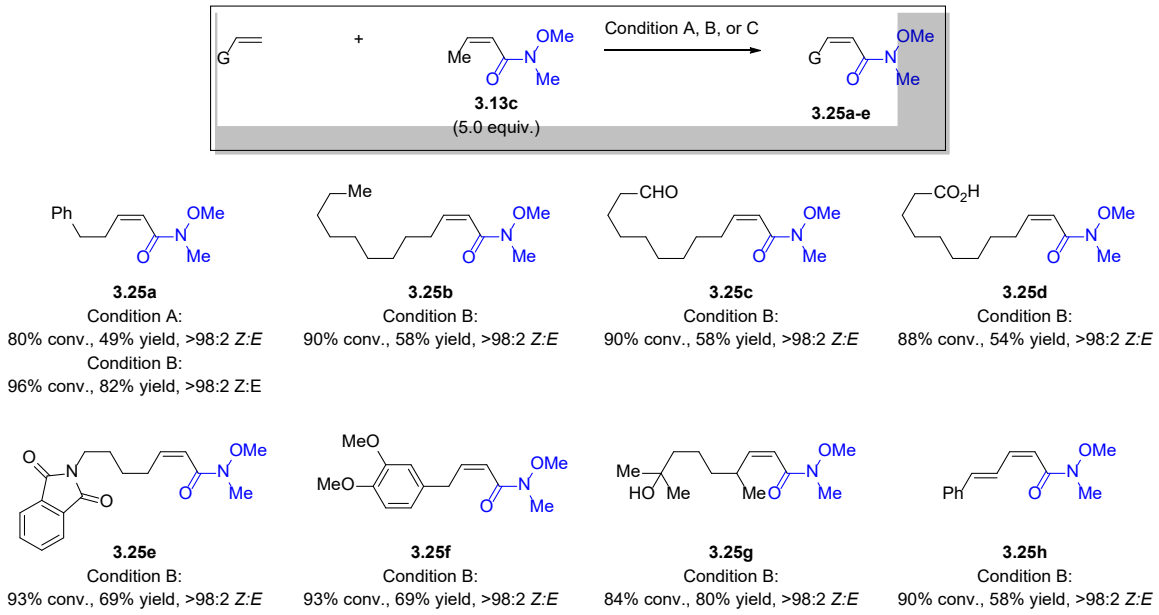
[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^1H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). Condition A, B, C same as in Scheme 3.14. For full details, see the Experimental Section.

3.4.3 Synthesis of *Z-α,β*-Unsaturated Weinreb Amides

Z-α,β-Unsaturated Weinreb amides were synthesized in 49–80% yield and >98:2 *Z:E* selectivity (Scheme 3.17). Products included those bearing an aldehyde (**3.25c**), an

acid (**3.25d**), an α-branched alkene (**3.25g**), or a conjugated diene (**3.25h**). The Weinreb amides can be easily converted to the corresponding *Z*-enone[31] or *Z*-enal.[32]

Scheme 3.17. CM Reactions that Afford *Z*-α,β-Unsaturated Weinreb Amides[a]



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). Condition A, B, C same as in Scheme 3.14. For full details, see the Experimental Section.

The application to synthesis of dihydrocompactin[4] highlights the considerable utility of the approach (Scheme 3.18). Thus, diol **3.26** was prepared from commercially available materials in two steps and 56% overall yield. Ensuing CM furnished *Z*-α,β-unsaturated Weinreb amide **3.27** in 73% yield with exceptional *Z* selectivity. After silyl ether formation, alkylation of the Weinreb amide resulted in the formation of *Z*-enone **3.28**, a precursor to dihydrocompactin, in 62% yield. Compared to the formerly reported

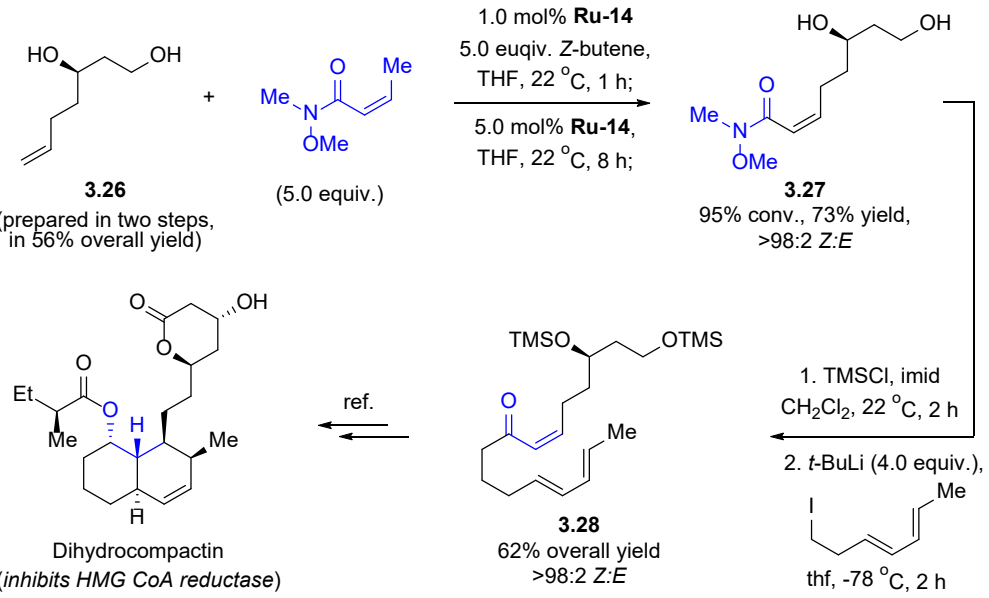
(31) Kojima, S.; Hidaka, T.; Yamakawa, A. *Chem. Lett*. **2005**, *34*, 470−471.

(32) For examples regarding conversion of a Weinreb amide to an aldehyde in a complex molecule setting, see: (a) Heckrodt, T. J.; Mulzer, J. *J. Am. Chem. Soc*. **2003**, *125*, 4680−4681. (b) Evans, D. A.; Nagorny, P.; McRae, K. J.; Reynolds, D. J.; Sonntag, L.-S.; Vounatsos, F.; Xu, R. *Angew. Chem., Int. Ed*. **2007**, *46*, 537−540.

sequence, which included a partial hydrogenation step (Lindlar),[4] the new route is shorter (5 vs 13 steps) and more efficient (25% vs 5% overall yield).

Attempts at developing CM reactions that generate *Z*-*α,β*-unsaturated tertiary amides were thwarted by complications due to the fact that preparations of such entities as pure *Z*-alkene starting materials is challenging (e.g., facile isomerization to *E* isomer during preparation of a dimethyl amide).

Scheme 3.18. Application to Synthesis of Dihydrocompactin[a]



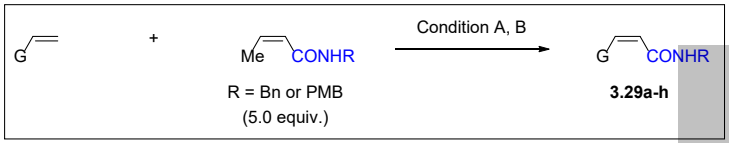
[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). For full details, see the Experimental Section.

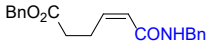
3.4.4 Synthesis of *Z*-*α,β*-Unsaturated Secondary and Primary Amides

An assortment of *Z*-*α,β*-unsaturated secondary amides were synthesized in 55%–76% yield, all in >98:2 *Z:E* ratio (Scheme 3.19). Thus, amides that contain a benzyl (**3.29a,e,f**), a *p*-methoxy benzyl (PMB) (**3.29b-d,g**), or an *iso*-butyl group (**3.29h**) N-substitution were synthesized. As mentioned, complexes **Ru-10** and **Ru-14** afforded this set of products with similar efficiency.

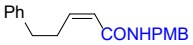
Z-α,β-Unsaturated primary amides were converted to the corresponding nitriles by treatment with the Burgess reagent,[33,34] (**3.31**, Scheme 3.20), a type of alkene that cannot be directly prepared by the catalytic CM[35] (similar to *Z*-enones[30] and *Z*-enals).[31] As the examples in Scheme 3.20 indicate, substrates that underwent efficient transformation contained a hydroxy group (**3.30a-c**). The reason for this is not clear at the present time.

Scheme 3.19. CM Reactions that Afford *Z-α,β*-Unsaturated Secondary Amides[a]

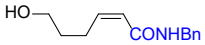




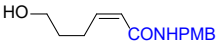
3.29a
Condition A:
75% conv., 49% yield, >98:2 *Z:E*
Condition B:
86% conv., 61% yield, >98:2 Z:E



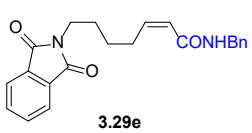
3.29b
Condition B:
88% conv., 61% yield, >98:2 *Z:E*



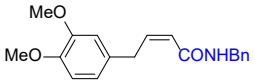
3.29c
Condition B:
87% conv., 70% yield, >98:2 *Z:E*



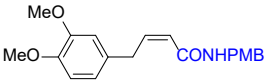
3.29d
Condition A:
77% conv., 55% yield, >98:2 *Z:E*
Condition B:
95% conv., 76% yield, >98:2 **Z:E**



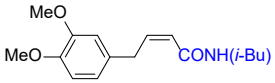
3.29e
Condition B:
70% conv., 55% yield, >98:2 *Z:E*



3.29f
Condition B:
92% conv., 59% yield, 98:2 *Z:E*



3.29g
Condition B:
83% conv., 63% yield, >98:2 *Z:E*



3.29h
Condition B:
90% conv., 58% yield, >98:2 *Z:E*

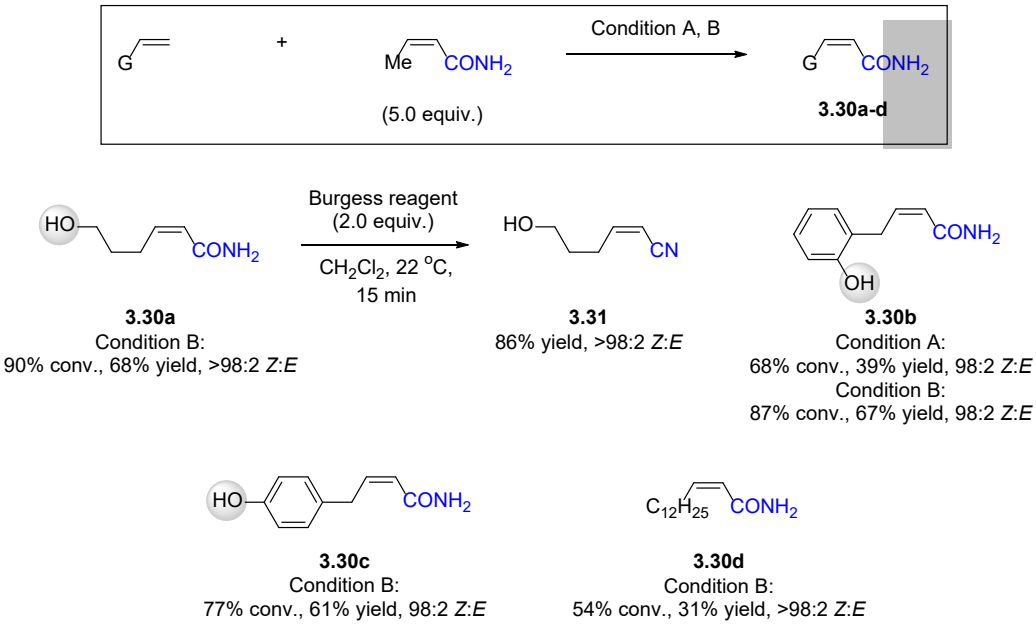
[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^{1}H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). Condition A, B same as in Scheme 2.14. For full details, see the Experimental Section.

(33) Claremon, D. A.; Phillips, B. T. *Tetrahedron Lett*. **1988**, *29*, 2155−2158.

(34) Although (Z)-alkenyl nitriles can be prepared by catalytic cross metathesis, *Z:E* ratios did not exceed 90:10, until recently. (a) Crowe, W. E.; Goldberg, D. R. *J. Am. Chem. Soc*. **1995**, *117*, 5162−5163. (b) Randl, S.; Gessler, S.; Wakamatsu, H.; Blechert, S. *Synlett* **2001**, *2001*, 430−432. (c) Miao, X.; Dixneuf, P. H.; Fischmeister, C.; Bruneau, C. *Green Chem*. **2011**, *13*, 2258−2271. (d) Gawin, R.; Tracz, A.; Chwalba, M.; Kozakiewicz, A.; Trzaskowski, B.; Skowerski, K. *ACS Catal*. **2017**, *7*, 5443−5449.

(35) For a recent catalytic CM approach for stereoselective synthesis of alkenyl nitriles with Mo-based complexes, see: Mu, Y.; Nguyen, T. T.; Koh, M. J.; Schrock, R. R.; Hoveyda, A. H. *Nat. Chem*. **2019**, *11*, 478–487.

Scheme 3.20. CM for Synthesis of *Z*-*α,β*-Unsaturated Primary Amides[a]



[a]Reactions were performed under N_2 atm. Conversion and *Z:E* ratios determined by analysis of ^1H NMR spectra of unpurified product mixtures (±2%). Yields for purified products (±5%). Condition A, B same as in Scheme 2.14. For full details, see the Experimental Section.

We were unable to synthesize aryl- or heteroaryl-substituted *Z*-*α,β*-unsaturated carbonyl compounds through catalytic CM (<5% conversion). However, such compounds may be easily generated by catalytic cross-coupling[36] between aryl or heteroaryl boronates and *Z*-3-iodo-2-propenoic acid, all of which are readily available.

3.5 Conclusions

By analyzing CM reactions of *Z*-*α,β*-unsaturated carbonyl compounds in detail, we identified a major pathway by which a Ru catechothiolate complex can decompose. By exploiting this knowledge we were able to design Ru catechothiolate complex, one that contains an unsaturated NHC ligand, and which is uniquely effective in promoting Z-

(36) (a) Yamada, T.; Watanabe, T.; Beppu, T.; Fukuyama, N.; Torii, K.; Uozumi, Y. *Chem. Eur. J.* **2010**, *16*, 11311−11319. (b) Chemler, S. R.; Trauner, D.; Danishefsky, S. J. *Angew. Chem., Int. Ed.* **2001**, *40*, 4544−4568.

selective stereoretentive processes . The diminished σ-donating ability and the particular positioning of the N-aryl groups of an unsaturated NHC ligand, the *trans* influence between the NHC ligand and apical sulfide ligand is weaker in the new unsaturated NHC–Ru complexes. There is also less steric pressure between the NHC ligand and metallacyclobutane ring. Consequently, the productive CM pathway is more favored because the energy barrier to **mcb**$_{\textbf{productive}}$ is lower, while the nonproductive pathway is less favored owing to costly structural distortion of the corresponding metallacycle intermediate (**mcb**$_{\textbf{nonproductive}}$).

We find that Ru complexes that contain a saturated and an unsaturated NHC ligand possess distinct catalytic profiles in CM reactions involving *Z*-*α,β*-unsaturated esters, acids, and Weinreb amides. In contrast, similar reactivity trends were observed in CM reactions of relatively electron-rich alkenes (e.g., 1,2-alkyl-disubstituted alkenes and *Z*-*α,β*-unsaturated secondary and primary amides). Neither of the catalyst types were found to be effective for CM reactions with the more electron-deficient alkenes such as *Z*-enones, *Z*-enals, and *Z*-*α,β*-unsaturated nitriles. The observed reactivity trends are congruent with stabilization effects exerted by an ester, a carboxylic acid, or a Weinreb amide on C_α of a metallacyclobutane intermediate (**mcb**$_{\textbf{nonproductive}}$). The strong stabilization of a highly electron-withdrawing group likely facilitates the distortion of **mcb**$_{\textbf{nonproductive}}$ to facilitate the decomposition of a Ru-based catalyst.

The advances describe above provide a much needed catalytic CM pathway for stereoselective synthesis of *Z*-*α,β*-unsaturated esters, acids, Weinreb amides, and secondary and primary amides. Formal synthesis of stagonolide E and hydrocompactin were used to highlight the considerable applicability of the catalytic approach.

3.6 Experimental

3.6.1 General

Unless otherwise noted, transformations were performed with distilled and degassed solvents under an atmosphere of dry N_2, in oven (135 °C) or flame-dried glassware with standard dry box or vacuum line techniques. ^{1}H NMR spectra were recorded on a Varian Unity INOVA 400 (400 MHz), 500 (500 MHz) or a 600 (600 MHz) spectrometer. Chemical shifts are reported in ppm from tetramethylsilane with the solvent resonance resulting from incomplete deuterium incorporation as the internal standard ($CDCl_3$: δ 7.26 ppm, CD_2Cl_2: δ 5.32 ppm, C_6D_6: δ 7.16 ppm, DMSO-d_6: δ 2.50 ppm). Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, br = broad, m = multiplet), and coupling constants (Hz), integration. ^{13}C NMR spectra were recorded on a Varian Unity INOVA 400 (100 MHz), 500 (125MHz), or 600 (150 MHz) spectrometers with complete proton decoupling. Chemical shifts are reported in ppm from tetramethylsilane with the solvent resonance as the internal standard ($CDCl_3$: δ 77.16 ppm, CD_2Cl_2: δ 53.84 ppm, C_6D_6: δ 128.06 ppm; DMSO-d_6: δ 39.52 ppm). High-resolution mass spectrometry was performed on a Micromass LCT ESI-MS and JEOL Accu TOF Dart (positive mode) at the Boston College Mass Spectrometry Facility. Enantiomeric ratios were determined by HPLC analysis (high-performance liquid chromatography) with a Shimadzu chromatograph [Chiral Technologies Chiralcel OD-H (4.6 x 250 mm)] in comparison with authentic racemic materials. Specific rotations were measured on a Rudolph Research Analytical Autopol IV Polarimeter. Melting points were determined using a Thomas Hoover Uni-melt capillary melting point apparatus. X-ray structures were obtained, as detailed in the cif file that has been provided, with a

Microfocus sealed Cu tube from Incote. Infrared (IR) spectra were recorded on a Bruker FTIR Alpha (ATR Mode) spectrometer, ν_{max} in cm^{-1}. Bands are characterized as broad (br), strong (s), medium (m), or weak (w). Values for *E*:*Z* ratios of products were determined by analysis of ^1H NMR spectra.

Solvents

Tetrahydrofuran (THF) was distilled over Na/benzophenone. CH_2Cl_2 and Et_2O was purified under a positive pressure of dry Ar gas by a modified Innovative Technologies purification system. $CDCl_3$, C_6D_6, CD_2Cl_2 and DMSO-d_6 were purchased from Cambridge Isotope Laboratories and stored over activated 4Å molecular sieves prior to use. THF-d_8 was purchased from Oakwood company and distilled over Na/benzophenone. Purification of products was carried out with reagent grade solvents (Fisher).

Organometallic Complexes

Ru-10 was prepared according to a previously reported procedure.[37]

Reagents

Acetyl chloride: purchased from Fisher Scientific and used as received.

4-Allyl-1,2-dimethoxybenzene: purchased from Aldrich and used as received.

2-Allylphenol: purchased from Aldrich and used as received.

4-Allylphenol: purchased from Aldrich and used as received.

8-Bromo-1-octene: purchased from Oakwood and used as received.

(*E*)-Buta-1,3-dien-1-ylbenzene: purchased from Aldrich and used as received.

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(37) Johns, A. M.; Ahmed, T. S.; Jackson, B. W.; Grubbs, G. H.; Pederson, R. L. *Org. Lett*. **2016**, *18*, 772−775.

(*Z*)-2-Butene: purchased from Aldrich and was dissolved in anhydrous THF and stored in the freezer at –50 °C; weight percent (wt%) was calculated based on the ^{1}H NMR analysis of the mixture.

But-3-en-1-ylbenzene: purchased from Aldrich and used as received.

***tert*-Butylalcohol**: purchased from Aldrich and used as received.

***tert*-Butyl 2,2,2-trichloroacetimidate**: purchased from Oakwood and used as received.

***n*-Butyllithium (2.5 M in hexanes)**: purchased from Aldrich and used as received.

***tert*-Butyllithium (1.7 M in hexanes)**: purchased from Aldrich and used as received.

(*Z*)-2-Butenoic acid: purchased from Aurora and used as received.

2-Butynoic acid: purchased from Oakwood and used as received.

***tert*-Butyldimethylsilyl chloride (TBSCl)**: purchased from Oakwood and used as received.

Benylbromide: purchased from Aldrich and used as received.

3-Buten-1-ol: purchased from Aldrich and used as received.

Carbon tetrachloride: purchased from Acros and used after distillation over CaH_2.

Dess–Martin periodinane: purchased from Oakwood and used as received.

2,3-Dichloro-5,6-dicyano-1,4-benzoquinone (DDQ): purchased from Alfa and used as received.

Diethyl allylphosphonate: purchased from Aldrich and used as received.

***N*,*N*-Diisopropylethylamine**: purchased from Alfa and used as received.

***N*-(3-Dimethylaminopropyl)-*N*′-ethylcarbodiimide hydrochloride (EDCI)**: purchased from Advanced ChemTech and used as received.

2,6-Dimethyloct-7-en-2-ol (dihydromyrcenol): purchased from Aldrich and used as received.

2-Fluoro-6-methylaniline: purchased from Oakwood and used as received.

Formic acid: purchased from Oakwood and used as received.

Glyoxal (40 wt% in H_2O): purchased from Aldrich and used as received.

(*Z*)-3-Hexene: purchased from Alfa and used as received.

5-Hexenoic acid: purchased from Aldrich and used as received.

(*S*)-Hex-5-en-2-ol: purchased from Aldrich and used as received.

5-Hexen-1-ol: purchased from Aldrich and used as received.

First-generation phosphine-free ("Hoveyda–Grubbs") Ru complex: purchased from Materia and used as received.

Hydrogen chloride (2M in Et_2O): purchased from Acros and used as received.

Hydroquinidine (anthraquinone-1,4-diyl) diether $(DHQD)_2AQN$): purchased from Aldrich and used as received.

Hydroxybenzotriazole hydrate (HOBt): purchased from Advanced ChemTech and used as received.

Imidazole: purchased from Oakwood and used as received.

Isobutylamine: purchased from Aldrich and used as received.

Lithium aluminum hydride: purchased from Aldrich and used as received

Lithium perchlorate: purchased from Aldrich and used as received.

4-Methoxybenzylamine: purchased from Aldrich and used as received.

Methyl *N*-(triethylammoniumsulfonyl)carbamate (**Burgess reagent**): purchased from Oakwood and used as received.

8-Nonen-1-ol: purchased from TCI and used as received.

Paraformaldehyde: purchased from Fluka and used as received.

4-Penten-1-ol: purchased from Aldrich and used as received.

4-Pentenal: purchased from Alfa and used as received

Potassium carbonate: purchased from Fisher Scientific and used as received.

Potassium *tert*-butoxide: purchased from Aldrich and used as received.

Potassium bis(trimethylsilyl)amide: purchased from Aldrich and used as received.

Potassium ferricyanide: purchased from Aldrich and used as received.

Potassium osmate: purchased from Aldrich and used as received.

Silver chloride: purchased from Strem and used as received.

1-Tetradecene: purchased from Aldrich and used as received.

Tetrabutylammonium fluoride (1 M in THF): purchased from Oakwood and used as received.

Trimethylsilyl chloride: purchased from Oakwood and used as received.

Undec-10-enal: purchased from Aldrich and used as received.

Benzyl pent-4-enoate: (from 4-pentenoic acid (Aldrich)) was prepared according to a reported procedures.[38]

3,6-Dichlorobenzene-1,2-dithiol zinc salt: (from 3,6-dichlorobenzene-1,2-dithiol (Aldrich)) was prepared according to a reported procedure.[39]

(*E*)-Hepta-2,6-dien-1-ol: (from pent-4-enal (Aldrich)) was prepared according to a reported procedure.[40]

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(38) Nookaraju, U.; Kumar, P. *RSC Adv.* **2015***, 5*, 63311−63317.

(39) Koh, M. J.; Khan, R. K. M.; Torker, S.; Yu, M.; Mikus, M.; Hoveyda, A. H. *Nature* **2015**, *517*, 181–186.

(40) Murphy, S. K.; Coulter, M. M.; Dong, V. M. *Chem. Sci*. **2012**, *3*, 355−358.

(*Z*)-Hex-3-ene-3,4-d_2: (from 3-hexyne (Aldrich)) was prepared according to a reported procedure.[41]

2-(Hex-5-en-1-yl)isoindoline-1,3-dione: (from phthalimide (Aldrich)) was prepared according to a reported procedure.[42]

(*S*)-1-((Hex-5-en-2-yloxy)methyl)-4-methoxybenzene: (from (*S*)-hex-5-en-2-ol (Aldrich))was prepared according to a reported procedure.[43]

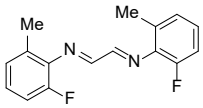
(2*E*,4*E*)-8-Iodoocta-2,4-diene: (from 5-chloropent-1-yne (Aldrich)) was prepared according to a reported procedure.[44]

***O*-Trimethylsilyl hydroquinidine**: (from hydroquinidine (Aldrich)) was prepared in analogy to a reported procedure.[45]

3.6.2 Preparation of Ru Complexes and Cross-Metathesis with (*Z*)-3-Hexene

Procedure for Synthesis of NHC Ligands

***N*^{1},*N*^{2}-Bis(2-fluoro-6-methylphenyl)ethane-1,2-diimine**



Based on a previously reported procedure[46], a 250 mL round-bottom flask was charged with an aqueous solution of glyoxal (40 wt %, 1.84 mL, 16 mmol), anhydrous Na_2SO_4 (13.6 g, 96 mmol, oven-dried overnight), and CH_2Cl_2 (40 mL). The mixture was allowed to stir for 30 min, after which 2-fluoro-6-methylaniline (4.00 g, 32 mmol), formic acid (85 μL, 2.24 mmol), and a second portion of anhydrous

(41) Kroll, J. H.; Donahue, N. M.; Cee, V. J.; Demerjian, K. L.; Anderson, J. G. *J. Am. Chem. Soc*. **2002**, *124*, 8518−8519.

(42) Fukuda, H.; Nishiyama, Y.; Nakamura, S.; Ohno, Y.; Eguchi, T.; Iwabuchi, Y.; Usui, T.; Kanoh, N. *Chem. Asian. J*. **2012**, *7*, 2872−2881.

(43) Panarese, J. D. & Waters, S. P. *Org. Lett*. **2009**, *11*, 5086−5088.

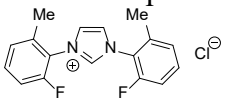
(44) Sammakia, T.; John, D. M.; Kim, G.; Berliner, M. A. *J. Am. Chem. Soc*. **2005**, *127*, 6504−6505.

(45) Zhu, C.; Shen, X.; Nelson, S. G. *J. Am. Chem. Soc*. **2004**, *126*, 5352−5353.

(46) Kündig, E. P.; Seidel, T. M.; Jia, Y. -X.; Bernardinelli, G. *Angew. Chem., Int. Ed.* **2007**, *46*, 8484–8487.

Na_2SO_4 (13.6 g, 96 mmol, oven-dried overnight) were added. The heterogeneous mixture was allowed to stir vigorously for 12 h, filtered to remove Na_2SO_4, and concentrated *in vacuo*. The residual (a mixture of solid and liquid) was filtered, and the solid was washed with hexanes (10 mL × 3) to afford N^1,N^2-bis(2-fluoro-6-methylphenyl)ethane-1,2-diimine as yellow solid (1.838 g, 6.75 mmol, 42% yield). **IR (neat)**: 2960 (w), 1607 (m), 1470 (m), 1258 (m), 1243 (m), 1191 (m), 1020 (m), 939 (m), 772 (s), 740 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 8.39 (t, *J* = 1.9 Hz, 2H), 7.14–6.94 (m, 6H), 2.34 (s, 6H); **^{13}C NMR (150 MHz, $CDCl_3$):** 165.1 (d, *J* = 6.5 Hz), 152.7 (d, *J* = 248.5 Hz), 137.1 (d, *J* = 9.8 Hz), 134.9, 126.8 (d, *J* = 8.5 Hz), 126.0 (d, *J* = 3.0 Hz), 18.1 (d, *J* = 2.6 Hz); **^{19}F NMR (376 MHz, $CDCl_3$)**: δ –129.32 to –129.37 (m); **HRMS[M+H]$^+$**: Calcd for $C_{16}H_{15}F_2N_2$: 273.1198, found: 273.1197.

1,3-Bis(2-fluoro-6-methylphenyl)-1H-imidazol-3-ium chloride

Based on a previously reported procedure[47], an oven-dried 4-dram vial was charged with 

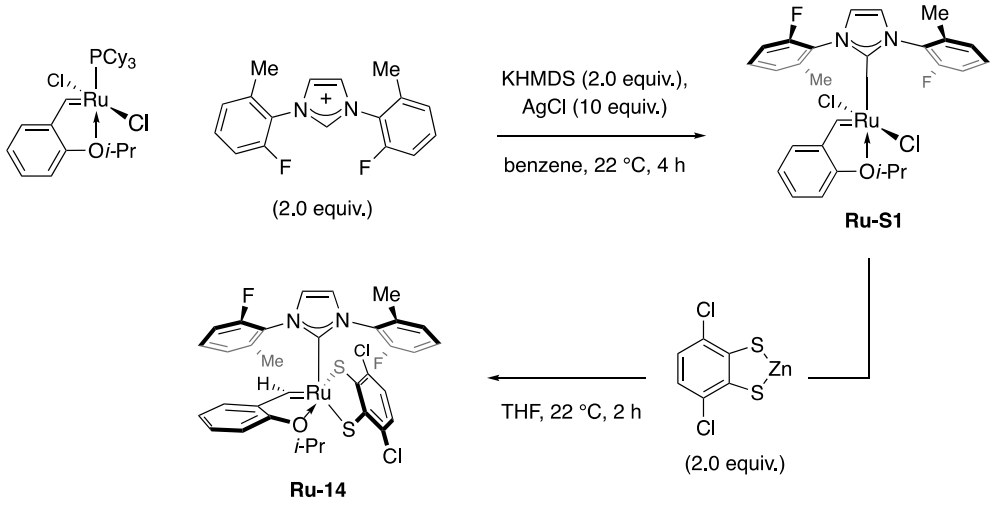
N^1,N^2-bis(2-fluoro-6-methylphenyl)ethane-1,2-diimine (838 mg, 3.08 mmol, 1.0 equiv.), paraformaldehyde (277.2 mg, 9.24 mmol, 3.0 equiv.), and toluene (8.0 mL). Under vigorous stirring, HCl (4.0 M in Et_2O, 1.00 mL, 4.0 mmol, 1.3 equiv.) was slowly added in a dropwise fashion to the mixture with a total addition time of 30 min. The mixture was allowed to stir for 12 h, after which the toluene supernatant was decanted. The solid residue was dried *in vacuo* and purified by silica gel chromatography (2% to 4% to 8% MeOH in CH_2Cl_2) to afford 1,3-bis(2-fluoro-6-methylphenyl)-1H-imidazol-3-ium chloride as light purple solid (526 mg, 53% yield). **IR (neat)**: 3350 (br, m), 3024 (m), 2921 (m), 1547 (s), 1475 (s), 1278 (m), 1267 (m), 1229 (m), 1025 (m), 786 (s) cm^{-1}; **^{1}H NMR**

(47) Dible, B. R.; Cowley, R. E.; Holland, P. L. *Organometallics* **2011**, *30*, 5123−5132.

(600 MHz, DMSO-*d*$_6$): δ 10.24 (s, 1H), 8.50 (s, 2H), 7.66 (q, *J* = 7.5 Hz, 2H), 7.50 (t, *J* = 8.9 Hz, 2H), 7.43 (d, *J* = 7.5 Hz, 2H), 2.31 (s, 6H); **^{13}C NMR (150 MHz, DMSO-*d*$_6$):** δ 156.2 (d, *J* = 250.9 Hz), 140.2, 137.0, 132.6 (d, *J* = 8.7 Hz), 127.1 (d, *J* = 3.2 Hz), 125.0, 121.8 (d, *J* = 12.7 Hz), 114.3 (d, *J* = 18.9 Hz), 16.7; **^{19}F NMR (376 MHz, DMSO-*d*$_6$)**: δ –123.8 (dd, *J* = 9.6, 5.7 Hz); **HRMS[M-Cl]$^+$**: Calcd for $C_{17}H_{15}F_2N_2^+$: 285.1198, found: 285.1206.

Preparation of Ru-Based Complexes

Scheme S1



Ru-S1. In a N_2-filled glovebox, a 6-dram vial was charged with potassium bis(trimethylsilyl)amide (82 mg, 0.411 mmol, 2.0 equiv.) and 1,3-bis(2-fluoro-6-methylphenyl)-1H-imidazol-3-ium chloride (132 mg, 0.411 mmol, 2.0 equiv.) and 5 mL THF. The mixture was allowed to stir at 22 °C for 30 min. First-generation phosphine-free Ru complex (123 mg, 0206 mmol, 1.0 equiv.) was added and the mixture was allowed to stir for 1 h, after which silver chloride (286 mg, 2.06 mmol, 10 equiv.) was introduced and stirring was allowed to continue for an additional hour. Filtration and removal of the volatiles *in vacuo* afforded black oil, which was purified by silica gel chromatography (20–100% Et_2O in hexanes) to afford the product as green solid as a mixture of *N*-aryl rotamers

(86 mg, 0.142 mmol, 69% yield). **^{1}H NMR (600 MHz, C_6D_6)** (1:1.5 mixture of rotamers): δ 16.78 (s, 0.37 H), 16.72 (s, 0.57 H), 7.18 (d, *J* = 11.5 Hz, 2H), 7.00 (q, *J* = 7.4 Hz, 2H), 6.90–6.79 (m, 4H), 6.73 (t, *J* = 7.4 Hz, 1H), 6.44 (d, *J* = 8.0 Hz, 1H), 6.28 (d, *J* = 5.3 Hz, 2H), 4.58 (dt, *J* = 11.5, 5.6 Hz, 1H), 2.37 (s, 6H), 1.48 (t, *J* = 5.5 Hz, 6H); **^{19}F NMR (470 MHz, $CDCl_3$)**: δ –114.1 (br), –115.3 (br); **^{13}C NMR (150 MHz, CD_2Cl_2):** (1:1.5 mixture of rotamers, all peaks are listed due to differentiation of rotamer peaks and C-F coupling peaks are non-trivial) δ 287.6, 287.3, 286.6, 286.3, 180.1, 179.9, 160.6, 160.5, 158.9, 158.8, 152.9, 152.9, 145.2, 145.2, 141.3, 131.6, 131.5, 131.5, 131.5, 131.4, 131.4, 129.6, 129.5, 127.8, 127.8, 127.8, 127.7, 126.7, 126.7, 126.6, 126.5, 126.5, 125.8, 125.8, 125.7, 125.6, 123.0, 122.9, 122.3, 122.2, 114.6, 114.4, 114.4, 114.3, 114.3, 114.1, 113.5, 113.4, 76.0, 75.8, 32.3, 32.1, 31.7, 27.6, 27.5, 27.4, 26.3, 26.2, 21.6, 21.5, 18.7, 18.6.

Ru-14. A 1-dram vial containing a stir bar was charged with 3,6-dichlorobenzene-1,2-dithiol zinc salt (77.9 mg, 0.284 mmol, 2.0 equiv.) under N_2 atm., and then a solution of **Ru-S1** (86 mg, 0.142 mmol, 1.0 equiv.) in THF (2 mL) was added. The mixture was allowed to stir for 2 h at 22 °C, at which time the volatiles were removed in vacuo. The residual tetrahydrofuran was removed by co-evaporation with pentane. The resulting yellow solid was dissolved in CH_2Cl_2 and passed through a short column of celite (2 cm in height) in a pipette (~0.5 cm in diameter) with CH_2Cl_2. After removal of the volatiles from the filtrate and co-evaporation with pentane, **Ru-14** was isolated as brown solid and further crystallized from hexane/ CH_2Cl_2 (91 mg, 0.122 mmol, 86% yield). **^{1}H NMR (500 MHz, CD_2Cl_2)**: (several rotamers in solution in ratios of 1:0.13:0.06:0.06; the major conformer are presented): δ 14.65 (s, 1H), 7.31 (t, *J* = 7.8 Hz, 1H), 7.22 (d, *J* = 1.9 Hz, 1H), 7.13–7.06 (m, 2H), 7.02 (d, *J* = 8.4 Hz, 1H), 6.98–6.92 (m, 2H), 6.87 (dd, *J* = 17.1, 7.7 Hz, 2H), 6.82

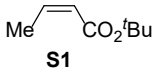
(d, J = 8.0 Hz, 1H), 6.77 (d, J = 8.0 Hz, 2H), 6.72 (q, J = 7.2 Hz, 1H), 6.18 (t, J = 8.9 Hz, 1H), 5.31–5.24 (m, 1H), 2.37 (s, 3H), 2.19 (s, 3H), 1.71 (d, J = 6.2 Hz, 3H), 1.57 (d, J = 6.1 Hz, 3H); **^{19}F NMR (470 MHz, CD_2Cl_2)**: δ –118.3 (br), –124.1 (br); **^{13}C NMR (150 MHz, CD_2Cl_2): (**major rotamer**)** δ 251.6 (br), 189.5 (br), 158.1 (d, J = 249.0 Hz), 157.6 (d, J = 249.3 Hz), 156.5, 154.6, 143.0, 140.9, 140.7, 138.5, 131.3, 131.2 (d, J = 8.7 Hz), 130.8 (d, J = 8.6 Hz), 129.7, 128.2, 126.4 (d, J = 3.3 Hz), 126.0 (d, J = 3.3 Hz), 124.8, 124.3, 123.1, 122.2, 121.6, 113.7 (d, J = 19.8 Hz), 113.4 (d, J = 19.9 Hz), 112.7, 77.7, 22.3 (d, J = 3.4 Hz), 22.2 (d, J = 3.4 Hz), 22.1, 19.3 (d, J = 2.2 Hz), 17.8 (d, J = 2.4 Hz).

Synthesis of the Substrates

Benzyl (*Z*)-but-2-enoate (3.13a) An 8-dram vial was charged with potassium carbonate (152.0 mg, 1.1 mmol, 1.1 equiv.), (*Z*)-2-butenoic acid (86.1 mg, 1.0 mmol, 1.0 equiv.) and 2.0 mL DMF, and the mixture was allowed to stir for 20 min at 22 °C, after which benzyl bromide (188 mg, 1.1 mmol, 1.1 equiv.) was added and the mixture was allowed to stir for 12 h. The reaction was quenched by the addition of a saturated solution of NH_4Cl (10 mL) and the organic layer was washed with Et_2O (50 mL × 3). The combined organic layers were washed with brine, dried over Na_2SO_4 and concentrated *in vacuo*. The resulting black oil was purified by silica gel chromatography (2–10% Et_2O in hexanes) to afford **3.13a** (169.5 mg, 0.96 mmol, 96% yield) as colorless oil. The characterization data are consistent with those previously reported.[48] **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 7.41–7.30 (m, 5H), 6.36 (dq, J = 11.5, 7.3 Hz, 1H), 5.85 (dq, J = 11.5, 1.7 Hz, 1H), 5.17 (s, 2H), 2.16 (dd, J = 7.3, 1.8 Hz, 3H); **HRMS[M+H]$^+$**: Calcd for $C_{11}H_{13}O_2$: 177.0910, found: 177.0904.

***tert*-Butyl (*Z*)-but-2-enoate (S1)**

(48) Peter, D.; Bruckner, R. *Chem. Eur. J*. **2017**, *23*, 12104−12109.



S1

An 8-dram vial was charged with (*Z*)-2-butenoic acid (86.1 mg, 1.0 mmol, 1.0 equiv.), *tert*-butyl 2,2,2-trichloroacetimidate (327.8 mg, 1.5 mmol, 1.5 equiv.) and CH_2Cl_2 (5.0 mL). The mixture was allowed to stir for 12 h after which the volatiles were removed *in vacuo*. The resulting yellow oil was purified by silica gel chromatography (2–10% Et_2O in hexanes) to afford **S1** (116.6 mg, 0.82 mmol, 82% yield) as colorless oil. The characterization data are consistent with those previously reported.[49] **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 6.22 (dq, *J* = 11.5, 7.2 Hz, 1H), 5.79–5.63 (m, 1H), 2.18–2.02 (m, 3H), 1.49 (s, 9H); **HRMS[M+H]$^+$**: Calcd for $C_8H_{15}O_2$: 143.1067, found: 143.1072.

(*Z*)-But-2-enoic acid (3.13b). A 100 mL round-bottom flask was charged with but-2-ynoic acid (500.0 mg, 5.95 mmol) and anhydrous Et_2O (20 mL); this was followed by the addition of 5% Pd/$BaSO_4$ (125 mg) and quinoline (25 mg, 0.19 mmol, 3.2 mol%) The mixture was allowed to stir under H_2 atm (balloon) at 22 °C for 1 h. Reaction progress was monitored by ^{1}H NMR analysis ($CDCl_3$). Accordingly, when hydrogenation was found to be complete, the mixture was passed through a pad of Celite, and the filtrate was concentrated *in vacuo*, affording pale yellow oil, which was purified by silica gel chromatography (5–15% EtOAc in hexanes) to afford benzyl (*Z*)-but-2-enoic acid (300.4 mg, 3.49 mmol, 59% yield) in >98:2 *Z*:*E* selectivity as colorless liquid. **IR (neat):** 3046 (w), 2944 (w), 1688 (s), 1641 (s), 1449 (m), 1227 (s), 820 (m), 727 (m), 415 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 12.23 (br, 1H), 6.47 (dq, *J* = 11.5, 7.3 Hz, 1H), 5.88-5.79 (m, 1H), 2.16 (dd, *J* = 7.3, 1.8 Hz, 3H). **^{13}C NMR (150 MHz, $CDCl_3$):** δ 172.6, 148.0, 120.4, 15.8. **HRMS[M+H]$^+$**: Calcd for $C_4H_7O_2$: 87.0446, Found: 87.0450.

(49) Tommasi, S.; Perrone, S.; Rosato, F.; Salomone, A.; Troisi, L. *Synthesis* **2012**, *44*, 423−430.

(*Z*)-*N*-methoxy-*N*-methylbut-2-enamide (3.13c). A 100 mL round-bottom flask was charged with *N*-methoxy-*N*-methylbut-2-ynamide (635.7 mg, 5.00 mmol), 5% Pd/$BaSO_4$ (125 mg) and and quinoline (25 mg, 0.19 mmol, 3.8 mol%). The mixture was allowed to stir under H_2 atm (balloon) at 22 °C. Reaction progress was monitored by ^{1}H NMR analysis ($CDCl_3$). Accordingly, when hydrogenation was found to be complete, the mixture was passed through a pad of Celite, and the filtrate was concentrated *in vacuo*, affording pale yellow oil, which was purified by silica gel chromatography (5–15% EtOAc in hexanes) to afford (*Z*)-*N*-methoxy-*N*-methylbut-2-enamide (356.8 mg, 2.76 mmol, 55% yield) in >98:2 *Z*:*E* selectivity as colorless liquid. **IR (neat):** 2937 (w), 1656 (s), 1633 (m), 1441 (m), 1001 (m), 1274 (m), 818 (m), 456 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 6.18−6.16 (m, 2H), 3.62−3.58 (m, 3H), 3.15−3.12 (m, 3H), 2.04−2.02 (m, 3H); **^{13}C NMR (125 MHz, $CDCl_3$):** δ 167.6, 141.8, 119.1, 61.4, 32.0, 15.3; **HRMS[M+H]$^+$**: Calcd for $C_6H_{12}NO_2$: 130.0868, Found: 130.0863.

(*Z*)-*N*-Benzylbut-2-enamide (3.13d). An 8-dram vial was charged with (*Z*)-2-butenoic acid (86.1 mg, 1.0 mmol, 1.0 equiv.) and CH_2Cl_2 (4.0 mL). The following were subsequently added: benzylamine (96 mg, 0.9 mmol, 0.9 equiv.), *N*-(3-dimethylaminopropyl)-*N*′-ethylcarbodiimide hydrochloride (EDCI, 229 mg, 1.2 mmol, 1.2 equiv.), hydroxybenzotriazole hydrate (HOBt, 184 mg, 1.2 mmol, 1.2 equiv.), and *N*,*N*-diisopropylethylamine (310.2 mg, 2.4 mmol, 2.4 equiv.). The mixture was allowed to stir for 1 h and then the volatiles were removed *in vacuo*. The resulting yellow solid was purified by silica gel chromatography to afford **3.13d** (119 mg, 0.68 mmol, 75% yield) as colorless oil. **IR (neat)**: 3288 (m, br), 3061 (m), 3027 (m), 2913 (w), 1658 (s), 1631 (s), 1536 (s), 1495 (m), 1433 (m), 1357 (m), 1269 (m), 1232 (m), 1027 (w), 809 (m), 743 (m),

718 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 7.36–7.27 (m, 5H), 6.19–6.07 (m, 1H), 5.79 (s, br, 1H), 5.73 (dt, *J* = 11.4, 1.7 Hz, 1H), 4.48 (t, *J* = 4.9 Hz, 2H), 2.15 (dt, *J* = 7.2, 1.8 Hz, 3H); **^{13}C NMR (125 MHz, $CDCl_3$)**: δ 166.6, 140.8, 138.5, 128.8, 128.0, 127.6, 123.0, 43.4, 15.3; **HRMS[M+H]$^+$**: Calcd for $C_{11}H_{14}NO$: 176.1067, found: 176.1072.

(*Z*)-But-2-enamide (3.13e). A 50 mL round-bottom flask was charged with 5 mL CH_2Cl_2/H_2O (20/1) solution of (*Z*)-*N*-(4-methoxybenzyl)but-2-enamide (102.5 mg, 0.5 mmol, 1.0 equiv.), after which DDQ (170.2 mg, 0.75 mmol, 1.5 equiv.) was added and the mixture was allowed to stir for 4 h at 22 °C. The reaction was quenched by the addition of a saturated solution of Na_2SO_3 (20 mL). The aqueous layer was washed with EtOAc (20 mL × 3), and the organic layers were combined, dried over Na_2SO_4, concentrated under reduced pressure, and the resulting purple solid was purified by silica gel chromatography (50–100% EtOAc in hexanes) to afford **3.13e** (37.4 mg, 0.44 mmol, 88% yield) as off-white solid. **M.p.**: 115−116 °C; **IR (neat)**: 3393 (m), 3201 (m), 1668 (s), 1636 (m), 1610 (s), 1448 (m), 1366 (m), 1322 (m), 1260 (m), 817 (m), 709 (m); **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 6.17 (dq, *J* = 11.7, 7.2 Hz, 1H), 5.77 (dd, *J* = 11.5, 1.7 Hz, 1H), 5.46 (br, 2H), 2.13 (dd, *J* = 7.2, 1.2 Hz, 3H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 168.66, 141.75, 122.28, 15.24; **HRMS[M+H]$^+$**: Calcd for C_4H_8NO: 86.0600, found: 86.0605.

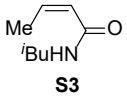
(*Z*)-*N*-(4-Methoxybenzyl)but-2-enamide (S2)

S2

A 50 mL round-bottom flask was charged with (*Z*)-2-butenoic acid (86.1 mg, 1.0 mmol, 1.0 equiv.) and CH_2Cl_2 (4.0 mL). The following were subsequently added: 4-methoxybenzylamine (123.5 mg, 0.9 mmol, 0.9 equiv.), *N*-(3-dimethylaminopropyl)-*N*′-ethylcarbodiimide hydrochloride (EDCI, 229 mg, 1.2 mmol, 1.2 equiv.), hydroxybenzotriazole hydrate (HOBt, 184 mg, 1.2 mmol, 1.2 equiv.), and *N*,*N*-

diisopropylethylamine (310.2 mg, 2.4 mmol, 2.4 equiv.). The mixture was allowed to stir for 1 h and the volatiles were removed *in vacuo*. The resulting yellow solid was purified by silica gel chromatography to afford **S2** (149.6 mg, 0.73 mmol, 81% yield) as off-white solid. **M.p.**: 76−77 °C; **IR (neat)**: 3298 (s), 3061 (w), 3039 (w), 2955 (w), 2916 (w), 1659 (m), 1624 (s), 1539 (s), 1513 (m), 1459 (m), 1247 (m), 1233 (m), 1218 (m), 1175 (m), 1108 (m), 1027 (m), 816 (m), 696 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 7.25–7.20 (m, 2H), 6.89–6.83 (m, 2H), 6.11 (dq, *J* = 11.4, 7.2 Hz, 1H), 5.70 (dq, *J* = 11.4, 1.7 Hz, 1H), 5.64 (s, br, 1H), 4.41 (d, *J* = 5.7 Hz, 2H), 3.80 (s, 3H), 2.15 (dd, *J* = 7.2, 1.8 Hz, 3H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 166.5, 159.2, 140.7, 130.6, 129.4, 123.1, 114.2, 55.5, 42.9, 15.3; **HRMS[M+H]$^+$**: Calcd for $C_{12}H_{16}NO_2$: 206.1176, found: 206.1174.

(*Z*)-*N*-Isobutylbut-2-enamide (S3)



S3

A 50 mL round-bottom flask was charged with (*Z*)-2-butenoic acid (86.1 mg, 1.0 mmol, 1.0 equiv.) and CH_2Cl_2 (4.0 mL). The following were then added sequentially: Isobutylamine (65.8 mg, 0.9 mmol, 0.9 equiv.), *N*-(3-dimethylaminopropyl)-*N*′-ethylcarbodiimide hydrochloride (EDCI, 229 mg, 1.2 mmol, 1.2 equiv.), hydroxybenzotriazole hydrate (HOBt, 184 mg, 1.2 mmol, 1.2 equiv.), and *N*,*N*-diisopropylethylamine (310.2 mg, 2.4 mmol, 2.4 equiv.). The mixture was allowed to stir for 1 h and the volatiles were removed *in vacuo*. The resulting yellow oil was purified by silica gel chromatography (10–50% EtOAc in hexanes) to afford **S3** (91.5 mg, 0.65 mmol, 72% yield) as off-white solid. **M.p.**: 45 ºC; **IR (neat)**: 3292 (m, br), 3073 (w), 3028 (w), 2955 (m), 2924 (m), 2868 (m), 1658 (s), 1630 (s), 1541 (s), 1465 (m), 1434 (m), 1386 (m), 1268 (m), 1232 (m), 1157 (m), 914 (w), 808 (w) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 6.13–5.99 (m, 1H), 5.71 (dq, *J* = 11.4, 1.7 Hz, 1H), 5.64 (s, br, 1H), 3.10 (td, *J* = 6.8, 6.1,

1.3 Hz, 2H), 2.10 (dd, *J* = 7.2, 1.7 Hz, 3H), 1.78 (dp, *J* = 13.4, 6.7 Hz, 1H), 0.91 (dd, *J* = 6.7, 1.1 Hz, 6H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 166.9, 139.7, 123.5, 46.7, 28.7, 20.3, 15.1; **HRMS[M+H]$^+$**: Calcd for $C_8H_{16}NO$: 142.1226, found: 142.1229.

Cross-Metathesis with (Z)-3-Hexene

Benzyl (*Z*)-pent-2-enoate (3.15a). In a glove box, an oven-dried vial equipped with a magnetic stir bar was charged with (*Z*)-3-hexene (84.2 mg, 1.00 mmol, 10.0 equiv.) and benzyl (*Z*)-but-2-enoate (17.6 mg, 0.100 mmol, 1.00 equiv.) in THF (200 μL). To this mixture was added a THF solution (400 μL) of **Ru-14** (3.7 mg, 0.005 mmol, 5.0 mol %). The mixture was allowed to stir for 8 h at 22 °C, after which the reaction was quenched by exposing the solution to air and the addition of undistilled Et_2O. Removal of the volatiles *in vacuo* afforded black oil, which was purified by silica gel chromatography (5–15% EtOAc in hexanes) to afford **3.15a** (14.8 mg, 0.078 mmol, 78% yield) in >98:2 *Z*:*E* selectivity as colorless oil. **IR (neat):** 3035 (w), 2964 (w), 1719 (s), 1642 (m), 1166 (s), 821 (m), 696 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.39−7.30 (m, 5H), 6.25 (dt, *J* = 11.5, 7.5 Hz, 1H), 5.80 (dt, *J* = 11.5, 1.7 Hz, 1H), 5.16 (s, 2H), 2.68 (pd, *J* = 7.5, 1.7 Hz, 2H), 1.06 (t, *J* = 7.6 Hz, 3H). **^{13}C NMR (100 MHz, $CDCl_3$):** δ 166.3, 152.8, 136.3, 128.7, 128.3, 128.3, 118.9, 65.8, 22.7, 13.6. **HRMS[M+H]$^+$**: Calcd for $C_{12}H_{15}O_2$: 191.1430, Found: 191.1425. The same procedure was employed for the reaction of **Ru-10**.

(*Z*)-Pent-2-enoic acid (3.15b). The same procedure as described above was followed. The resulting black oil residue was purified by silica gel chromatography (5–10% EtOAc in hexanes) to afford olefin **3.15b** (7.0 mg, 0.070 mmol, 70% yield) in 98:2 *Z*:*E* selectivity as colorless oil. The corresponding spectral data are consistent with those previously

reported.[50] **^{1}H NMR (400 MHz, $CDCl_3$):** δ carboxylic acid proton is invisible, 6.35 (dt, *J* = 11.5, 7.5 Hz, 1H), 5.76 (dt, *J* = 11.5, 1.7 Hz, 1H), 2.67 (pd, *J* = 7.6, 1.7 Hz, 2H), 1.06 (t, *J* = 7.6 Hz, 3H). Carboxylic acid proton was not observable. **^{13}C NMR (100 MHz, $CDCl_3$):** δ 172.3, 155.0, 118.7, 22.8, 13.5. The same procedure was employed for the reaction of **Ru-10**.

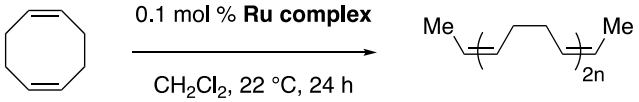
(*Z*)-*N*-Methoxy-*N*-methylpent-2-enamide (3.15c). The same procedure as described above was followed. The resulting black oil residue was purified by silica gel chromatography (10–20% EtOAc in hexanes) to afford **3.15c** (9.7 mg, 0.068 mmol, 68% yield) in >98:2 *Z*:*E* selectivity as colorless oil. **IR (neat):** 2958 (m), 2923 (s), 2852 (m), 1643 (w), 800 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.16 (d, *J* = 11.6 Hz, 1H), 6.05 (dt, *J* = 11.6, 7.2 Hz, 1H), 3.63 (s, 3H), 3.16 (s, 3H), 2.57 (p, *J* = 7.5 Hz, 2H), 1.00 (t, *J* = 7.6 Hz, 3H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 167.5, 148.9, 117.6, 61.5, 32.2, 22.5, 13.8; **HRMS[M+H]$^+$**: Calcd for $C_7H_{14}NO_2$: 144.1019, Found: 144.1023. The same procedure was employed for the reaction of **Ru-10**.

(*Z*)-*N*-Benzylpent-2-enamide (3.15d). The same procedure as described above was followed. The resulting black oil residue was purified by silica gel chromatography (10–20% EtOAc in hexanes) to afford olefin product (15.9 mg, 0.084 mmol, 84% yield) in >98:2 *Z*:*E* selectivity as colorless oil. **IR (neat):** 3285 (s), 3063 (w), 1671 (w), 1628 (s), 1552 (s), 1276 (s), 820 (m), 693 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.30 (m, 5H), 6.00 (dt, *J* = 11.4, 7.4 Hz, 1H), 5.77 (br, 1H), 5.67 (d, *J* = 11.4 Hz, 1H), 4.47 (d, *J* = 5.8 Hz, 2H), 3.60−2.45 (m, 2H), 1.05 (t, *J* = 7.6 Hz, 3H); **^{13}C NMR (125 MHz, $CDCl_3$):** δ 166.5, 147.9, 138.5, 128.8, 128.0, 127.6, 121.5, 43.5, 22.4, 13.9; **HRMS[M+H]$^+$**: Calcd for

(50) Qi, L.; Mui, Y. F.; Lo, S. W.; Lui, M. Y.; Akien, G. R.; Horváth, I. T. *ACS Catal*. **2014**, *4*, 1470−1477.

$C_{12}H_{16}NO$: 190.1232, Found: 190.1229. The same procedure was employed for the reaction of **Ru-10**.

(*Z*)-Pent-2-enamide (3.15e). The same procedure as described above was followed. The resulting black oil was purified by silica gel chromatography (50~100% ethyl acetate in hexanes) and filtered through a small plug of activated charcoal to afford product in >98:2 *Z*:*E* selectivity as colorless oil (4.4 mg, 0.0444 mmol, 89% yield). The characterization data are consistent with those previously reported.[51] **^{1}H NMR (500 MHz, $CDCl_3$)**: δ 6.04 (dt, *J* = 11.5, 7.4 Hz, 1H), 5.71 (d, *J* = 11.5 Hz, 1H), 5.52 (d, *J* = 84.1 Hz, 2H), 2.65 (p, *J* = 8.5, 8.0 Hz, 2H), 1.04 (t, *J* = 7.6 Hz, 3H); **HRMS[2M+H]$^+$**: Calcd for $C_{10}H_{19}N_2O_2$: 199.1441, found: 199.1438. The same procedure was employed for the reaction of **Ru-10**.



with **Ru-10**: 82% conv., 71% yield, >98:2 *Z*:*E*
with **Ru-14**: 80% conv., 66% yield, >98:2 *Z*:*E*

Polymerization of cyclooctdiene. In an N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with 1,5-cyclooctadiene (108 mg, 1.00 mmol, after purification by passing through a plug of basic alumina). A solution of **Ru-14** (0.70 mg, 0.001 mmol) in CH_2Cl_2 (0.2 mL) was added and the resulting solution was allowed to stir at 22 °C for 24 h, after which MeOH (2.0 mL) was added, causing the polymer to precipitate. The polymer was washed again with MeOH (2.0 mL) and dried *in vacuo* (1.0

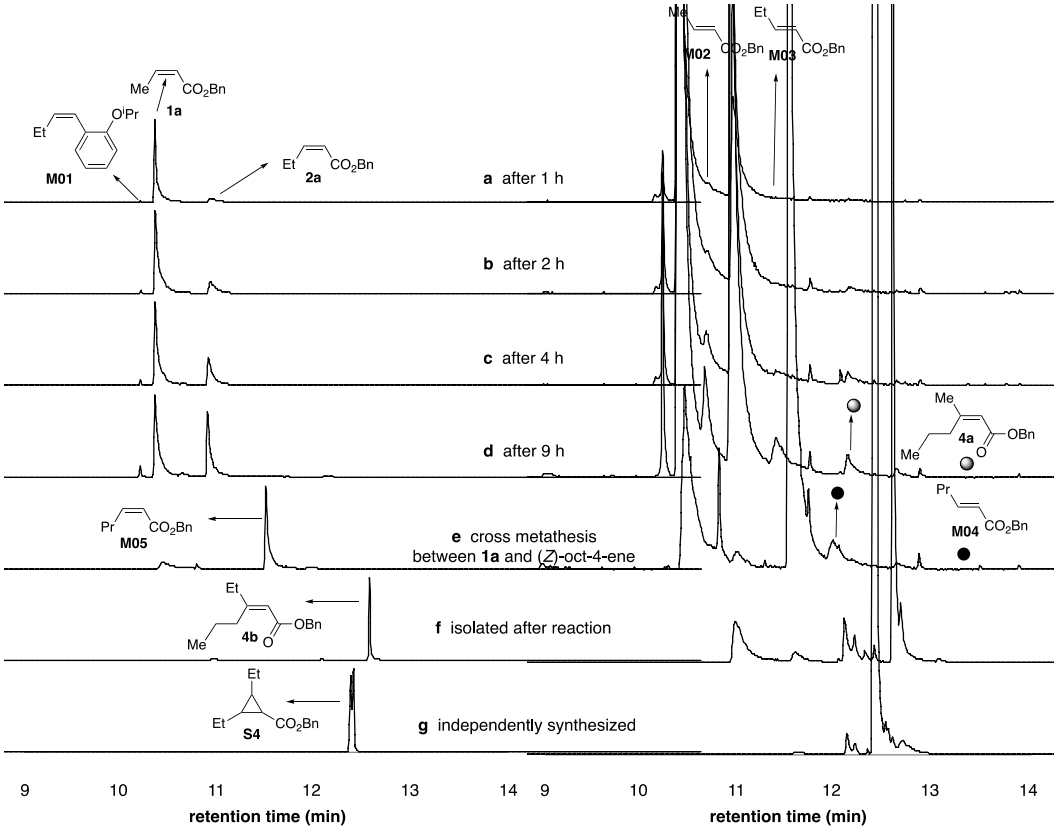
(51) Victorio, C.; Javier, F.; Jose, G. *Chem. Eur. J.* **2008**, 14, 6601−6605.

x 10^{-1} torr) to afford polycyclooctadiene (71.3 mg, 66% yield). The characterization data are consistent with those previously reported.[52]

3.6.3 Mechanistic Studies

Identification of Decomposition Products

In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with a THF solution (200 μL, pre-made stock solution) of benzyl (*Z*)-but-2-enoate (17.6 mg, 0.100 mmol, 1.00 equiv.), (*Z*)-hex-3-ene (84.2 mg, 1.00 mmol, 10.0 equiv.) and a THF solution (400 μL, pre-made stock solution) of **Ru-10** (3.7 mg, 0.005 mmol, 1.00 equiv.). The mixture was allowed to stir at 22 °C, while aliquots were removed and analyzed by GC-MS after 1, 2, 4 and 9 h. The same procedure was employed for **Ru-14**.



(52) Khan, R. K.; M., Toker, S.; Hoveyda, A. H. *J. Am. Chem. Soc*. **2013**, *135*, 10258−10261.

Fig. S1. Identification of decomposition products generated by a reaction carried out in the presence of **Ru-10** (GC-MS analysis; unscaled GC traces (left); intensity scaled by a factor of 15 (right)).

Analysis: In the case of the reaction carried out with **Ru-10**, <10% **3.15a** was detected after 1 h (GC-MS; Fig. S1a). Conversion reached nearly 50% after 9 h (Fig. S1d). Based on MS analysis and an independently prepared sample of **M05** (Fig. S3 and Fig. S1e), we confirmed the formation of isomerization byproducts **M02**, **M03**, and **M04**. Importantly, we confirmed the formation of trisubstituted enoates **3.16a** and **3.16b** (~70:30; see DFT Section for further analysis). We were unable to detect cyclopropanation product after the reaction, which we independently synthesized as mixture of two isomers through cyclopropane formation method with a Rh-based complex (Fig. S1g).

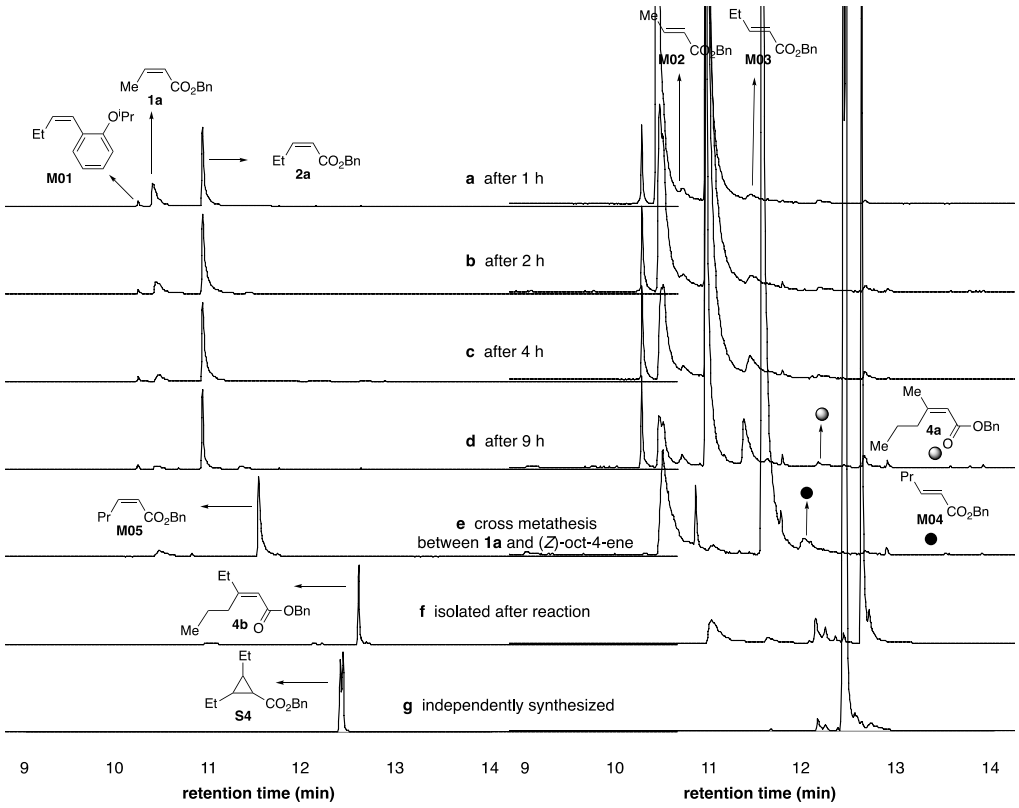


Fig. S2. Identification of decomposition products generated by a reaction carried out in the presence of **Ru-14** (GC-MS analysis; unscaled GC traces (left); intensity scaled by a factor of 15 (right)).

Analysis: In the case of the reaction carried out with **Ru-14**, (*Z*)-but-2-enoate **3.13a** was converted to **2a** after 1 h (GC analysis; left trace, Fig. S2a). Apart from the efficiency difference, the other notable distinction relative to the transformation with **Ru-10** is the reversal in **3.16a**:**3.16b** ratio derived (~20:80, Fig. S2d). Because the concentration of (*Z*)-pent-2-enoate **2a** increases as the reaction progresses, increasing amounts of **3.16b** are generated (right trace, Fig. S2d; compared to Fig. S2a). Subjection of **3.16b** to GC-MS confirmed that **3.16b** is the same species that is produced in the course of the reaction (Fig. S2f). The stereochemical identity of **3.16b** was ascertained through appropriate nOe experiments (Fig. S4). The resulting data (Et group and alkenyl protons in *cis* relationship) are consistent with the pathway predicted by DFT studies. The structure of **3.16a** was confirmed by MS fragment analysis (Fig. S3).

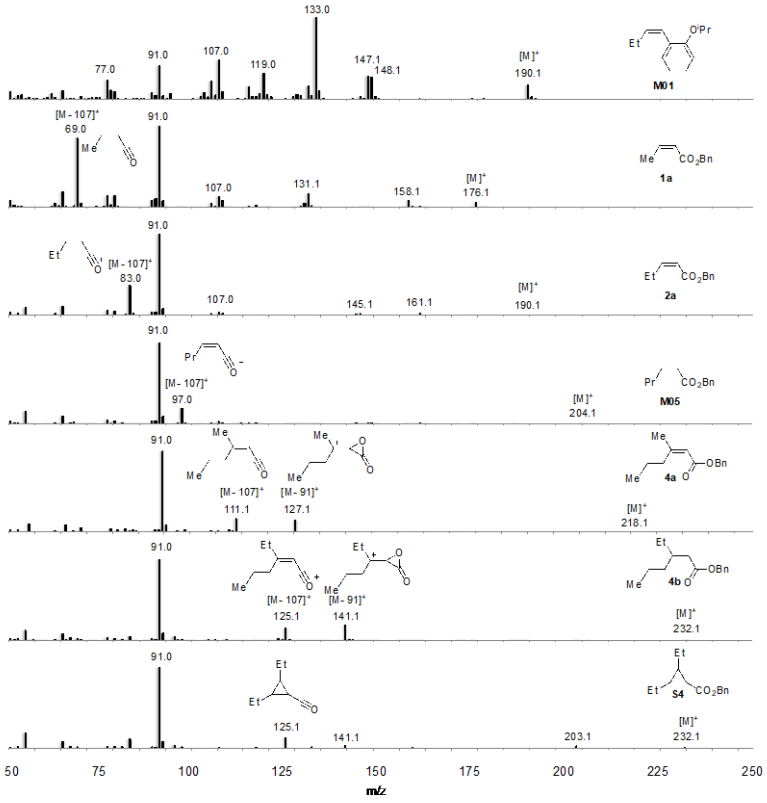


Fig. S3. Mass spectra and proposed fragmentation for the most relevant species and byproducts observed during CM between (*Z*)-hex-3-ene and benzyl (*Z*)-but-2-enoate.

Analysis: All compounds display a peak corresponding to their molecular weight $[M]^+$. All spectra display a peak at m/z = 91, which corresponds to the tropylium ion derived from the benzyl protecting group. All benzyl ester substrates show a peak at $[M-107]^+$, which is the acylium ion after loss of benzyloxide. The spectra containing trisubstituted enoates **3.16a** and **3.16b** contain an additional peak at m/z = $[M-91]^+$, which is either absent or far weaker in the spectra of the other benzyl esters. We propose that appearance of this peak depends on the possible formation of a stabilized tertiary carbocation.

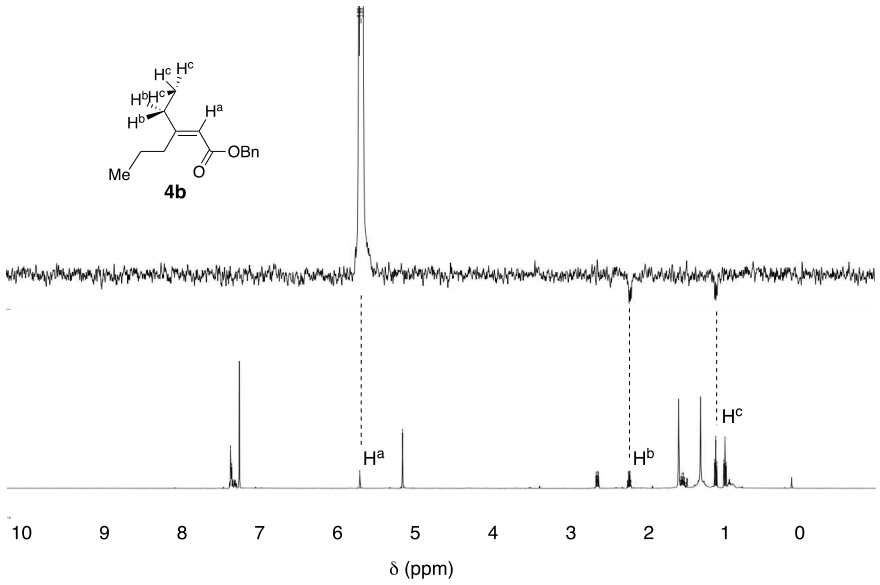
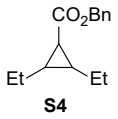


Fig. S4. Determination of the stereochemical identity of **3.16b** (NOE experiments recorded in $CDCl_3$ at 500 MHz).

Benzyl (*Z*)-3-ethylhex-2-enoate (3.16b). IR (neat): 2961 (m), 2925 (s), 1717 (s), 1142 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.39-7.29 (m, 5H), 5.69 (s, 1H), 5.13 (s, 2H), 2.60 (t, *J* = 7.5 Hz, 2H), 2.21−2.16 (m, 2H), 1.53−1.45 (m, 2H), 1.06 (t, *J* = 7.4 Hz, 3H), 0.94 (t, *J* = 7.4 Hz, 3H); **^{13}C NMR (125 MHz, $CDCl_3$):** δ 166.9, 166.6, 136.6, 128.7, 128.3, 128.2, 114.1, 65.6, 34.5, 31.4, 22.1, 14.4, 12.2; **HRMS[M+H]$^+$**: Calcd for $C_{15}H_{21}O_2$: 233.1536, Found: 233.1537.

Benzyl 2,3-diethylcyclopropane-1-carboxylate (S4)



S4

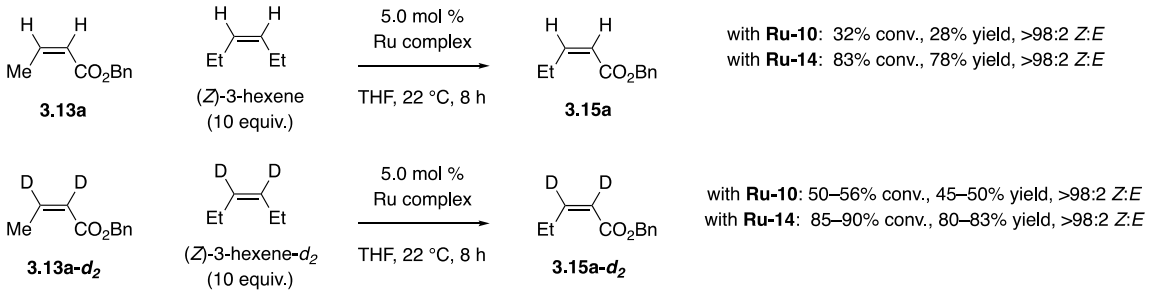
In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with benzyl 2-diazoacetate (88.1 mg, 0.500 mmol, 1.00 equiv.) and (*Z*)-hex-3-ene (210.4 mg, 2.50 mmol, 5.00 equiv.) in CH_2Cl_2 (300 μL). To this solution was added $Rh_2(OAc)_4$ (2.2 mg, 0.005 mmol, 5.0 mol %), causing significant N_2 evolution. After five min, the vessel was sealed, and the mixture was allowed to stir for 12 h at 22 °C. The reaction was quenched by the addition of undistilled Et_2O and the volatiles were removed *in vacuo*. The resulting green oil was purified by silica gel chromatography (5–15% EtOAc in hexanes) to afford **S4** (diastereomeric mixture; 34.3 mg, 0.148 mmol, 30% yield) as colorless oil. **IR (neat):** 2962 (m), 2930 (w), 1723 (s), 1455 (m), 1164 (s), 1141 (s), 736 (m), 696 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.39−7.29 (m, 5H), 5.10−5.09 (m, 2H), 1.72−1.64 (m, 2H), 1.49−1.12 (m, 5H), 1.02−0.99 (m, 3H), 0.94−0.90 (m, 3H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 174.8, 172.2, 136.7, 136.5, 128.7, 128.6, 128.3, 128.2, 128.1, 128.1, 66.2, 65.8, 30.3, 27.7, 26.6, 20.7, 20.2, 15.8, 14.2, 14.1; **HRMS[M+H]$^+$**: Calcd for $C_{15}H_{21}O_2$: 233.1536, Found: 233.1531.

***β*-Hydride Elimination**

In a N_2-filled glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with (*Z*)-hex-3-ene-3,4-d_2 (86.2 mg, 1.00 mmol, 10.0 equiv.) and benzyl (*Z*)-but-2-enoate-3,4-d_2 (17.8 mg, 0.100 mmol, 1.00 equiv.), and THF (200 μL). To this mixture was added **Ru-10** (3.7 mg, 0.005 mmol, 5.0 mol %; stock solution in THF, 400 μL), and was allowed to stir for 8 h at 22 °C. The reaction was quenched by the addition of undistilled Et_2O and the volatiles were removed *in vacuo* to leave behind black oil, which was purified by silica gel chromatography (5–15% EtOAc in hexanes) to afford **3.15a** or **3.15a-*d*$_2$** (15.4 mg,

0.080 mmol, 80% yield) in >98:2 *Z*:*E* ratio and 95% deuterium incorporation as colorless oil. The same procedure was used for a reaction with **Ru-14**.

Scheme S2



Analysis: With **Ru-10**, for reaction of deuterium-labeled substrates with **Ru-10**, there was a boost in efficiency (from 32% to 50−56% conv.), whereas in the case of **Ru-14** conversion was high regardless of whether deuterium-labeled alkenes were used or not (83 vs. 85−90% conv.). These data indicate that when the rate of decomposition by β-hydride elimination reduced, there is diminished gap between the efficiency of cross-metathesis reactions performed in the presence of **Ru-10** and **Ru-14**.

Benzyl (*Z*)-pent-2-enoate-2,3-*d*$_2$ (3.13a-*d*$_2$). To a solution of benzyl but-2-ynoate (870.4 mg, 5.00 mmol, 1.0 equiv.) in 20 mL anhydrous Et_2O was added 5% $Pd/BaSO_4$ (150 mg), quinoline (30 mg, 0.23 mmol, 4.6 mol%) under D_2 atm. (balloon) at 22 °C. Reaction progress was monitored by analyzing the composition of an aliquot (^{1}H NMR spectroscopy). Once hydrogenation was complete, the solution was allowed to pass through a pad of Celite. The volatiles were removed *in vacuo*, and the resulting pale yellow oil was purified by silica gel chromatography (5–15% EtOAc in hexanes) to afford **3.13a-*d*$_2$** (540 mg, 3.03 mmol, 61% yield) in >98:2 *Z*:*E* selectivity and 96% D incorporation as colorless oil. **IR (neat):** 3034 (w), 1713 (s), 1620 (m), 1251 (s), 1128 (s), 1087 (m), 696 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.40−7.30 (m, 5H), 5.17 (s, 2H), 2.15 (s, 3H); **^{13}C NMR**

(100 MHz, $CDCl_3$): δ 166.4, 145.5-145.2 (m), 136.3, 128.7, 128.3, 128.2, 120.3-119.9 (m), 65.8, 15.4; **HRMS[M+H]$^+$**: Calcd for $C_{11}H_{11}D_2O_2$: 179.1036, Found: 179.1043.

Benzyl (*Z*)-pent-2-enoate-2,3-d_2 (3.15a-d_2). IR (neat): 3034 (w), 2964 (w), 2934 (w), 1717 (s), 1618 (m), 1243 (s), 1141 (s), 1104 (m), 697 (w) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.38−7.32 (m, 5H), 5.16 (s, 2H), 2.67 (q, J = 7.4 Hz, 2H), 1.05 (t, J = 7.6 Hz, 3H); **^{13}C NMR (125 MHz, $CDCl_3$):** δ 166.3, 152.5−152.2 (m), 136.4, 128.7, 128.3, 128.3, 118.8−118.4 (m), 65.8, 22.5, 13.6; **HRMS[M+H]$^+$**: Calcd for $C_{12}H_{13}D_2O_2$: 193.1192, Found: 193.1209.

Cross-Metathesis Between (*Z*)-3-Hexene and Benzyl (*Z*)-but-2-enoate

In a glove box, a pair of oven-dried NMR tubes were charged with a THF-d_8 solution (200 μL, pre-made stock) of benzyl (*Z*)-but-2-enoate (17.6 mg, 0.100 mmol, 1.00 equiv.), (*Z*)-hex-3-ene (84.2 mg, 1.00 mmol, 10.0 equiv.), and anthracene (internal standard, 8.9 mg, 0.050 mmol, 0.500 equiv.). One sample was diluted with THF-d_8 (400 μL) and the corresponding ^{1}H NMR spectrum

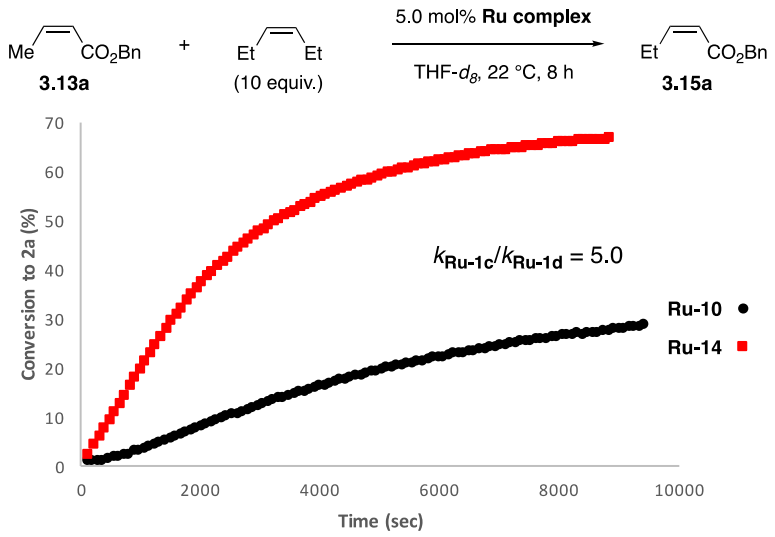


Fig. S5. Reaction profile for cross-metathesis between (*Z*)-hex-3-ene and benzyl (*Z*)-but-2-enoate.

was recorded (t_0). To the other sample was added a THF-d_8 solution (400 μL, pre-made stock solution) of **Ru-10** (3.7 mg, 0.005 mmol, 5.0 mol %; through a syringe and with shaking). Reaction progress was monitored by ^{1}H NMR analysis for 8 h at 25 °C. The same protocol was followed for a similar experiment with **Ru-14**.

Analysis: A significant rate difference can be observed when cross-metathesis between benzyl (*Z*)-but-2-enoate and (*Z*)-hex-3-ene catalyzed by **Ru-10** and **Ru-14** is monitored by ^{1}H NMR over time (Fig. S5). The rate for cross metathesis to product is five times faster with **Ru-14** as compared to **Ru-10**.

Analysis of Initiation Rates

With benzyl (*Z*)-but-2-enoate: In a glovebox, an oven-dried vial equipped with a magnetic stir bar was charged with a THF solution (100 μL, pre-made stock solution) of anthracene (internal standard, 0.891 mg, 0.005 mmol, 1.00 equiv.) and a THF solution of **Ru-10** (3.7 mg, 0.005 mmol, 1.00 equiv.; stock solution, 400 μL). The mixture was allowed to stir for five min at 22 °C, after which an aliquot was removed and diluted with CD_2Cl_2 (600 μL) and the corresponding ^{1}H NMR spectrum was recorded (t_0). A solution of benzyl (*Z*)-but-2-enoate (17.6 mg, 0.100 mmol, 20.0 equiv., 100 μL THF) was added and the resulting solution was allowed to stir for 8 h at 22 °C. Reaction progress was again analyzed as described above (^{1}H NMR; t_{end}). The same protocol was used for the corresponding experiment with **Ru-14**.

With (*Z*)-hex-3-ene: In a N_2-filled glovebox, an oven-dried NMR tube equipped with a septum was charged with a thf-d_8 solution (100 μL, pre-made stock solution) of anthracene (internal standard, 0.891 mg, 0.005 mmol, 1.00 equiv.) and a THF-d_8 solution (400 μL, pre-made stock solution) of **Ru-10** (3.7 mg, 0.005 mmol, 1.0 equiv.). Then, the reaction

vessel was sealed and taken out the glovebox, and a ^{1}H NMR spectrum of the sample was acquired (^{1}H NMR at t_0). A THF-d_8 solution (100 µL, pre-made stock solution) of (*Z*)-hex-3-ene (84.2 mg, 1.00 mmol, 200 equiv.) was added into the NMR tube through the septum via syringe and stirred manually. The reaction was then monitored by ^{1}H NMR for 8 h at 25 °C. The same procedure was employed for **Ru-14**.

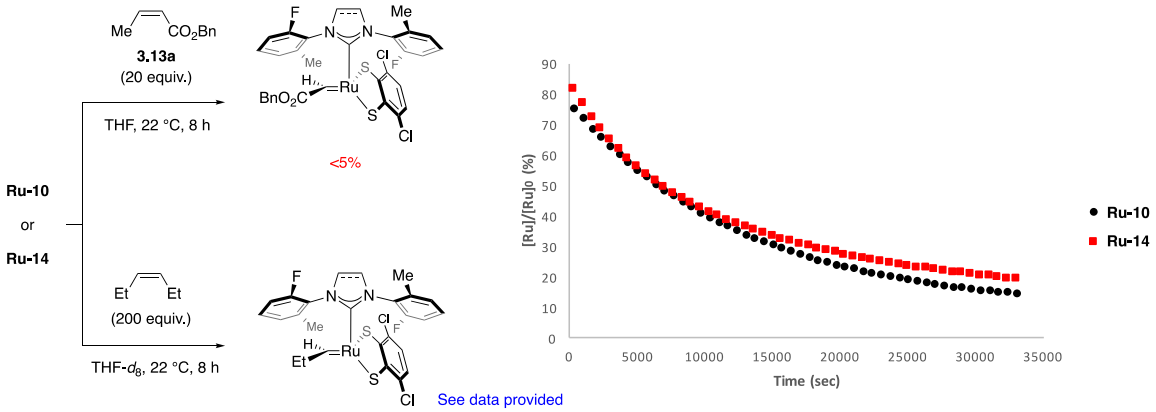


Fig. S6. Initiation studies with benzyl (*Z*)-but-2-enoate and (*Z*)-hex-3-ene.

Analysis: Regardless of the complex used, whereas there is no initiation with electron-deficient benzyl (*Z*)-but-2-enoate, there is facile transformation with the more electron-rich (*Z*)-hex-3-ene. Furthermore, the kinetic profile indicates that reaction with (*Z*)-hex-3-ene occurs at a similar rate when **Ru-10** or **Ru-14** is used. These data reveal that a difference in the rate of catalyst initiation is not the reason for the observed difference in olefin metathesis efficiency (Fig. S6).

Relative Rates of Homo-Metathesis and Cross-Metathesis Reactions

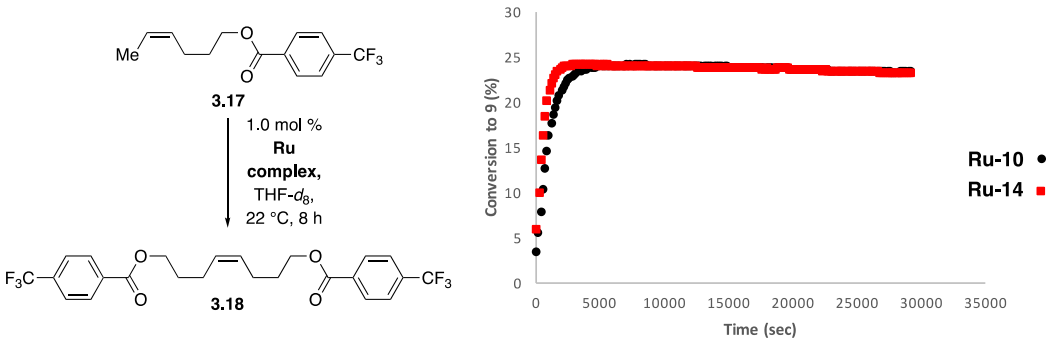


Fig. S7. Progress of a homo-metathesis reaction (by ^{19}F NMR spectroscopy).

Analysis: Regardless of whether **Ru-10** or **Ru-14** is used, homo-metathesis of electron-rich substrate **3.17** proceeds at a similar rate.

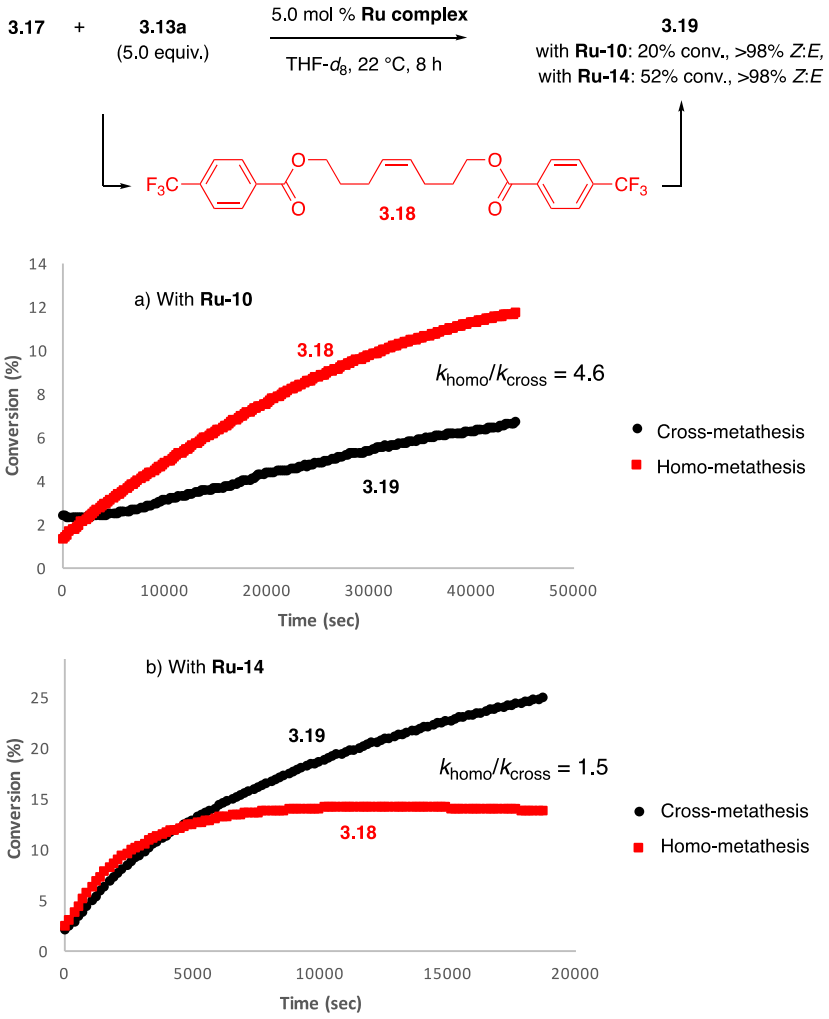


Fig. S8. Progress of a homo-metathesis vs. cross-metathesis (by ^{19}F NMR spectroscopy).

Analysis: For cross-metathesis between **3.17** and ester **3.13a**, the rates for homo-metathesis (**3.17** to **3.18**) are faster than cross-metathesis (**3.17** to **3.19**) for both Ru complexes. However, the rate difference for **Ru-10** (k_{homo}/k_{cross} = 4.6) is larger than **Ru-14** (k_{homo}/k_{cross} = 1.5). Considering compound **3.13a** is a more challenging coupling partner (more electron-deficient than **8**), the greater chemo-selectivity for the more electron-rich olefin suggests that **Ru-10** is less reactive than **Ru-14**. Besides, the initial rates of both homo-metathesis and cross metathesis with **Ru-14** are faster than the rates with **Ru-10**. This further verify that **Ru-10** is less reactive than **Ru-14**, especially towards the metathesis with electron-deficient substrates.

(*Z*)-Hex-4-en-1-yl 4-(trifluoromethyl) benzoate (3.17). To a solution of 4-(trifluoromethyl) benzoic acid (570.4 mg, 3.0 mmol, 1.0 equiv.), EDCI (690.1 mg, 3.6 mmol, 1.2 equiv.), and DMAP (36.7 mg, 0.30 mmol, 0.100 equiv.) in CH_2Cl_2 (4.5 mL) was added (*Z*)-hex-4-en-1-ol (300.5 mg, 3.0 mmol, 1.0 equiv.). After 12 h, the volatiles were removed *in vacuo*, and the resulting gray oil residue was purified by silica gel chromatography (5–15% EtOAc in hexanes) to afford (*Z*)-hex-4-en-1-yl 4-(trifluoromethyl) benzoate (365.4 mg, 1.34 mmol, 45% yield) in >98:2 *Z*:*E* ratio as colorless oil. **IR (neat):** 2690 (w), 2033 (w), 1726 (s), 1326 (s), 1276 (s), 1131 (m), 863 (w), 704 (w) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.16 (d, *J* = 8.4 Hz, 2H), 7.71 (d, *J* = 8.2 Hz, 2H), 5.56–5.49 (m, 1H), 5.44–5.39 (m, 1H), 4.36 (t, *J* = 6.6 Hz, 2H), 2.22 (q, *J* = 7.2 Hz, 2H), 1.86 (p, *J* = 6.9 Hz, 2H), 1.61 (d, *J* = 6.7 Hz, 3H); **^{13}C NMR (125 MHz, $CDCl_3$):** δ 165.5, 134.5 (q, *J* = 32.8 Hz), 130.1, 129.0, 125.5 (q, *J* = 3.8 Hz), 125.3, 123.8 (q, *J* = 273.4 Hz), 65.2, 28.6, 23.4, 12.9. **^{19}F NMR (564 MHz, THF-d_8):** δ –64.1 (s); **HRMS[M+H]$^+$**: Calcd for $C_{14}H_{16}O_2F_3$: 273.1097, Found: 273.1099.

(*Z*)-Oct-4-ene-1,8-diyl bis(4-(trifluoromethyl) benzoate (3.18). Colorless oil. **IR (neat):** 2958 (w), 1722 (s), 1324 (s), 1273 (s), 1125 (s), 1100 (s), 862 (w), 704 (w) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.13 (d, *J* = 8.2 Hz, 4H), 7.68 (d, *J* = 8.3 Hz, 4H), 5.48 (m, 2H), 4.34 (t, *J* = 6.6 Hz, 4H), 2.22 (q, *J* = 7.1 Hz, 4H), 1.85 (p, *J* = 6.8 Hz, 4H); **^{13}C NMR (125 MHz, $CDCl_3$):** δ 165.5, 134.5 (q, *J* = 32.3 Hz), 133.7, 130.0, 129.6, 125.5 (q, *J* = 3.8 Hz), 123.8 (q, *J* = 273.0 Hz), 65.1, 28.7, 23.8; **^{19}F NMR (564 MHz, THF-*d*$_8$):** δ –64.1 (s); **HRMS[M+H]$^+$**: Calcd for $C_{24}H_{23}O_4F_6$: 489.1495, Found: 489.1499.

(*Z*)-6-(Benzyloxy)-6-oxohex-4-en-1-yl 4-(trifluoromethyl) benzoate (3.19). Colorless oil. **IR (neat):** 2957 (w), 1718 (s), 1324 (s), 1273 (s), 1161 (s), 1120 (s), 863 (m), 698 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.15 (d, *J* = 8.1 Hz, 2H), 7.70 (d, *J* = 8.1 Hz, 2H), 7.54–7.29 (m, 5H), 6.30 (dt, *J* = 11.5, 7.6 Hz, 1H), 5.90 (dd, *J* = 11.5, 1.8 Hz, 1H), 5.14 (s, 2H), 4.38 (t, *J* = 6.5 Hz, 2H), 2.86 (q, *J* = 7.4 Hz, 2H), 1.96 (p, *J* = 7.1 Hz, 2H); **^{13}C NMR (125 MHz, $CDCl_3$):** δ 166.0, 165.5, 149.2, 136.2, 134.5 (q, *J* = 32.6 Hz), 133.7, 130.1, 128.7, 128.3, 128.3, 125.5 (q, *J* = 3.7 Hz), 123.8 (q, J = 273.0 Hz), 120.7, 66.0, 65.0, 28.2, 25.8; **^{19}F NMR (564 MHz, THF-*d*$_8$):** δ -64.1 (s); **HRMS[M+H]$^+$**: Calcd for $C_{21}H_{20}O_4F_3$: 393.1308, Found: 393.1319.

Control Experiments

a. Homo-Metathesis vs. Cross-Metathesis Reactions

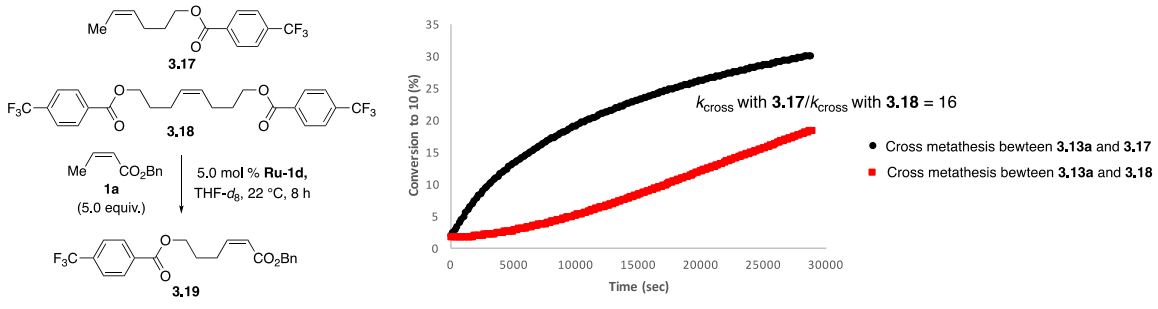


Fig. S9. Relatives rates of homo-metathesis and cross-metathesis (by ^{19}F NMR spectroscopy).

Analysis: The data in Fig. S9 illustrate that cross-metathesis between benzyl (*Z*)-but-2-enoate (**3.13a**) is more efficient with enoate **3.17** than alkyl-substituted olefin **3.18**. The initial rate of the former reaction is 16 times faster than the cross-metathesis with **3.18**, indicating that it is unlikely that **3.19** is generated by the reaction that involves **Ru-14** and **3.18** at the early stages of the process (initial rates).

b. Effect of A Lewis Base Additive on Homo-Metathesis of 3.17

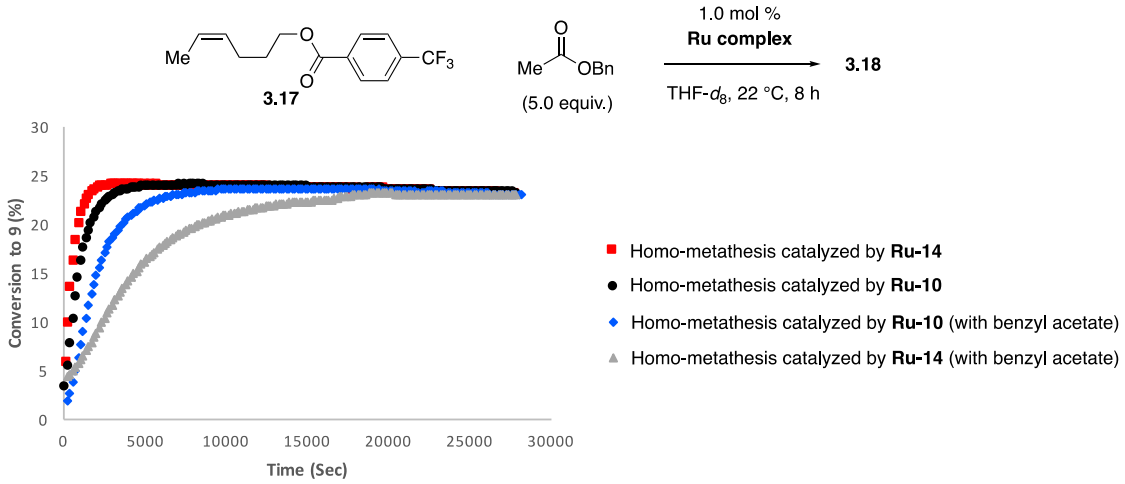


Fig. S10. Examination of the effect of a Lewis base on the rate of cross-metathesis (by ^{19}F NMR spectroscopy).

Analysis: The presence of a carboxylic ester is detrimental to the rate of homo-metathesis, but more so when **Ru-14** is used (vs. **Ru-10**). This may be attributed to higher Lewis acidity of **Ru-14**.

3.6.4 Method Development

Cross-Metathesis Procedures

Condition A: In a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with a THF solution of the alkene substrate (0.050 mmol) and the appropriate amount of *Z*-2-butene (used as received) and a THF solution of **Ru-14** (1.0 mol %; 0.50 M). The mixture was allowed to stir for 1 h at 22 °C, after which the volatiles

were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was then charged with the α,β-unsaturated alkene, a THF solution of **Ru-14** (5.0 mol %; 0.25 M), the system was placed under 100 torr ~~h~~ vacuum for 1 h, and the solution was allowed to stir for 19 h at 22 °C. The reaction was quenched by the addition of undistilled Et_2O and the volatiles were removed *in vacuo*. The resulting residue (typically black oil) was purified by silica gel chromatography to afford the desired product.

Condition B: In a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with a THF solution of the alkene substrate (0.050 mmol) and the appropriate amount of *Z*-2-butene (used as received) and a THF solution of **Ru-14** (1.0 mol %; 0.50 M). The mixture was allowed to stir for 1 h at 22 °C, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was charged with the α,β-unsaturated alkene, a THF solution of **Ru-14** (4.0 mol %; 0.25 M), the system was placed under 100 torr vacuum for 1 h, and the solution was allowed to stir for 8 h at 22 °C. The flask containing the residue was again charged with a THF solution of **Ru-14** (4.0 mol %; 0.25 M), the system was placed under 100 torr vacuum for 1 h, and the solution was allowed to stir for 12 h at 22 °C. The reaction was quenched by the addition of undistilled Et_2O and the volatiles were removed *in vacuo*. The resulting residue (typically black oil) was purified by silica gel chromatography to afford the desired product.

Condition C: In a glove box, an oven-dried vial equipped with a magnetic stir bar was charged with a THF solution of the alkene substrate (0.050 mmol) and a THF solution of **Ru-14** (4.0 mol %; 0.25 M). The system was placed under 100 torr vacuum for 1 h and the solution was allowed to stir for 8 h at 22 °C. The mixture was again charged with a THF solution of **Ru-14** (4.0 mol %; 0.25 M), and the system was placed under 100 torr vacuum

for 1 h, and the solution was allowed to stir for 12 h at 22 °C. The reaction was quenched by the addition of undistilled Et_2O and the volatiles were removed *in vacuo*. The resulting residue (typically black oil) was purified by silica gel chromatography.

Condition D: In a glove box, an oven-dried vial equipped with a magnetic stir bar was charged with a THF solution of the alkene substrate (0.050 mmol) and the appropriate amount of *Z*-2-butene (used as received) and a THF solution of **Ru-14** (2.0 mol %; 0.50 M). The mixture was allowed to stir for 1 h at 22 °C, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The flask containing the residue was charged with the α,β-unsaturated alkene, a THF solution of **Ru-14** (4.0 mol %; 0.25 M), the system was placed under 100 torr vacuum for 1 h, and the solution was allowed to stir for 8 h at 22 °C. The flask containing the residue was again charged with a THF solution of **Ru-14** (4.0 mol %; 0.25 M), the system was placed under 100 torr vacuum for 1 h, and the solution was allowed to stir for 12 h at 22 °C. The reaction was quenched by the addition of undistilled Et_2O and the volatiles were removed *in vacuo*. The resulting residue (typically black oil) was purified by silica gel chromatography to afford the desired product.

(*Z*)-α,β-Unsaturated Esters

Benzyl (*Z*)-9-bromonon-2-enoate (3.21b). Colorless oil. **IR (neat)**: 2930 (m), 2855 (m), 1719 (s), 1642 (m), 1164 (s), 817 (m), 737 (m), 697 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.39–7.30 (m, 5H), 6.25 (dt, *J* = 11.5, 7.6 Hz, 1H), 5.83 (dt, *J* = 11.5, 1.7 Hz, 1H), 5.16 (s, 2H), 3.39 (t, *J* = 6.9 Hz, 2H), 2.67 (qd, *J* = 7.5, 1.7 Hz, 2H), 1.85 (p, *J* = 14.3, 6.9 Hz, 2H), 1.51–1.31 (m, 6H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 166.3, 151.1, 136.3, 128.7, 128.4, 128.3, 119.7, 76.8, 65.9, 34.0, 32.9, 29.1, 28.9, 28.5, 28.1; **HRMS[M+H]$^+$**: Calcd for $C_{16}H_{22}BrO_2$: 325.0804, found: 325.0803.

Benzyl (*Z*)-5-phenylpent-2-enoate (3.21c). Colorless oil. **IR (neat)**: 3086 (w), 3063 (w), 3029 (m), 2926 (m), 1718 (s), 1643 (m), 1496 (m), 1454 (m), 1414 (m), 1213 (m), 1173 (s), 1157 (s), 1080 (m), 1003 (m), 735 (m), 697 (m); **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.40–7.31 (m, 5H), 7.27 (d, *J* = 6.9 Hz, 2H), 7.19 (t, *J* = 6.9 Hz, 3H), 6.28 (dt, *J* = 11.5, 7.5 Hz, 1H), 5.84 (d, *J* = 11.5 Hz, 1H), 5.15 (s, 2H), 3.00 (q, *J* = 7.6 Hz, 2H), 2.76 (t, *J* = 7.7 Hz, 2H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 166.2, 149.8, 141.2, 136.3, 128.7, 128.6, 128.5, 128.4, 128.3, 126.2, 120.2, 65.9, 35.2, 30.7; **HRMS[M+H]$^+$**: Calcd for $C_{18}H_{19}O_2$: 267.1385, found: 267.1384.

Benzyl (*Z*)-7-(1,3-dioxoisoindolin-2-yl)hept-2-enoate (3.21d). Colorless oil. **IR (neat)**: 2939 (w), 1704 (s), 1395 (m), 1163 (m), 719 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.87–7.80 (m, 2H), 7.74–7.68 (m, 2H), 7.40–7.27 (m, 5H), 6.22 (dt, *J* = 11.5, 7.6 Hz, 1H), 5.83 (dt, *J* = 11.5, 1.7 Hz, 1H), 5.14 (s, 2H), 3.69 (t, *J* = 7.2 Hz, 2H), 2.72 (qd, *J* = 7.5, 1.7 Hz, 2H), 1.77–1.66 (m, 2H), 1.55–1.46 (m, 2H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 168.5, 166.2, 150.3, 136.3, 134.0, 132.3, 128.7, 128.4, 128.3, 123.3, 120.1, 65.9, 37.9, 28.6, 28.4, 26.4; **HRMS[M+H]$^+$**: Calcd for $C_{22}H_{22}O_4N$: 364.1549, found: 364.1554.

Benzyl (*Z*)-10-hydroxydec-2-enoate (3.21e). Colorless oil. **IR (neat)**: 2927 (m), 1719 (s), 1642 (m), 1165 (s), 737 (m), 697 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.40–7.29 (m, 5H), 6.25 (dt, *J* = 11.5, 7.6 Hz, 1H), 5.82 (dt, *J* = 11.5, 1.7 Hz, 1H), 5.16 (s, 2H), 3.63 (t, *J* = 6.6 Hz, 2H), 2.66 (qd, *J* = 7.5, 1.7 Hz, 2H), 1.60–1.51 (m, 2H), 1.49–1.40 (m, 2H), 1.37–1.28 (m, 6H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 166.3, 151.4, 136.3, 128.7, 128.3, 128.3, 119.5, 65.8, 63.1, 32.9, 29.3, 29.2, 29.2, 29.0, 25.7; **HRMS[M+H]$^+$**: Calcd for $C_{17}H_{25}O_3$: 277.1812, found: 277.1804.

Benzyl (*Z*)-12-oxododec-2-enoate (3.21f). Colorless oil. **IR (neat)**: 2925 (m), 2854 (m), 1720 (s), 1642 (m), 1163 (s), 737 (m), 687 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 9.76 (t, *J* = 1.9 Hz, 1H), 7.40–7.29 (m, 5H), 6.25 (dt, *J* = 11.5, 7.5 Hz, 1H), 5.82 (dt, *J* = 11.5, 1.7 Hz, 1H), 5.16 (s, 2H), 2.66 (qd, *J* = 7.5, 1.7 Hz, 2H), 2.41 (td, *J* = 7.4, 1.9 Hz, 2H), 1.68–1.57 (m, 2H), 1.48–1.38 (m, 2H), 1.36–1.24 (m, 8H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 203.0, 166.3, 151.4, 136.3, 128.7, 128.3, 128.3, 119.5, 65.8, 44.0, 29.4, 29.3, 29.3, 29.3, 29.2, 29.1, 22.2; **HRMS[M+H]$^+$**: Calcd for $C_{19}H_{27}O_3$: 303.196, found: 303.1972.

(*Z*)-7-(benzyloxy)-7-oxohept-5-enoic acid (3.21g). Colorless oil. **IR (neat)**: 1707 (s), 1415 (m), 1173 (m), 1154 (m), 738 (m), 697 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.41–7.29 (m, 5H), 6.23 (dt, *J* = 11.5, 7.6 Hz, 1H), 5.87 (dt, *J* = 11.5, 1.7 Hz, 1H), 5.15 (s, 2H), 2.73 (qd, *J* = 7.5, 1.7 Hz, 2H), 2.39 (t, *J* = 7.6 Hz, 2H), 1.80 (p, *J* = 7.6 Hz, 2H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 178.0, 166.1, 149.4, 136.2, 128.7, 128.4, 128.4, 120.6, 66.0, 33.2, 28.4, 24.0; **HRMS[M+H]$^+$**: Calcd for $C_{14}H_{17}O_4$: 249.1127, found: 249.1127.

Benzyl (2*Z*,4*E*)-5-phenylpenta-2,4-dienoate (3.21h). Colorless oil. **IR (neat)**: 1709 (m), 1622 (m), 1164 (s), 999 (m), 959 (m), 755 (m), 696 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 8.14 (ddd, *J* = 15.7, 11.4, 1.1 Hz, 1H), 7.51 – 7.27 (m, 10H), 6.86–6.74 (m, 2H), 5.78 (dt, *J* = 11.2, 0.9 Hz, 1H), 5.22 (s, 2H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 166.4, 145.4, 141.6, 136.4, 136.3, 129.2, 128.9, 128.7, 128.4, 128.4, 127.7, 125.1, 117.3, 66.1; **HRMS[M+H]$^+$**: Calcd for $C_{18}H_{17}O_2$: 265.1229, found: 265.1220.

Benzyl (Z)-4-(1H-indol-3-yl)but-2-enoate (3.21i). Colorless oil. **IR (neat)**: 3408 (m), 3054 (m), 3031 (m), 2951 (w), 1708 (m), 1637 (m), 1454 (m), 1411 (m), 1367 (m), 1190 (m), 1159 (s), 1123 (m), 1091 (m), 815 (m), 739 (s), 696 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 7.97 (s, br, 1H), 7.59 (d, J = 7.9 Hz, 1H), 7.44–7.30 (m, 6H), 7.21 (t, *J* = 7.4 Hz,

1H), 7.11 (t, *J* = 7.5 Hz, 1H), 7.03 (d, *J* = 1.9 Hz, 1H), 6.50 (dt, *J* = 11.4, 7.4 Hz, 1H), 5.91 (dt, *J* = 11.4, 1.7 Hz, 1H), 5.24 (s, 2H), 4.17 (d, J = 7.4 Hz, 2H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 166.4, 149.5, 136.5, 136.3, 128.7, 128.4, 128.3, 127.4, 122.3, 121.9, 119.6, 119.2, 119.1, 113.9, 111.3, 66.0, 25.4; **HRMS[M+H]$^+$**: Calcd for $C_{19}H_{18}NO_2$:292.1332, found:292.1336.

Benzyl (*Z*)-4-(3,4-dimethoxyphenyl)but-2-enoate (3.21j). Colorless oil. **IR (neat)**: 1717 (m), 1514 (m), 1261 (m), 1236 (m), 1156 (s), 1029 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.42–7.31 (m, 5H), 6.82–6.72 (m, 3H), 6.38 (dt, *J* = 11.4, 7.6 Hz, 1H), 5.90 (d, *J* = 11.4 Hz, 1H), 5.21 (s, 2H), 3.97 (d, *J* = 7.6 Hz, 2H), 3.85 (d, *J* = 11.9 Hz, 6H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 166.3, 149.2, 149.1, 147.8, 136.2, 132.0, 128.7, 128.4, 128.4, 120.6, 119.5, 112.0, 111.5, 66.1, 56.1, 56.0, 34.9; **HRMS[M+H]$^+$**: Calcd for $C_{19}H_{21}O_4$: 313.1440, found: 313.1434.

Benzyl (Z)-4-(4-hydroxyphenyl)but-2-enoate (3.21k). Colorless oil. **IR (neat)**: 3428 (br), 3066 (w), 3033 (w), 2956 (w), 1716 (m), 1694 (m), 1641 (m), 1512 (s), 1442 (m), 1412 (m), 1210 (s), 1190 (s), 1158 (s), 824 (m), 752 (m), 736 (m), 697 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 7.44–7.31 (m, 5H), 7.14–7.03 (m, 2H), 6.88–6.71 (m, 2H), 6.36 (dt, *J* = 11.4, 7.6 Hz, 1H), 5.89 (dt, *J* = 11.4, 1.8 Hz, 1H), 5.21 (s, 2H), 4.79 (s, br, 1H), 3.96 (dd, *J* = 7.6, 1.7 Hz, 2H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 166.36, 154.22, 149.27, 136.16, 131.64, 129.91, 128.73, 128.40, 128.37, 119.42, 115.59, 66.08, 34.46; **HRMS[M+H]$^+$**: Calcd for $C_{17}H_{17}O_3$: 269.1178, found: 269.1177.

***tert*-Butyl (*Z*)-6-hydroxyhex-2-enoate (3.21l).** Colorless oil. **IR (neat)**: 2933 (m), 1713 (m), 1367 (m), 1219 (m), 1149 (s), 820 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.11 (dt, *J* = 11.5, 8.3 Hz, 1H), 5.78 (dt, *J* = 11.5, 1.3 Hz, 1H), 3.61 (q, *J* = 6.1 Hz, 2H), 2.75–2.66

(m, 3H), 1.71 (dt, *J* = 12.3, 6.1 Hz, 2H), 1.48 (s, 9H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 166.9, 147.6, 122.8, 80.9, 61.0, 31.2, 28.3, 24.8; **HRMS[M+H]$^+$**: Calcd for $C_{10}H_{19}O_3$: 187.1334, found: 187.1332.

***tert*-Butyl (*Z*)-8-hydroxy-4,8-dimethylnon-2-enoate (3.21m).** Colorless oil. **IR (neat)**: 2970 (m), 2933 (m), 1715 (m), 1367 (m), 1153 (s), 824 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.84 (dd, *J* = 11.6, 10.2 Hz, 1H), 5.62 (dd, *J* = 11.6, 0.9 Hz, 1H), 3.53–3.40 (m, 1H), 1.48 (s, 9H), 1.40–1.23 (m, 5H), 1.19 (s, 6H), 1.00 (d, *J* = 6.7 Hz, 3H); **^{13}C NMR (100 MHz, $CDCl_3$):** δ 166.2, 154.3, 120.5, 80.2, 71.1, 44.0, 37.5, 32.5, 29.5, 29.3, 28.4, 22.1, 20.6; **HRMS[M+H]$^+$**: Calcd for $C_{15}H_{29}O_3$: 257.2117, found: 257.2111.

Benzyl (*Z*)-6-hydroxyhex-2-enoate (3.21n) In a N_2-filled glove box, an oven-dried vial equipped with a magnetic stir bar was charged with (*Z*)-hex-4-en-1-ol (5.0 mg, 0.050 mmol), benzyl (*Z*)-but-2-enoate (44.1 mg, 0.25 mmol) and a THF solution of **Ru-1d** (1.9 mg, 0.0025 mmol), the system was placed under 100 torr vacuum for 1 h, and then the solution was allowed to stir for 7 h at 22 °C. The reaction was quenched by the addition of undistilled Et_2O and the volatiles were removed *in vacuo*. The resulting residue (typically black oil) was purified by silica gel chromatography to afford **3.21n** in >98:2 *Z*:*E* ratio as colorless oil (5.7 mg, 0.026 mmol, 52% yield). **IR (neat)**: 3465 (br, m), 2937 (m), 2875 (m), 1718 (s), 1641 (m), 1454 (m), 1415 (m), 815 (m), 737 (m), 697 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.41–7.31 (m, 5H), 6.31–6.23 (m, 1H), 5.91 (dd, J = 11.5, 1.4 Hz, 1H), 5.17 (s, 2H), 3.62 (s, 2H), 2.75 (q, J = 8.1, 7.5 Hz, 2H), 2.39 (s, 1H), 1.73 (p, J = 5.9 Hz, 2H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 167.0, 145.0, 138.1, 128.9, 128.1, 127.8, 123.5, 60.1, 43.7, 30.6, 24.7; **HRMS[M+H]$^+$**: Calcd for $C_{13}H_{17}O_3$: 221.1178, found: 221.1176.

(*Z*)-*α,β*-Unsaturated Acids

(*Z*)-12-(Ferrenyloxy)dodec-2-enoic acid (3.22a). Colorless oil. **IR (neat)**: 2922 (m), 2851 (m), 1707 (s), 1690 (s), 821 (m), 502 (w), 485 (w) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ carboxylic acid proton is invisible, 6.36−6.32 (m, 1H), 5.79 (d, *J* = 11.4 Hz, 1H), 5.00−4.62 (m, 2H), 4.51−4.26 (m, 2H), 4.20 (m, 5H), 2.66 (q, *J* = 7.4 Hz, 2H), 1.72 (p, *J* = 6.8 Hz, 2H), 1.45−1.35 (m, 14H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 172.0, 170.7, 153.5, 119.0, 71.7, 71.3, 70.3, 69.9, 64.5, 29.6, 29.4, 29.4, 29.3, 29.3, 29.1, 29.0, 26.2; **HRMS[M+H]$^+$**: Calcd for $C_{23}H_{31}FeO_4$: 427.1567, found: 427.1565.

(*Z*)-5-Phenylpent-2-enoic acid (3.22b). Colorless oil. **IR (neat)**: 2925 (m), 1692 (s), 1638 (m), 1435 (m), 1240 (m), 698 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 11.39 (br, 1H), 7.30 (t, *J* = 7.6 Hz, 2H), 7.24−7.18 (m, 3H), 6.38 (dt, *J* = 11.5, 7.5 Hz, 1H), 5.82 (d, *J* = 11.5 Hz, 1H), 3.03–2.99 (m, 2H), 2.79 (t, *J* = 7.7 Hz, 2H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 171.4, 152.1, 141.1, 128.58, 128.59, 126.2, 119.7, 35.1, 30.8; **HRMS[M+H]$^+$**: Calcd for $C_{11}H_{13}O_2$: 177.0916, found: 177.0909.

(*Z*)-4-(*1H*-indol-3-yl)but-2-enoic acid (3.22c). Colorless oil. **IR (neat)**: 3119 (w), 2982 9m), 2930 (w), 2906 (w), 1487 (w), 1391 (m),1369 (m), 1269 (m), 1152 (m), 1100 (m), 1027 (s), 963 (s), 882(m), 797 (m), 740 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.98 (s, 1H), 7.61 (d, *J* = 7.8 Hz, 1H), 7.37 (d, *J* = 8.1Hz, 3H), 7.21 (t, J = 7.5 Hz, 1H), 7.13 (t, J = 7.5 Hz, 1H), 7.05 (s, 1H), 6.60 (dt, *J* = 11.5, 7.4 Hz, 1H), 5.90 (d, *J* = 11.4 Hz, 1H), 4.17 (d, *J* = 7.3 Hz, 2H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 169.6, 151.4, 136.3, 127.2, 122.2, 121.8, 119.5, 118.8, 118.2, 113.5, 111.1, 25.3; **HRMS[M+H]$^+$**: Calcd for $C_{12}H_{12}O_2$:202.0863, found:202.0866.

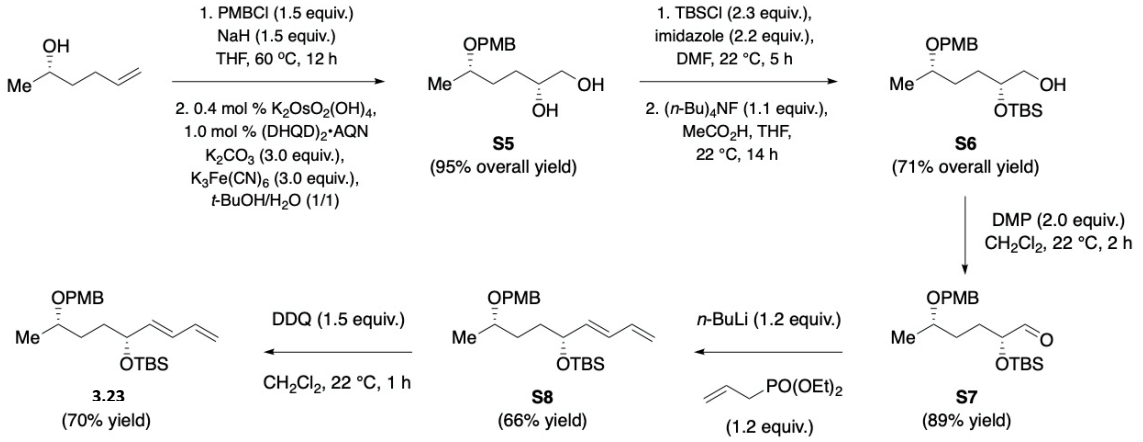
(*Z*)-12-Oxododec-2-enoic acid (3.22d). Colorless oil. **IR (neat)**: 3064 (m), 2923 (s), 2854 (m), 1734 (w), 1658 (m), 1457 (w), 699 (w) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ

carboxylic acid proton is invisible, 9.77−9.76 (m, 1H), 6.35 (dt, *J* = 11.4, 7.5 Hz, 1H), 5.79 (d, *J* = 12.0 Hz, 1H), 2.68−2.63 (m, 2H), 2.44−2.40 (m, 2H), 1.64−1.59 (m, 2H), 1.46−1.41 (m, 2H), 1.35−1.27 (m, 8H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 203.1, 170.9, 153.5, 118.9, 44.0, 29.9, 29.4, 29.28, 29.27, 29.2, 29.0, 22.2; **HRMS[M+H]$^+$**: Calcd for $C_{12}H_{23}O_2$: 199.1698, found: 199.1688.

(*Z*)-8-Hydroxy-4,8-dimethylnon-2-enoic acid (3.22e). Colorless oil. **IR (neat)**: 2966 (m), 2930 (m), 1696 (s), 1640 (m), 1376 (m), 1227 (m), 830 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)**: δ carboxylic acid proton is invisible, 6.12−6.02 (m, 1H), 5.75 (d, *J* = 11.6 Hz, 1H), 3.53 (br, 1H), 1.53−1.23 (m, 7H), 1.20 (s, 6H), 1.02 (d, *J* = 6.6 Hz, 3H); **^{13}C NMR (125 MHz, $CDCl_3$)**: δ 170.8, 158.6, 117.8, 71.2, 43.9, 37.5, 32.8, 29.5, 29.2, 22.1, 20.5; **HRMS[M+H-H_2O]$^+$**: Calcd for $C_{11}H_{19}O_2$: 183.1385, found: 183.1384.

Application to Stagonolide E

Scheme S3



(2*R*,5*S*)-5-((4-Methoxybenzyl)oxy)hexane-1,2-diol (S5). Based on a reported procedure,[7] a 50 mL round-bottom flask equipped with a stir bar was charged with *p*-methoxybenzyl chloride (234.9 mg, 1.5 mmol, 1.5 equiv.), NaH (60 mg, 1.5 mmol, 1.5 equiv.) and 10 mL THF. The mixture was allowed to stir for 0.5 at 22 °C h, after which (*S*)-hex-5-en-2-ol (100.2 mg, 1.0 mmol, 1.0 equiv.) was added to the mixture. The mixture was allowed to

stir at 60 °C for 12 h, after which excess ethanolamine (5 mL) was added. The mixture was allowed to stir for anther 5 h, and then the mixture was charged with Et_2O/hexane (20 mL/10 mL) and a saturated solution of NH_4Cl (20 mL) were added. The organic layer was separated and the aqueous layer was washed with Et_2O (20 mL × 3). The combined organic layers were dried over $MgSO_4$, and the volatiles were removed *in vacuo*. The resulting yellow oil was used without further purification. A 100 mL round-bottom flask was charged with (DHQD)AQN (8.6 mg, 0.010 mmol, 1.0 mol %), potassium ferricyanide (990 mg, 3.0 mmol, 3.0 equiv.), potassium osmate (1.4 mg, 0.004 mmol, 0.4 mol %), potassium carbonate (420 mg, 3.0 mmol, 3.0 equiv.), and *t*-BuOH/H_2O (1/1, 10 mL). The mixture was allowed to cool to 0 °C and (*S*)-1-((hex-5-en-2-yloxy)methyl)-4-methoxybenzene (220.3 mg, 1.0 mmol, 1.0 equiv.) was added, and then allowed to stir for 12 h at 0 °C. Sodium thiosulfate (800 mg) was added slowly and the suspension was allowed to warm to 22 °C with vigorous stirring. Ethyl acetate (50 mL) was added and the organic layer was separated. The aqueous layer was washed with EtOAc (40 mL × 3). The combined organic layers were dried over $MgSO_4$, and concentrated *in vacuo*. The resulting yellow oil was purified by silica gel chromatography (50–100% EtOAc in hexanes) to afford **S5** as colorless oil (241.5 mg, 0.95 mmol, 95% yield) in 90:10 d.r. The characterization data are consistent with those previously reported.[53] **$[\alpha]_D^{20}$** +33.8 (c 0.3, $CHCl_3$); **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.31–7.21 (m, 2H), 6.88 (d, *J* = 8.6 Hz, 2H), 4.55 (d, *J* = 11.2 Hz, 1H), 4.36 (d, *J* = 11.2 Hz, 1H), 3.80 (s, 3H), 3.69–3.51 (m, 3H), 3.42 (t, *J* = 11.3 Hz, 1H), 1.70–1.56 (m, 3H), 1.54–1.47 (m, 1H), 1.21 (d, *J* = 6.1 Hz, 3H); **HRMS[M+H]$^+$**: Calcd for $C_{14}H_{23}O_4$: 255.1591, found: 255.1587.

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(53) Liu, J.; Zhang, L.; He, J.; He, L.; Ma, B.; Pan, X.; She, X. *Tetrahedron: Asymmetry* **2008**, *19*, 906−911.

(2*R*,5*S*)-2-((*tert*-Butyldimethylsilyl)oxy)-5-((4-methoxybenzyl)oxy)hexan-1-ol (S6). A 100 mL round-bottom flask was charged with (2*R*,5*S*)-5-((4-methoxybenzyl)oxy)hexane-1,2-diol (456.8 mg, 1.8 mmol, 1.0 equiv.), and THF were added (10 ml); this was followed by imidazole (157 mg, 4.1 mmol, 2.3 equiv.), and TBSCl (603 mg, 4.0 mmol, 2.2 equiv.). The resulting mixture was allowed to stir for 12 h at 22 °C. After complete consumption of the starting material, acetic acid (0.5 mL) and tetrabutylammonium fluoride (1.0 M in THF, 2.3 mL, 2.3 mmol, 2.3 equiv.) were added, and the resulting solution was allowed to stir for 14 h at 22 °C. The reaction was quenched by the addition of a saturated solution of NH_4Cl (dropwise). The mixture was washed with EtOAc (50 mL × 3), and the combined organic layers were dried over $MgSO_4$ and the volatiles were removed in vacuo, leaving behind a red oil, which was purified by silica gel chromatography (5–10% EtOAc in hexanes) to afford **S6** as colorless oil (470 mg, 1.28 mmol, 71% yield). **$[\alpha]_D^{20}$** +3.7 (*c* 0.43, $CHCl_3$); **IR (neat)**: 2952 (m), 2928 (m), 2856 (m), 1613 (m), 1513 (m), 1462 (m), 1373 (m), 1301 (m), 1246 (s), 1172 (m), 1036 (s), 957 (m), 833 (s), 774 (s) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 7.29–7.22 (m, 2H), 6.90–6.84 (m, 2H), 4.50 (d, *J* = 11.4 Hz, 1H), 4.37 (d, *J* = 11.3 Hz, 1H), 3.80 (s, 3H), 3.76–3.66 (m, 1H), 3.59–3.50 (m, 1H), 3.50–3.40 (m, 2H), 1.86 (t, *J* = 6.3 Hz, 1H), 1.70–1.37 (m, 4H), 1.18 (d, *J* = 6.1 Hz, 3H), 0.90 (s, 9H), 0.07 (s, 6H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 159.2, 131.2, 129.4, 113.9, 74.5, 72.9, 70.1, 66.3, 55.4, 32.2, 29.9, 26.0, 19.8, 18.3, –4.3, –4.4; **HRMS[M+H]$^+$**: Calcd for $C_{20}H_{37}O_4Si$: 369.2456, found: 369.2446.

(2*R*,5*S*)-2-((*tert*-Butyldimethylsilyl)oxy)-5-((4-methoxybenzyl)oxy)hexanal (S7). A 100 mL flask was charged with (2*R*,5*S*)-2-((tert-butyldimethylsilyl)oxy)-5-((4-methoxybenzyl)oxy)hexan-1-ol (222.2 mg, 0.6 mmol, 1.0 equiv.), and CH_2Cl_2 (5.0 mL).

Dess-Martin periodinane (509 mg, 1.2 mmol, 2.0 equiv.) was then added, and the resulting mixture was allowed to stir for 2 h at 22 °C, after which it was added to an aqueous solution of 10% Na_2SO_3 and a saturated solution of aqueous $NaHCO_3$ (10 mL/10 mL).The resulting biphasic mixture was allowed to stir until both layers became colorless. The two layers were separated and the aqueous layer was washed with EtOAc (50 mL × 3). The combined organic layers were washed with brine, dried over Na_2SO_4 and the volatiles were removed *in vacuo*. The yellow oil, was purified by silica gel chromatography (5–10% EtOAc in hexanes) to afford **S7** as colorless oil (196 mg, 0.534 mmol, 89% yield). **$[\alpha]_D^{20}$** +9.0 (*c* 0.28, $CHCl_3$); **IR (neat)**: 2954 (m), 2929 (m), 2856 (m), 1729 (m), 1612 (m), 1513 (m), 1463 (m), 1301 (m), 1248 (s), 1212 (m), 1036 (m), 939 (w), 835 (s), 778 (m**)** cm^{-1}**; ^{1}H NMR (400 MHz, $CDCl_3$)**: δ 9.57 (d, *J* = 1.6 Hz, 1H), 7.25 (d, *J* = 7.1 Hz, 2H), 6.87 (d, *J* = 8.5 Hz, 2H), 4.49 (d, *J* = 11.4 Hz, 1H), 4.36 (d, *J* = 11.4 Hz, 1H), 3.92 (td, *J* = 5.9, 5.2, 3.2 Hz, 1H), 3.80 (s, 3H), 3.50 (dt, *J* = 11.4, 5.3 Hz, 1H), 1.86–1.46 (m, 4H), 1.18 (d, *J* = 6.1 Hz, 3H), 0.92 (s, 9H), 0.06 (d, *J* = 7.5 Hz, 6H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 204.2, 159.2, 131.1, 129.4, 113.9, 77.6, 73.7, 70.0, 55.4, 31.4, 28.5, 25.9, 19.6, 18.3, –4.5, –4.8; **HRMS[M+H]$^+$**: Calcd for $C_{20}H_{35}O_4Si$: 367.1950, found: 367.1949.

***tert*-Butyl(((5*R*,8*S*,*E*)-8-((4-methoxybenzyl)oxy)nona-1,3-dien-5-yl)oxy)dimethylsilane (S8).** An 8-dram vial was charged with diethyl allylphosphonate (22 mg, 0.12 mmol, 1.2 equiv.) and THF (1.0 mL). The solution was allowed to cool to –78 °C, after which it was charged with *n*-BuLi (1.7 M in hexane, 53 μL, 0.12 mmol, 1.2 equiv.). After 15 min, a solution of (2*R*,5*S*)-2-((*t*-butyldimethylsilyl)oxy)-5-((4-methoxybenzyl)oxy)hexanal (36 mg, 0.1 mmol, 1.0 equiv.) in HMPA (43 mg, 0.24 mmol, 2.4 equiv.), and THF (2.0 mL) were added. The mixture was allowed to stir for 2 h at –

78 °C and then stir for 12 h at 22 °C. The reaction was quenched by addition of a saturated solution of NH_4Cl (10 mL). The organic layer was separated, and the aqueous layer was washed with Et_2O (10 mL × 3). The combined organic ether layers were washed with brine, dried over Na_2SO_4 and the volatiles were removed *in vacuo*. The resulting yellow oil was purified by silica gel chromatography (2–5% Et_2O in hexanes) to afford **S8** as colorless oil (26.9 mg, 0.066 mmol, 66% yield). **$[\alpha]_D^{20}$** –4.2 (*c* 0.15, $CHCl_3$); **IR (neat)**: 2952 (m), 2928 (m), 2855 (m), 1612 (m), 1512 (m), 1462 (m), 1372 (m), 1339 (m), 1246 (s), 1206 (m), 1067 (s), 1003 (m), 950 (m), 833 (s), 773 (s) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 7.28–7.22 (m, 2H), 6.87 (d, *J* = 8.5 Hz, 2H), 6.31 (dt, *J* = 16.9, 10.3 Hz, 1H), 6.11 (dd, *J* = 15.2, 10.5 Hz, 1H), 5.64 (dd, *J* = 15.2, 6.4 Hz, 1H), 5.16 (d, *J* = 16.9 Hz, 1H), 5.05 (d, *J* = 10.9 Hz, 1H), 4.48 (d, *J* = 11.4 Hz, 1H), 4.38 (d, *J* = 11.4 Hz, 1H), 4.11 (q, *J* = 6.0 Hz, 1H), 3.80 (s, 3H), 3.48 (q, *J* = 5.9 Hz, 1H), 1.72–1.39 (m, 4H), 1.17 (d, *J* = 6.1 Hz, 3H), 0.90 (s, 9H), 0.03 (d, *J* = 7.7 Hz, 6H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 159.2, 137.6, 136.8, 131.3, 130.1, 129.3, 116.7, 113.9, 74.4, 73.0, 70.0, 55.4, 34.1, 32.0, 26.1, 19.8, 18.4, –4.2, –4.7; **HRMS[M+H]$^+$**: Calcd for $C_{23}H_{42}NO_3Si$: 408.2929, found: 408.2937.

(2*S*,5*R*,*E*)-5-((*tert*-Butyldimethylsilyl)oxy)nona-6,8-dien-2-ol (3.23). An 8-dram vial was charged with CH_2Cl_2/H_2O (20/1, 5.0 mL) solution of *tert*-butyl(((5*R*,8*S*,*E*)-8-((4-methoxybenzyl)oxy)nona-1,3-dien-5-yl)oxy)dimethylsilane (170 mg, 0.44 mmol, 1.0 equiv.), and DDQ (148 mg, 0.65 mmol, 1.5 equiv.) was then added. The mixture was allowed to stir for 1 h at 22 °C, after which the reaction was quenched by the addition of a saturated solutuion of Na_2SO_3 (50 mL). The organic layer was separated, and the aqueous layer was washed with EtOAc (50 mL × 3). The organic layers were then combined, dried over Na_2SO_4, and concentrated under reduced pressure. The resulting black oil was purified

by silica gel chromatography (5–10% EtOAc in hexanes) to afford **3.23** as colorless oil (83 mg, 0.308 mmol, 70% yield). **[α]D 20** –5.7 (*c* 0.35, $CHCl_3$); **IR (neat)**: 3370 (br), 2953 (m), 2928 (m), 2856 (m), 1718 (w), 1471 (m), 1375 (m), 1251 (m), 1074 (m), 1005 (m), 833 (s), 774 (s), 669 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)**: δ 6.32 (dt, *J* = 16.9, 10.3 Hz, 1H), 6.14 (dd, *J* = 15.7, 10.6 Hz, 1H), 5.66 (dd, *J* = 15.2, 6.6 Hz, 1H), 5.17 (d, *J* = 17.2 Hz, 1H), 5.06 (d, *J* = 10.1 Hz, 1H), 4.20 (q, *J* = 5.9 Hz, 1H), 3.80 (dt, *J* = 11.0, 5.3 Hz, 1H), 1.70–1.56 (m, 2H), 1.49 (m, 2H), 1.18 (d, *J* = 6.2 Hz, 3H), 0.90 (s, 9H), 0.05 (d, *J* = 11.7 Hz, 6H); **^{13}C NMR (125 MHz, $CDCl_3$)**: δ 137.2, 136.7, 130.4, 116.9, 73.1, 68.1, 34.7, 34.3, 26.0, 23.6, 18.4, –4.2, –4.6; **HRMS[M+H]$^+$**: Calcd for $C_{15}H_{31}O_2Si$: 271.2088, found: 271.2079.

(2*Z*,4*E*,6*R*,9*S*)-6-((*tert*-Butyldimethylsilyl)oxy)-9-hydroxydeca-2,4-dienoic acid (3.24). In a glovebox, an oven-dried vial equipped with a magnetic stir bar was sequentially charged with (2*S*,5*R*,*E*)-5-((*t*-butyldimethylsilyl)oxy)nona-6,8-dien-2-ol (13.5 mg, 0.05 mmol), *Z*-butene (THF solution, 12 wt %, 115 mg, 0.25 mmol), and **Ru-14** (0.8 mg, 0.001 mmol, in 200 μL THF). The mixture was allowed to stir for 1 h at 22 °C, after which the volatiles were removed *in vacuo* (100 torr, 2 min). The vessel was then charged with (in this precise order) (*Z*)-but-2-enoic acid (21.5 mg, 0.25 mmol), a solution of **Ru-14** (1.5 mg, 0.002 mmol in 200 μL THF), and subjected to 100 torr vacuum for 1 h. The resulting solution was allowed to stir for 8 h at 22 °C. The mixture was then charged with a solution of **Ru-14** (1.5 mg, 0.002 mmol in 200 μL THF) and subjected to 100 torr vacuum for 30 min, and allowed to stir for 12 h at 22 °C. At this point, the reaction was quenched by the addition of undistilled Et_2O while the mixture was exposed to air, and the volatiles were removed *in vacuo.* The resulting black oil was purified by silica gel chromatography (10%

to 50% EtOAc in hexanes) and filtered through a small plug of activated charcoal to afford product in >98:2 *Z*:*E* ratio as colorless oil (8.3 mg, 0.0265 mmol, 53% yield). The characterization data are consistent with those previously reported.[54] **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.46 (dd, *J* = 15.2, 11.6 Hz, 1H), 6.66 (t, *J* = 11.4 Hz, 1H), 6.05 (dd, *J* = 15.3, 5.9 Hz, 1H), 5.67 (d, *J* = 11.3 Hz, 1H), 4.33 (q, *J* = 5.7 Hz, 1H), 3.80 (dt, *J* = 12.2, 6.0 Hz, 1H), 1.76–1.57 (m, 3H), 1.51 (dt, *J* = 19.6, 9.5 Hz, 2H), 1.19 (d, *J* = 6.2 Hz, 3H), 0.91 (s, 9H), 0.07 (s, 3H), 0.05 (s, 3H); **HRMS[M+H]$^+$**: Calcd for $C_{16}H_{31}O_4Si$: 315.1986, found: 315.1999.

(*Z*)-*α*,*β*-Unsaturated Weinreb Amides

(*Z*)-*N*-Methoxy-*N*-methyl-5-phenylpent-2-enamide (3.25a). Colorless oil. **IR (neat):** 3026 (brs), 1655 (s), 1394 (m), 1347 (m), 1178 (w), 1000 (m), 794 (m), 637 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.41−6.81 (m, 5H), 6.25 (d, *J* = 10.7 Hz, 1H), 6.13 (dt, *J* = 11.7, 7.3 Hz, 1H), 3.61 (s, 3H), 3.20 (s, 3H), 2.97 (q, *J* = 6.9 Hz, 2H), 2.78 (t, *J* = 7.6 Hz, 2H). **^{13}C NMR (125 MHz, $CDCl_3$):** δ 167.6, 146.2, 141.6, 128.7, 128.4, 126.0, 118.9, 61.6, 35.4, 32.2, 30.6. **HRMS[M+H]$^+$**: Calcd for $C_{13}H_{18}NO_2$: 220.1338, found: 220.1339.

(*Z*)-*N*-Methoxy-*N*-methyldodec-2-enamide (3.25b). Colorless oil. **IR (neat):** 2855 (m), 1631 (s), 1513 (s), 1394 (m), 998 (m), 727 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$,)** δ 6.22 (d, *J* = 11.4 Hz, 1H), 6.11 (dt, *J* = 11.6, 7.3 Hz, 1H), 3.67 (s, 3H), 3.21 (s, 3H), 2.61 (q, *J* = 7.1 Hz, 2H), 1.43 (p, *J* = 7.4 Hz, 2H), 1.34-1.25 (m, 12H), 0.87 (t, *J* = 7.0 Hz, 3H). **^{13}C NMR (150 MHz, $CDCl_3$)** δ 168.1, 147.9, 118.1, 61.6, 32.1, 29.9, 29.7, 29.6, 29.53, 29.49, 29.46, 29.3, 22.8, 14.3. **HRMS[M]$^+$**: Calcd for $C_{14}H_{28}NO_2$: 242.2120, found: 242.2118.

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(54) Chatterjee, S.; Ghadigaonkar, S.; Sur, P.; Sharma, A.; Chattopadhyay, S. *J. Org. Chem*. **2014**, *79*, 8067−8076.

(*Z*)-*N*-Methoxy-*N*-methyl-12-oxododec-2-enamide (3.25c). Colorless oil. **IR (neat):** 2924 (s), 2854 (m), 1723 (m), 1656 (s), 997 (m), 433 (w) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 9.76 (s, 1H), 6.23 (d, *J* = 10.3 Hz, 1H), 6.11 (dt, *J* = 11.7, 7.4 Hz, 1H), 3.67 (s, 3H), 3.21 (s, 3H), 2.61 (d, *J* = 7.2 Hz, 2H), 2.41 (t, *J* = 6.8 Hz, 2H), 1.62 (p, *J* = 7.7 Hz, 2H), 1.43 (p, *J* = 7.3 Hz, 2H), 1.34−1.29 (m, 8H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 203.1, 167.8, 147.8, 118.4, 61.6, 44.1, 29.9, 29.4, 29.4, 29.4, 29.3, 29.2, 22.2, 15.4; **HRMS[M]$^+$**: Calcd for $C_{14}H_{26}NO_3$: 256.1913, found: 256.1926.

(*Z*)-12-(Methoxy(methyl)amino)-12-oxododec-10-enoic acid (3.25d). Colorless oil. **IR (neat):** 2924 (s), 2854 (m), 1733 (m), 1708 (s), 1656 (m), 1179 (m), 999 (m), 724 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)** δ carboxylic acid proton is too broad to be visible, 6.23 (d, *J* = 9.2 Hz, 1H), 6.11 (dt, *J* = 11.6, 7.3 Hz, 1H), 3.68 (s, 3H), 3.21 (s, 3H), 2.60 (q, *J* = 7.5 Hz, 2H), 2.33 (t, *J* = 7.4 Hz, 2H), 1.66-1.60 (m, 2H), 1.46-1.40 (m, 2H), 1.34–1.31 (m, 8H). **^{13}C NMR (125 MHz, $CDCl_3$)** δ 178.8, 167.8, 147.9, 118.1, 61.6, 34.0, 32.2, 29.9, 29.3, 29.3, 29.2, 29.3, 29.1, 24.8; **HRMS[M]$^+$**: Calcd for $C_{14}H_{26}NO_4$: 272.1862, found: 272.1857.

(*Z*)-7-(1,3-Dioxoisoindolin-2-yl)-*N*-methoxy-*N*-methylhept-2-enamide (3.25e). Colorless oil. **IR (neat):** 2925 (brs), 2854 (w), 1708 (s), 1655 (m), 1395 (m), 794 (w), 720 (w) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)** δ 7.85−7.82 (m, 2H), 7.71−7.69 (m, 2H), 6.24 (d, *J* = 10.6 Hz, 1H), 6.08 (dt, *J* = 11.7, 7.4 Hz, 1H), 3.70 (t, *J* =7.2 Hz, 2H), 3.67 (s, 3H), 3.20 (s, 3H), 2.68 (q, *J* = 7.1 Hz, 2H), 1.73 (p, *J* = 7.5 Hz, 2H), 1.51 (p, *J* = 7.5 Hz, 2H). **^{13}C NMR (150 MHz, $CDCl_3$)** δ 168.5, 146.8, 134.0, 132.3, 125.7, 123.3, 118.8, 61.7, 38.1, 32.1, 28.6, 28.4, 26.7. **HRMS[M+H]$^+$**: Calcd for $C_{17}H_{21}N_2O_4$: 317.1501, found: 317.1503.

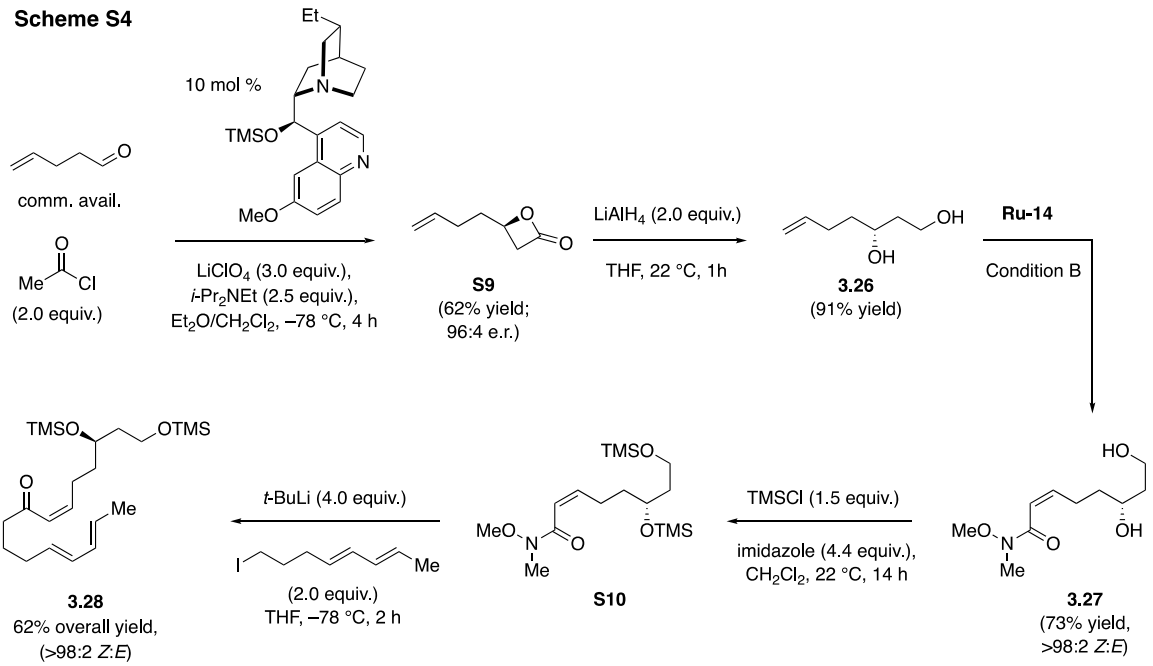
(*Z*)-4-(3,4-Dimethoxyphenyl)-*N*-methoxy-*N*-methylbut-2-enamide (3.25f). Colorless oil. **IR (neat):** 2966 (w), 1617 (s), 1430 (m), 1347 (m), 961 (m), 696 (m) cm^{-1}; **^{1}H NMR**

(600 MHz, $CDCl_3$) δ 6.81−6.80 (m, 3H), 6.31 (d, *J* = 10.0 Hz, 1H), 6.29−6.15 (m, 1H), 3.93 (d, *J* = 6.8 Hz, 2H), 3.86 (d, *J* = 7.4 Hz, 6H), 3.70 (s, 3H), 3.25 (s, 3H). **^{13}C NMR (150 MHz, $CDCl_3$)** δ 167.5, 149.1, 147.6, 145.7, 132.8, 120.6, 118.2, 112.2, 111.5, 61.7, 56.1, 56.0, 35.0, 32.2. **HRMS[M]$^+$**: Calcd for $C_{14}H_{24}NO_4$: 266.1393, found: 266.1402.

(*Z*)-8-Hydroxy-*N*-methoxy-*N*-4,8-trimethylnon-2-enamide (3.25g). Colorless oil. **IR (neat):** 3440 (brs), 2965 (m), 2934 (m), 1652 (s), 1629 (m), 999 (m), 806 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$):** δ 6.19 (d, *J* = 9.8 Hz, 1H), 5.84 (t, *J* = 10.9 Hz, 1H), 3.68 (s, 3H), 3.46 (brs, 1H), 3.21 (s, 3H), 1.63−1.32 (m, 7H), 1.19 (s, 3H), 1.17 (s, 3H), 1.00 (d, *J* = 6.6 Hz, 3H); **^{13}C NMR (150 MHz, $CDCl_3$):** δ 167.8, 153.1, 117.2, 70.9, 61.6, 43.7, 37.4, 32.5, 32.2, 30.0, 28.9, 21.9, 20.8; **HRMS[M+H]$^+$**: Calcd for $C_{13}H_{26}NO_3$: 244.1913, found: 244.1902.

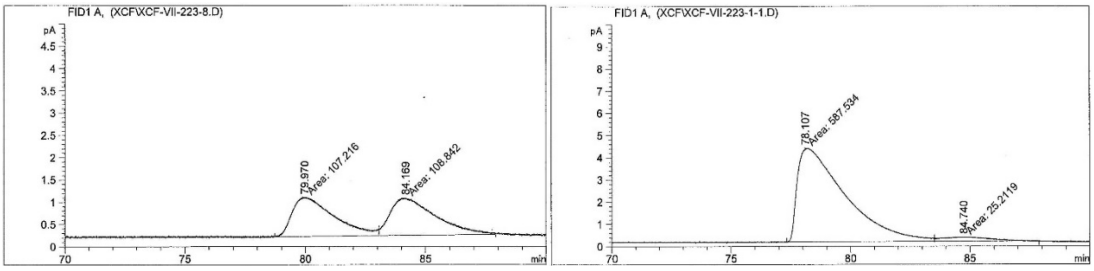
(2*Z*,4*E*)-*N*-Methoxy-*N*-methyl-5-phenylpenta-2,4-dienamide (3.25h). Colorless oil. **IR (neat):** 3060 (brs), 2934 (w), 1643 (s), 1617 (m), 1295 (m), 696 (m), 655 (w) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)** δ 8.20 (dd, *J* = 15.5, 11.5 Hz, 1H), 7.50 (d, *J* = 8.1 Hz, 2H), 7.40−7.13 (m, 3H), 6.76 (d, *J* = 15.8 Hz, 1H), 6.68 (t, *J* = 11.3 Hz, 1H), 6.23 (d, *J* = 11.3 Hz, 1H), 3.70 (s, 3H), 3.25 (s, 3H); **^{13}C NMR (125 MHz, $CDCl_3$)** δ 167.5, 143.1, 140.4, 136.7, 128.78, 128.75, 127.6, 125.7, 115.7, 61.8, 32.4; **HRMS[M+H]$^+$**: Calcd for $C_{13}H_{16}NO_2$: 218.1181, found: 218.1190.

Application to Dihydrocompactin



(*R*)-4-(But-3-en-1-yl)oxetan-2-one (S9). Based on a previously repotred procedure,[9] an 8-dram vial equipped with a magnetic stir bar was charged with *O*-trimethylsilyl quinidine (39.6 mg, 0.10 mmol, 0.10 equiv.), lithium perchlorate (53.2 mg, 0.50 mmol, 0.50 equiv.), and Et_2O (1.0 mL). The solution was allowed to stir at 22 °C until it became homogenous, at which point CH_2Cl_2 (2.0 mL) was added and the mixture was allowed to cool to –78 °C. Diisopropylethylamine (323 mg, 2.5 mmol, 2.5 equiv.) and 4-pentenal (84.12 mg, 1.0 mmol, 1.0 equiv.) were then added sequentially, after which acetyl chloride (157 mg, 2.0 mmol, 2.0 equiv., in 0.5 mL CH_2Cl_2) was slowly introduced over 1 h (at –78 °C). The mixture was allowed to stir for 12 h at –78 °C, after which it was charged with Et_2O (10 mL) and the mixture was allowed to warm to room temperature. The solution was filtered and the volatiles were removed *in vacuo* to afford yellow oil, which was purified by silica gel chromatography (10–20% Et_2O in hexanes) to give **S9** as colorless oil. $[\alpha]_D^{20}$ +19.6 (c 0.68, $CHCl_3$); **IR (neat)**: 3076 (w), 2975 (m), 2929 (m), 1815 (s), 1640 (m), 1442 (m), 1411 (m), 1376 (m), 1302 (m), 1202 (m), 1120 (m), 994 (m), 960 (m), 914 (m), 853 (m),

824 (m), 780 (m), 526 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 5.81 (ddt, *J* = 16.8, 10.2, 6.6 Hz, 1H), 5.14–5.00 (m, 2H), 4.53 (dtd, *J* = 7.6, 5.8, 4.3 Hz, 1H), 3.52 (dd, *J* = 16.3, 5.8 Hz, 1H), 3.08 (dd, *J* = 16.3, 4.3 Hz, 1H), 2.32–2.10 (m, 2H), 2.05–1.94 (m, 1H), 1.91–1.80 (m, 1H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 168.2, 136.5, 116.2, 70.8, 43.0, 34.0, 29.3. **HRMS[M+H]$^+$**: Calcd for $C_7H_{11}O_2$: 127.0754, found: 127.0760. Enantiomeric purity was determined by GC analysis [CDB/DM column, flow rate 0.2 mL/min, method: 100 °C for 100 min].



Peak #	Time (min)	Area (%)	Peak #	Time (min)	Area (%)
1	79.970	49.624	1	78.107	95.885
2	84.169	50.376	2	84.740	4.115

(*R*)-Hept-6-ene-1,3-diol (3.26). An 8-dram vial equipped with a magnetic stir bar was charged with lithium aluminum hydride (30.0 mg, 0.80 mmol, 2.0 equiv.) and THF (1.0 ml). The mixture was allowed to cool to 0 °C and (*R*)-4-(but-3-en-1-yl)oxetan-2-one (50.0 mg, 0.40 mmol, 1.0 equiv.in 1.0 mL THF) was added. The mixture was allowed to warm to 22 °A saturated solution of potassium sodium tartrate (5.0 mL) and Et_2O (5.0 mL) were added, and the resulting mixture was allowed to stir for 0.5 h at 22 °C. The organic and aqueous layers were separated and the aqueous layer was washed with EtOAc (20 mL × 3). The combined organic layers were washed with brine, dried over Na_2SO_4 and concentrated *in vacuo*. The resulting yellow oil was purified by silica gel chromatography

(20–100% EtOAc in hexanes) to afford **3.26** as colorless oil (47.1 mg, 0.362 mmol, 91% yield). **$[\alpha]_D^{20}$** +4.3 (*c* 0.34, $CHCl_3$); **IR (neat)**: 3339 (br), 3077 (m), 2935 (m), 1640 (m), 1442 (m), 1331 (m), 1057 (m), 995 (m), 911 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 5.85 (ddt, *J* = 17.0, 10.3, 6.8 Hz, 1H), 5.06 (dt, *J* = 17.1, 1.5 Hz, 1H), 5.02–4.96 (m, 1H), 3.98–3.77 (m, 3H), 2.33 (d, *J* = 3.6 Hz, 1H), 2.26–2.09 (m, 3H), 1.76–1.56 (m, 4H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 138.5, 115.2, 72.0, 62.0, 38.5, 36.9, 30.1; **HRMS[M+H]$^+$**: Calcd for $C_7H_{15}O_2$: 131.1067, found: 131.1066.

(*R*,*Z*)-6,8-Dihydroxy-*N*-methoxy-*N*-methyloct-2-enamide (3.27). Colorless oil. **$[\alpha]_D^{20}$** –84.9 (*c* 0.5, $CHCl_3$); **IR (neat)**: 3381 (br), 2934 (m), 1647 (s), 1617 (s), 1440 (m), 1398 (m), 1362 (m), 1180 (m), 1103 (m), 1059 (s), 1028 (m), 996 (m), 796 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 6.35 (d, *J* = 10.9 Hz, 1H), 6.09 (td, *J* = 11.3, 6.4 Hz, 1H), 5.37 (s, 1H), 3.87–3.77 (m, 3H), 3.69 (s, 3H), 3.44 (s, 1H), 3.23 (s, 3H), 3.08 (q, *J* = 10.9, 10.2 Hz, 1H), 2.21 (dq, *J* = 10.5, 4.9 Hz, 1H), 1.71 (m, 2H), 1.62 (m, 1H), 1.58–1.50 (m, 1H); **^{13}C NMR (125 MHz, $CDCl_3$)**: δ 168.0, 145.9, 120.1, 70.1, 62.4, 61.7, 38.1, 35.8, 32.1, 25.2; **HRMS[M+H]$^+$**: Calcd for $C_{10}H_{20}NO_4$: 218.1387, found: 218.1381.

(*R*,*Z*)-*N*-Methoxy-*N*-methyl-6,8-bis((trimethylsilyl)oxy)oct-2-enamide (S10). An 8-dram vial was charged with a CH_2Cl_2 (1 mL) solution of (*R*,*Z*)-6,8-dihydroxy-*N*-methoxy-*N*-methyloct-2-enamide (9.0 mg, 0.04 mmol), TMSCl (22.6 mg, 0.2 mmol, 5.0 equiv.), and imidazole (12.0 mg, 0.18 mmol, 4.4 equiv.). The mixture was allowed to stir for 12 h at 22 °C, after which the volatiles were directly removed *in vacuo*. The resulting yellow oil was purified by chromatography with a 150 mesh neutral Al_2O_3 column (2–5% EtOAc in hexanes) to afford **S10** as colorless oil (12.6 mg, 0.035 mmol, 87% yield). **$[\alpha]_D^{20}$** –12.0 (*c* 0.34, $CDCl_3$); **IR (neat)**: 2955 (m), 1660 (m), 1426 (m), 1344 (m), 1249 (m), 1178 (m),

1092 (m), 1043 (m), 1002 (m), 880 (m), 838 (s), 748 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)**: δ 6.23 (d, *J* = 11.0 Hz, 1H), 6.11 (dt, *J* = 11.6, 7.3 Hz, 1H), 3.83 (p, *J* = 6.5 Hz, 1H), 3.67 (s, 3H), 3.63 (t, *J* = 6.6 Hz, 2H), 3.20 (s, 3H), 2.66 (q, *J* = 7.2 Hz, 2H), 1.75–1.62 (m, 2H), 1.60–1.55 (m, 2H), 0.11 (s, 9H), 0.10 (s, 9H); **^{13}C NMR (150 MHz, CD_2Cl_2)**: δ 167.7, 147.1, 118.7, 69.5, 61.8, 59.6, 40.5, 37.6, 25.7, 0.5, –0.4; **HRMS[M+H]$^+$**: Calcd for $C_{16}H_{36}NO_4Si_2$: 362.2177, found: 362.2164.

(*R*,6*Z*,12*E*,14*E*)-1,3-Bis((trimethylsilyl)oxy)hexadeca-6,12,14-trien-8-one (3.28). An 6-dram vial was charged with a THF solution (1.0 mL) of (2*E*,4*E*)-8-iodoocta-2,4-diene (16.5 mg, 0.07 mmol, 2.0 equiv.). The solution was allowed to cool to –78 °C, after which, *t*-BuLi (1.7 M in hexane, 82 μL, 0.14 mmol, 4.0 equiv.) was added, and the mixture was allowed to stir for 1 h (at –78 °C). A THF solution (2.0 mL) of (*R*,*Z*)-*N*-methoxy-*N*-methyl-6,8-bis((trimethylsilyl)oxy)oct-2-enamide (12.6 mg, 0.035 mmol, 1.0 equiv.) was added and the mixture was allowed to stir for 2 h at –78 °C. The reaction was then quenched by the addition of a saturated solution of aqueous NH_4Cl. The aqueous layer was washed with EtOAc (10 mL × 3), and the combined organic layers were washed with brine, dried over Na_2SO_4, and concentrated *in vacuo*. The resulting yellow oil was purified by chromatography with a 150 mesh neutral Al_2O_3 column (1–5% EtOAc in hexanes) to afford **3.28** as colorless oil (9.3 mg, 0.0228 mmol, 65% yield). The characterization data are consistent with those previously reported.[9] **^{1}H NMR (500 MHz, $CDCl_3$)**: δ 6.17–5.96 (m, 4H), 5.66–5.55 (m, 1H), 5.54–5.47 (m, 1H), 3.90–3.78 (m, 1H), 3.63 (t, *J* = 6.8 Hz, 2H), 2.65 (q, *J* = 8.7 Hz, 2H), 2.44 (t, *J* = 7.3 Hz, 2H), 2.13–2.04 (m, 2H), 1.69 (m, 7H), 1.53–1.49 (m, 2H), 0.12 (s, 9H), 0.10 (s, 9H); **HRMS[M+H]$^+$**: Calcd for $C_{22}H_{43}O_3Si_2$: 411.2745, found: 411.2761.

(*Z*)-*α,β*-Unsaturated Secondary and Primary Amides

Benzyl (*Z*)-6-(benzylamino)-6-oxohex-4-enoate (3.29a). Colorless oil. **IR (neat)**: 3304 (br), 3063 (m), 3031 (m), 2947 (m), 2922 (m), 1733 (s), 1661 (m), 1633 (m), 1537 (m), 1497 (m), 1454 (m), 1424 (m), 1381 (m), 1235 (m), 1155 (m), 737 (m), 697 (m) cm^{-1}; **^{1}H NMR (500 MHz, $CDCl_3$)**: δ 7.39–7.25 (m, 10H), 6.40 (s, br, 1H), 5.95 (dt, *J* = 10.5, 7.6 Hz, 1H), 5.77 (d, *J* = 11.4 Hz, 1H), 5.10 (s, 2H), 4.49 (d, *J* = 5.7 Hz, 2H), 2.91 (q, *J* = 7.1 Hz, 2H), 2.55 (t, *J* = 6.8 Hz, 2H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 173.2, 166.2, 141.7, 138.5, 136.0, 128.8, 128.7, 128.4, 128.0, 127.6, 124.2, 66.6, 43.5, 33.5, 24.2; **HRMS[M+H]$^+$**: Calcd for $C_{20}H_{22}O_3N$: 324.1600, found: 324.1597.

(*Z*)-*N*-(4-Methoxybenzyl)-5-phenylpent-2-enamide (3.29b). Colorless oil. **IR (neat)**: 3297 (m), 3026 (m), 2928 (m), 2835 (w), 1658 (s), 1628 (m), 1512 (s), 1453 (m), 1356 (m), 1245 (m), 1175 (m), 1033 (m), 817 (m), 699 (m) cm^{-1}; **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 7.26 (t, *J* = 7.5 Hz, 2H), 7.19 (m, 5H), 6.86 (d, *J* = 8.6 Hz, 2H), 5.99 (dt, *J* = 11.5, 7.5 Hz, 1H), 5.70 (d, *J* = 11.5 Hz, 1H), 5.52 (s, 1H), 4.36 (d, *J* = 5.7 Hz, 2H), 3.80 (s, 3H), 2.98 (q, *J* = 7.4 Hz, 2H), 2.77 (t, *J* = 7.5 Hz, 2H); **^{13}C NMR (125 MHz, $CDCl_3$)**: δ 166.3, 159.2, 144.0, 141.4, 130.5, 129.4, 128.7, 128.5, 126.1, 123.1, 114.2, 55.4, 42.9, 35.4, 30.5; **HRMS[M+H]$^+$**: Calcd for $C_{19}H_{22}NO_2$: 296.1645, found: 296.1648.

(*Z*)-*N*-Benzyl-6-hydroxyhex-2-enamide (3.29c). Colorless oil. **IR (neat)**: 3285 (br), 3064 (m), 3029 (m), 2870 (m), 1656 (s), 1629 (m), 1544 (m), 1496 (m), 1454 (m), 1426 (m), 1272 (m), 1242 (m), 1071 (m), 1029 (m), 811 (m), 739 (m), 698 (m) cm-1; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 7.38–7.27 (m, 5H), 6.01 (dt, *J* = 11.4, 8.6 Hz, 1H), 5.93 (brs, 1H), 5.82 (d, *J* = 11.5 Hz, 1H), 4.49 (d, *J* = 5.7 Hz, 2H), 3.88 (t, *J* = 6.3 Hz, 1H), 3.60 (q, *J* = 5.2 Hz, 2H), 2.88–2.70 (m, 2H), 1.81–1.61 (m, 2H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 167.0, 145.1,

138.1, 128.9, 128.1, 127.8, 123.5, 60.1, 43.7, 30.6, 24.8; **HRMS[M+H]$^+$**: Calcd for $C_{13}H_{18}NO_2$: 220.1338, found: 220.1334.

(*Z*)-6-Hydroxy-*N*-(4-methoxybenzyl)hex-2-enamide (3.29d). Colorless oil. **IR (neat)**: 3291 (br), 2933 (m), 1656 (m), 1612 (s), 1586 (m), 1543 (m), 1512 (s), 1463 (m), 1301 (m), 1245 (s), 1175 (m), 1033 (m), 813 (m) cm^{-1}; **^{1}H NMR (600 MHz, CDCl$_3$)**: δ 7.21 (d, *J* = 8.3 Hz, 2H), 6.86 (d, *J* = 8.3 Hz, 2H), 6.02 – 5.95 (m, 2H), 5.80 (d, *J* = 11.4 Hz, 1H), 4.40 (d, *J* = 5.6 Hz, 2H), 4.02 (s, 1H), 3.79 (s, 3H), 3.58 (d, *J* = 5.4 Hz, 2H), 2.74 (q, *J* = 7.8 Hz, 2H), 1.70 (p, *J* = 5.8 Hz, 2H); **^{13}C NMR (125 MHz, CDCl$_3$)**: δ 166.9, 159.3, 144.8, 130.2, 129.5, 123.6, 114.3, 60.1, 55.5, 43.2, 30.6, 24.7; **HRMS[M+H]$^+$**: Calcd for $C_{14}H_{20}NO_3$: 250.1438, found: 250.1447.

(*Z*)-*N*-Benzyl-7-(1,3-dioxoisoindolin-2-yl)hept-2-enamide (3.29e). Colorless oil. **IR (neat)**: 3360 (br), 3061 (w), 3029 (w), 2928 (m), 2857 (w), 1770 (m), 1707 (s), 1662 (m), 1531 (m), 1436 (m), 1396 (m), 1370 (m), 1336 (m), 1235 (m), 1040 (m), 719 (m), 699 (m) cm^{-1}; **^{1}H NMR (500 MHz, CDCl$_3$)**: δ 7.84–7.75 (m, 2H), 7.71–7.63 (m, 2H), 7.29−7.20 (m, 5H), 5.99–5.89 (m, 1H), 5.78 (s, br, 1H), 5.68 (d, *J* = 11.4 Hz, 1H), 4.43 (d, *J* = 5.4 Hz, 2H), 3.64 (t, *J* = 7.0 Hz, 2H), 2.70 (q, *J* = 7.0 Hz, 2H), 1.68 (p, *J* = 6.2 Hz, 2H), 1.46 (p, *J* = 7.4 Hz, 2H); **^{13}C NMR (100 MHz, CDCl$_3$)**: δ 168.6, 166.3, 145.2, 138.5, 134.0, 132.3, 128.8, 128.1, 127.6, 123.3, 122.7, 43.5, 37.9, 28.3, 28.3, 26.6; **HRMS[M+H]$^+$**: Calcd for $C_{22}H_{23}O_3N_2$: 363.1709, found: 363.1712.

(*Z*)-*N*-Benzyl-4-(3,4-dimethoxyphenyl)but-2-enamide (3.29f). Colorless oil. **IR (neat)**: 3305 (br), 3062 (w), 3029 (w), 2932 (w), 1659 (m), 1631 (m), 1590 (m), 1512 (s), 1453 (m), 1259 (m), 1233 (m),1188 (m), 1027 (m), 809 (m), 756 (m), 699 (m) cm^{-1}; **^{1}H NMR (500 MHz, CDCl$_3$)**: δ 7.32 (dq, *J* = 15.0, 8.0 Hz, 5H), 6.83 – 6.75 (m, 3H), 6.17 (dt, *J* =

11.3, 7.6 Hz, 1H), 5.81 (s, 1H), 5.76 (d, *J* = 12.3 Hz, 1H), 4.51 (d, *J* = 5.7 Hz, 2H), 4.02 (d, *J* = 7.6 Hz, 2H), 3.85 (s, 6H); **^{13}C NMR (125 MHz, CDCl$_3$)**: δ 166.2, 149.2, 147.7, 144.7, 138.4, 132.8, 128.9, 128.0, 127.7, 122.0, 120.6, 112.2, 111.5, 56.1, 56.0, 43.6, 34.6; **HRMS[M+H]$^+$**: Calcd for $C_{19}H_{22}NO_3$: 312.1600, found: 312.1594.

(*Z*)-4-(3,4-Dimethoxyphenyl)-*N*-(4-methoxybenzyl)but-2-enamide (3.29g). Colorless oil. **IR (neat)**: 3301 (br), 2998 (w), 2934 (m), 1659 (m), 1628 (m), 1589 (m), 1512 (s), 1463 (m), 1235 (m), 1175 (m), 1153 (m), 1139 (m), 1028 (m), 815 (m) cm^{-1}; **^{1}H NMR (500 MHz, CDCl$_3$)**: δ 7.24 (d, *J* = 8.5 Hz, 2H), 6.87 (d, *J* = 8.5 Hz, 2H), 6.82 – 6.76 (m, 3H), 6.16 (dt, *J* = 11.3, 7.6 Hz, 1H), 5.74 (d, *J* = 11.3 Hz, 2H), 4.44 (d, *J* = 5.6 Hz, 2H), 4.01 (d, *J* = 7.5 Hz, 2H), 3.85 (s, 6H), 3.80 (s, 3H); **^{13}C NMR (125 MHz, CDCl$_3$)**: δ 166.2, 159.2, 149.2, 147.6, 144.5, 132.8, 130.4, 129.4, 122.1, 120.5, 114.3, 112.1, 111.5, 56.1, 56.0, 55.5, 43.1, 34.6; **HRMS[M+H]$^+$**: Calcd for $C_{20}H_{24}NO_4$:342.1700, found: 342.1697.

(*Z*)-4-(3,4-Dimethoxyphenyl)-*N*-isobutylbut-2-enamide (3.29h). Colorless oil. **IR (neat)**: 3305 (m), 2959 (m), 2929 (m), 2870 (w), 1654 (m), 1625 (m), 1589 (m), 1547 (m), 1514 (m), 1416 (m), 1261 (s), 1234 (m), 1172 (m), 1025 (m), 810 (m), 760 (m) cm^{-1}; **^{1}H NMR (400 MHz, CDCl$_3$)**: δ 6.81−6.76 (m, 3H), 6.12 (dt, *J* = 11.3, 7.6 Hz, 1H), 5.75 (dt, *J* = 11.3, 1.6 Hz, 1H), 5.56 (br, 1H), 3.98 (dd, *J* = 7.6, 1.5 Hz, 2H), 3.85 (d, *J* = 3.5 Hz, 6H), 3.15 (t, *J* = 6.5 Hz, 2H), 1.81 (dp, *J* = 13.4, 6.7 Hz, 1H), 0.93 (d, *J* = 6.7 Hz, 6H); **^{13}C NMR (100 MHz, CDCl$_3$)**: δ 166.5, 149.2, 147.6, 143.9, 132.9, 122.4, 120.5, 112.1, 111.5, 56.1, 56.0, 46.8, 34.6, 28.7, 20.3; **HRMS[M+H]$^+$**: Calcd for $C_{16}H_{24}NO_3$: 278.1756, found: 278.1763.

(*Z*)-6-Hydroxyhex-2-enamide (3.30a). Off-white solid. **M.p.**: 73–74 °C; **IR (neat)**: 3337 (br), 2928 (m), 2873 (m), 1664 (m), 1603 (m), 1439 (m), 1328 (m), 1259 (m), 1171 (m),

1063 (m), 811 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 6.05 (dt, *J* = 11.5, 8.6 Hz, 1H), 5.88 (d, *J* = 11.5 Hz, 1H), 5.69 (br, 2H), 3.72 (s, br, 1H), 3.59 (t, *J* = 5.5 Hz, 4H), 2.82–2.63 (m, 2H), 1.71 (dt, *J* = 13.1, 6.0 Hz, 2H); **^{13}C NMR (150 MHz, $CDCl_3$)**: δ 169.1, 146.1, 122.7, 60.2, 30.6, 24.7; **HRMS[M+H]$^+$**: Calcd for $C_6H_{12}NO_2$: 130.0863, found: 130.0868.

(*Z*)-4-(2-Hydroxyphenyl)but-2-enamide (3.30b). Off-white solid. **M.p.**: 121 °C; **IR (neat)**: 3360 (br), 3204 (m), 3031 (m), 2924 (m), 1696 (s), 1667 (m), 1600 (s), 1570 (m), 1489 (s), 1467 (m), 1270 (m), 1245 (m), 1118 (m), 807 (m), 757 (s), 748 (m), 709 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 9.23 (s, 1H), 7.20–7.08 (m, 2H), 6.89 (d, *J* = 8.5 Hz, 1H), 6.81 (t, *J* = 7.4 Hz, 1H), 6.21 (dt, *J* = 11.1, 9.1 Hz, 1H), 5.84 (d, *J* = 11.4 Hz, 1H), 5.63 (s, br, 2H), 3.85 (d, *J* = 9.1 Hz, 2H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 170.1, 156.4, 145.4, 130.8, 128.7, 122.2, 119.8, 119.7, 117.1, 31.6; **HRMS[M+H]$^+$**: Calcd for $C_{10}H_{12}NO_2$: 178.0863, found: 178.0853.

(*Z*)-4-(4-Hydroxyphenyl)but-2-enamide (3.30c). Off-white solid. **M.p.**: 121 °C; **IR (neat)**: 3359 (m), 3200 (m), 3031 (m), 2924 (m), 1697 (m), 1668 (m), 1644 (m), 1600 (s), 1570 (m), 1490 (m), 1467 (m), 757 (m), 748 (m) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 9.23 (s, 1H), 7.19–7.07 (m, 2H), 6.89 (d, *J* = 8.2 Hz, 1H), 6.81 (t, *J* = 7.3 Hz, 1H), 6.26–6.15 (m, 1H), 5.84 (d, *J* = 11.5 Hz, 1H), 5.64 (s, br, 1H), 3.85 (d, *J* = 9.1 Hz, 2H); **^{13}C NMR (150 MHz, CD_3OD)**: δ 171.6, 156.8, 146.1, 132.1, 130.5, 122.2, 116.3, 34.9; **HRMS[M+H]$^+$**: Calcd for $C_{10}H_{12}NO_2$: 178.0863, found: 178.0860.

(*Z*)-Pentadec-2-enamide (3.30d). Colorless oil. **IR (neat)**: 3368 (m), 3191 (w), 2954 (s), 2917 (s), 2849 (m), 1668 (m), 1621 (m), 1466 (m), 1339 (w), 732 (w) cm^{-1}; **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 6.06 (dt, *J* = 11.5, 7.5 Hz, 2H), 5.73 (dt, *J* = 11.5, 1.7 Hz, 2H), 5.32 (brs, 1H), 2.64 (qd, *J* = 7.4, 1.6 Hz, 2H), 1.43 (p, *J* = 6.6 Hz, 2H), 1.25 (s, 20H), 0.88 (t, *J* = 6.8

Hz, 3H); **^{13}C NMR (100 MHz, $CDCl_3$)**: δ 168.4, 147.6, 121.1, 53.6, 32.1, 29.8, 29.8, 29.7, 29.6, 29.5, 29.5, 29.4, 29.0, 22.8, 14.3; **HRMS[M+H]$^+$**: Calcd for $C_{15}H_{30}NO$: 240.2322, found: 240.2329.

(*Z*)-6-Hydroxyhex-2-enenitrile (3.31). In a N_2-filled glovebox, a 4-dram vial was charged with 0.5 mL CH_2Cl_2 solution of (*Z*)-5-phenylpent-2-enamide (4.4 mg, 0.034 mmol, 1.0 equiv.). The Burgess reagent (16.2 mg, 0.068 mmol, 2.0 equiv.) was added, and the resulting mixture was allowed to stir for 1 h at 22 °C. The volatiles were removed under reduced pressure, leaving behind a black oil, which was purified by silica gel chromatography (10–50% EtOAc in hexanes) to afford **3.31** as colorless oil (3.2 mg, 0.029 mmol, 86% yield). The characterization data are consistent with those previously reported.[55] **^{1}H NMR (600 MHz, $CDCl_3$)**: δ 6.54 (dt, *J* = 10.7, 7.6 Hz, 1H), 5.35 (d, *J* = 10.9 Hz, 1H), 3.71 (q, *J* = 6.1 Hz, 2H), 2.54 (q, *J* = 7.5 Hz, 2H), 1.76 (p, *J* = 6.6 Hz, 2H); **HRMS[M+H]$^+$**: Calcd for $C_6H_{10}NO$: 112.0757, found: 112.0762.

3.6.5 Computational Studies

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DFT studies[56] were performed with the Gaussian 09/Gaussian 16 suite of programs.[57] Geometries were optimized with the ωB97XD functional and the Def2SVP basis set.[58] The effect of a polar reaction medium (tetrahydrofuran, THF) was approximated by means of an integral equation formalism variant of the polarizable continuum model (IEFPCM).[59] Stationary points were probed through vibrational analysis and Gibbs free energy corrections were performed under standard conditions (298.15 K, 1.0 atm). Transition states have been verified through Intrinsic Reaction Coordinate calculations (IRC) employing the L(ocal) Q(uadratic) A(approximation) method,[60] followed by optimization of the end-points with the abovementioned optimization method. We also probed the

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performance of various density functionals through single point energy calculations at the geometries optimized with the level described above by means of the SMD solvation model[61] with THF as solvent and the larger Def2TZVPP[47] basis set. Since the correct density functional is not known, we tested several of the state-of-the-art approaches that have been developed over the past decade:[44,62] MN15,[44i] M06,[63] ωB97XD[64] and PBE0-D3BJ[44b, 65] and PBE0.**Error! Bookmark not defined.** We only report the MN15/Def2TZVPP//ωB97XD/Def2SVP$_{THF(SMD)}$, PBE0-D3BJ/Def2TZVPP//ωB97XD/ Def2SVP$_{THF(SMD)}$ and PBE0/Def2TZVPP//ωB97XD/Def2SVP$_{THF(SMD)}$ energies. A file for convenient viewing of computed geometries with the program Mercury 3.3 is appended as separate "coordinates.xyz" file in Section 7.[66]

Model Systems Used in the Calculations

To simplify the calculations, we used the following model systems (Scheme S5). In **Ru-10** and **Ru-14** the Cl substituents on the dithiolate ligand have been replaced by hydrogens. In addition, the calculations have been carried out with truncated dithiolate

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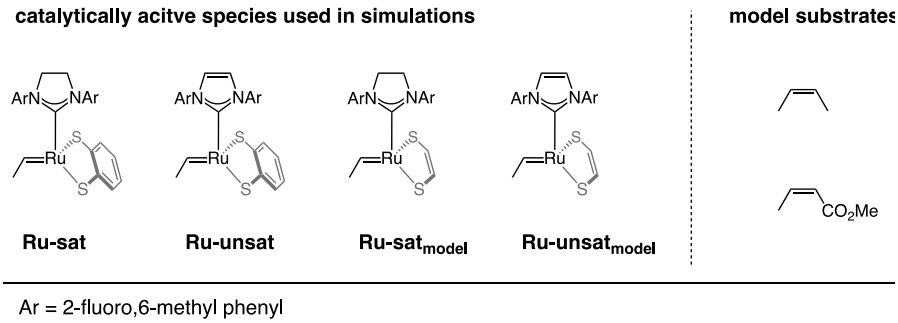
ligands (**Ru-10$_{model}$** and **Ru-14$_{model}$**). Furthermore, truncated model substrates have been applied (Scheme S5, right side).

Scheme S5. Model Systems Investigated through DFT



Competition Between Productive Olefin Metathesis and Decomposition Pathways

For insight regarding the rates of productive and nonproductive pathways, as well as various modes of decomposition with complexes **Ru-10** and **Ru-14**, the processes listed below (i–v) were investigated by DFT (optimization with ω–B97XD/Def2SVP$_{THF(IEFPCM)}$). Please note that only the structures associated with **Ru-10** are shown in Figs. S11-1 to S11-5.

(i) Distortion of trimethyl substituted metallacyclobutane **mcb$_a$** (relevant to homometathesis) to generate **mcb(dist)$_a$** via **ts(dist)$_a$** and subsequent decomposition by β-hydride elimination (→ **ts(BHE)$_a$** → **prod(BHE)$_a$**) and cyclopropantion (→ **ts(CP)$_a$** → **prod(CP)$_a$**; Fig. S11-1).

(ii) Nonproductive olefin metathesis, which is also relevant to homometathesis (**14e** → **ts1$_a$** → **mcb$_a$** → **ts2$_a$** → **14e**; Fig. S11-2).

(iii) Productive cross-metathesis, (**14e** → **ts1$_b$** → **mcb$_b$** → **ts2$_b$** → **14e**; Fig. S11-3).

(iv) Nonproductive olefin metathesis with methyl-(*Z*)-but-2-enoate (**14e** → **ts1$_c$** → **mcb$_c$** → **ts2$_c$** → **16e**), which involves the key metallacyclobutane intermediate (i.e., **mcb$_c$**), responsible for catalyst decomposition (Fig. S11-4).

(v) Distortion of trisubstituted metallacyclobutane **mcb$_c$**, bearing an ester group in α position, to generate **mcb(dist)$_c$** via **ts(dist)$_c$** and subsequent decomposition by β-hydride elimination (→ **ts(BHE)$_c$** → **prod(BHE)$_c$**) and cyclopropantion (→ **ts(CP)$_c$** → **prod(CP)$_c$**; see Fig. S11-5).

The corresponding free energy surfaces for **Ru-10** (blue curve) and **Ru-14** (red curve) associated with i−v are summarized in the diagrams below with three different levels of theory, namely, (MN15/Def2TZVPP//ωB97XD/Def2SVP$_{THF(SMD)}$, Fig. S11-6; PBE0-D3BJ/ Def2TZVPP//ωB97XD/Def2SVP$_{THF(SMD)}$, Fig. S11-7 and PBE0/Def2TZVPP//ωB97XD/ Def2SVP$_{THF(SMD)}$, Fig. S11-8). Overall, we find that in case of **Ru-10**, homocoupling (10.3 kcal/mol for **ts1$_a$**; blue curve in Fig. S11-6) is favored by nearly 3 kcal/mol over productive cross-metathesis (13.4 kcal/mol for **ts1$_b$**), whereas the barriers for metallacyclobutane distortion (**ts(dist)$_a$** and **ts(dist)$_c$**), the entry points to decomposition, are predicted to be notably higher in energy (24.4 and 18.0 kcal/mol, respectively; Fig. S11-6). Comparison of the latter two barriers reveals a major distinction, which might be the reason why stereoretentive cross-metathesis with α,β-unsaturated carboxylic acid derivatives are challenging. Specifically, we find that in **ts(dist)$_a$** the mcb Cα bearing a methyl substituent shifts into a *trans* position with respect to S(*cis*) (*cis* to the NHC), giving rise to unfavorable *trans* influence. In contrast, *trans* influence is weaker in **ts(dist)$_c$** due to the inductive effect of the ester substituent at the mcb's Cα, resulting in a lower barrier to its formation. That **ts(dist)$_c$** is only 4.5 kcal/mol higher in energy than **ts1$_b$**

likely renders mcb distortion competitive with cross-metathesis, especially if one considers errors associated with DFT calculations (~2 kcal/mol).

Computationally Observed Difference between Ru-10 and Ru-14

Despite the experimentally observed differences between **Ru-10** and **Ru-14**, the corresponding free energy surface associated with **Ru-14** is quantitatively similar to the one corresponding to **Ru-10** (<1−2 kcal/mol energy difference corresponds to the error of the DFT method; red curve, Fig. S11-6). This renders direct comparison between saturated and unsaturated NHC ligands challenging based on DFT calculations, a fact that has been pointed out previously.[67] While Tolman electronic parameters (TEP),**Error! Bookmark not defined.**[c,68] which represent a measure of the combined σ-donor and π-acceptor properties, are similar for the corresponding saturated and unsaturated NHCs, pK_a measurements[69] and ^{31}P and ^{79}Se NMR chemical shifts of carbene-phosphinide[70] and carbene-selenium[71] adducts suggest that the saturated variants are stronger σ-donors as well as better π-acceptors. Furthermore, experimentally determined redox potentials for Ir[72] and Ru[73] complexes have led to the conclusion that saturated NHCs could be stronger or weaker

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overall electron donors than their unsaturated counterparts. Still, consistent with the potentially increased σ-donor strength of saturated NHCs is an expanded N−C−N angle, which raises the energy of the filled sp^2 orbital.**Error! Bookmark not defined.** Additionally, investigations regarding the steric properties between SIMes and IMes do not provide a conclusive measure of any reactivity differences that might arise from minor size differences (e.g., buried volume[74] or repulsiveness[75]). Nonetheless, based on structural parameters (Ru−S(*trans*) and Ru−C^{NHC} bond lengths) it might be suggested that the variations between transformations performed with **Ru-10** and **Ru-14** are rooted in a subtle but significant difference in the degree of *trans* influence – stronger in **Ru-10** than in **Ru-14** (see Sections 5.3 and 5.4, below).

Transition States for β-Hydride Elimination and Cyclopropanation

Unlike the abovementioned experimental results (no observation of a cyclopropanation side product) the MN15/Def2TZVPP//ωB97XD/$Def2SVP_{THF(SMD)}$ values predict that **ts(CP)$_c$** (CP, cyclopropanation) is 0.8 kcal/mol lower in energy than **ts(BHE)$_c$** (i.e., 13.1 vs. 13.9 kcal/mol, respectively for **Ru-10**; Fig. S11-6). Nonetheless, the calculations show that β-hydride elimination is 15.7 kcal/mol more exergonic (–11.4 vs. 4.2 kcal/mol, respectively for **prod(BHE)$_c$** and **prod(CP)$_c$**; Fig. S11-6). A similar qualitative trend is predicted at the PBE0-D3BJ/Def2TZVPP//ωB97XD/$Def2SVP_{THF(SMD)}$ level (Fig. S11-7), whereas functionals that do not account for dispersion (e.g., PBE0/Def2TZVPP//ωB97XD/$Def2SVP_{THF(SMD)}$) appear to be in line with the experimental trend (27.7 and 28.5 kcal/mol for **ts(BHE)$_c$** and **ts(CP)$_c$**, respectively; Fig. S11-8).

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(74) Clavier, H.; Nolan, S. P. *Chem. Commun.* **2010***, 46*, 841–861.

(75) Gusev, D. G. *Organometallics* **2009***, 28*, 6458–6461.

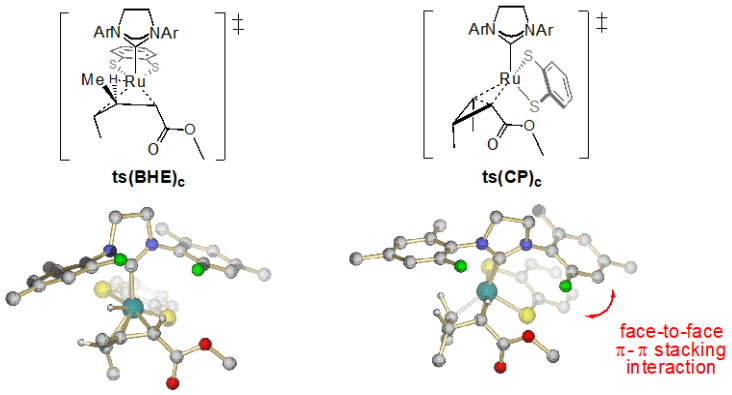
While correct modeling of dispersion interactions is crucial for achieving appropriate predictions of weak, non-covalent interactions in the gas phase,[76,44b,52] there have been recent concerns regarding the attenuation of dispersion interactions in solution, which render definitive statements on the relative energy of **ts(BHE)$_c$** and **ts(CP)$_c$** based on the present DFT data challenging.[77] Comparison of transition state structures for **ts(BHE)$_c$** and **ts(CP)$_c$** reveals that **ts(CP)$_c$** might be stabilized to a larger degree by attractive dispersion forces due to a more favored face-to-face π−π stacking interaction,[78] which is largely absent in **ts(BHE)$_c$** (Scheme S6). Hence, if dispersion is disregarded (i.e., by applying the PBE0 functional; Fig. S11-8) the relative order between **ts(BHE)$_c$** and **ts(CP)$_c$** is indeed reversed.

Scheme S6. Transition States for β-Hydride Elimination and Cyclopropanation

(76) For a review on dispersion interactions, see: Wagner, J. P.; Schreiner, P. R. *Angew. Chem., Int. Ed.* **2015***, 54*, 12274−12296.

(77) For studies regarding the attenuation of dispersion interactions in solution, see: (a) Yang, L.; Adam, C.; Nichol, G. S.; Cockroft, S. L. *Nat. Chem.* **2013***, 5*, 1006–1010. (b) Pollice, R.; Bot, M.; Kobylianskii, I. J.; Shenderovich, I.; Chen, P. *J. Am. Chem. Soc.* **2017***, 139*, 13126–13140.

(78) For a review on aryl–aryl interactions, see: Hunter, C. A., Lawson, K. R.; Perkins, J.; Urch, C. J. Aromatic interactions. *J. Chem. Soc., Perkin Trans.* **2001***, 2,* 651–669.



Free Energy Surfaces With Smaller Model Systems Ru-10$_{model}$ and Ru-14$_{model}$

To test the influence of dispersion further, we investigated the free energy surfaces with the smaller model systems, **Ru-10$_{model}$** and **Ru-14$_{model}$** (cf. Scheme S5). For the computed structures see Figs. S12-1 to S12-5. The corresponding free energy surfaces for **Ru-10$_{model}$** (blue curve) and **Ru-14$_{model}$** (red curve) are shown below with three different levels of theory (MN15/Def2TZVPP// ωB97XD/Def2SVP$_{THF(SMD)}$, Fig. S12-6; PBE0-D3BJ/Def2TZVPP// ωB97XD/Def2SVP$_{THF(SMD)}$, Fig. S12-7 and PBE0/Def2TZVPP//ωB97XD/Def2SVP$_{THF(SMD)}$, Fig. S12-8). As might be expected, **ts(BHE)$_c$** is predicted to be favored over **ts(CP)$_c$** with all density functionals examined, suggesting that dispersion interactions in solution should probably be taken with caution.

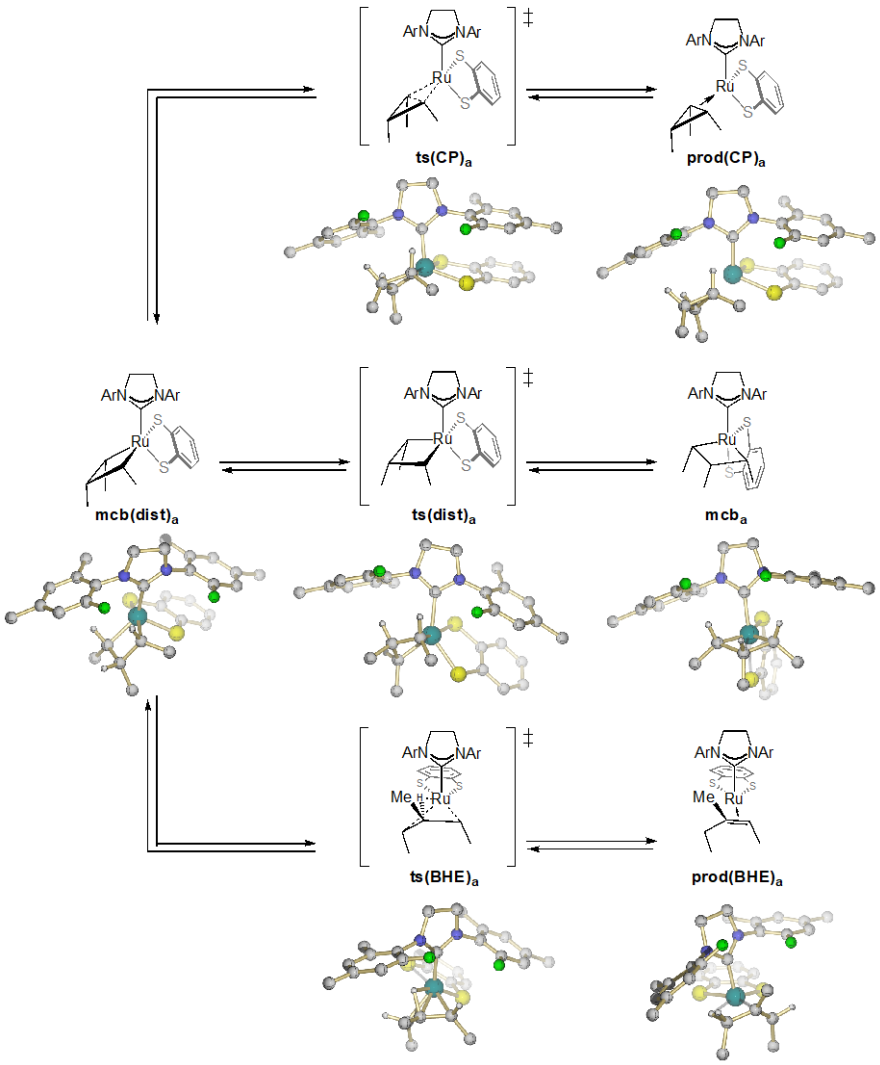


Fig. S11-1. Computed structures (ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$) for decomposition of **mcb$_a$** through β-hydride elimination and cyclopropanation. **ts(CP**) and **prod(CP)**, transition state and product for cyclopropanation; **ts(BHE)** and **prod(BHE)**, transition state and product for β-hydride elimination; **mcb**, metallacyclobutane; **ts(dist)**, transition state for metallacyclobutane distortion; **mcb(dist)**, distorted mcb after structural distortion.

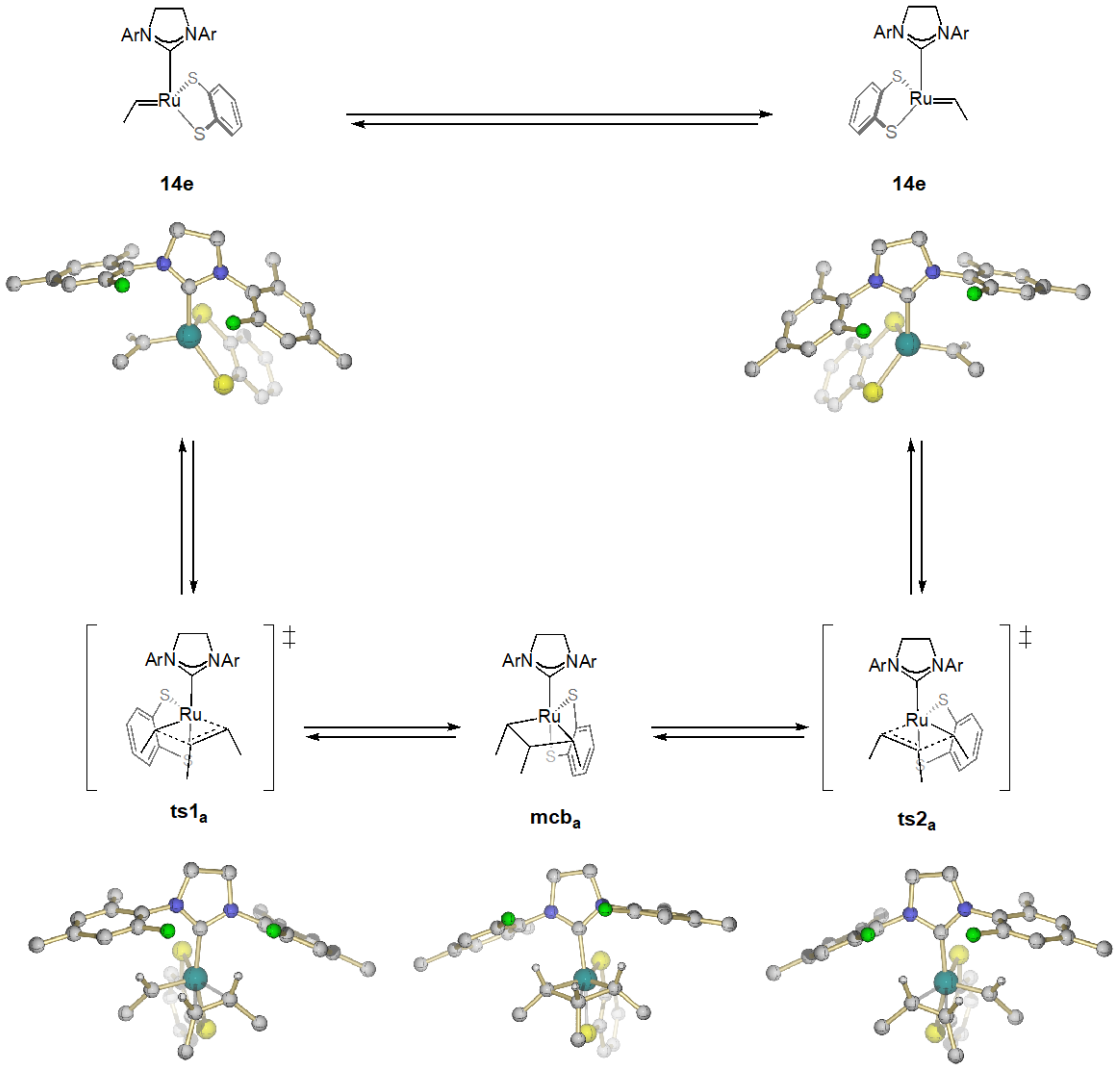


Fig. S11-2. Computed structures (ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$) for non-productive OM with cis-butene; **14e**, 14-electron intermediate; **mcb**, metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and breakage. ts, transition state; mcb, metallacyclobutane.

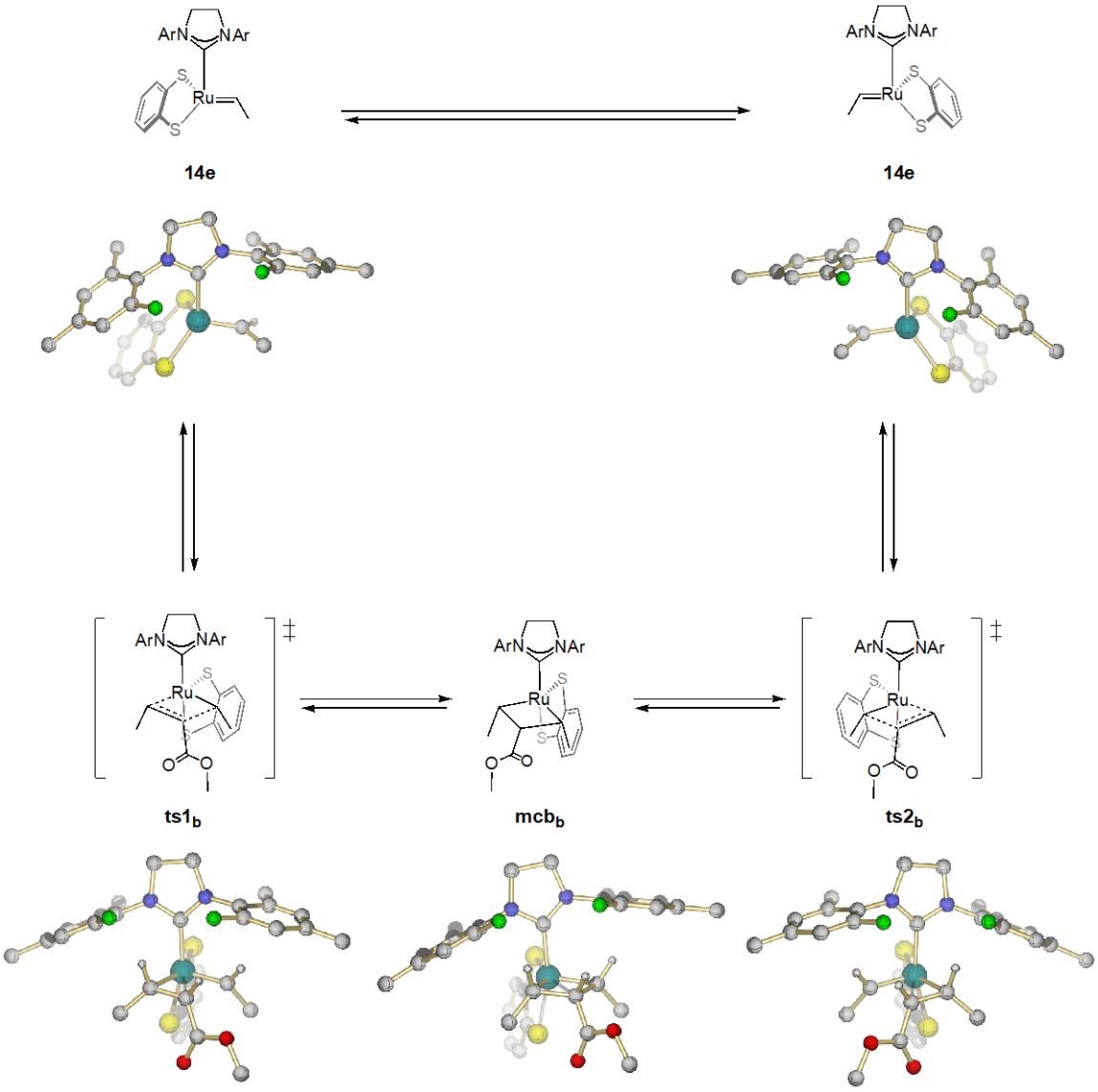


Fig. S11-3. Computed structures (ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$) for productive olefin metathesis with methyl (Z)-but-2-enoate. **14e**, 14-electron intermediate; **mcb**, metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and breakage.

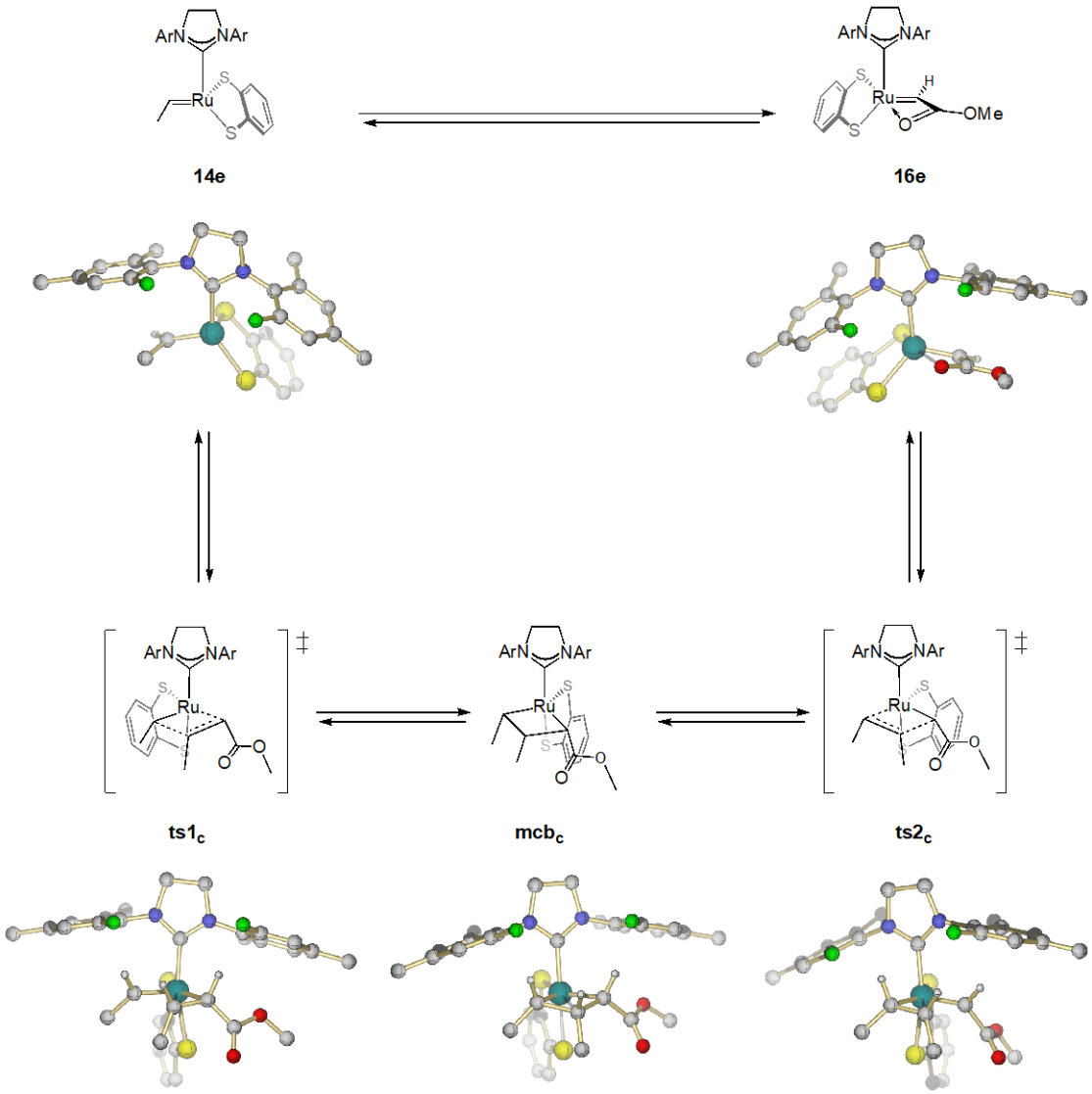


Fig. S11-4. Computed structures (ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$) for non-productive olefin metathesis with methyl (Z)-but-2-enoate. **14e**, 14-electron intermediate; **mcb**, metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and breakage; **16e**, 16-electron intermediate.

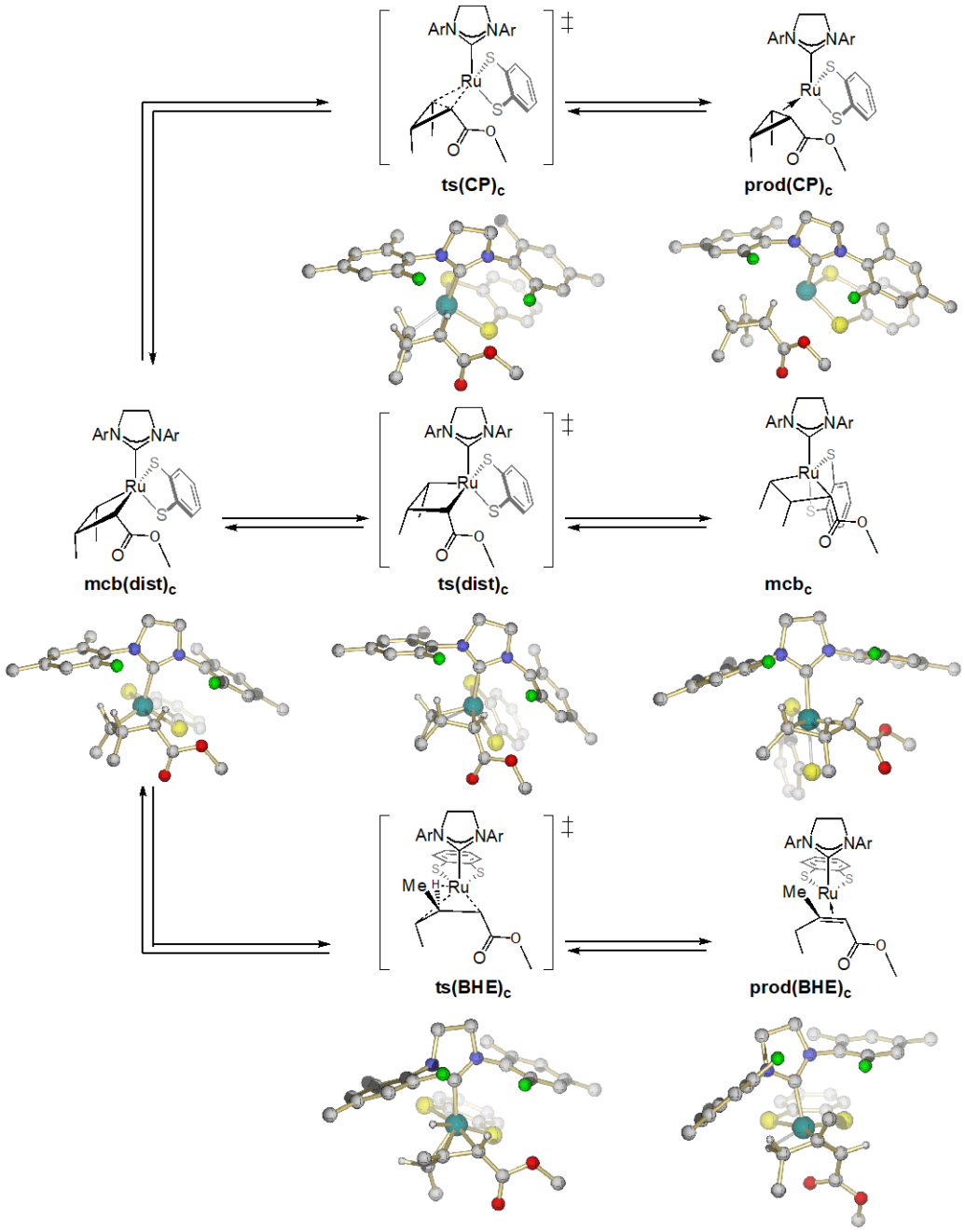


Fig. S11-5. Computed structures (ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$) for decomposition of **mcb$_c$** through β-hydride elimination and cyclopropanation. **ts(CP)** and **prod(CP)**, transition state and product for cyclopropanation; **ts(BHE)** and **prod(BHE)**, transition state and product for □-hydride elimination; **mcb**, metallacyclobutane; **ts(dist)**, transition state for metallacyclobutane distortion; **mcb(dist)**, distorted mcb after structural distortion.

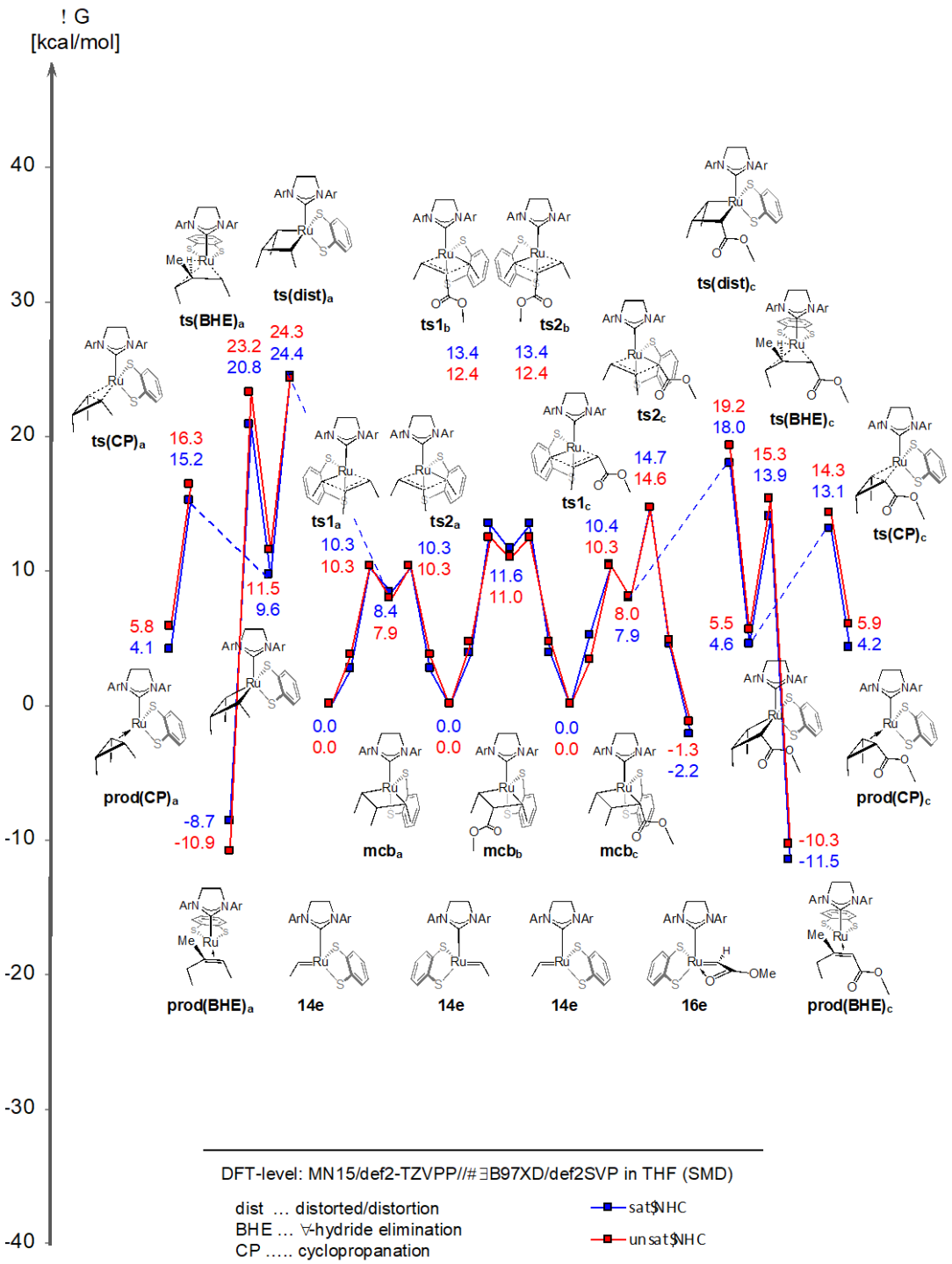


Fig. S11-6. Free energy surface (△G in kcal/mol relative to **14e**) for nonproductive olefin metathesis with cis-butene (index a), productive and nonproductive olefin metathesis with methyl (Z)-but-2-enoate (indices b and c), as well as decomposition through β-hydride elimination and cyclopropanation at the MN15/Def2TZVPP//ωB97XD/ Def2SVP$_{CH2Cl2(SMD)}$ level. **ts(CP)** and **prod(CP)**, transition state and product for cyclopropanation; **ts(BHE)** and **prod(BHE)**, transition state and product for β-hydride elimination; **ts(dist)**, transition state for metallacyclobutane distortion; **14e**, 14-electron intermediate; **mcb**, metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and breakage; **16e**, 16-electron intermediate.

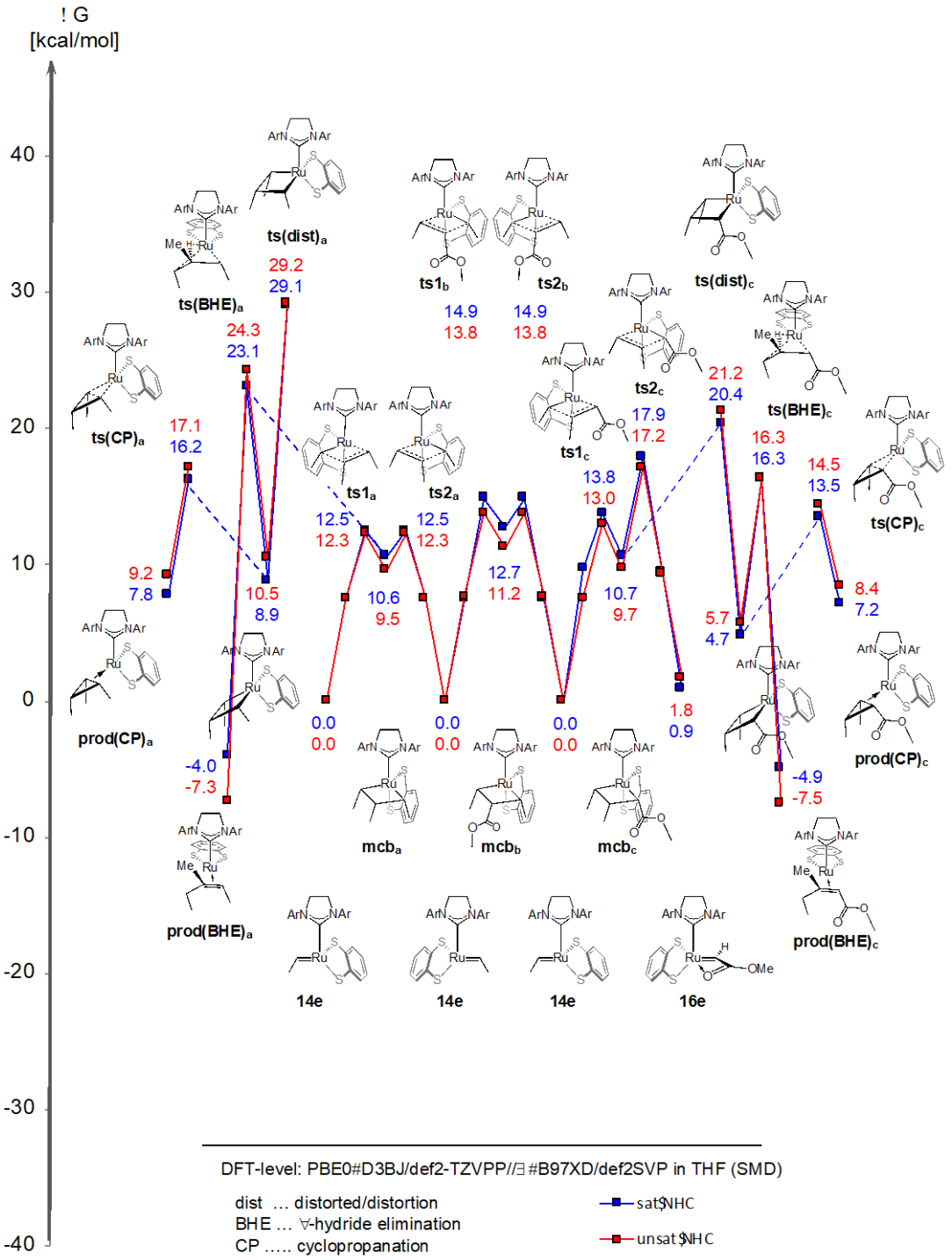


Fig. S11-7. Free energy surface (△G in kcal/mol relative to **14e**) for nonproductive olefin metathesis with cis-butene (index a), productive and nonproductive olefin metathesis with methyl (Z)-but-2-enoate (indices b and c), as well as decomposition through β-hydride elimination and cyclopropanation at the PBE0-D3BJ/Def2TZVPP// ωB97XD/Def2SVP$_{CH2Cl2(SMD)}$ level. **ts(CP)** and **prod(CP)**, transition state and product for cyclopropanation; **ts(BHE)** and **prod(BHE)**, transition state and product for β-hydride elimination; **ts(dist)**, transition state for metallacyclobutane distortion; **14e**, 14-electron intermediate; **mcb**, metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and breakage; **16e**, 16-electron intermediate.

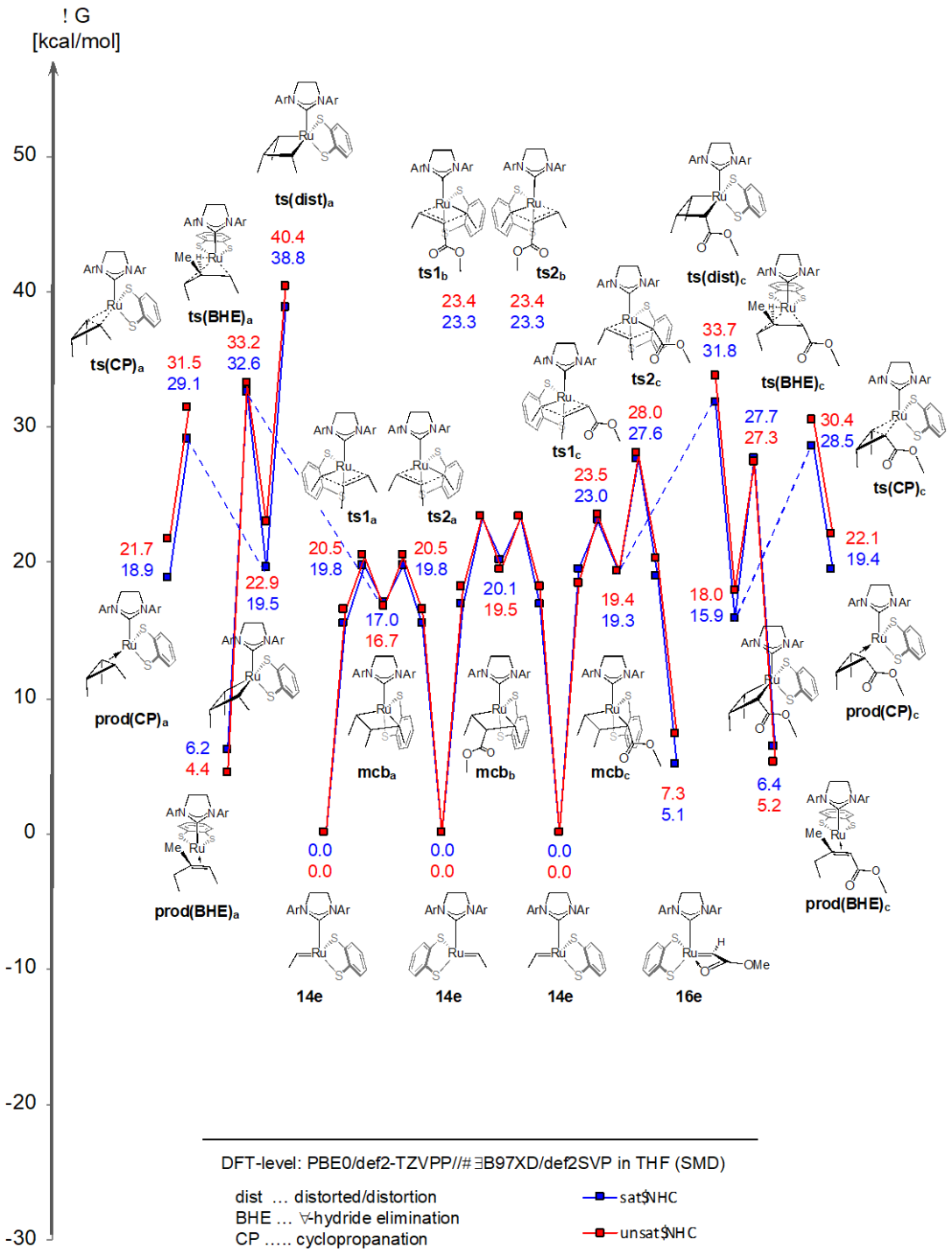


Fig. S11-8. Free energy surface (△G in kcal/mol relative to **14e**) for nonproductive olefin metathesis with cis-butene (index a), productive and nonproductive olefin metathesis with methyl (Z)-but-2-enoate (indices b and c), as well as decomposition through β-hydride elimination and cyclopropanation at the PBE0/Def2TZVPP//ωB97XD/ Def2SVP$_{CH2Cl2(SMD)}$ level. **ts(CP)** and **prod(CP)**, transition state and product for cyclopropanation; **ts(BHE)** and **prod(BHE)**, transition state and product for β-hydride elimination; **ts(dist)**, transition state for metallacyclobutane distortion; **14e**, 14-electron intermediate; **mcb**, metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and breakage; **16e**, 16-electron intermediate.

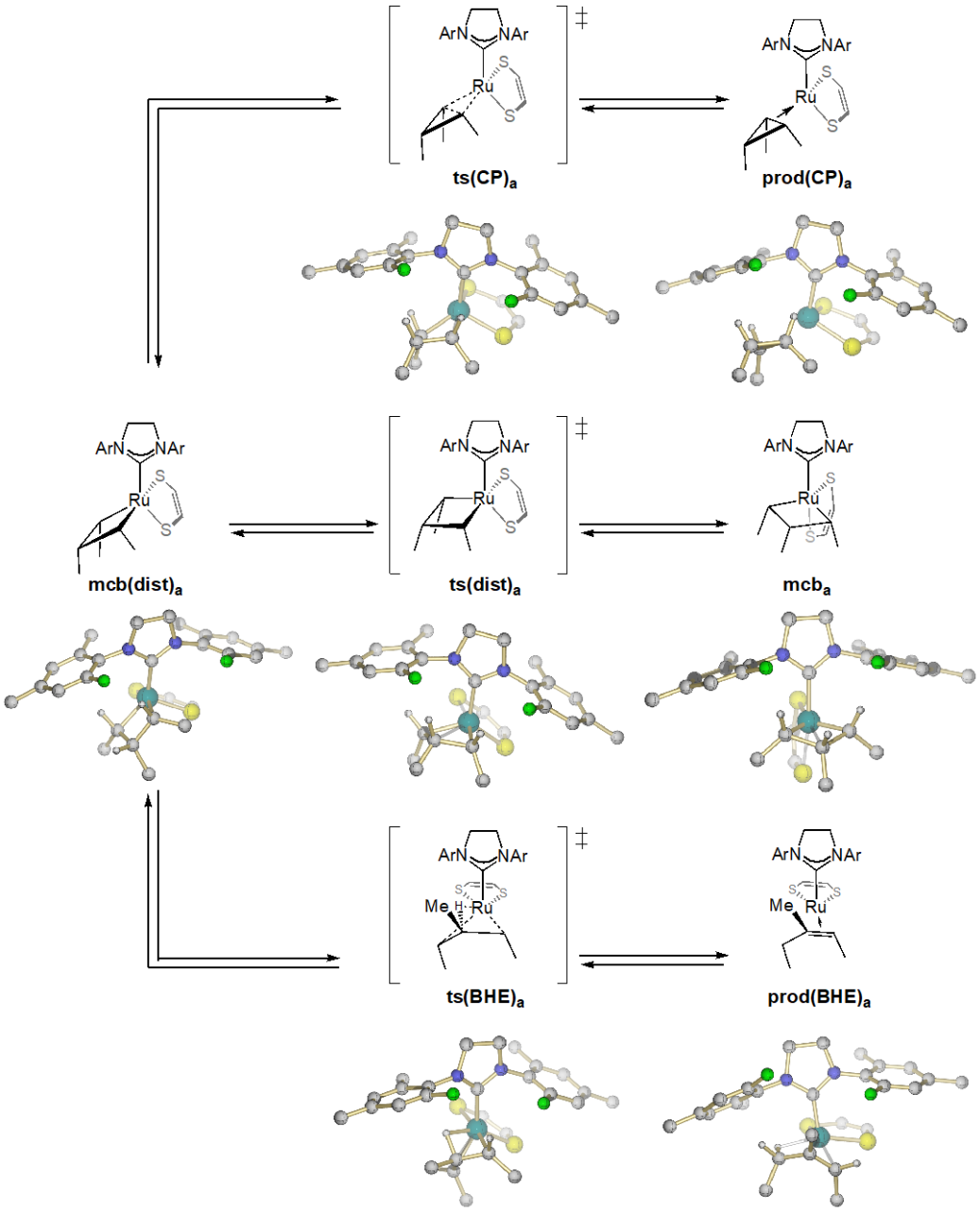


Fig. S12-1. Computed structures (model system; ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$) for decomposition of **mcb$_a$** through β-hydride elimination and cyclopropanation. **ts(CP)** and **prod(CP)**, transition state and product for cyclopropanation; **ts(BHE)** and **prod(BHE)**, transition state and product for β-hydride elimination; **mcb**, metallacyclobutane; **ts(dist)**, transition state for metallacyclobutane distortion; **mcb(dist)**, mcb after structural distortion.

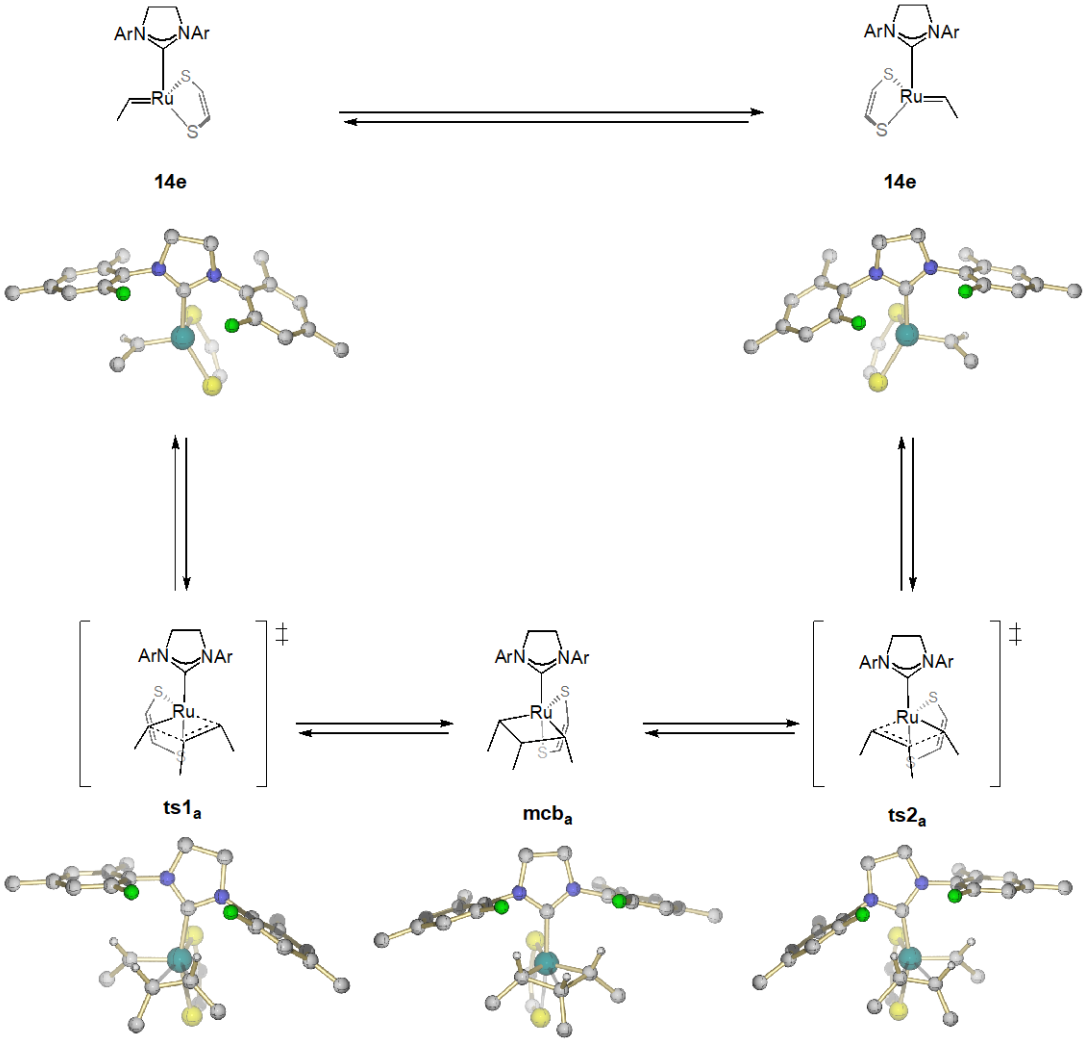


Fig. S12-2. Computed structures (model system; ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$) for nonproductive olefin metathesis with cis-butene. **14e**, 14-electron intermediate; **mcb**, metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and breakage.

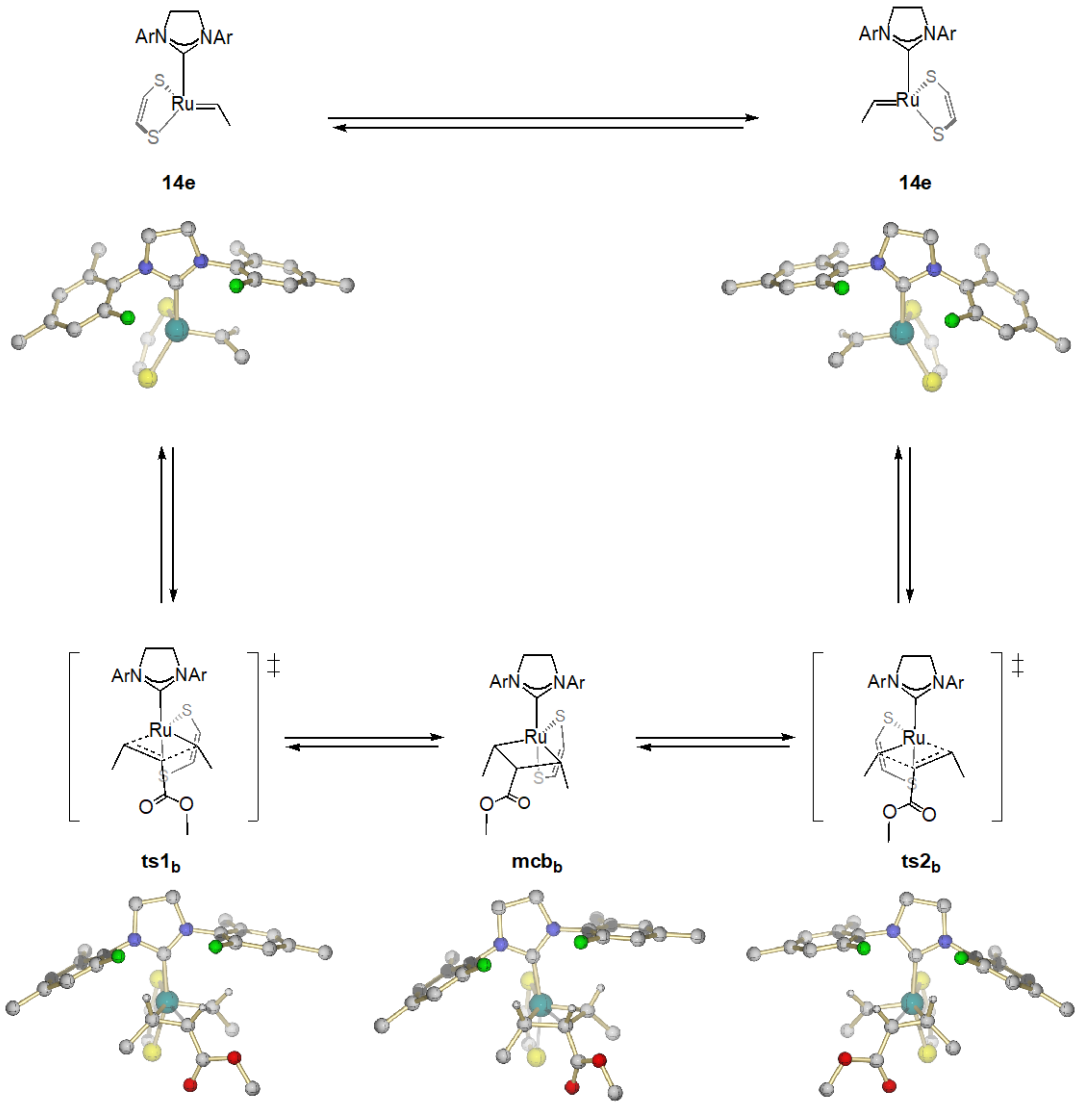


Fig. S12-3. Computed structures (model system; ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$) for productive olefin metathesis with methyl (Z)-but-2-enoate. **14e**, 14-electron intermediate; **mcb**, metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and cleavage.

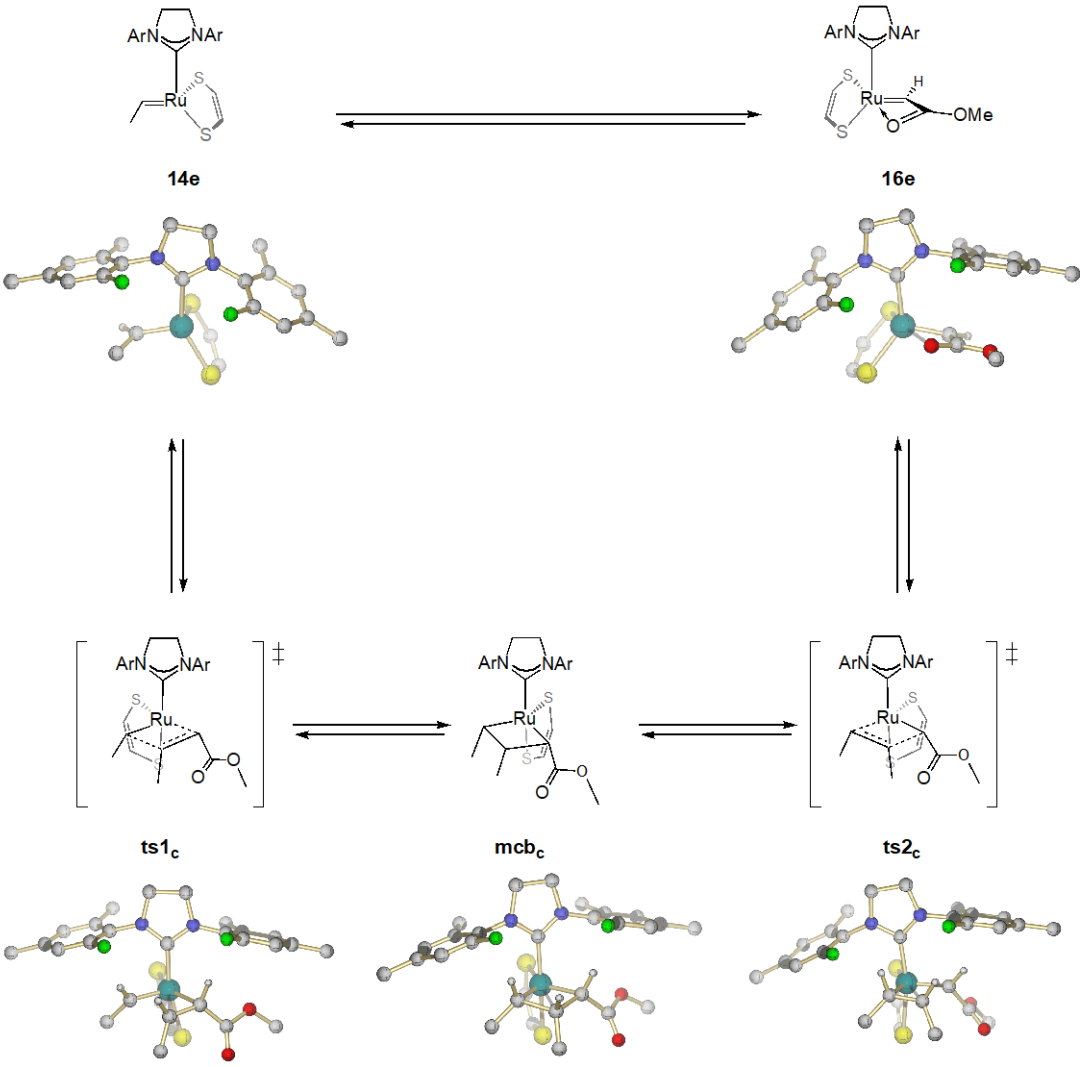


Fig. S12-4. Computed structures (model system; ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$) for nonproductive OM with methyl (*Z*)-but-2-enoate. **14e**, 14-electron intermediate; **mcb**, metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and breakage; **16e**, 16-electron intermediate.

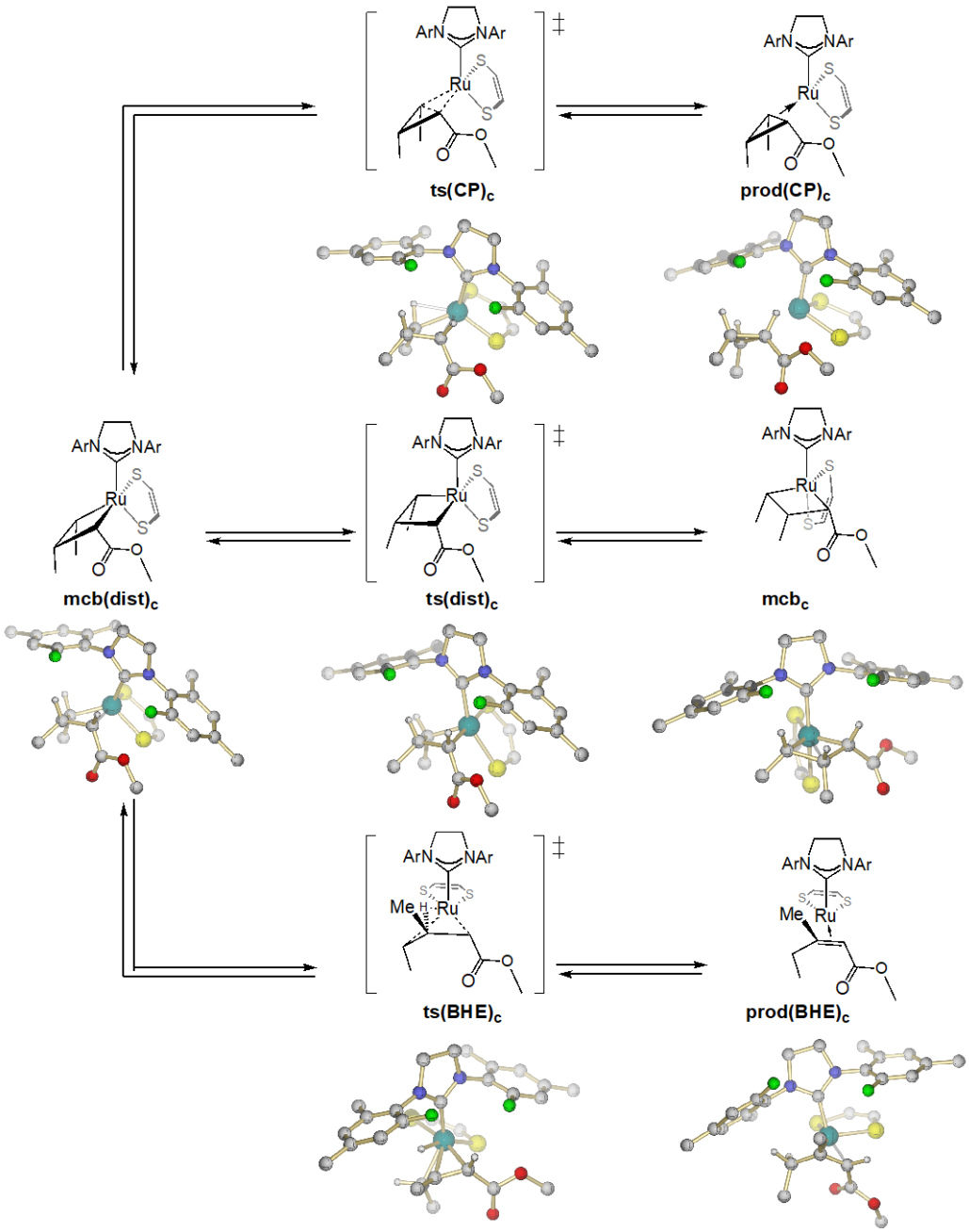


Fig. S12-5. Computed structures (model system; ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$) for decomposition of **mcb$_c$** through β-hydride elimination and cyclopropanation. **ts(CP)** and **prod(CP)**, transition state and product for cyclopropanation; **ts(BHE)** and **prod(BHE)**, transition state and product for β-hydride elimination; **mcb**, metallacyclobutane; **ts(dist)**, transition state for metallacyclobutane distortion; **mcb(dist)**, mcb after structural distortion.

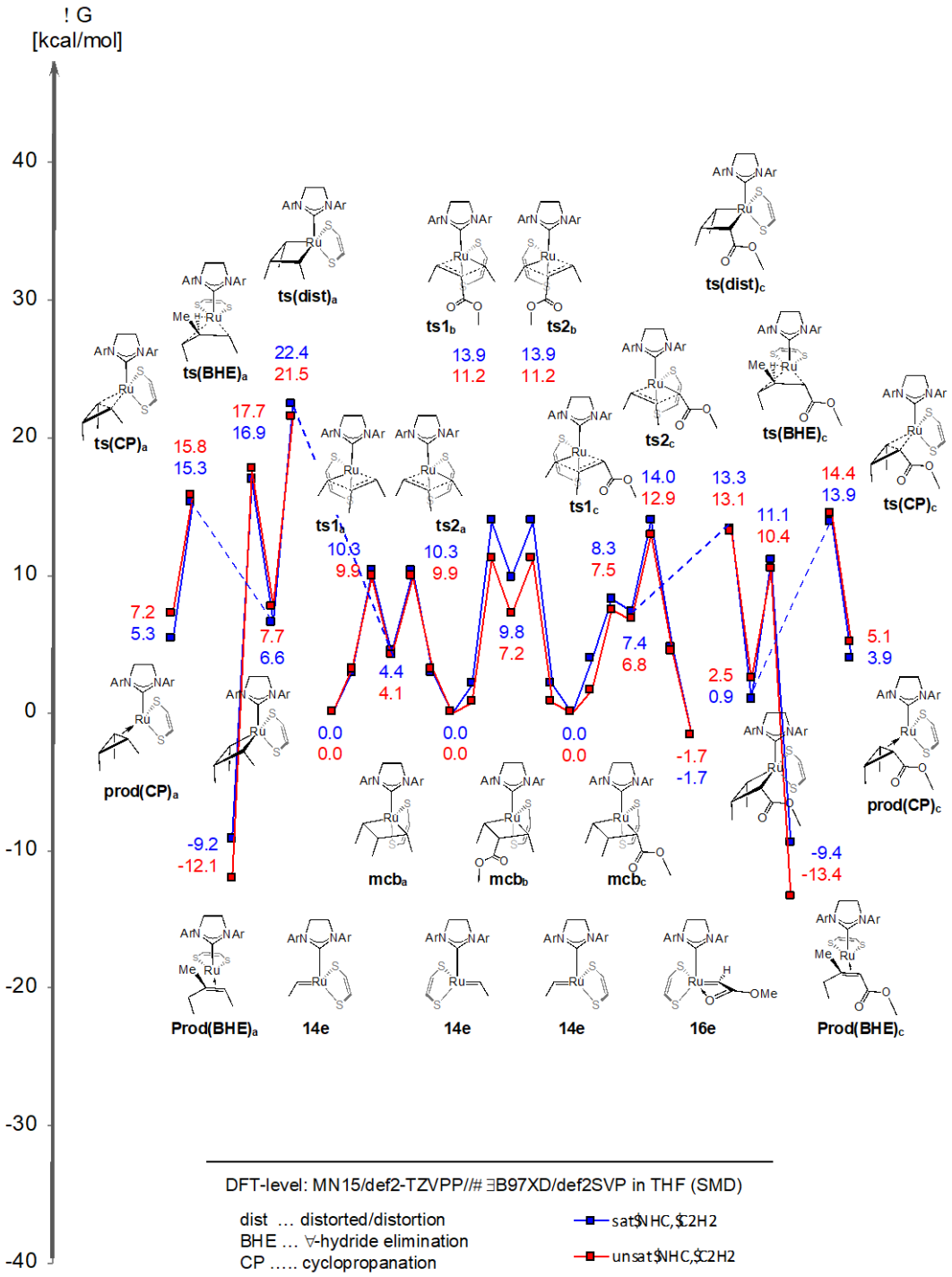


Fig. S12-6. Free energy surface (model system; △G in kcal/mol relative to **14e**) for nonproductive olefin metathesis with cis-butene (index a), productive and nonproductive olefin metathesis with methyl (*Z*)-but-2-enoate (indices b and c), as well as decomposition through β-hydride elimination and cyclopropanation at the MN15/Def2TZVPP//ωB97XD/ Def2SVP$_{CH2Cl2(SMD)}$ level. **ts(CP)** and **prod(CP)**, transition state and product for cyclopropanation; **ts(BHE)** and **prod(BHE)**, transition state and product for β-hydride elimination; **ts(dist)**, transition state for metallacyclobutane distortion; **14e**, 14-electron intermediate; **mcb**, metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and breakage; **16e**, 16-electron intermediate.

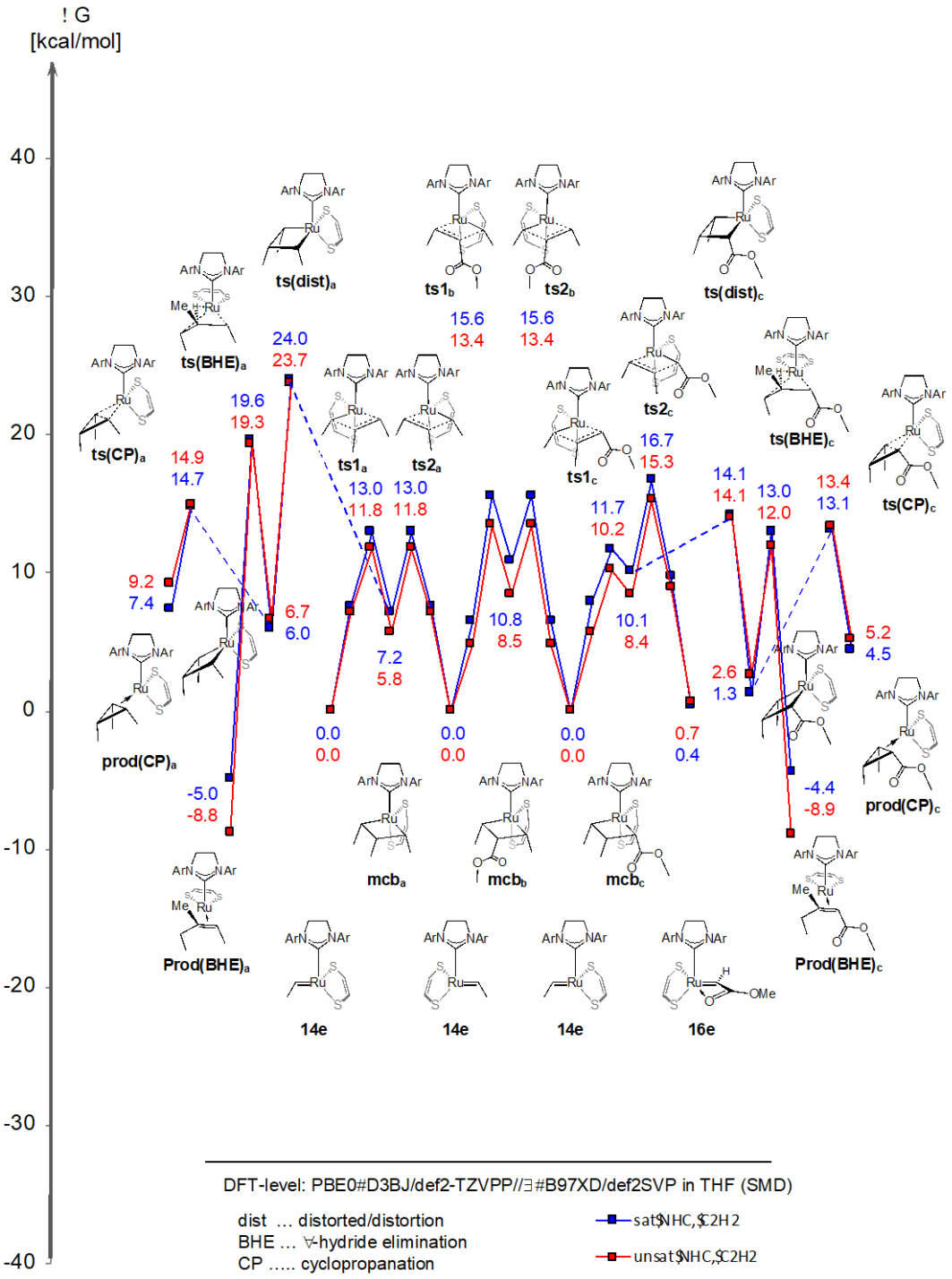


Fig. S12-7. Free energy surface (model system; △G in kcal/mol relative to **14e**) for nonproductive olefin metathesis with cis-butene (index a), productive and nonproductive olefin metathesis with methyl (Z)-but-2-enoate (indices b and c), as well as decomposition through β-hydride elimination and cyclopropanation at the PBE0-D3BJ/Def2TZVPP//ωB97XD/Def2SVP$_{CH2Cl2(SMD)}$ level. **ts(CP)** and **prod(CP)**, transition state and product for cyclopropanation; **ts(BHE)** and **prod(BHE)**, transition state and product for β-hydride elimination; **ts(dist)**, transition state for metallacyclobutane distortion; **14e**, 14-electron intermediate; **mcb**,

metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and breakage; **16e**, 16-electron intermediate.

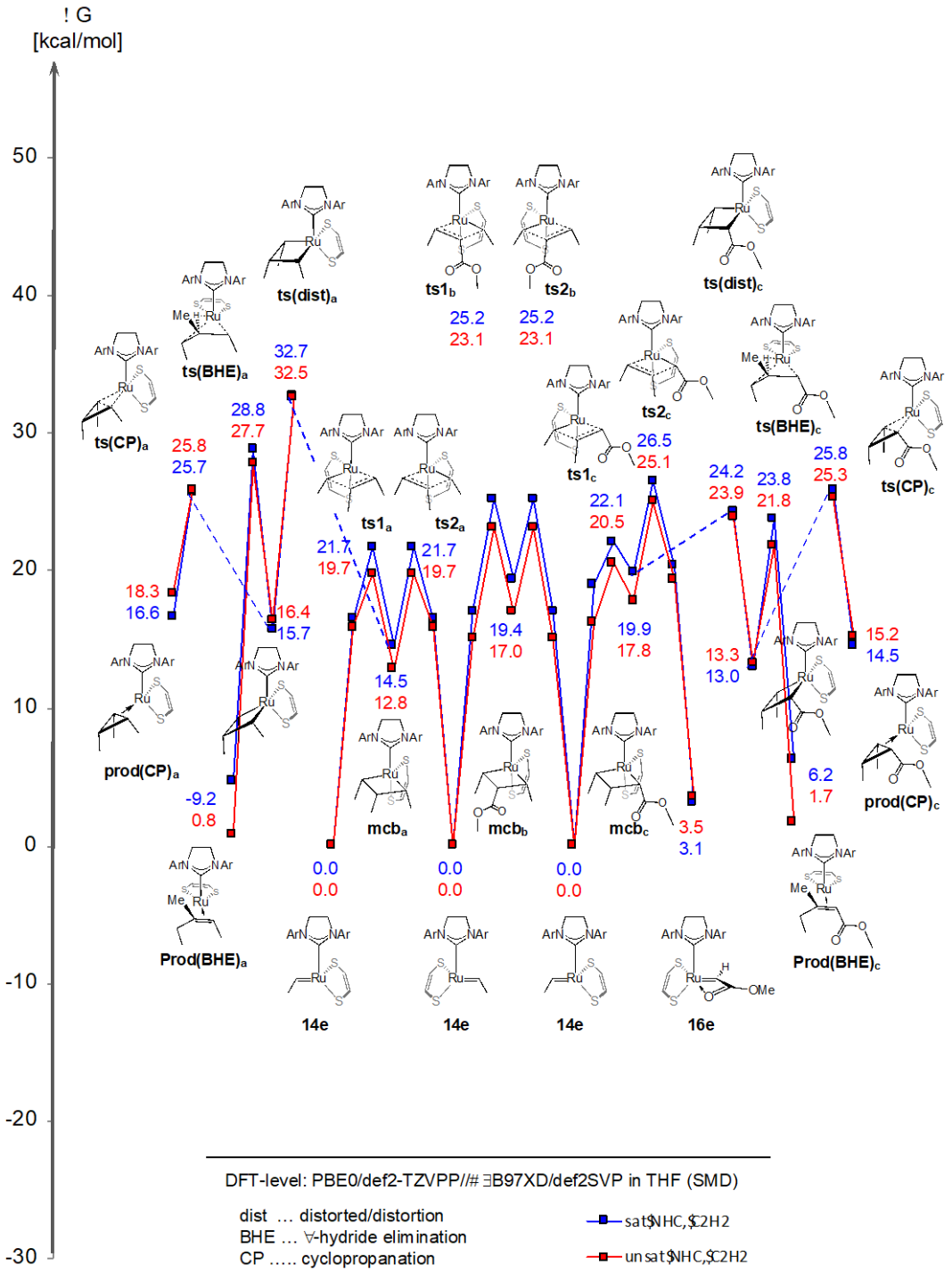


Fig. S12-8. Free energy surface (model system; △G in kcal/mol relative to **14e**) for nonproductive olefin metathesis with cis-butene (index a), productive and nonproductive olefin metathesis with methyl (Z)-but-2-enoate (indices b and c), as well as decomposition through β-hydride elimination and cyclopropanation at the PBE0/Def2TZVPP//ωB97XD/ Def2SVP$_{CH2Cl2(SMD)}$ level. **ts(CP)** and **prod(CP)**, transition state and product for

cyclopropanation; **ts(BHE)** and **prod(BHE)**, transition state and product for β-hydride elimination; **ts(dist)**, transition state for metallacyclobutane distortion; **14e**, 14-electron intermediate; **mcb**, metallacyclobutane; **ts1** and **ts2**, transition states for mcb formation and breakage; **16e**, 16-electron intermediate.

Origin of Reactivity Difference between Ru-10 and Ru-14

Evolution of trans Influence in the Sequence 14e → ts1b → mcbb

Analysis of bond lengths in the DFT optimized structures (ωB97XD/Def2SVP$_{THF(SMD)}$) supports the hypothesis that the saturated NHC ligand in **Ru-10** does exert a stronger *trans* influence (Fig. S13-1a). While *trans influence* is avoided in the 14-electron intermediate (**14e**), as indicated by the small C^{NHC}–Ru–S(*trans*) angle (143.9º), the Ru–S(*trans*) bond length increases during transition from **14e → ts1$_b$ → mcb$_b$** (2.336 → 2.405 → 2.423 Å). While a similar trend is observed for **Ru-14** (2.330 → 2.400 → 2.418 Å, values in grey box), the Ru– S(*trans*) bond length is shorter by 0.005 Å on average. In contrast, the Ru–C^{NHC} bond lengths are longer in the intermediates and transition states derived from **Ru-14** (2.062 → 2.103 → 2.122 Å vs 2.041 → 2.094 → 2.105 Å for **Ru-10**). A similar trend is observed with the smaller model systems (**Ru-10$_{model}$** and **Ru-14$_{model}$**, Fig. S13-1b).

Factors Governing Metallacyclobutane Distortion (mcbdist)

The structural distortion from **mcb$_a$ → ts(dist)$_a$ → mcb(dist)$_a$** involves the interconversion of two metallacyclobutane intermediates, which can both be described by a trigonal bipyramidal geometry (TBP). This process is likely facilitated by lowering of *trans* influence that exists between the NHC ligand (C^{NHC}) and the sulfur in *trans* position (S(*trans*)). While the C^{NHC}–Ru–S(*trans*) angle contracts from 165.5º → 138.1º → 111.5º the C^{1}–Ru–S(*cis*) angle expands (126.9º → 160.1º → 166.1º; Fig. S13-2a). Similar trends are observed for the sequence **mcb$_c$ → ts(dist)$_c$ → mcb(dist)$_c$**, with the distinction that the

C^1–Ru–S(*cis*) angle can adopt an almost perfectly linear geometry (140.4 º → 179.1 º → 173.8 º; Fig. S13-2b). This highlights the reduced *trans* influence between C^1 and S(*trans*) and underscores the greater propensity of **mcb$_c$** to undergo rearrangement. For the corresponding structural parameters in the smaller model systems (**Ru-10$_{model}$** and **Ru-14$_{model}$**) (see Fig. 13-3).

Transition States for *β*-Hydride Elimination

The geometries for transition states for β-hydride elimination are displayed in Fig. S13-4. For example, during transition from **mcb(dist)$_a$ → ts(BHE)$_a$** the C^3–Ru–C^{NHC} angle undergoes a minor expansion (121.5º → 131.0º; Fig. S13-4a) through which an open ligation site for transfer of the β-hydride is created. Since **ts(BHE)$_c$** is structurally related to the distorted metallacyclobutane **mcb(dist)$_c$**, the transition state for β-hydride elimination is lowered in energy because the *trans* influence between C^1 and S(*cis*) is weaker (Fig. S13-4b). For the corresponding structural parameters in the smaller model systems (**Ru-10$_{model}$** and **Ru-14$_{model}$**), see Fig. S13-5.

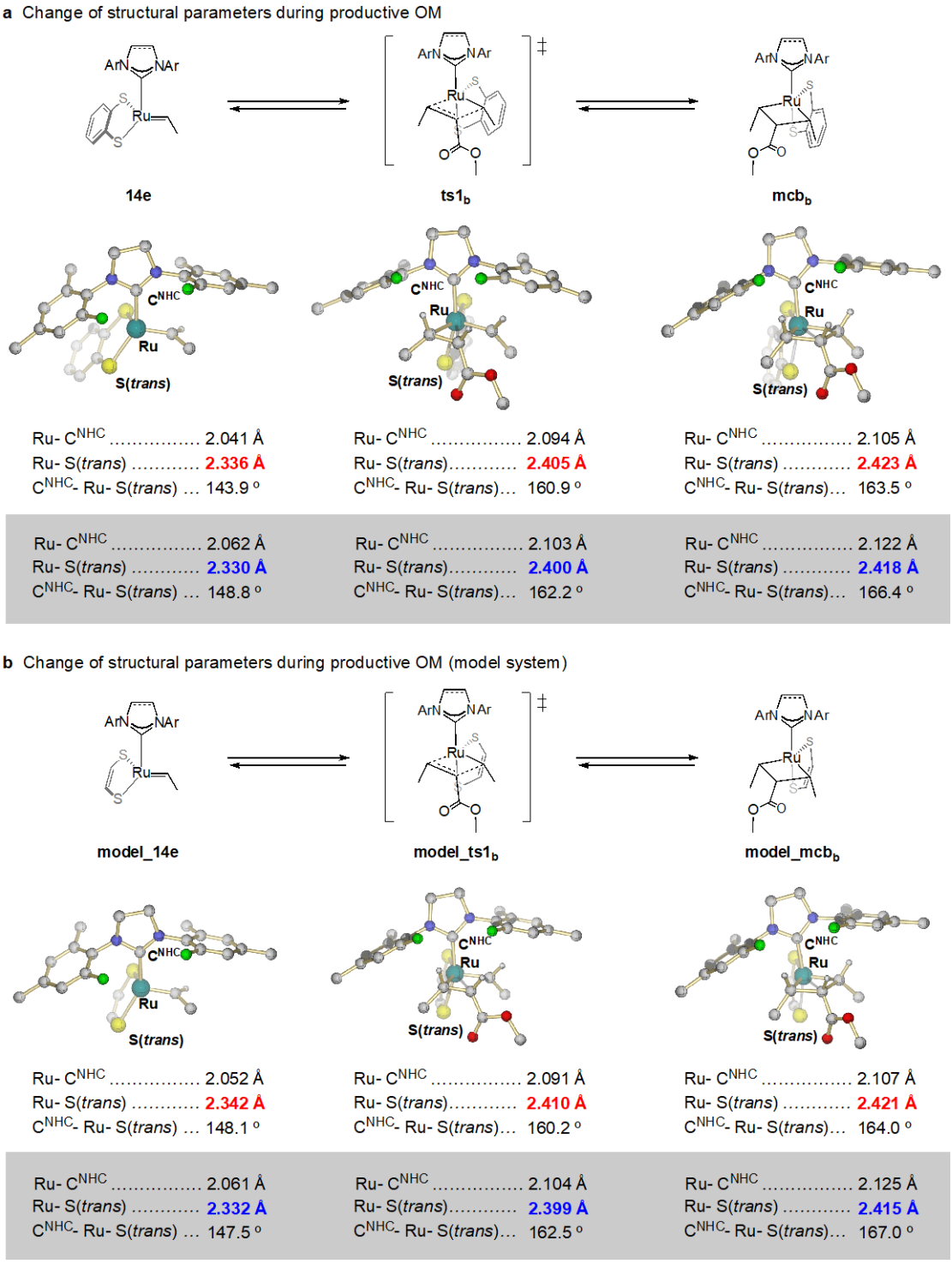
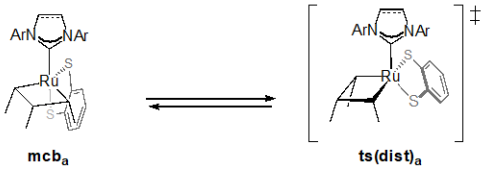
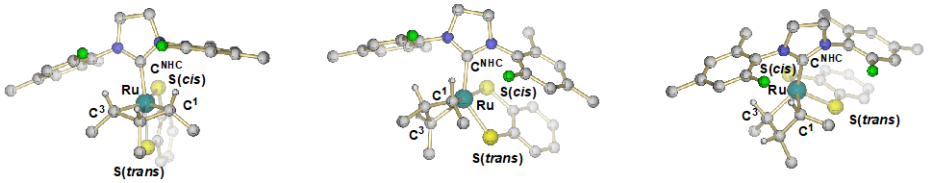


Fig. S13-1. Evolution of trans influence during productive olefin metathesis (index b) for real system (top) and smaller model system (bottom); structures have been obtained with ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$; only computed structures for complexes bearing saturated NHC ligands are displayed; bond lengths (Å) and angles (°) for corresponding analogues with unsaturated NHC are given in grey boxes. **14e**, 14-electron intermediate; **ts1**, transition states for mcb formation; **mcb**, metallacyclobutane.

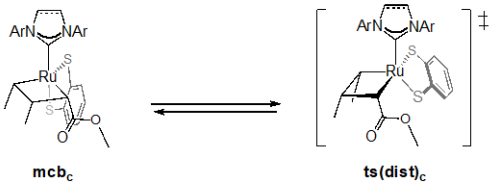
a Change of structural parameters during metallacyclobutane distortion of **mcb$_a$**

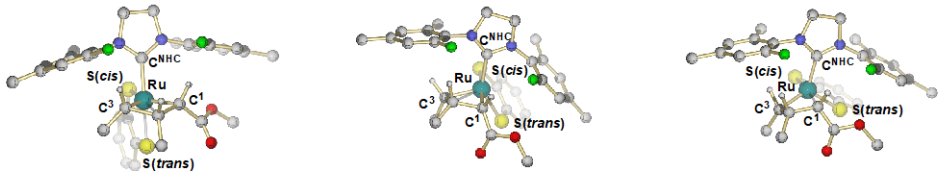




mcb$_a$	ts(dist)$_a$	mcb(dist)$_a$
Ru- C^{NHC} ..... 2.096 Å	Ru- C^{NHC} ..... 2.154 Å	Ru- C^{NHC} ..... 1.994 Å
Ru- S(*trans*)..... 2.425 Å	Ru- S(*trans*)..... 2.309 Å	Ru- S(*trans*)..... 2.200 Å
C^{NHC}- Ru- S(*trans*)... **165.6** °	C^{NHC}- Ru- S(*trans*)... **138.1** °	C^{NHC}- Ru- S(*trans*)... **111.5** °
C^1- Ru- S(*cis*)..... **126.9** °	C^1- Ru- S(*cis*)..... **160.1** °	C^1- Ru- S(*cis*)..... **166.1** °
C^3- Ru- C^{NHC} ..... 89.9 °	C^3- Ru- C^{NHC} ..... 130.6 °	C^3- Ru- C^{NHC} ..... 121.5 °
Ru- C^{NHC} ..... 2.106 Å	Ru- C^{NHC} ..... 2.169 Å	Ru- C^{NHC} ..... 2.009 Å
Ru- S(*trans*)..... 2.424 Å	Ru- S(*trans*)..... 2.310 Å	Ru- S(*trans*)..... 2.200 Å
C^{NHC}- Ru- S(*trans*)... **169.1** °	C^{NHC}- Ru- S(*trans*)... **136.9** °	C^{NHC}- Ru- S(*trans*)... **110.4** °
C^1- Ru- S(*cis*)..... **133.3** °	C^1- Ru- S(*cis*)..... **158.9** °	C^1- Ru- S(*cis*)..... **166.3** °
C^3- Ru- C^{NHC} ..... 90.2 °	C^3- Ru- C^{NHC} ..... 132.2 °	C^3- Ru- C^{NHC} ..... 121.6 °

b Change of structural parameters during metallacyclobutane distortion of **mcb$_c$**





mcb$_c$	ts(dist)$_c$	mcb(dist)$_c$
Ru- C^{NHC} ..... 2.101 Å	Ru- C^{NHC} ..... 2.053 Å	Ru- C^{NHC} ..... 2.000 Å
Ru- S(*trans*)..... 2.422 Å	Ru- S(*trans*)..... 2.321 Å	Ru- S(*trans*)..... 2.223 Å
C^{NHC}- Ru- S(*trans*)... **169.7** °	C^{NHC}- Ru- S(*trans*)... **143.5** °	C^{NHC}- Ru- S(*trans*)... **114.3** °
C^1- Ru- S(*cis*)..... **140.4** °	C^1- Ru- S(*cis*)..... **179.1** °	C^1- Ru- S(*cis*)..... **173.8** °
C^3- Ru- C^{NHC} ..... 91.0 °	C^3- Ru- C^{NHC} ..... 107.2 °	C^3- Ru- C^{NHC} ..... 115.8 °
Ru- C^{NHC} ..... 2.110 Å	Ru- C^{NHC} ..... 2.052 Å	Ru- C^{NHC} ..... 2.012 Å
Ru- S(*trans*)..... 2.416 Å	Ru- S(*trans*)..... 2.309 Å	Ru- S(*trans*)..... 2.226 Å
C^{NHC}- Ru- S(*trans*)... **170.1** °	C^{NHC}- Ru- S(*trans*)... **140.2** °	C^{NHC}- Ru- S(*trans*)... **113.6** °
C^1- Ru- S(*cis*)..... **141.8** °	C^1- Ru- S(*cis*)..... **178.0** °	C^1- Ru- S(*cis*)..... **175.2** °
C^3- Ru- C^{NHC} ..... 90.7 °	C^3- Ru- C^{NHC} ..... 106.5 °	C^3- Ru- C^{NHC} ..... 114.8 °

Fig. S13-2. Geometrical changes during metallacyclobutane distortion for the actual system starting from **mcb$_a$** (top) and **mcb$_c$** (bottom); structures have been obtained with ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$; only computed structures for complexes bearing saturated NHC ligands are displayed; bond lengths (Å) and angles (º) for corresponding analogues with unsaturated NHC are given in grey boxes. **mcb**, metallacyclobutane; **ts(dist)**, transition states for mcb distortion; **mcb(dist)**, metallacyclobutane after structural distortion.

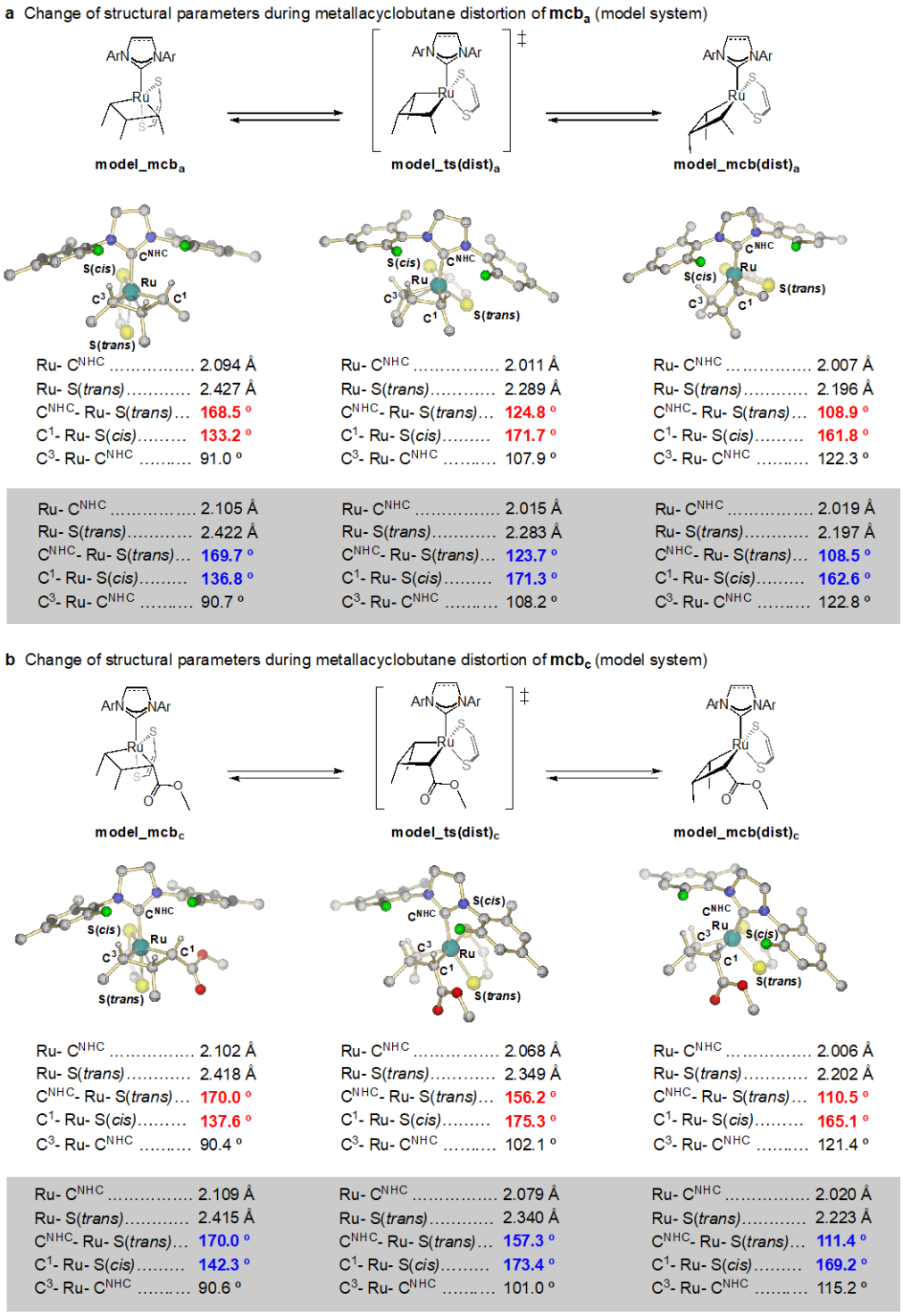


Fig. S13-3. Geometrical changes during metallacyclobutane distortion for the model system starting from **mcb$_a$** (top) and **mcb$_c$** (bottom); structures have been obtained with ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$; only computed structures for complexes bearing saturated NHC ligands are displayed; bond lengths (Å) and angles (º) for corresponding analogues with unsaturated NHC are given in grey boxes. **mcb**, metallacyclobutane; **ts(dist)**, transition states for mcb distortion; **mcb(dist)**, metallacyclobutane after structural distortion.

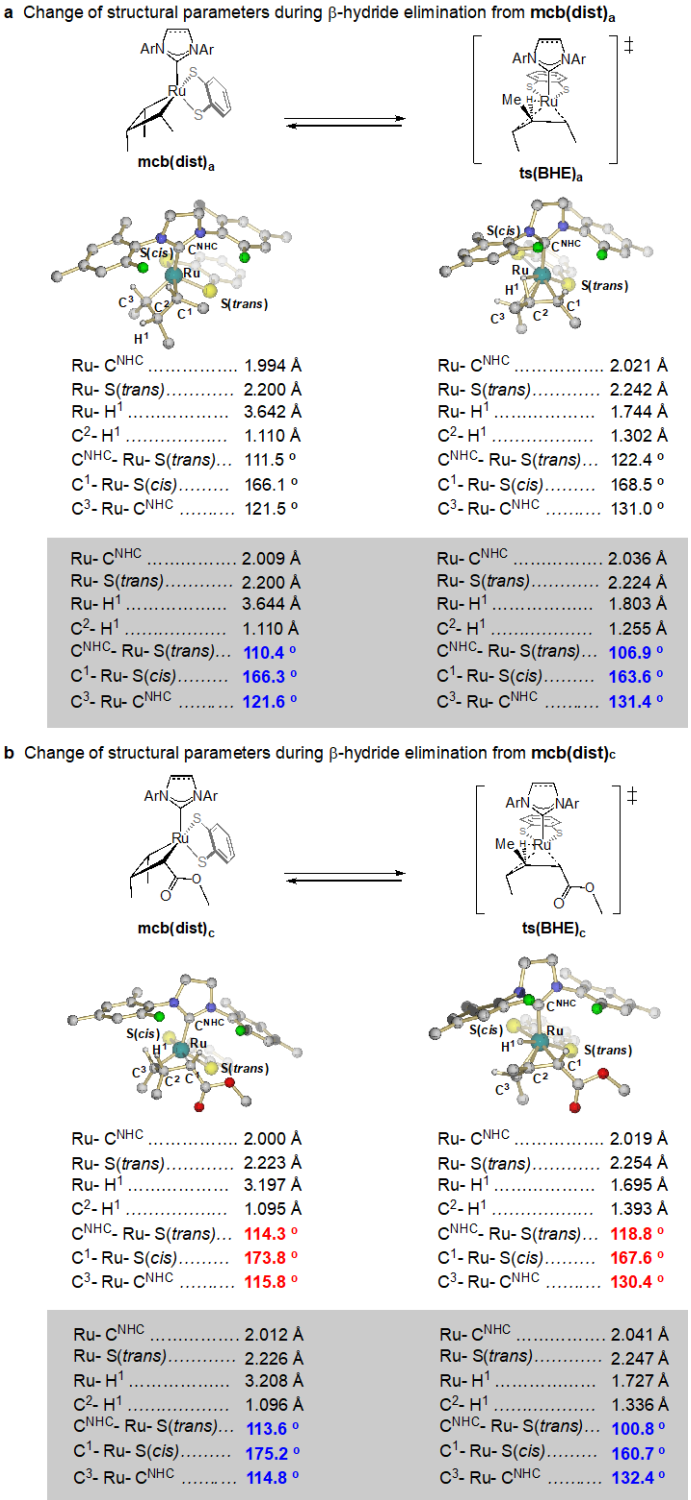


Fig. S13-4. Geometrical changes during β-hydride elimination for real system starting from **mcb(dist)$_a$** (top) and **mcb(dist)$_c$** (bottom); structures have been obtained with ωB97XD/Def2SVP$_{CH2Cl2\ (IEFPCM)}$; only computed structures for complexes bearing saturated NHC ligands are displayed; bond lengths (Å) and angles (º) for analogues with unsaturated NHC are

given in grey boxes. **mcb(dist)**, metallacyclobutane after structural distortion; **ts(BHE)**, transition state for □-hydride elimination.

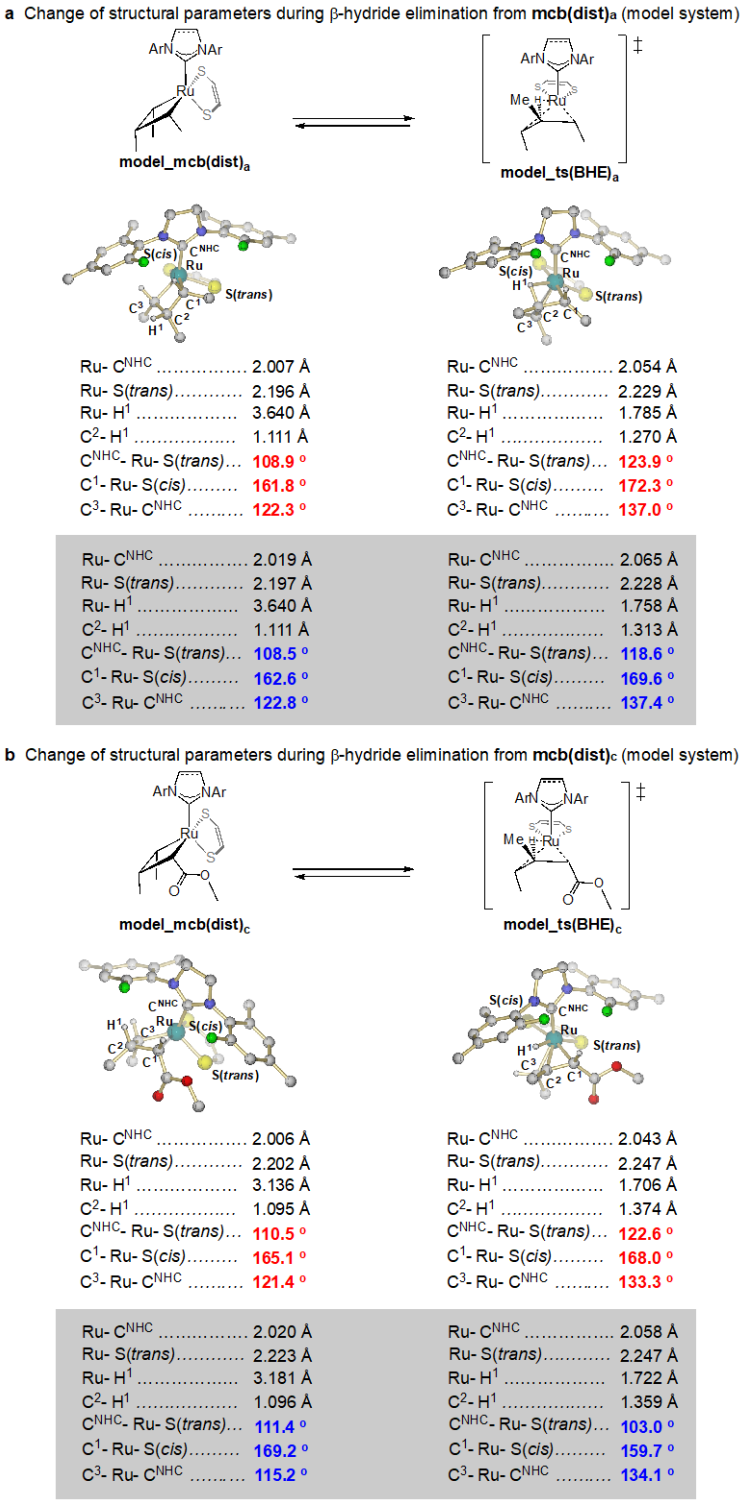


Fig. S13-5. Geometrical changes during β-hydride elimination for model system starting from **mcb(dist)$_a$** (top) and **mcb(dist)$_c$** (bottom); structures have been obtained with

ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$; only computed structures for complexes bearing saturated NHC ligands are displayed; bond lengths (Å) and angles (º) for corresponding analogues with unsaturated NHC are given in grey boxes. **mcb(dist)**, metallacyclobutane after structural distortion; **ts(BHE)**, transition state for □-hydride elimination.

Comparison of Ru–S(trans) and Ru−CNHC Bond Lengths Based on X-Ray and DFT

To secure further evidence for the stronger *trans* influence exerted by a saturated NHC ligand, we analyzed the Ru−S(*trans*) and Ru−C^{NHC} bond lengths in the X-ray structures obtained for **Ru-10** and **Ru-14** (Fig. S14-2). We find that the Ru−C^{NHC} bond lengths in the unsaturated system (2.055 and 2.062 Å; Fig. S14-2a) are approximately 0.02 Å shorter than those in the complex bearing the saturated NHC (2.083, 2.073 and 2.096 Å; Fig. S14-2b). The Ru−S(*trans*) bond lengths are also shorter (2.265 and 2.274 Å vs. 2.299, 2.283 and 2.283 Å; Fig. S14-2). The shorter Ru−C^{NHC} bond lengths in the X-ray structure of **Ru-14** appear to contradict the findings obtained in Section 5.3. Nonetheless, DFT optimized structures of the catalyst precursors reveal a longer Ru−C^{NHC} bond length for **Ru-14** compared to those for **Ru-10** (2.040 vs. 2.023 Å; Fig. S14-1). The discrepancy between the structures obtained through X-ray and DFT can likely be attributed to interference by crystal packing forces (Fig. S14-2). While there appears to be facile π−π stacking between the aryl unit on the dithiolate ligand and an N-aryl group within the NHC ligand in **Ru-14** (small C^{NHC}–Ru−S(*trans*) angle; Fig. S14-2a), the aryl–aryl association in **Ru-10** is disrupted by either the isopropoxy group (**mode A**), the 2-fluoro,6-methyl phenyl moiety (**mode B**), or the aromatic ring of the benzylidene (**mode C**) of a neighboring molecule in the crystal (Fig. S14-2b).

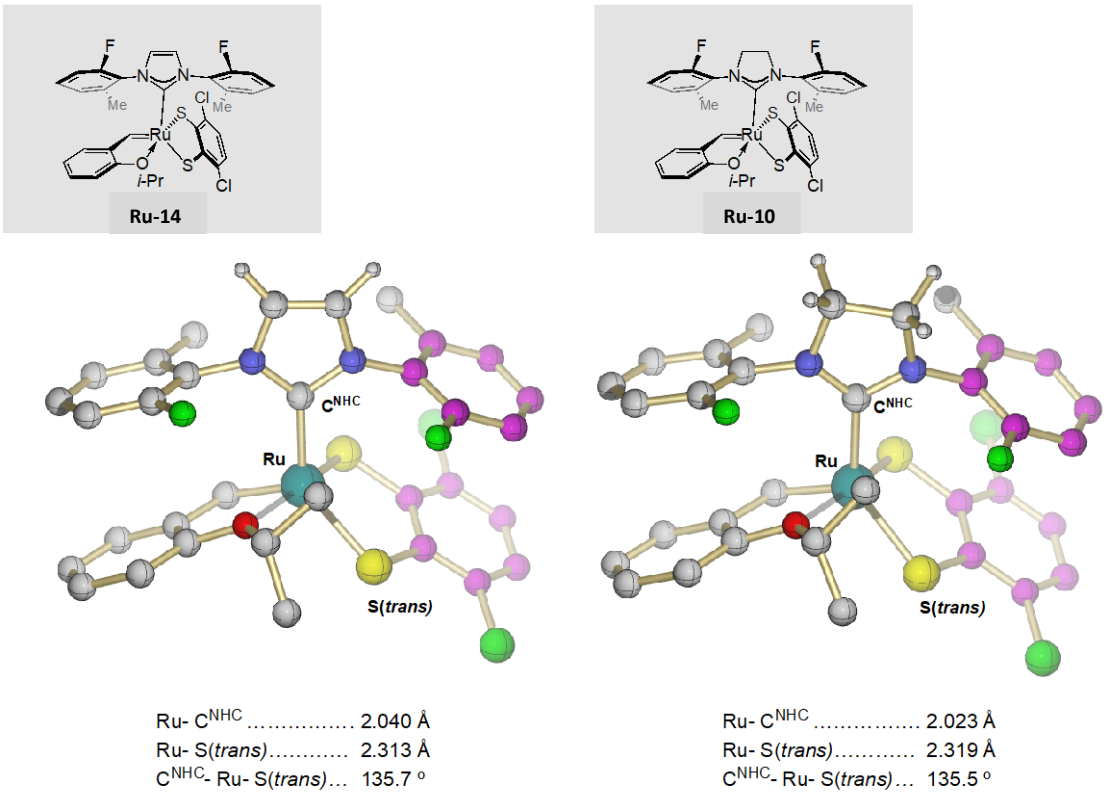


Fig. S14-1. Computed structures (ωB97XD/Def2SVP$_{CH2Cl2(IEFPCM)}$) of catalyst precursors **Ru-14** (left) and **Ru-10** (right).

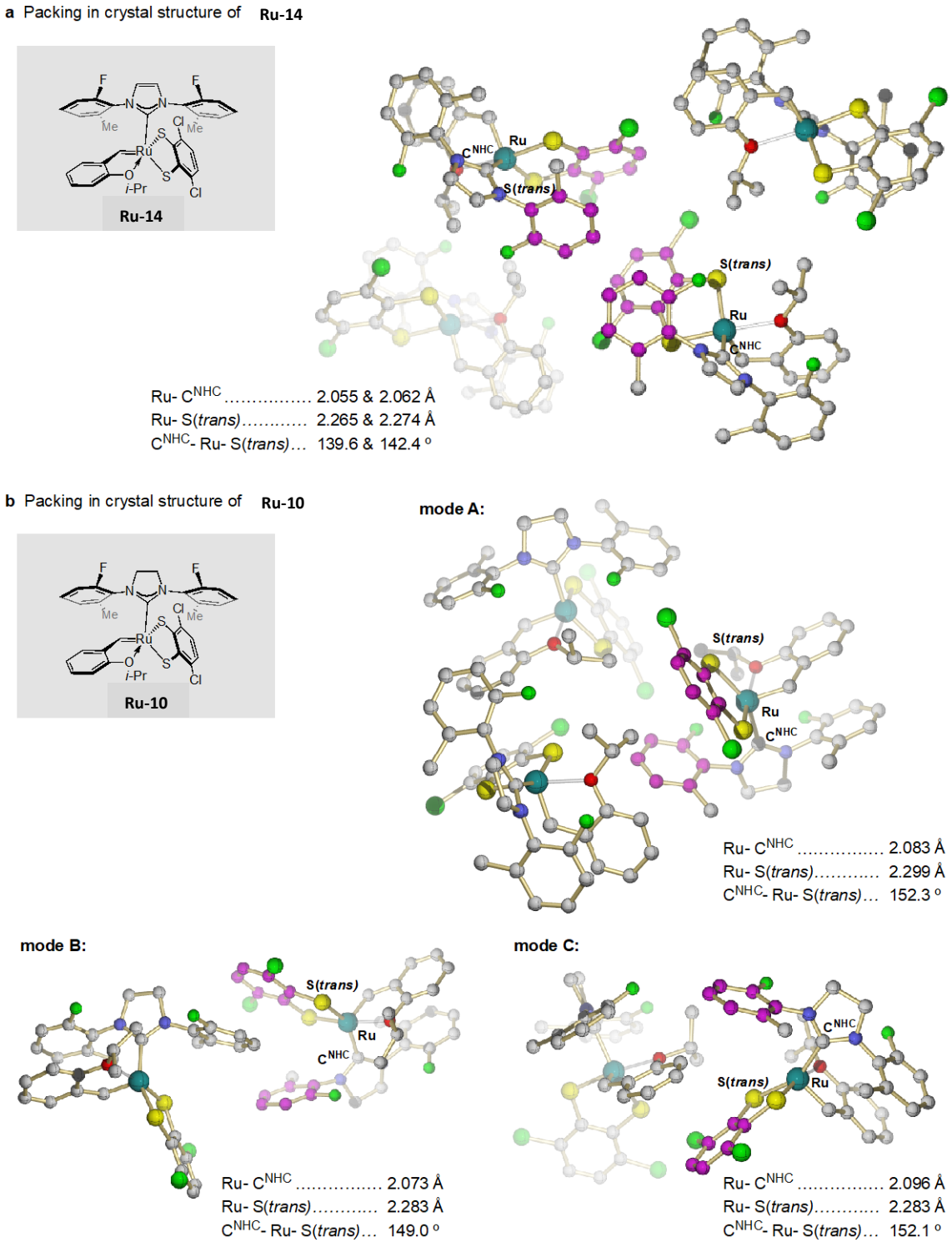
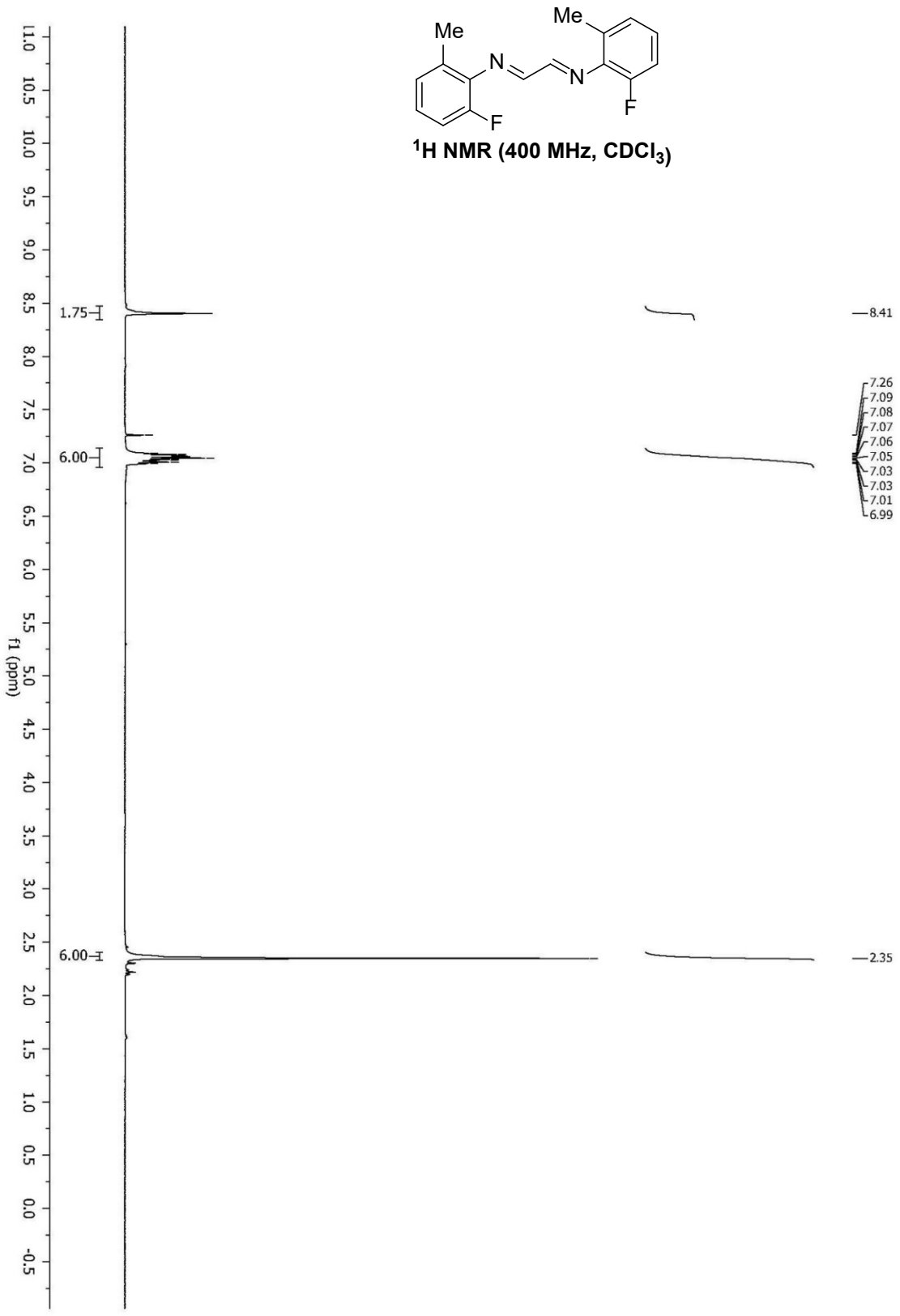
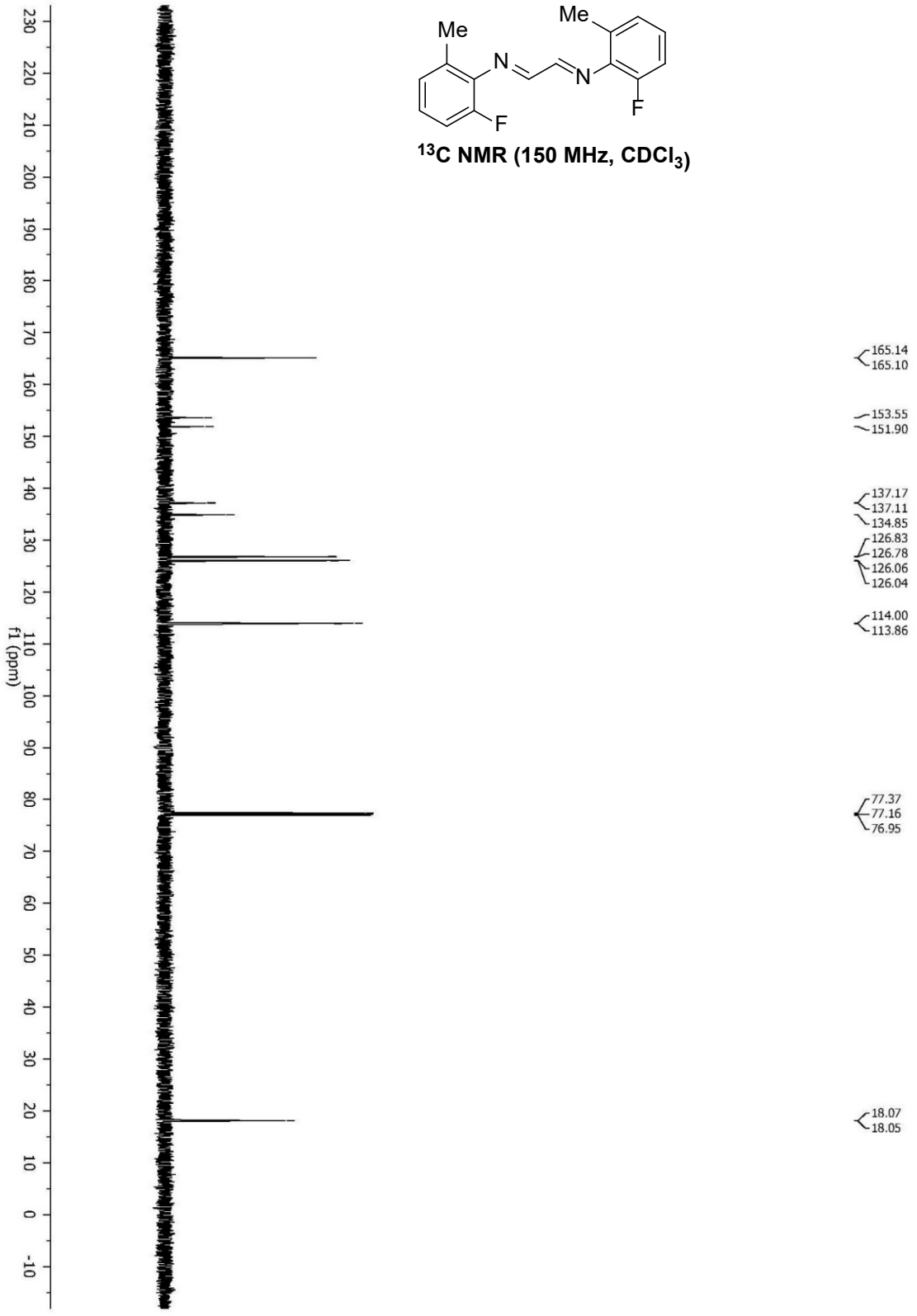
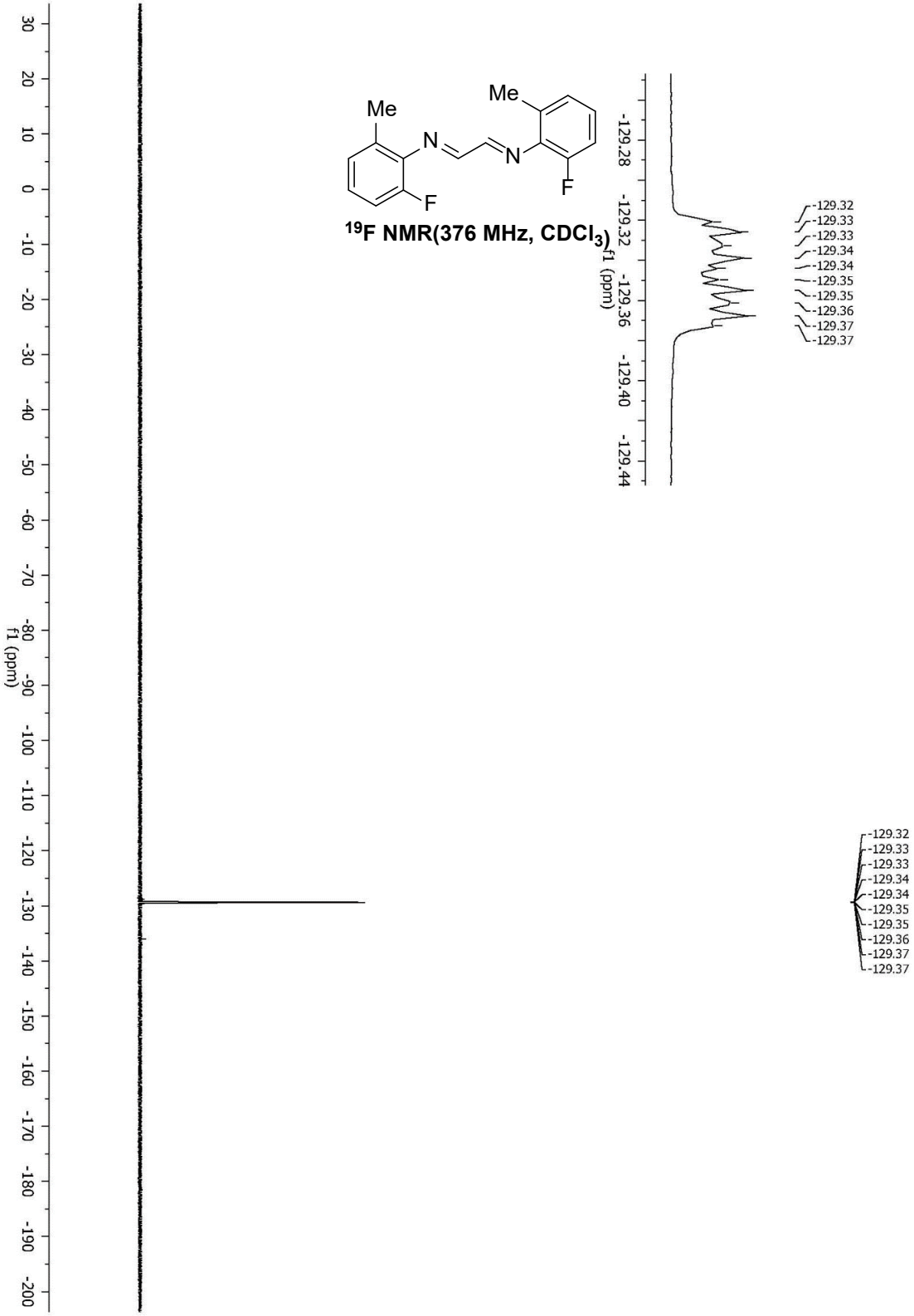


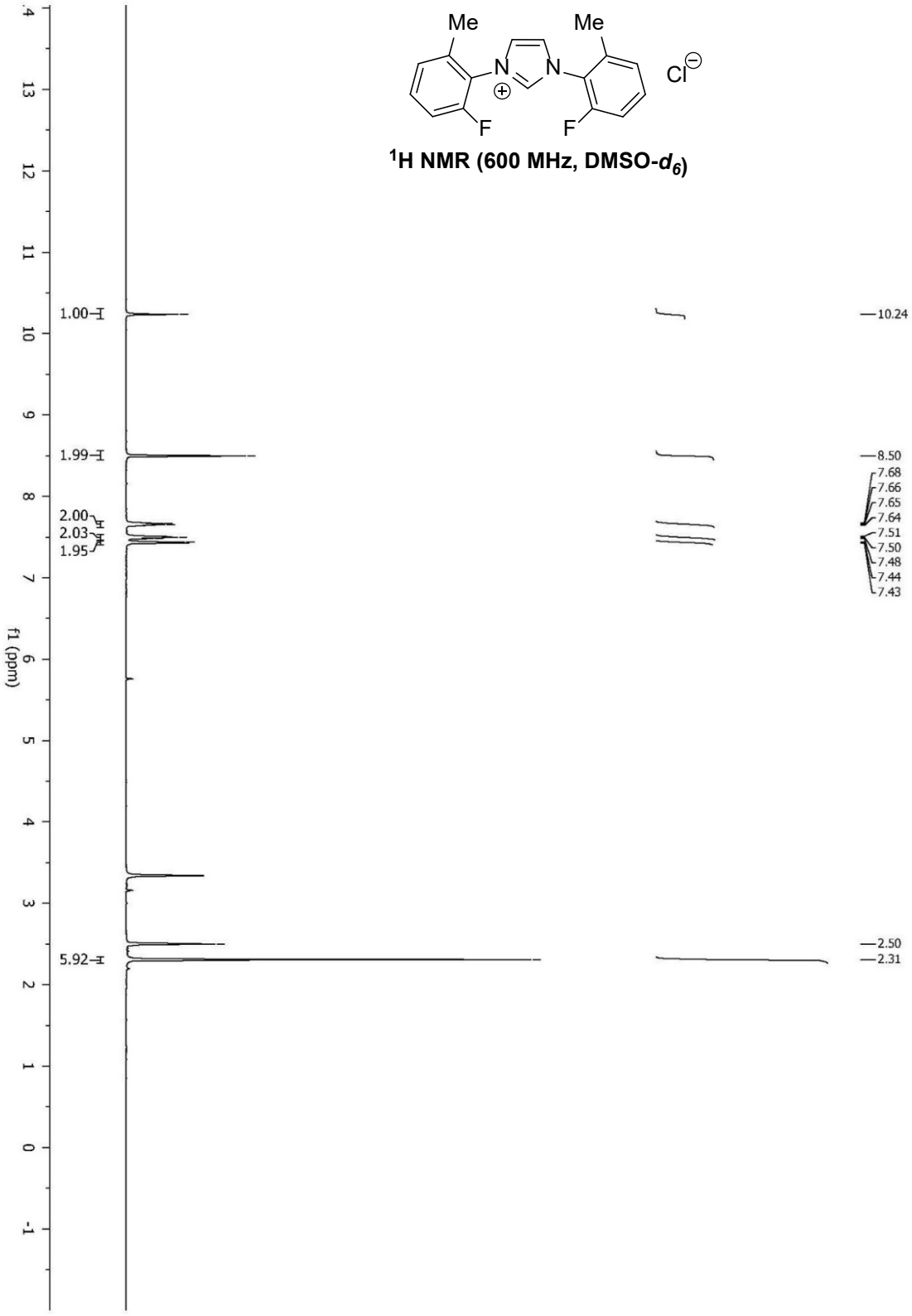
Fig. S14-2. Crystal packing in complexes **Ru-14** (**a**) and **Ru-10** (**b**).NMR Spectra

3.6.6 NMR Spectra

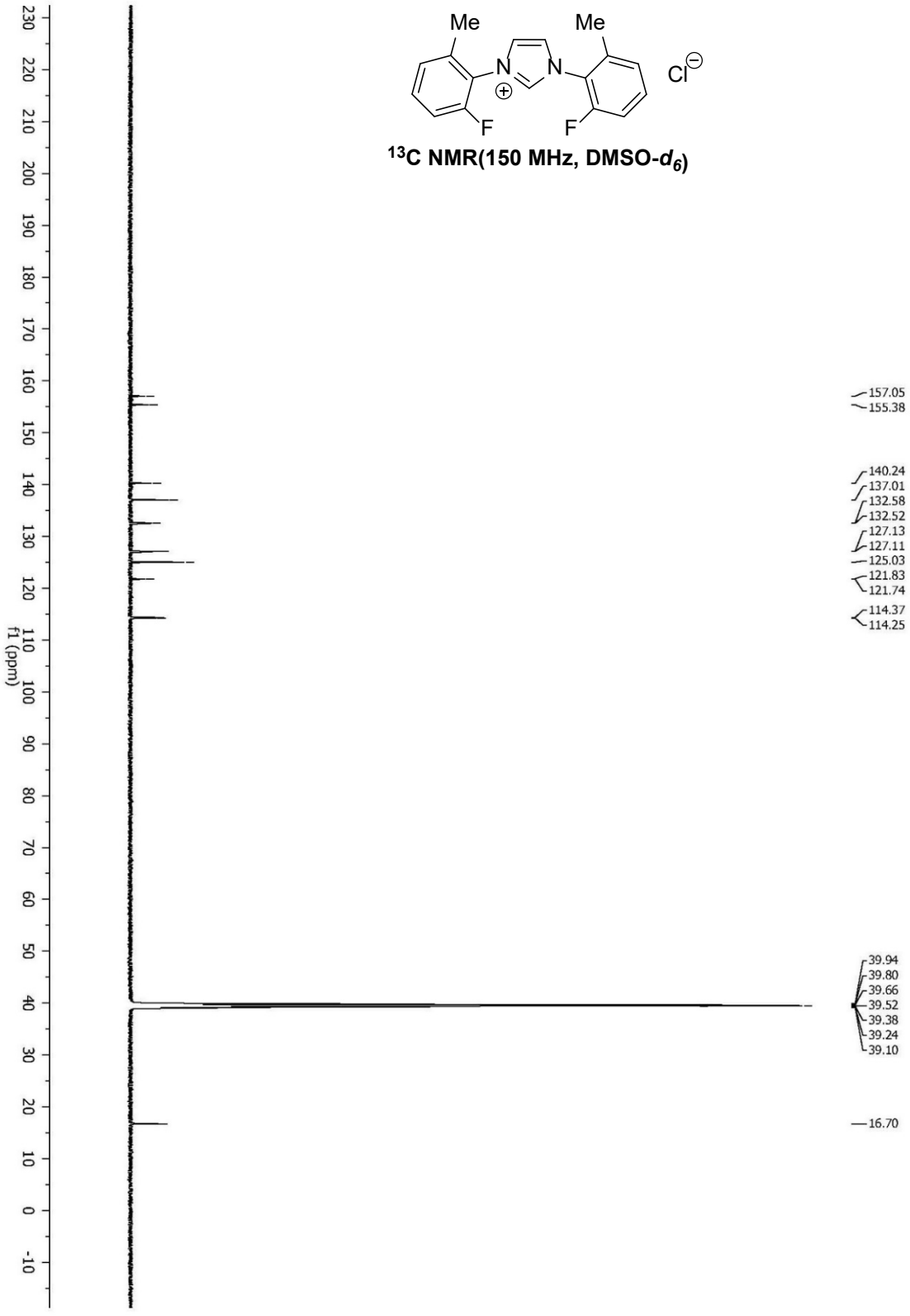

Me
Me
N
N
F
F
^{1}H NMR (400 MHz, CDCl$_3$)
1.75
6.00
6.00
8.41
2.35
7.26
7.09
7.08
7.07
7.06
7.05
7.03
7.03
7.01
6.99
f1 (ppm)


Me
Me
N
N
F
F
^{13}C NMR (150 MHz, CDCl$_3$)
f1 (ppm)
165.14
165.10
153.55
151.90
137.17
137.11
134.85
126.83
126.78
126.06
126.04
114.00
113.86
77.37
77.16
76.95
18.07
18.05

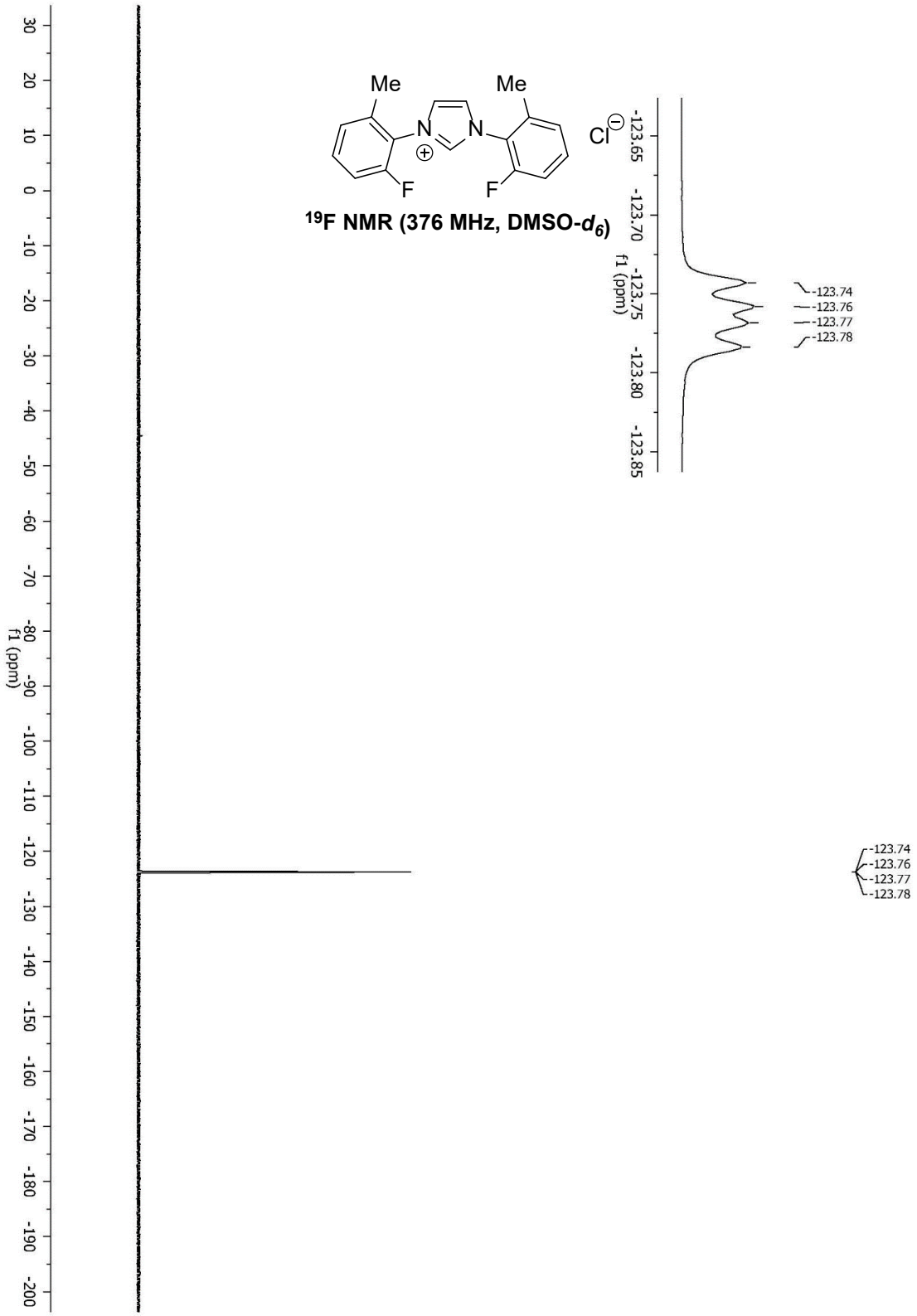

Me
Me
N
N
F
F
^{19}F NMR(376 MHz, CDCl$_3$)
f1 (ppm)
-129.28
-129.32
-129.36
-129.40
-129.44
-129.32
-129.33
-129.33
-129.34
-129.34
-129.35
-129.35
-129.36
-129.37
-129.37
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
f1 (ppm)



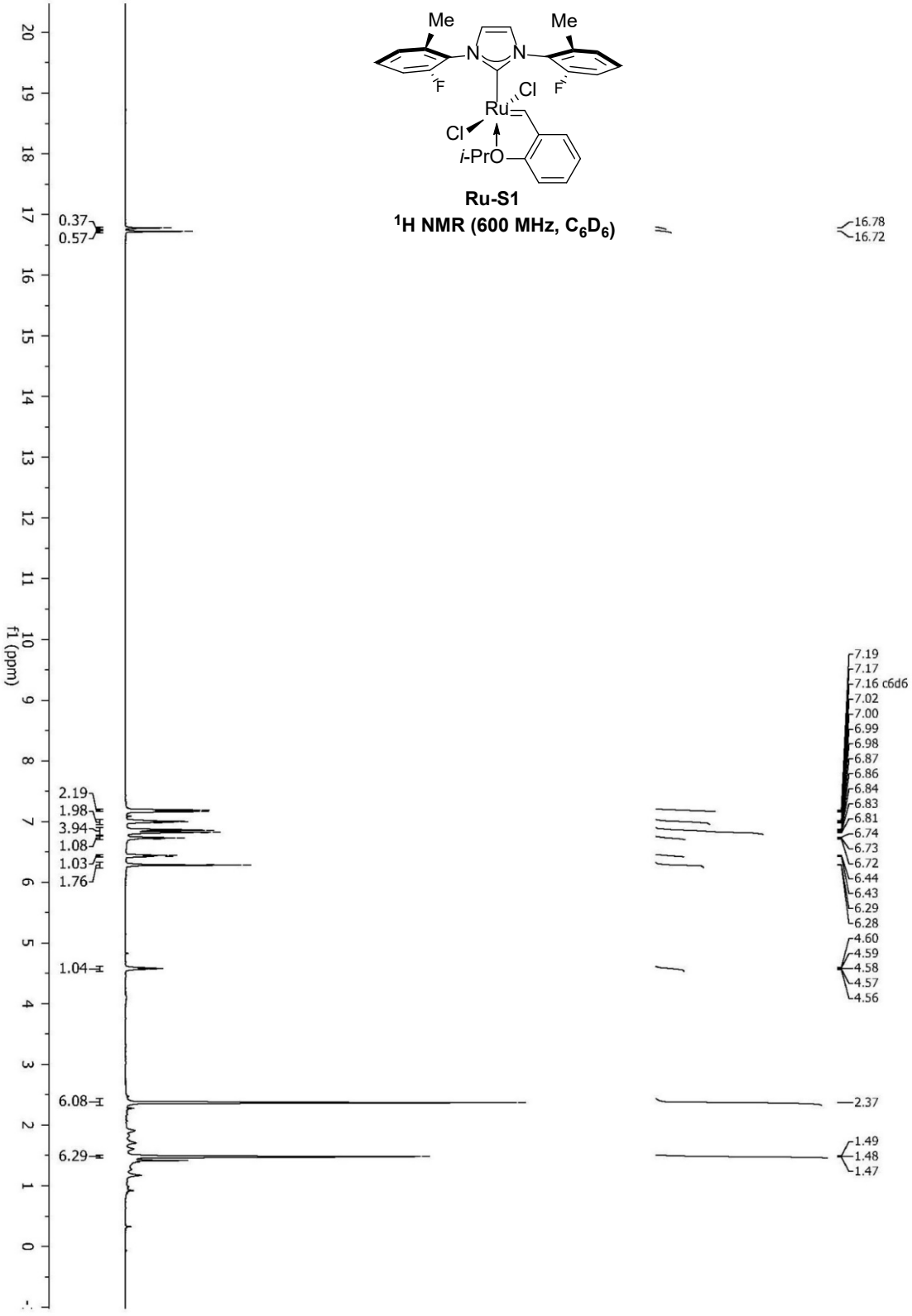
^{1}H NMR (600 MHz, DMSO-d_6)



^{13}C NMR(150 MHz, DMSO-d_6)

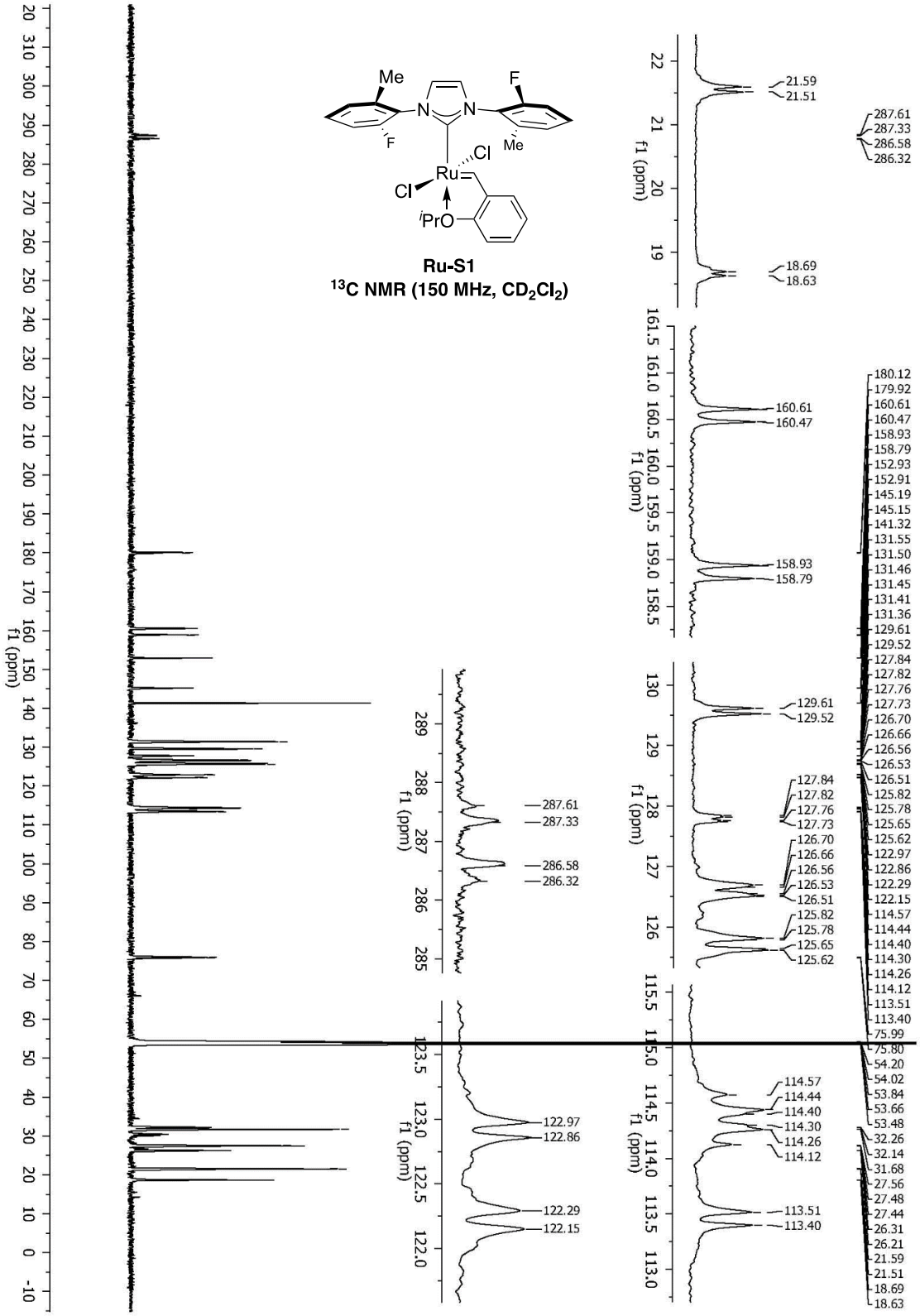


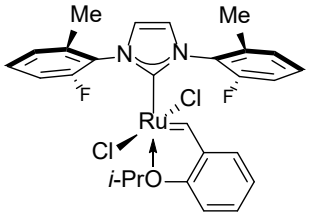
^{19}F NMR (376 MHz, DMSO-d_6)



Ru-S1

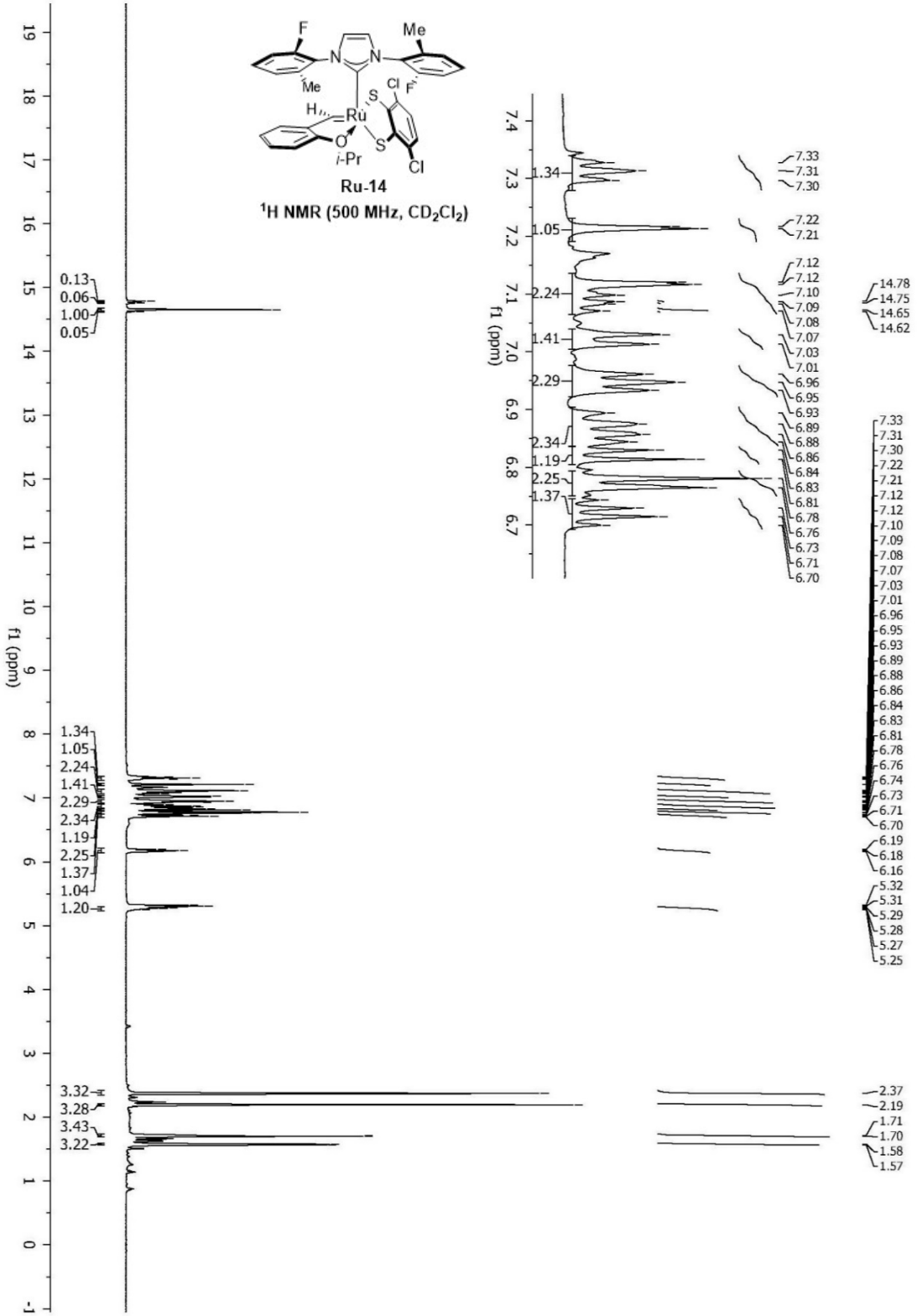
^{1}H NMR (600 MHz, C_6D_6)

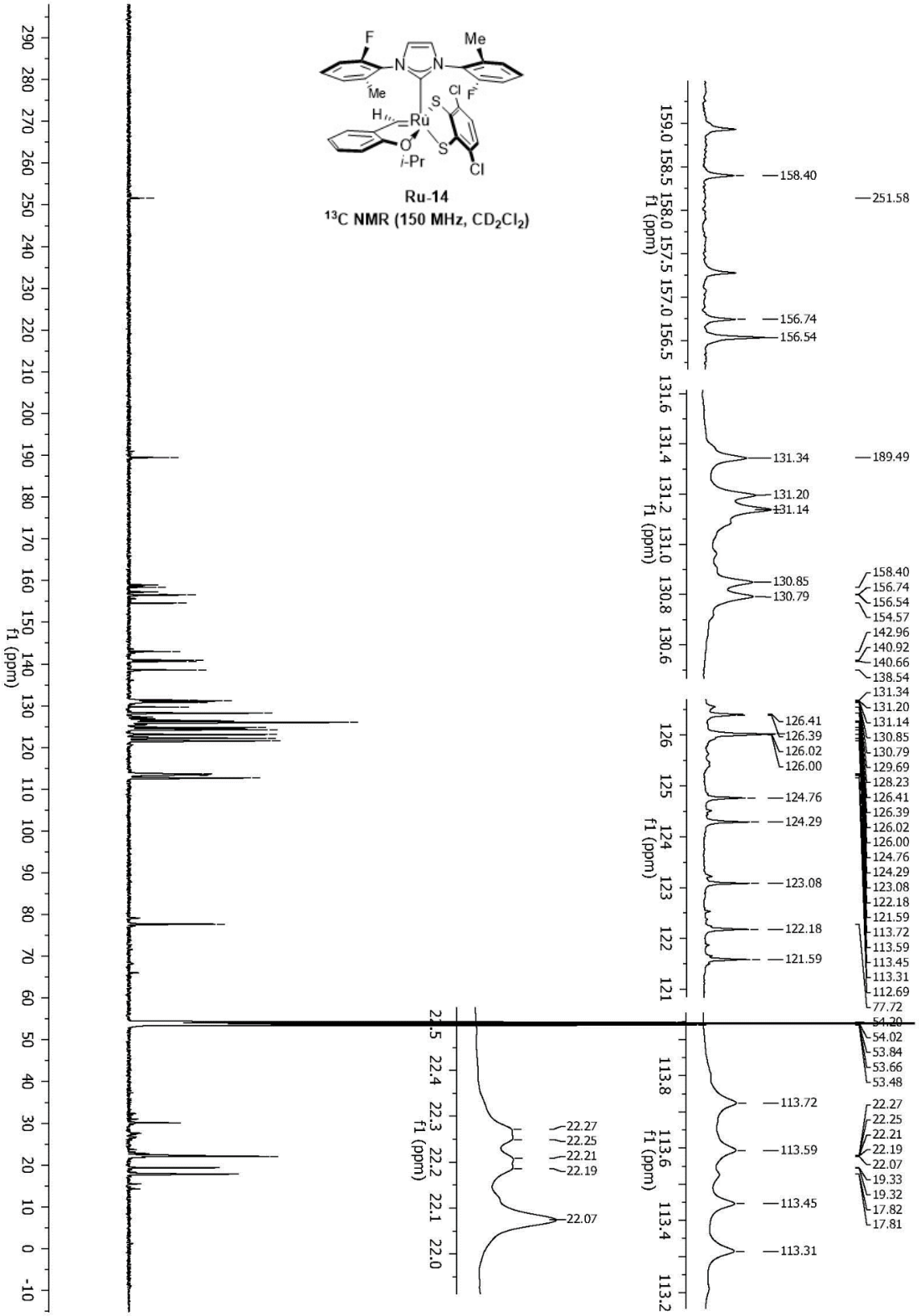

Me
F
N
N
F
Me
Cl
Ru
Cl
iPrO
Ru-S1
13C NMR (150 MHz, CD2Cl2)
f1 (ppm)
21.59
21.51
18.69
18.63
160.61
160.47
158.93
158.79
129.61
129.52
127.84
127.82
127.76
127.73
126.70
126.66
126.56
126.53
126.51
125.82
125.78
125.65
125.62
114.57
114.44
114.40
114.30
114.26
114.12
113.51
113.40
287.61
287.33
286.58
286.32
122.97
122.86
122.29
122.15

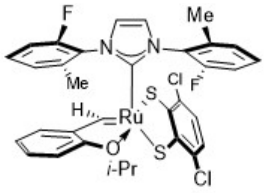


Ru-S1

^{19}F NMR (470 MHz, $CDCl_3$)

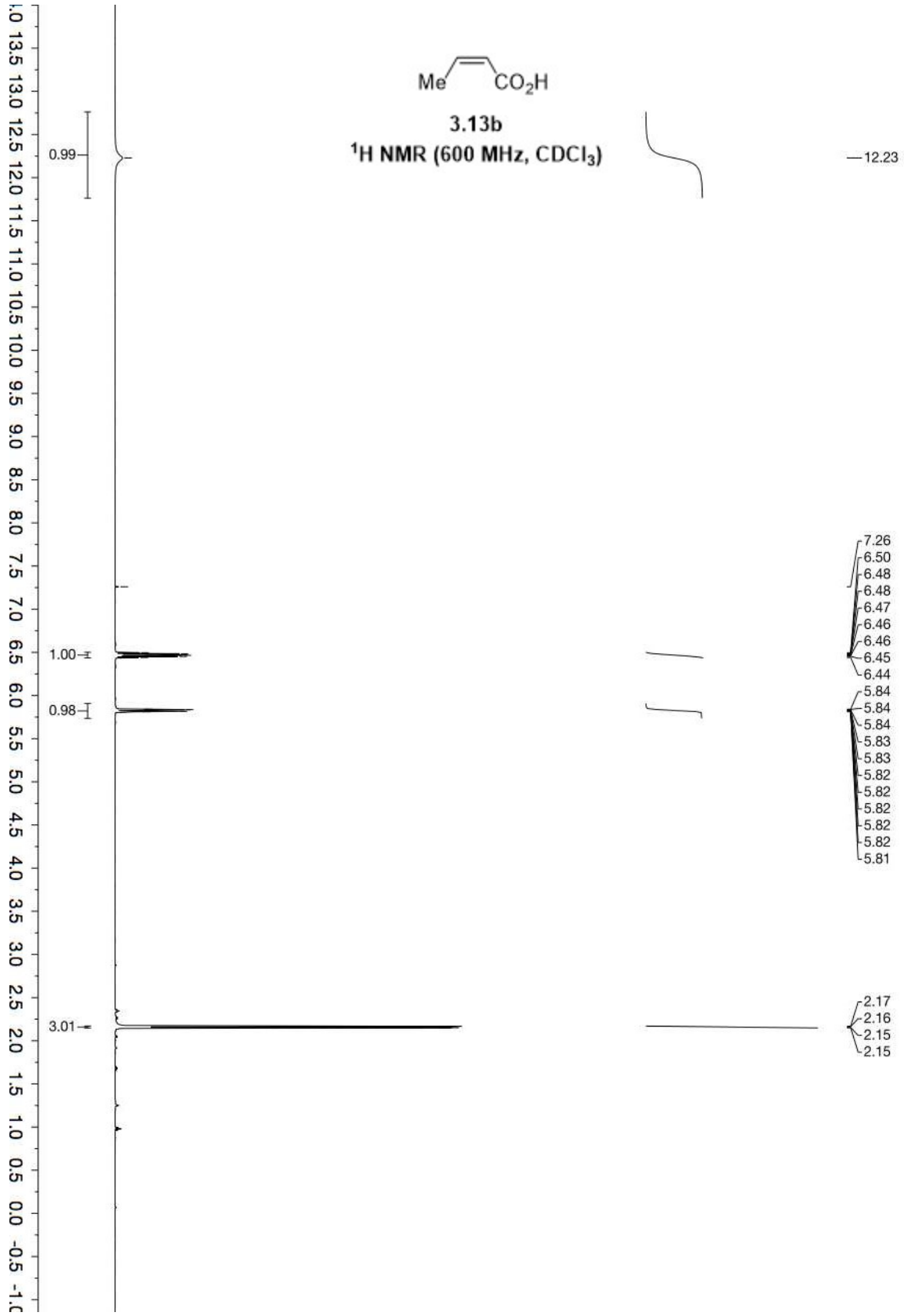

Ru-14
^{1}H NMR (500 MHz, CD_2Cl_2)
f1 (ppm)

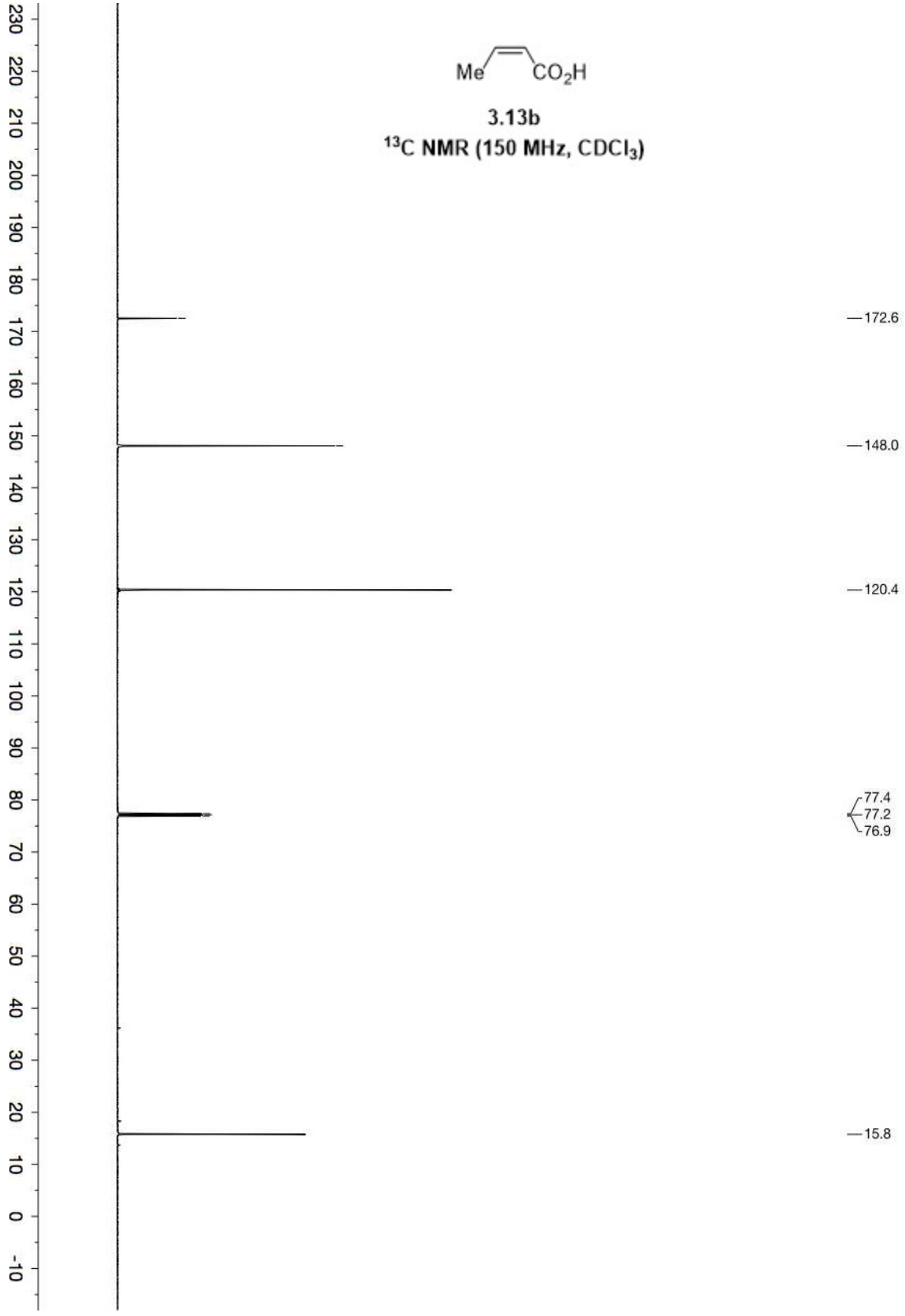

Ru-14
^{13}C NMR (150 MHz, CD_2Cl_2)
f1 (ppm)
158.40
156.74
156.54
251.58
131.34
131.20
131.14
189.49
130.85
130.79
126.41
126.39
126.02
126.00
124.76
124.29
123.08
122.18
121.59
113.72
113.59
113.45
113.31
22.27
22.25
22.21
22.19
22.07

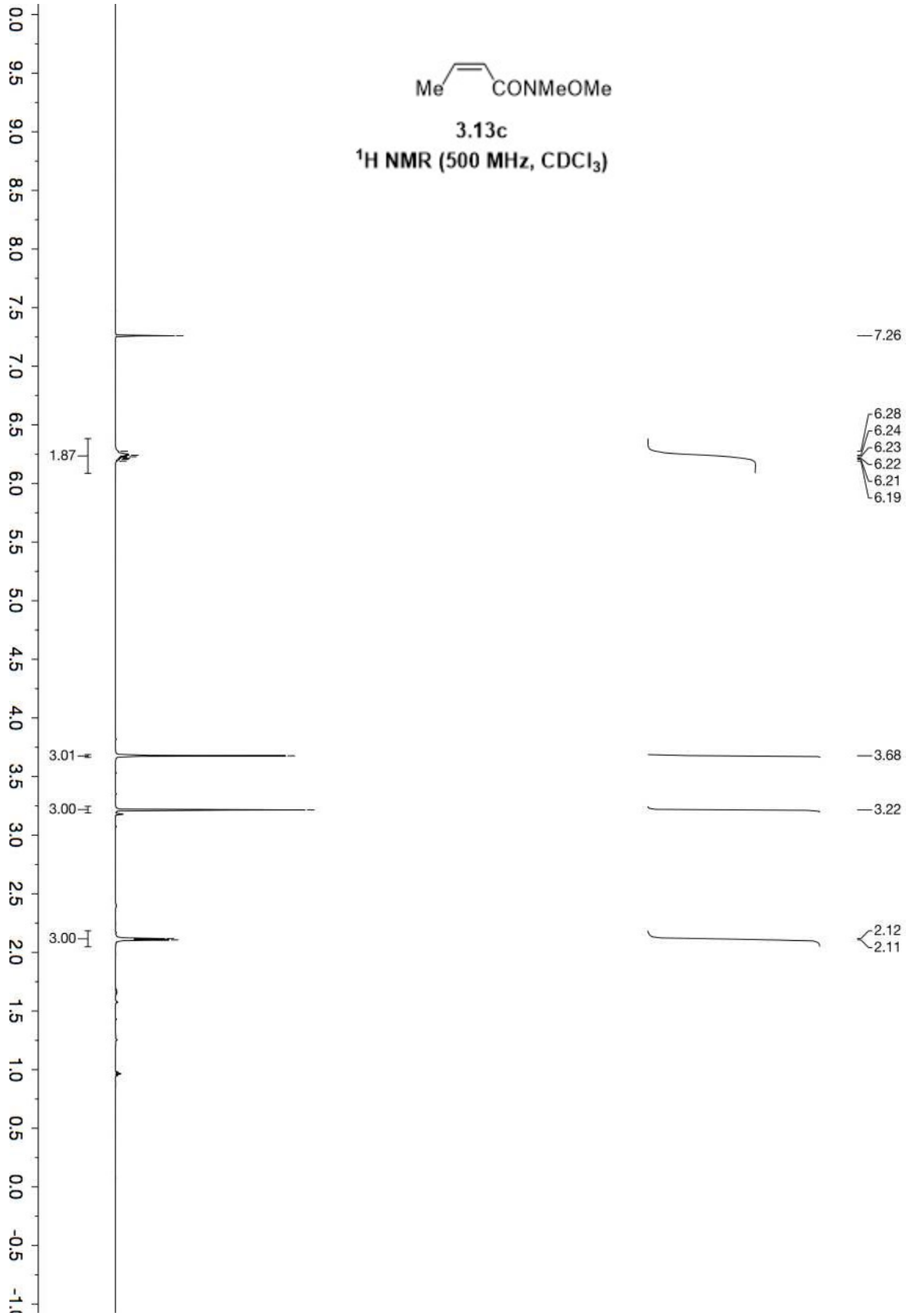


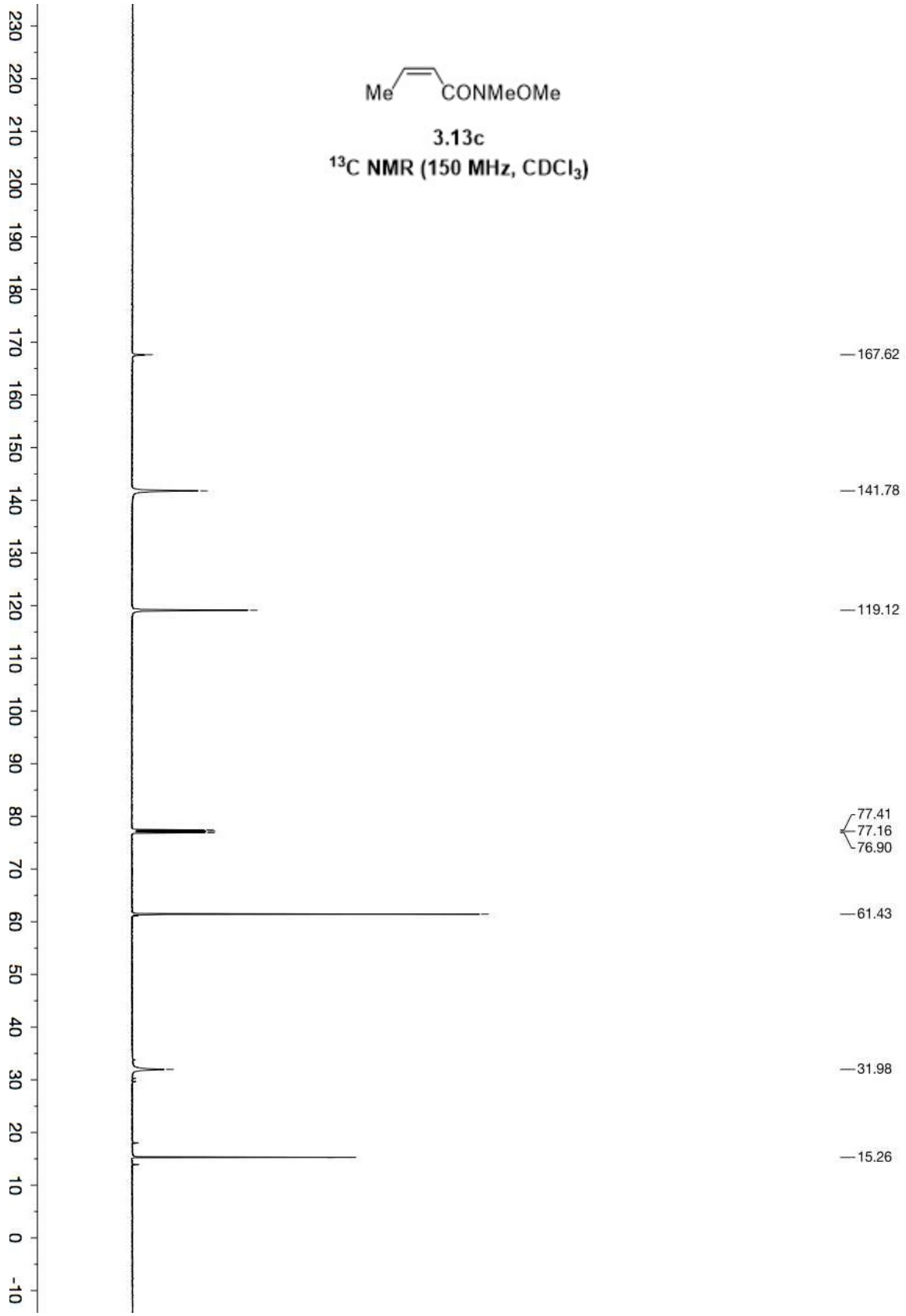
Ru-14

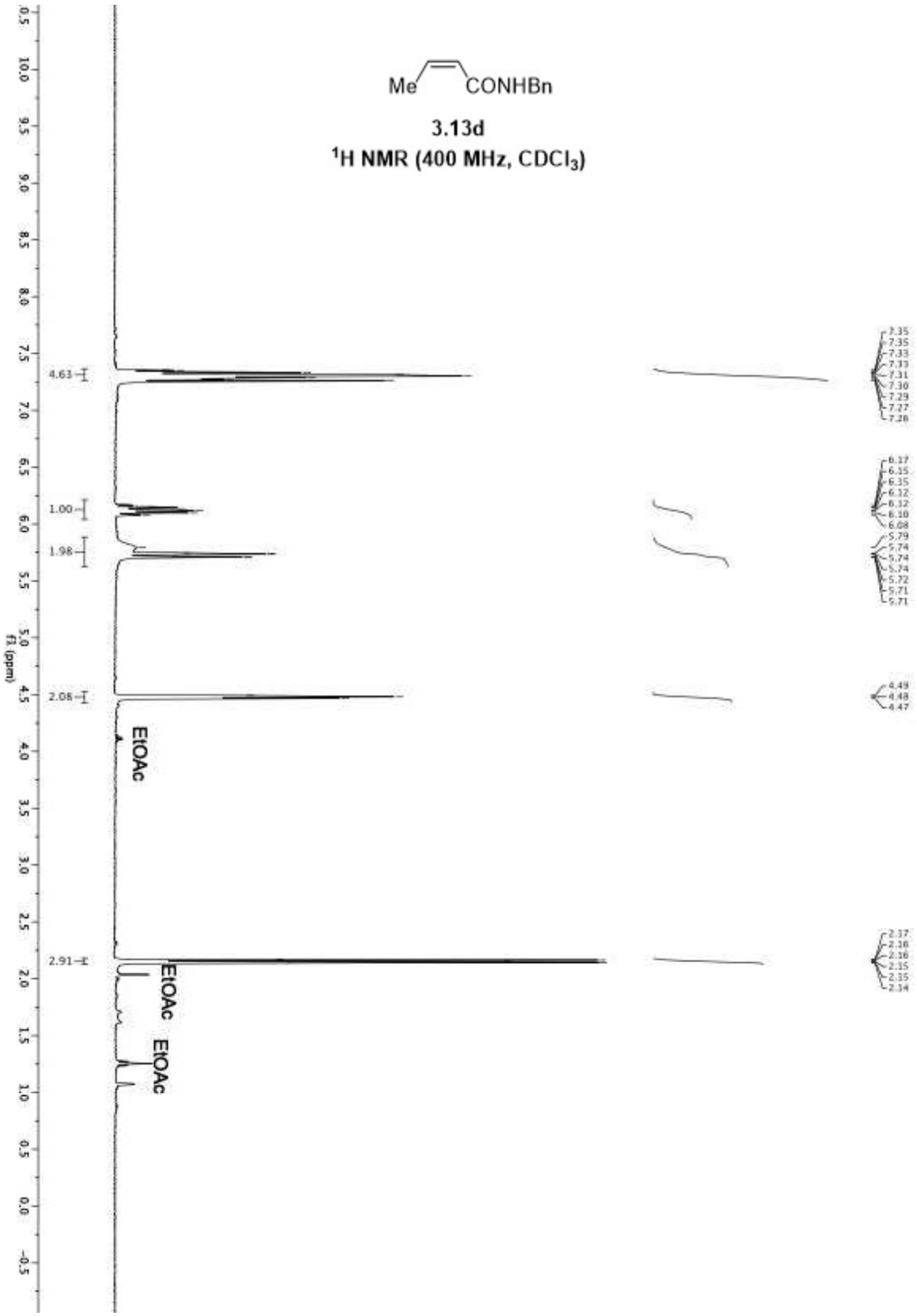
^{19}F NMR (470 MHz, CD_2Cl_2)

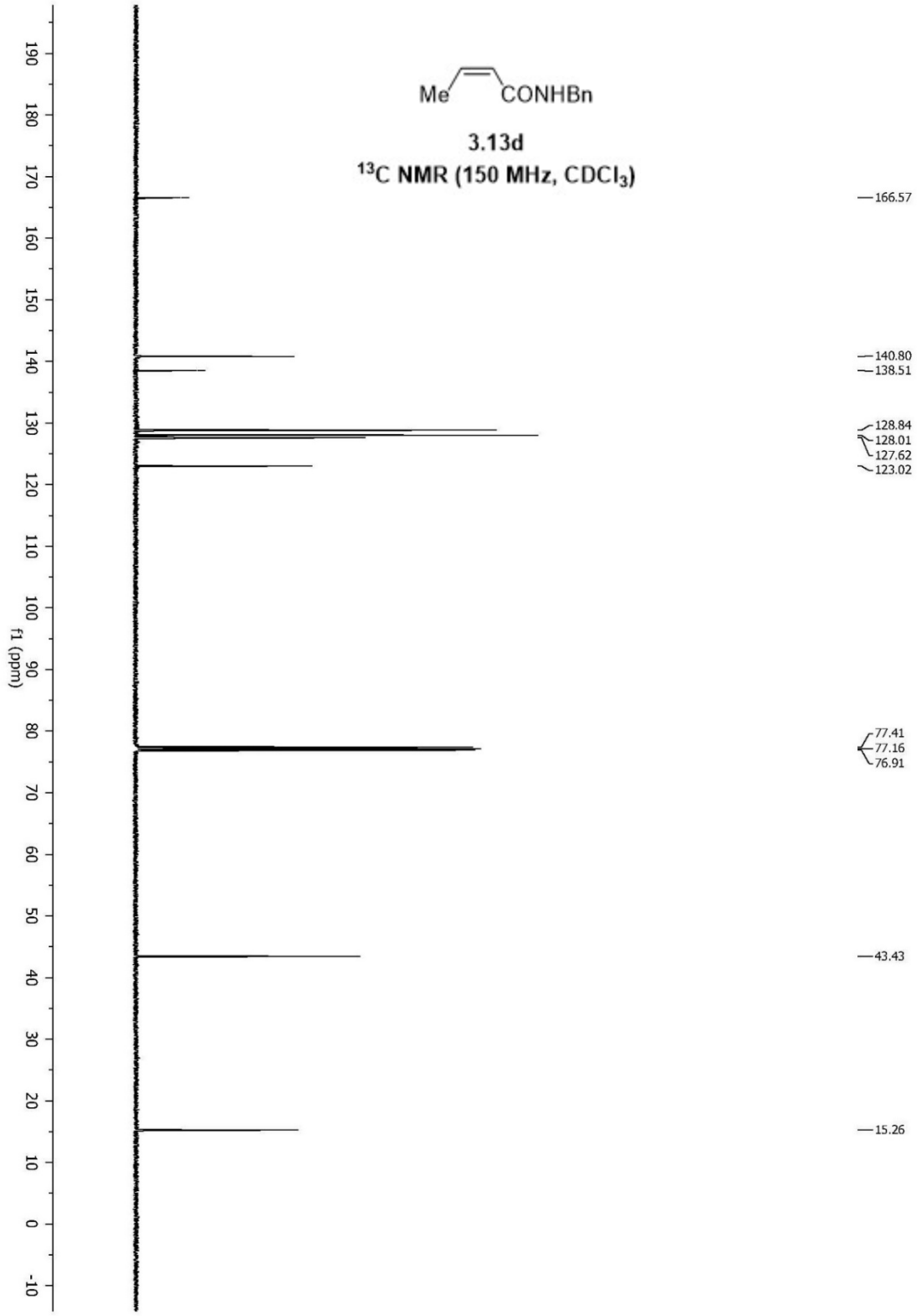

Me
CO2H
3.13b
1H NMR (600 MHz, CDCl3)
0.99
1.00
0.98
3.01
12.23
7.26
6.50
6.48
6.48
6.47
6.46
6.46
6.45
6.44
5.84
5.84
5.84
5.83
5.83
5.82
5.82
5.82
5.82
5.82
5.81
2.17
2.16
2.15
2.15

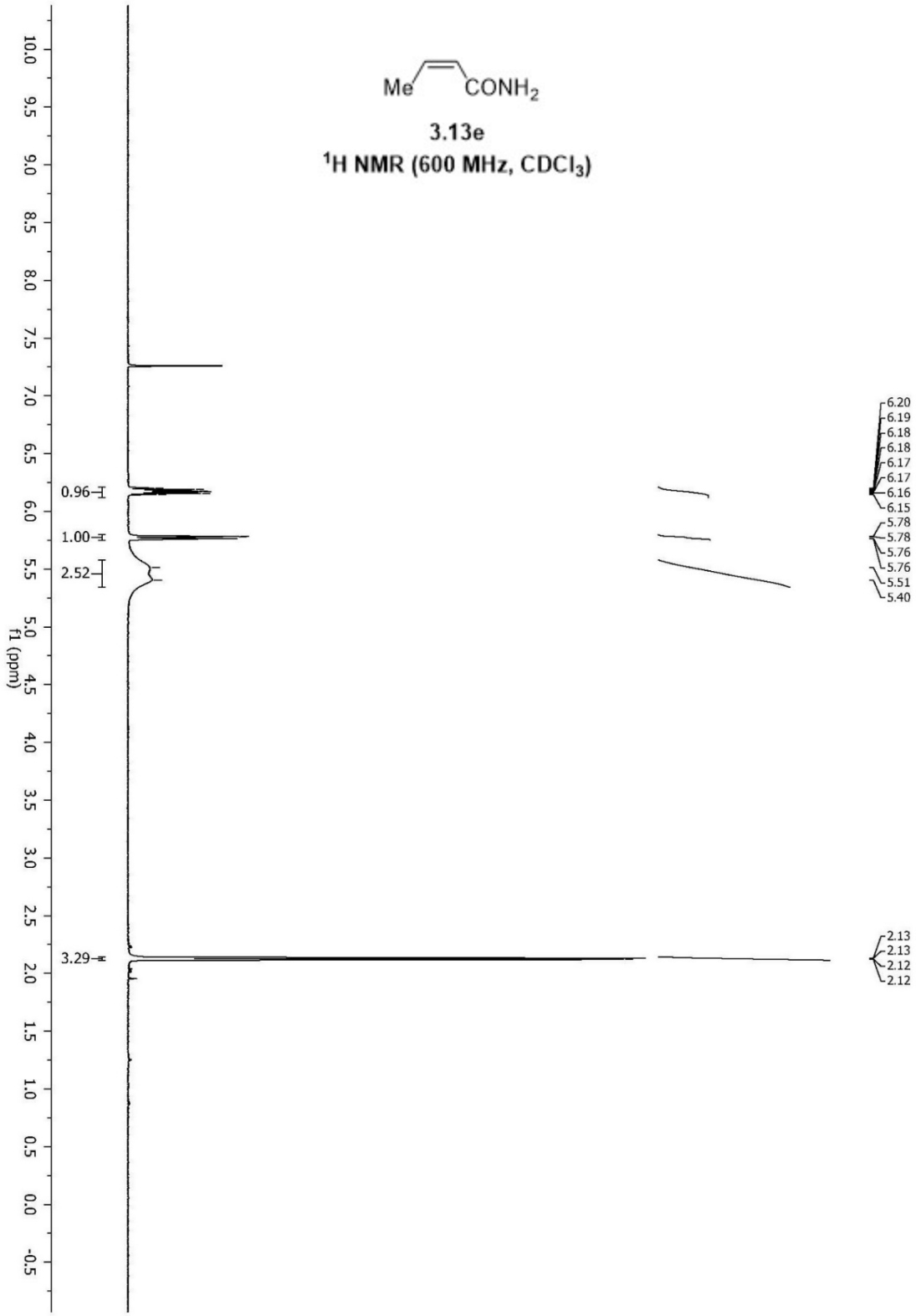

Me
CO2H
3.13b
13C NMR (150 MHz, CDCl3)
172.6
148.0
120.4
77.4
77.2
76.9
15.8
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10

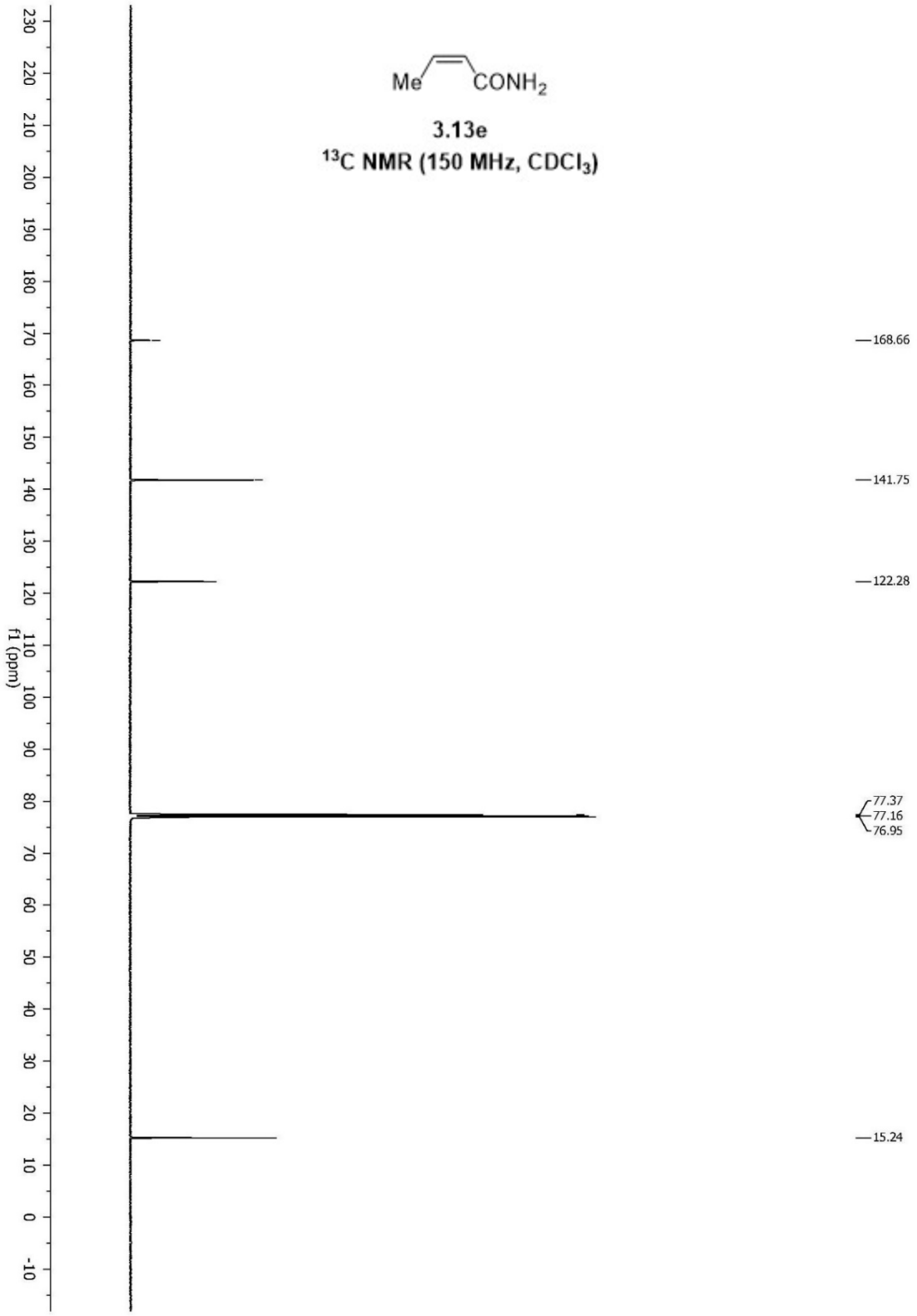

Me
CONMeOMe
3.13c
¹H NMR (500 MHz, CDCl₃)
7.26
6.28
6.24
6.23
6.22
6.21
6.19
1.87
3.01
3.00
3.00
3.68
3.22
2.12
2.11

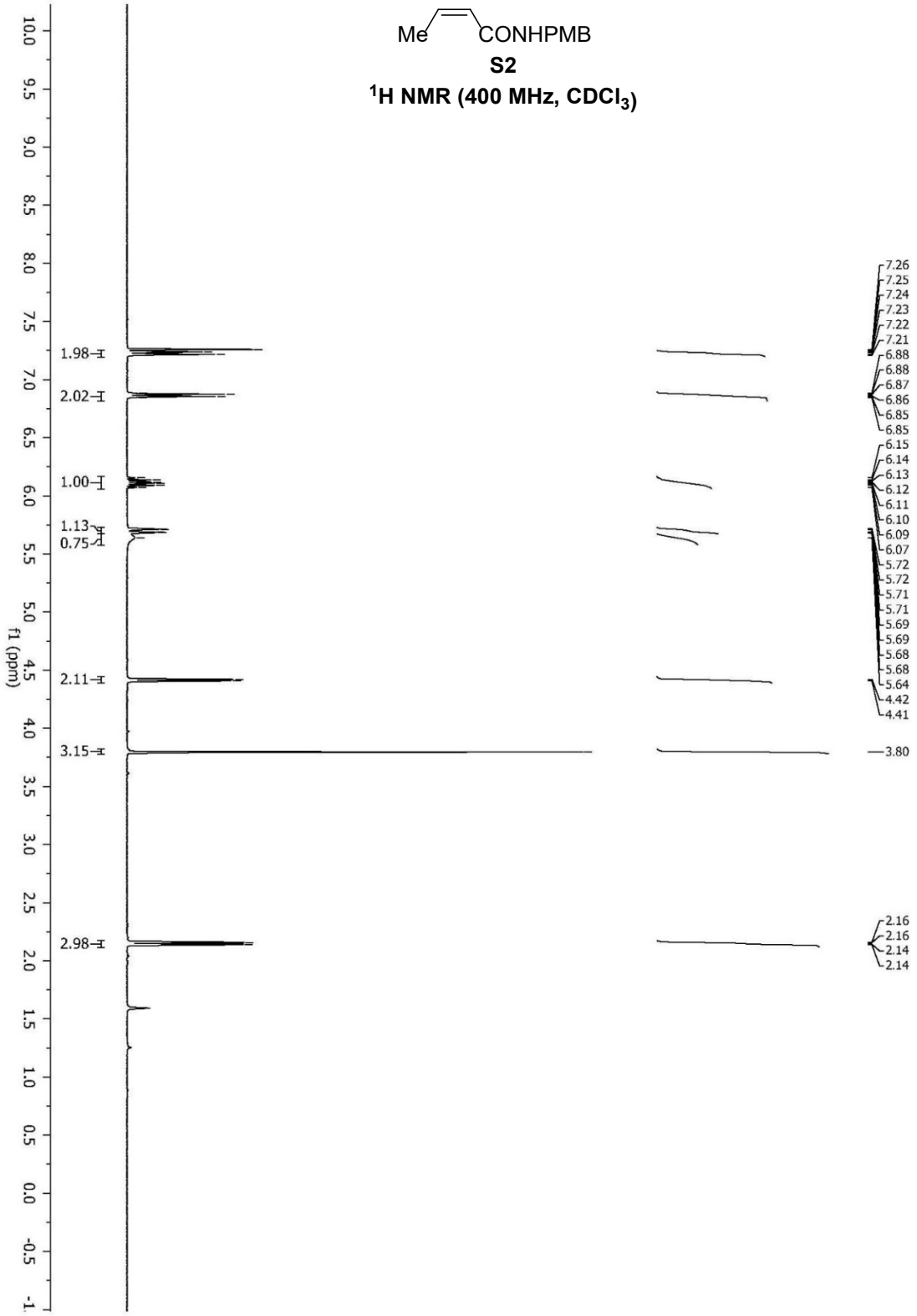

Me
CONMeOMe
3.13c
^{13}C NMR (150 MHz, $CDCl_3$)
167.62
141.78
119.12
77.41
77.16
76.90
61.43
31.98
15.26

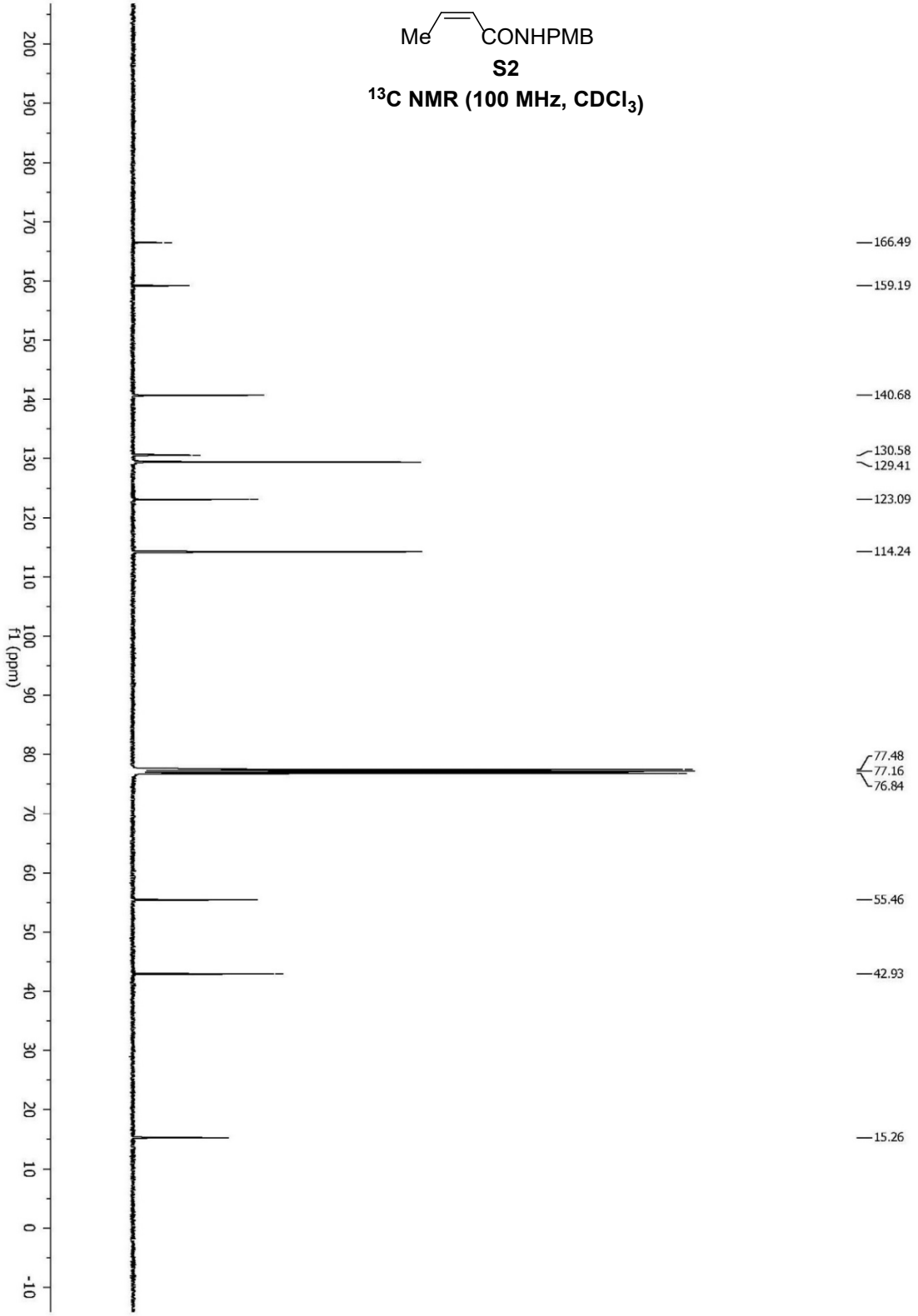

Me
CONHBn
3.13d
¹H NMR (400 MHz, CDCl₃)
4.63
1.00
1.98
2.08
2.91
EtOAc
EtOAc
EtOAc
f1 (ppm)

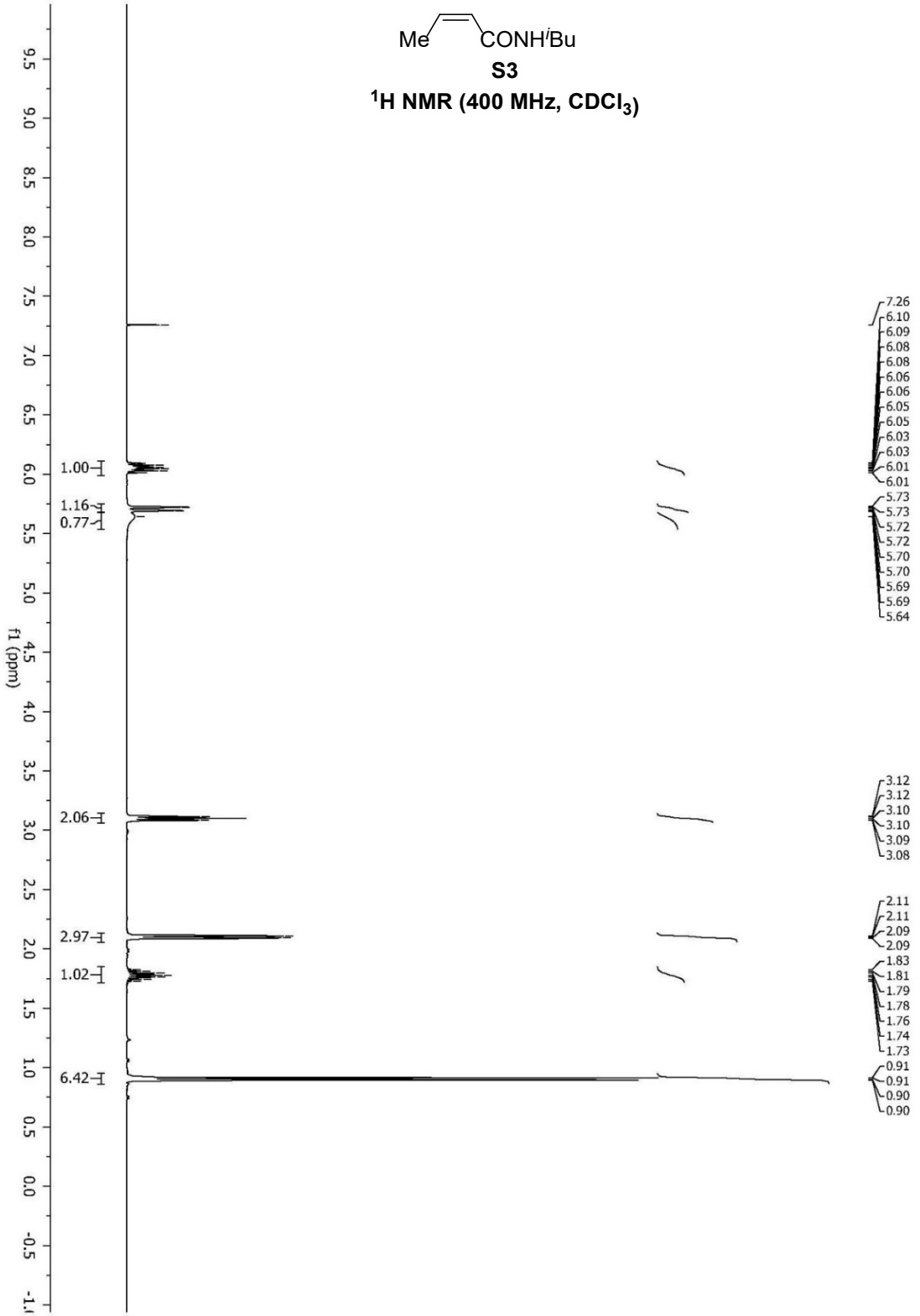

Me
CONHBn
3.13d
^{13}C NMR (150 MHz, $CDCl_3$)
166.57
140.80
138.51
128.84
128.01
127.62
123.02
77.41
77.16
76.91
43.43
15.26
f1 (ppm)

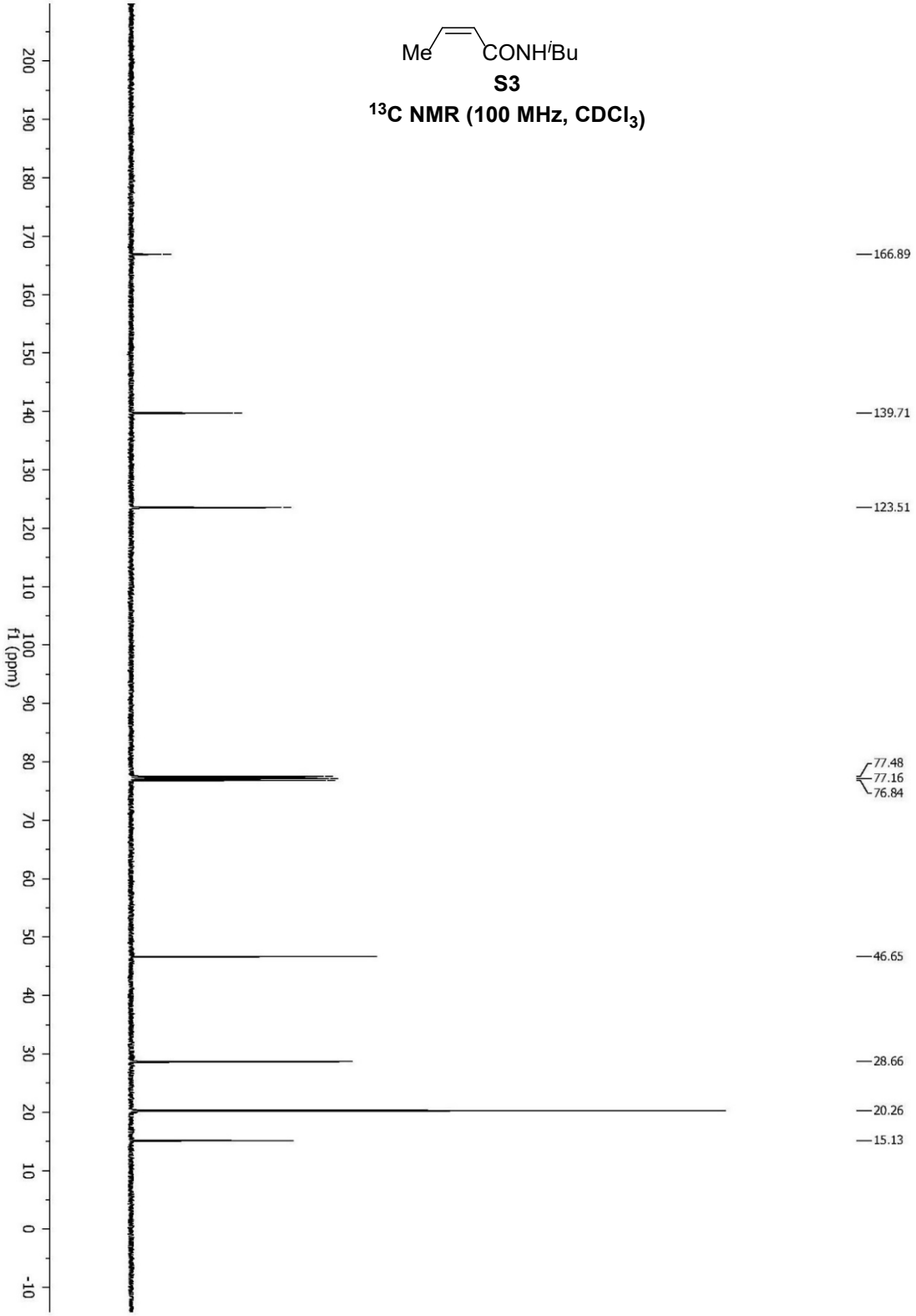

Me
CONH2
3.13e
1H NMR (600 MHz, CDCl3)
f1 (ppm)
0.96
1.00
2.52
3.29
6.20
6.19
6.18
6.18
6.17
6.17
6.16
6.15
5.78
5.78
5.76
5.76
5.51
5.40
2.13
2.13
2.12
2.12

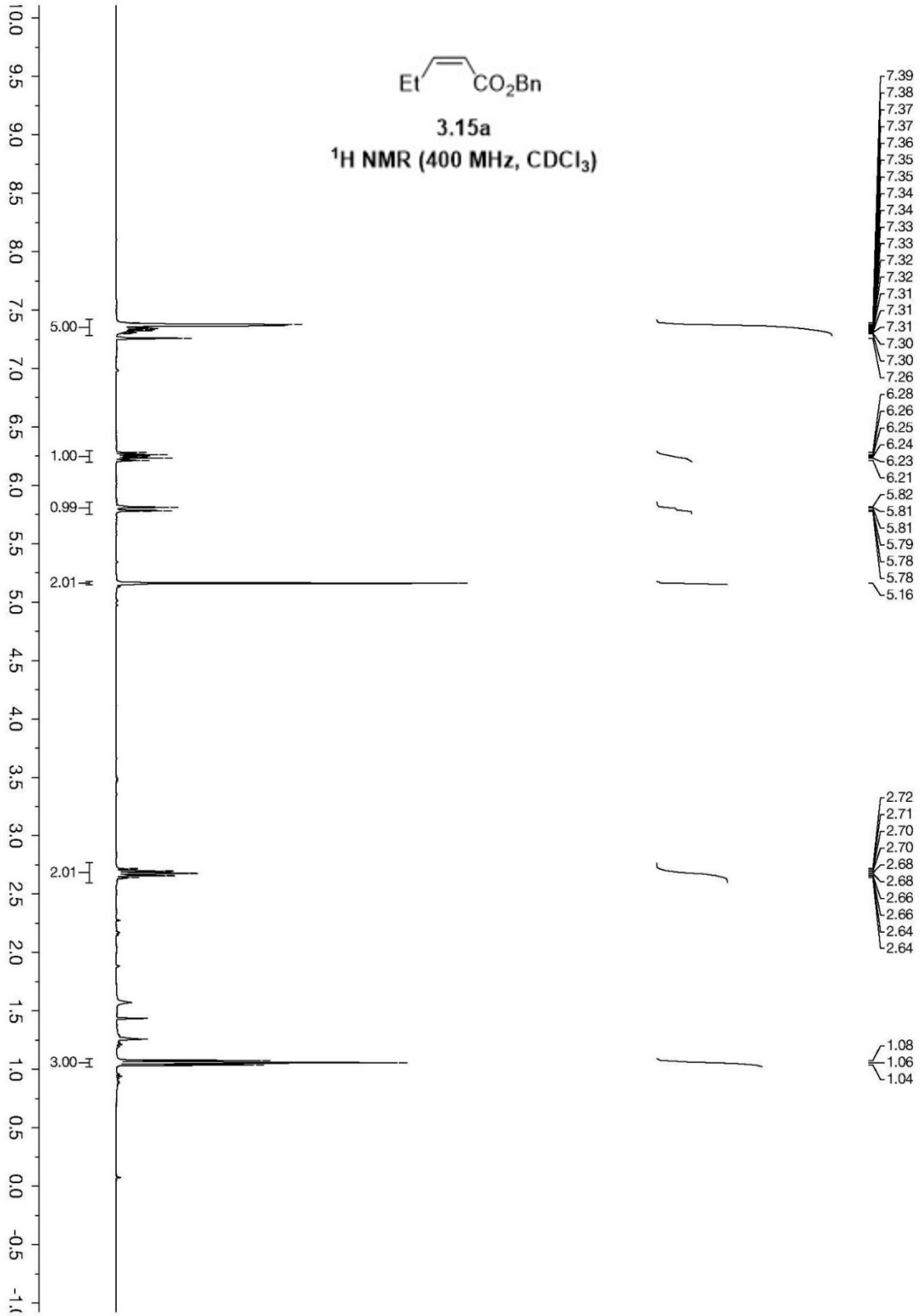

Me
CONH2
3.13e
13C NMR (150 MHz, CDCl3)
168.66
141.75
122.28
77.37
77.16
76.95
15.24
f1 (ppm)

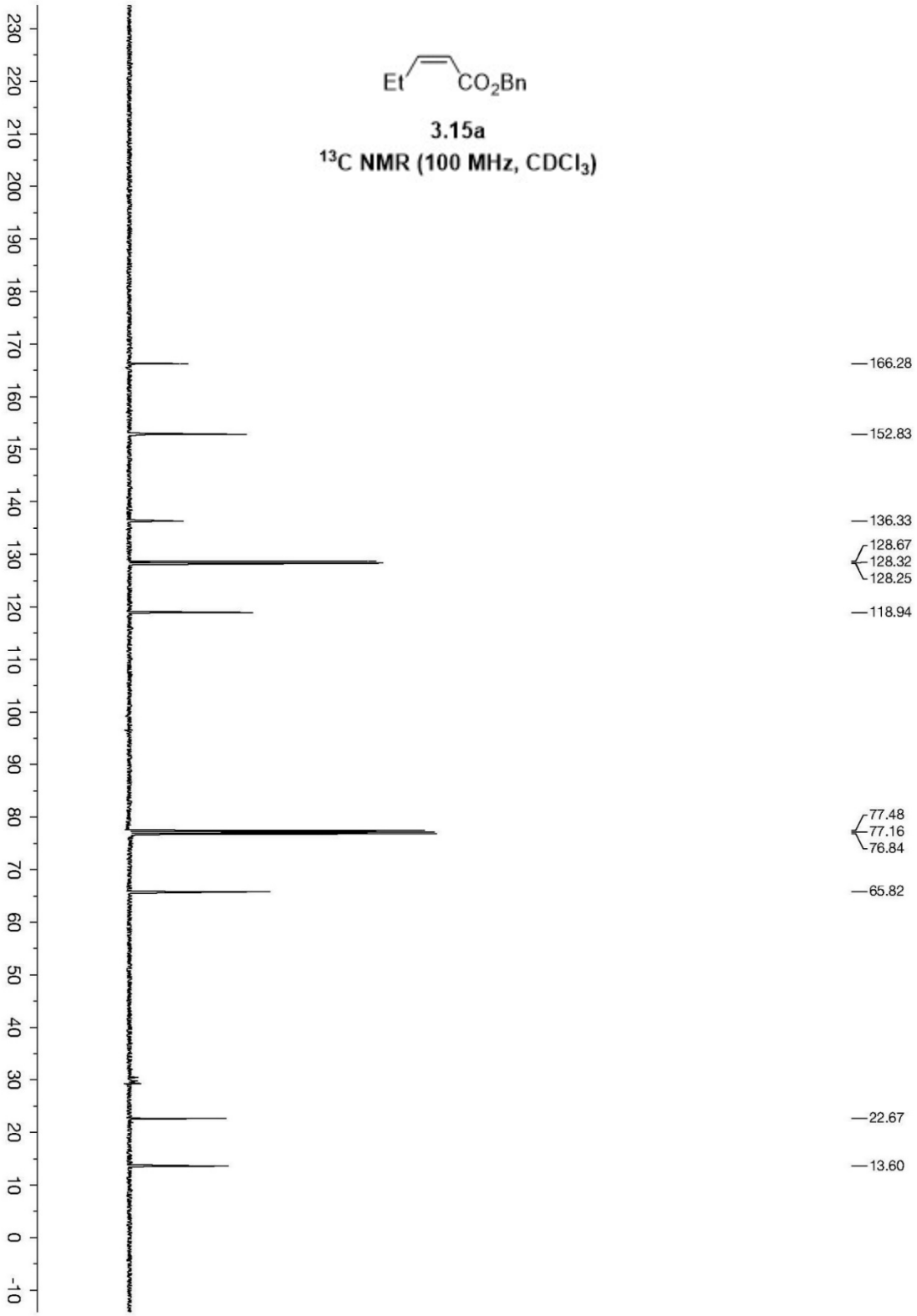

Me
CONHPMB
S2
1H NMR (400 MHz, CDCl3)
f1 (ppm)
1.98
2.02
1.00
1.13
0.75
2.11
3.15
2.98
7.26
7.25
7.24
7.23
7.22
7.21
6.88
6.88
6.87
6.86
6.85
6.85
6.15
6.14
6.13
6.12
6.11
6.10
6.09
6.07
5.72
5.72
5.71
5.71
5.69
5.69
5.68
5.68
5.64
4.42
4.41
3.80
2.16
2.16
2.14
2.14

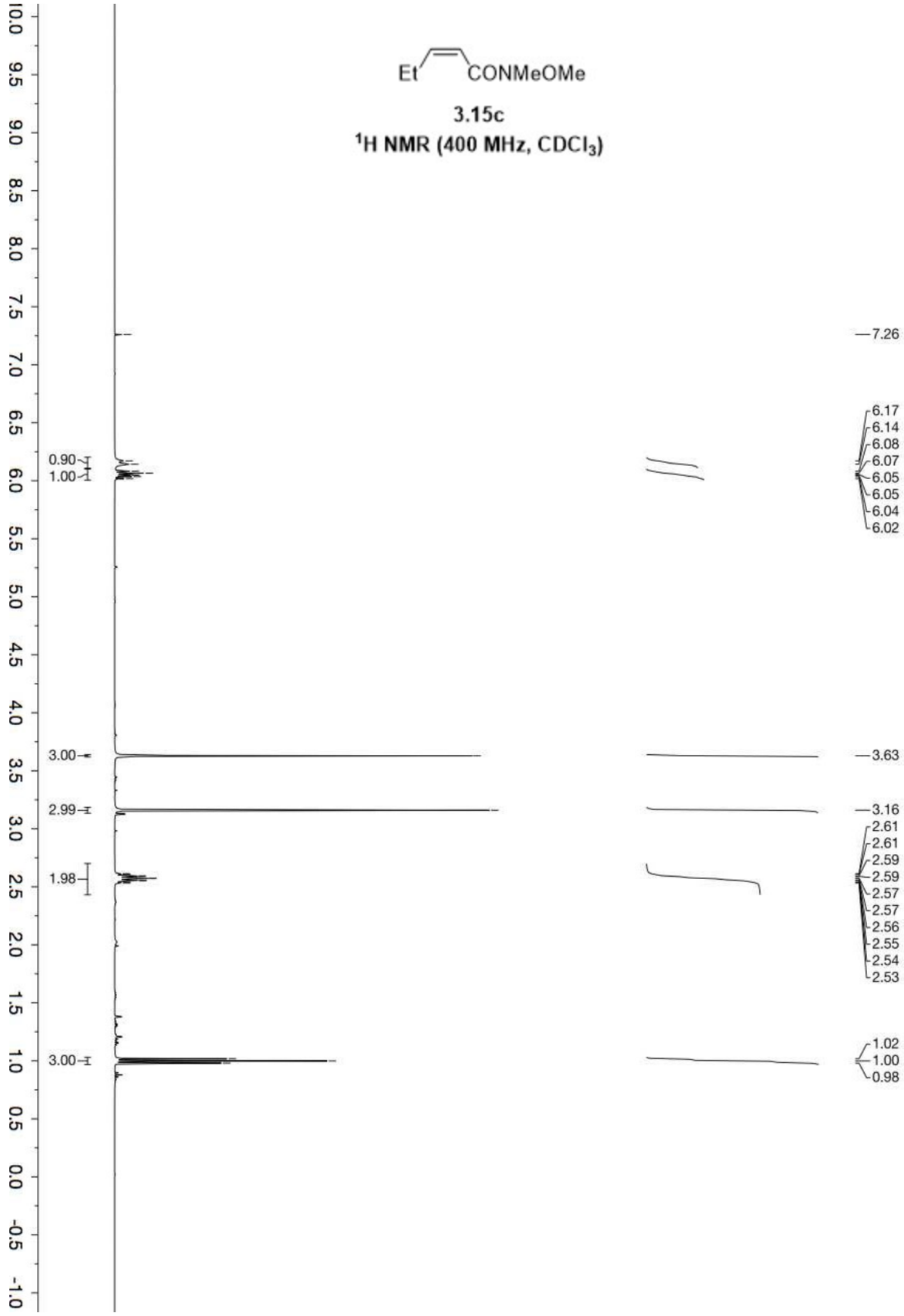

Me
CONHPMB
S2
13C NMR (100 MHz, CDCl3)
f1 (ppm)
166.49
159.19
140.68
130.58
129.41
123.09
114.24
77.48
77.16
76.84
55.46
42.93
15.26

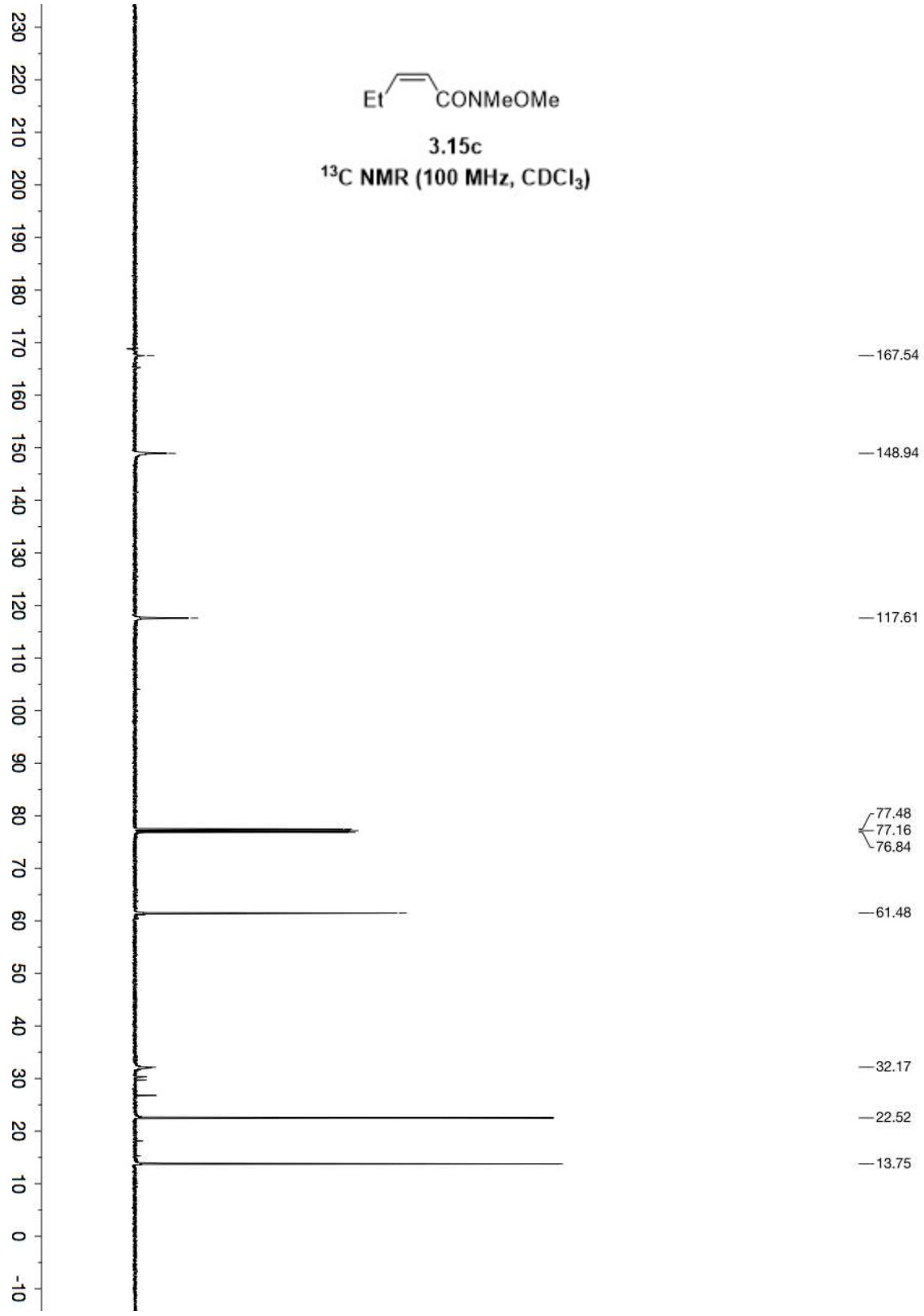

Me
CONHiBu
S3
1H NMR (400 MHz, CDCl3)
f1 (ppm)
1.00
1.16
0.77
2.06
2.97
1.02
6.42
7.26
6.10
6.09
6.08
6.08
6.06
6.06
6.05
6.05
6.03
6.03
6.01
6.01
5.73
5.73
5.72
5.72
5.70
5.70
5.69
5.69
5.64
3.12
3.12
3.10
3.10
3.09
3.08
2.11
2.11
2.09
2.09
1.83
1.81
1.79
1.78
1.76
1.74
1.73
0.91
0.91
0.90
0.90

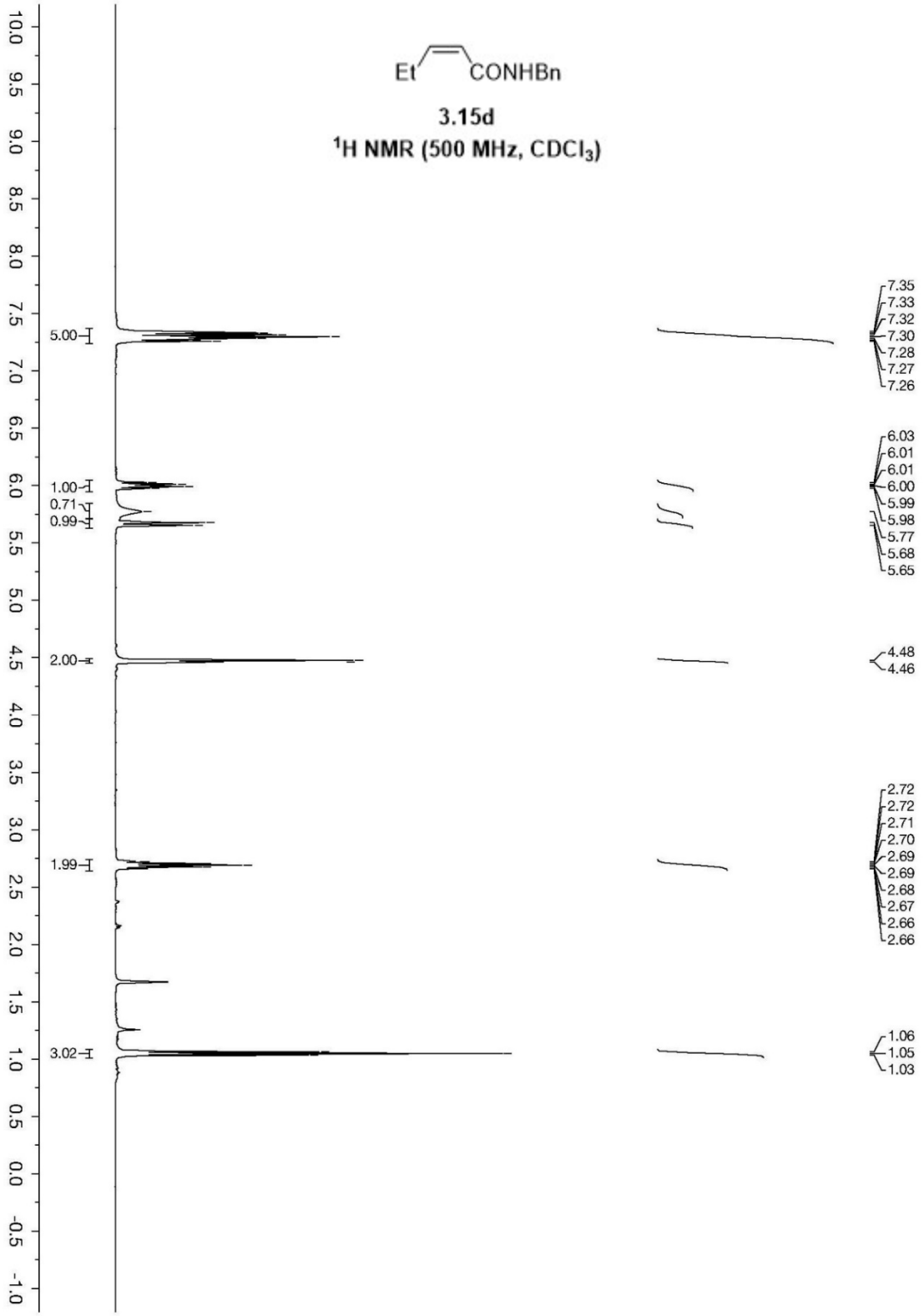

Me
CONHiBu
S3
13C NMR (100 MHz, CDCl3)
166.89
139.71
123.51
77.48
77.16
76.84
46.65
28.66
20.26
15.13
f1 (ppm)

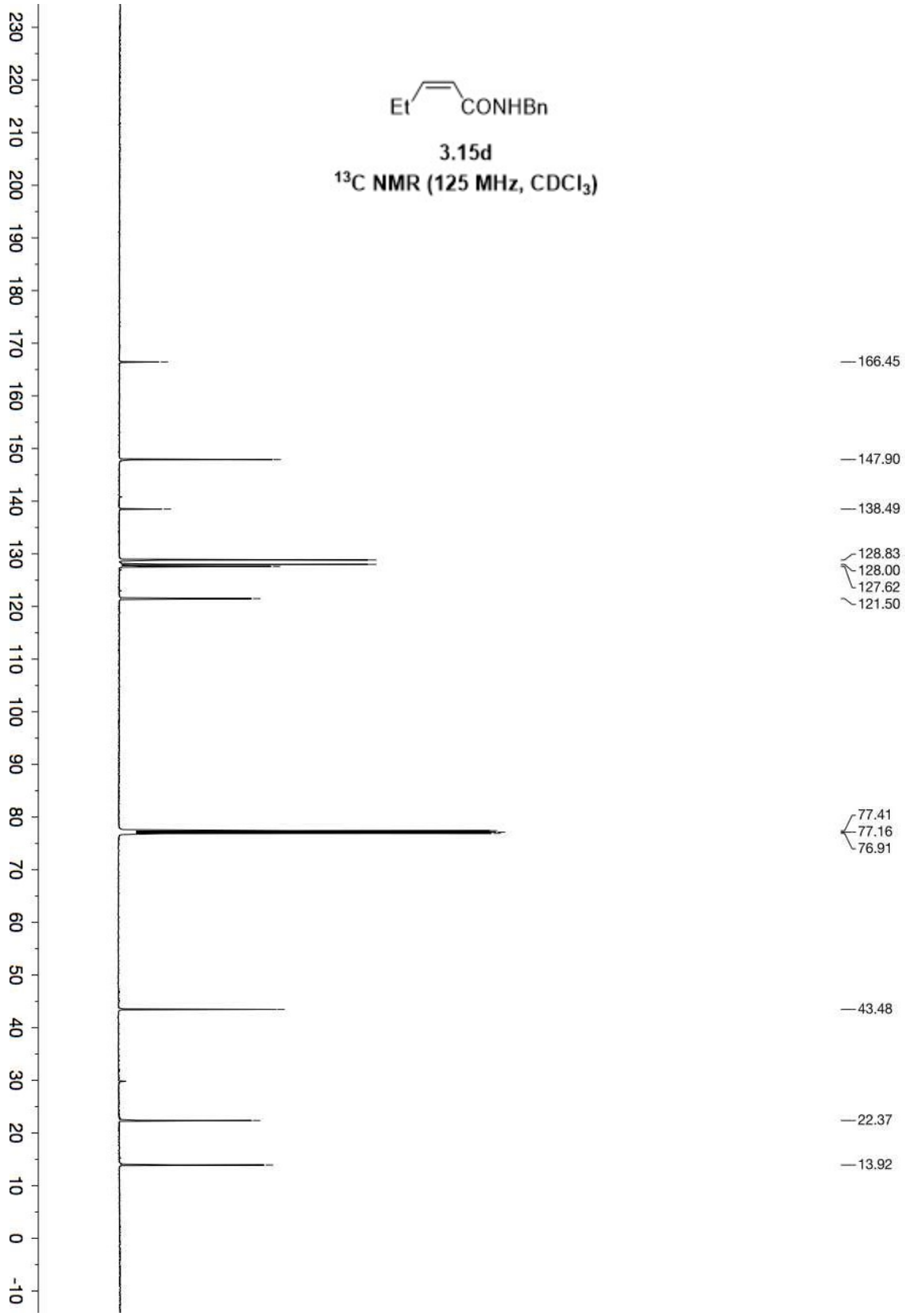

Et
CO2Bn
3.15a
1H NMR (400 MHz, CDCl3)
7.39
7.38
7.37
7.37
7.36
7.35
7.35
7.34
7.34
7.33
7.33
7.32
7.32
7.31
7.31
7.31
7.30
7.30
7.26
6.28
6.26
6.25
6.24
6.23
6.21
5.82
5.81
5.81
5.79
5.78
5.78
5.16
2.72
2.71
2.70
2.70
2.68
2.68
2.66
2.66
2.64
2.64
1.08
1.06
1.04
5.00
1.00
0.99
2.01
2.01
3.00

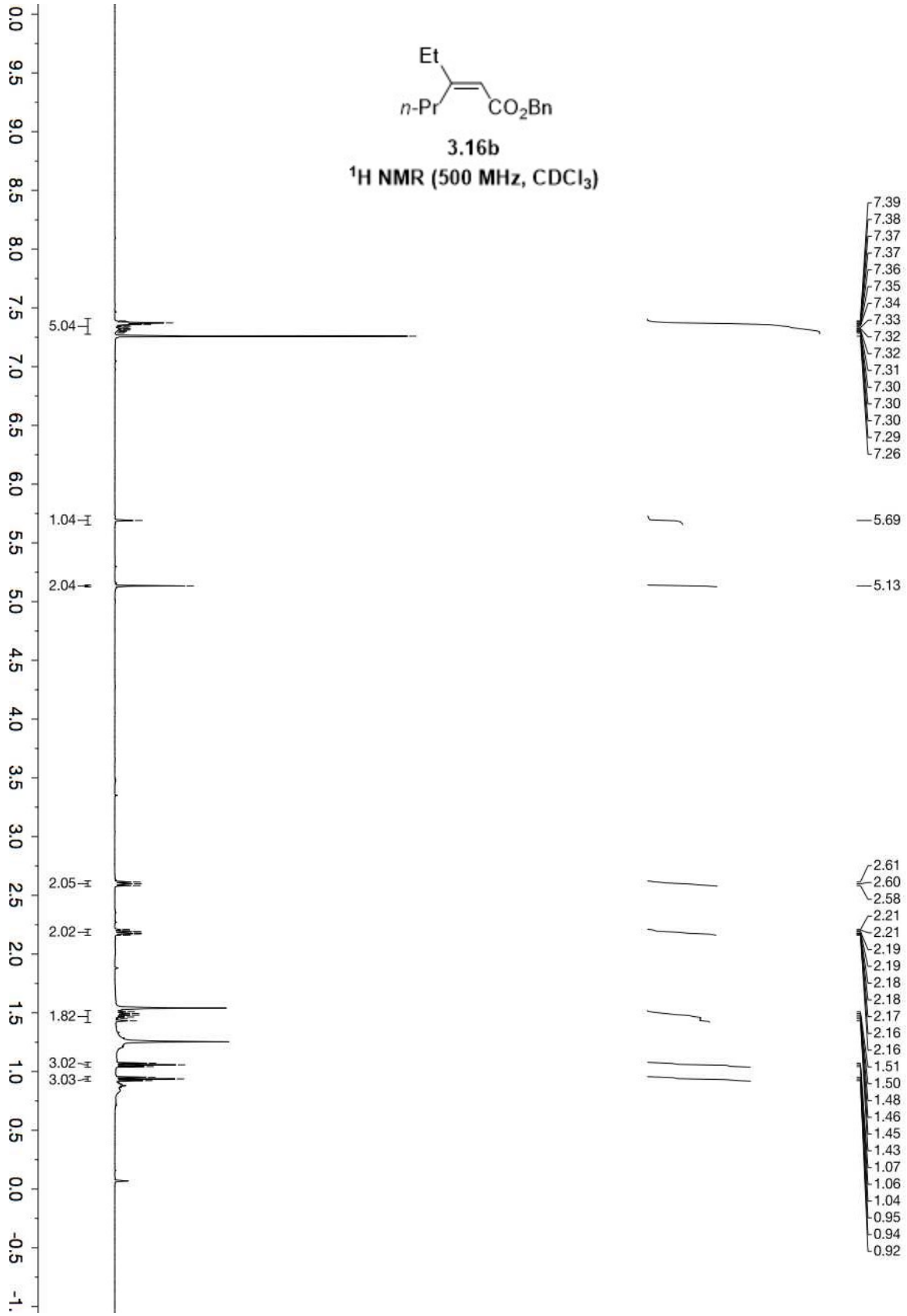

Et
CO2Bn
3.15a
13C NMR (100 MHz, CDCl3)
166.28
152.83
136.33
128.67
128.32
128.25
118.94
77.48
77.16
76.84
65.82
22.67
13.60
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10

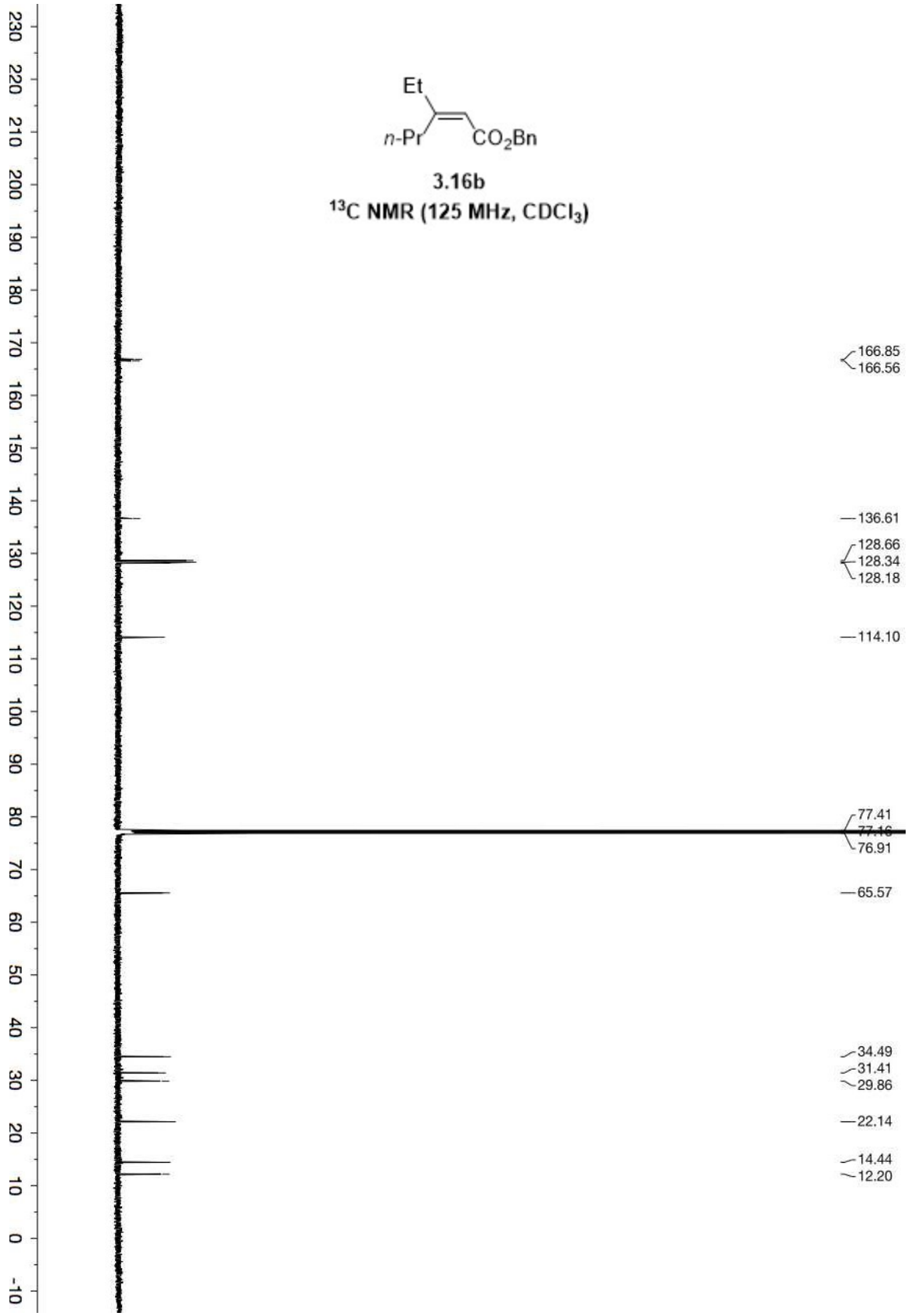

Et
CONMeOMe
3.15c
¹H NMR (400 MHz, CDCl₃)
7.26
6.17
6.14
6.08
6.07
6.05
6.05
6.04
6.02
3.63
3.16
2.61
2.61
2.59
2.59
2.57
2.57
2.56
2.55
2.54
2.53
1.02
1.00
0.98
0.90
1.00
3.00
2.99
1.98
3.00

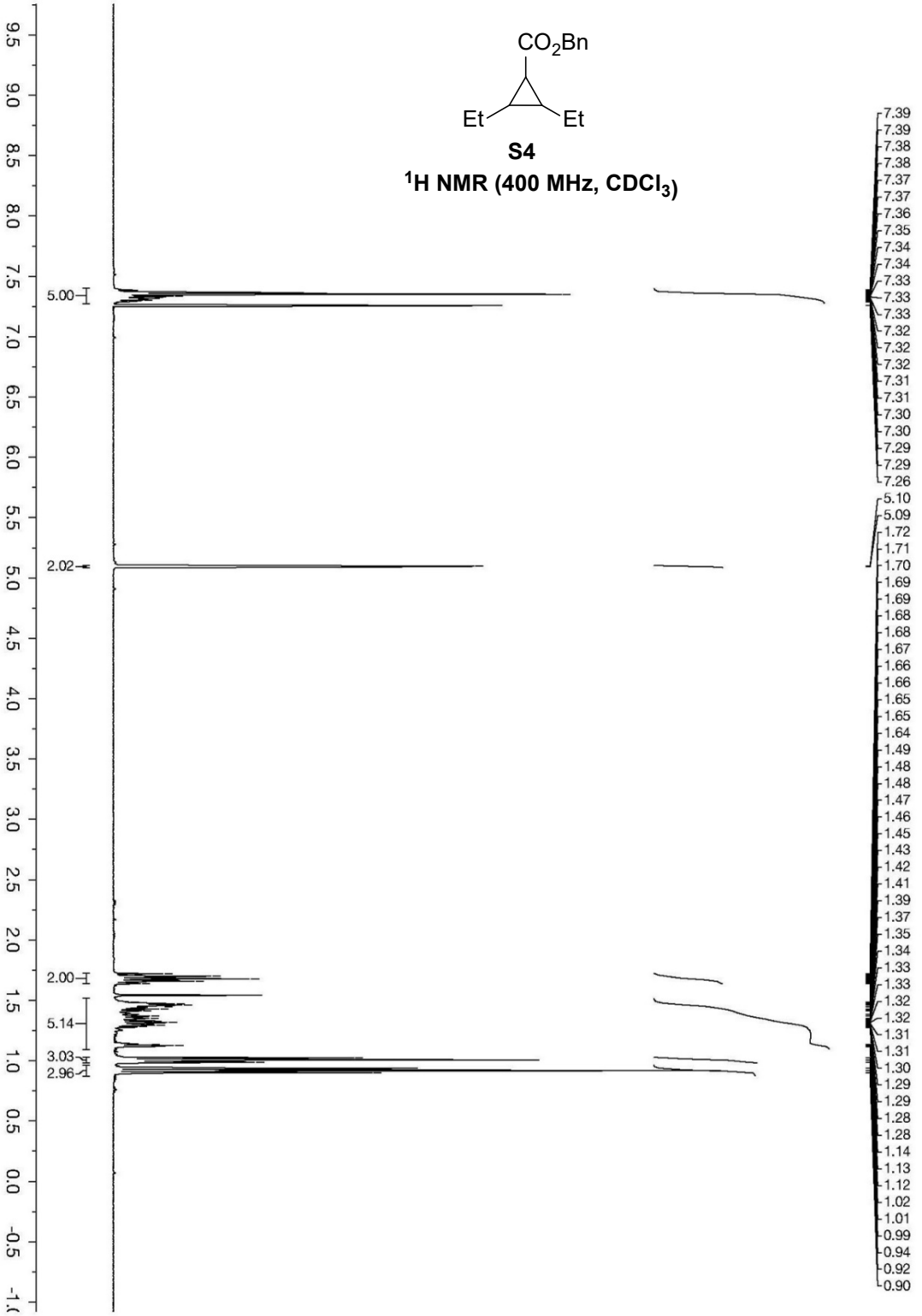

Et
CONMeOMe
3.15c
^{13}C NMR (100 MHz, $CDCl_3$)
167.54
148.94
117.61
77.48
77.16
76.84
61.48
32.17
22.52
13.75


Et
CONHBn
3.15d
^{1}H NMR (500 MHz, $CDCl_3$)
10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5 -1.0
5.00
1.00
0.71
0.99
2.00
1.99
3.02
7.35
7.33
7.32
7.30
7.28
7.27
7.26
6.03
6.01
6.01
6.00
5.99
5.98
5.77
5.68
5.65
4.48
4.46
2.72
2.72
2.71
2.70
2.69
2.69
2.68
2.67
2.66
2.66
1.06
1.05
1.03


Et
CONHBn
3.15d
^{13}C NMR (125 MHz, $CDCl_3$)
166.45
147.90
138.49
128.83
128.00
127.62
121.50
77.41
77.16
76.91
43.48
22.37
13.92

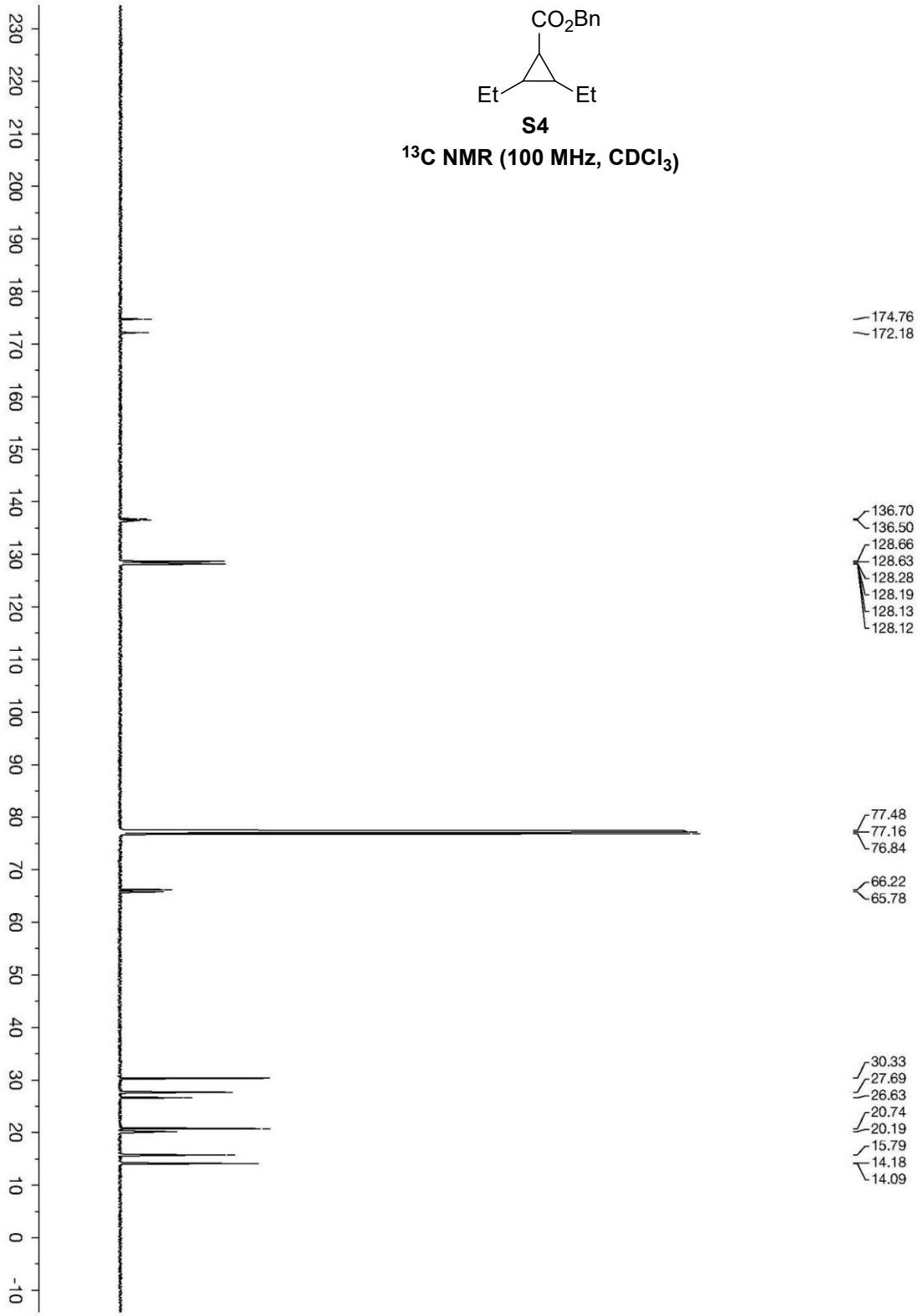

Et
n-Pr
CO2Bn
3.16b
1H NMR (500 MHz, CDCl3)
5.04
1.04
2.04
2.05
2.02
1.82
3.02
3.03
7.39
7.38
7.37
7.37
7.36
7.35
7.34
7.33
7.32
7.32
7.31
7.30
7.30
7.30
7.29
7.26
5.69
5.13
2.61
2.60
2.58
2.21
2.21
2.19
2.19
2.18
2.18
2.17
2.16
2.16
1.51
1.50
1.48
1.46
1.45
1.43
1.07
1.06
1.04
0.95
0.94
0.92


Et
n-Pr
CO2Bn
3.16b
13C NMR (125 MHz, CDCl3)
166.85
166.56
136.61
128.66
128.34
128.18
114.10
77.41
77.16
76.91
65.57
34.49
31.41
29.86
22.14
14.44
12.20



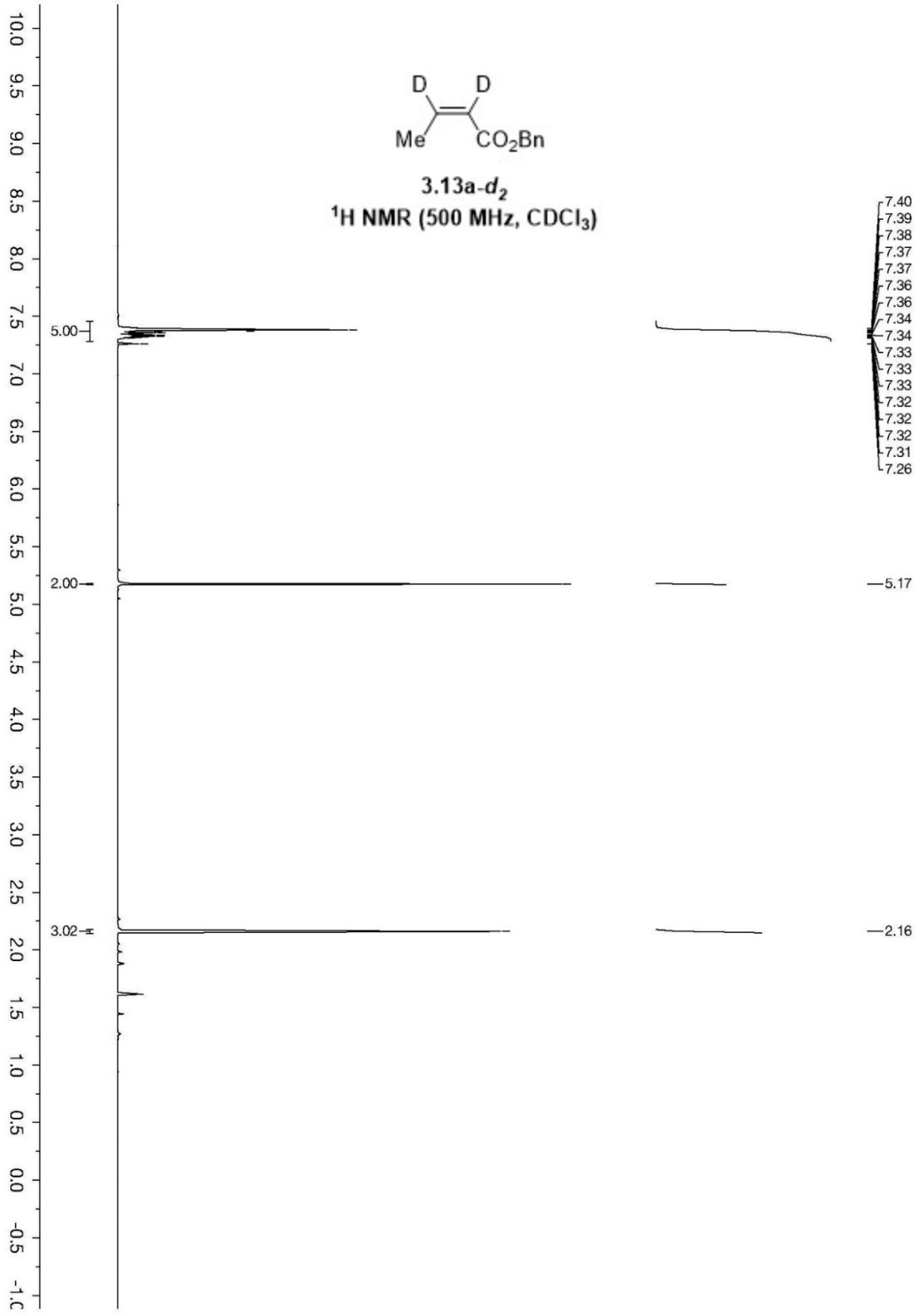
S4

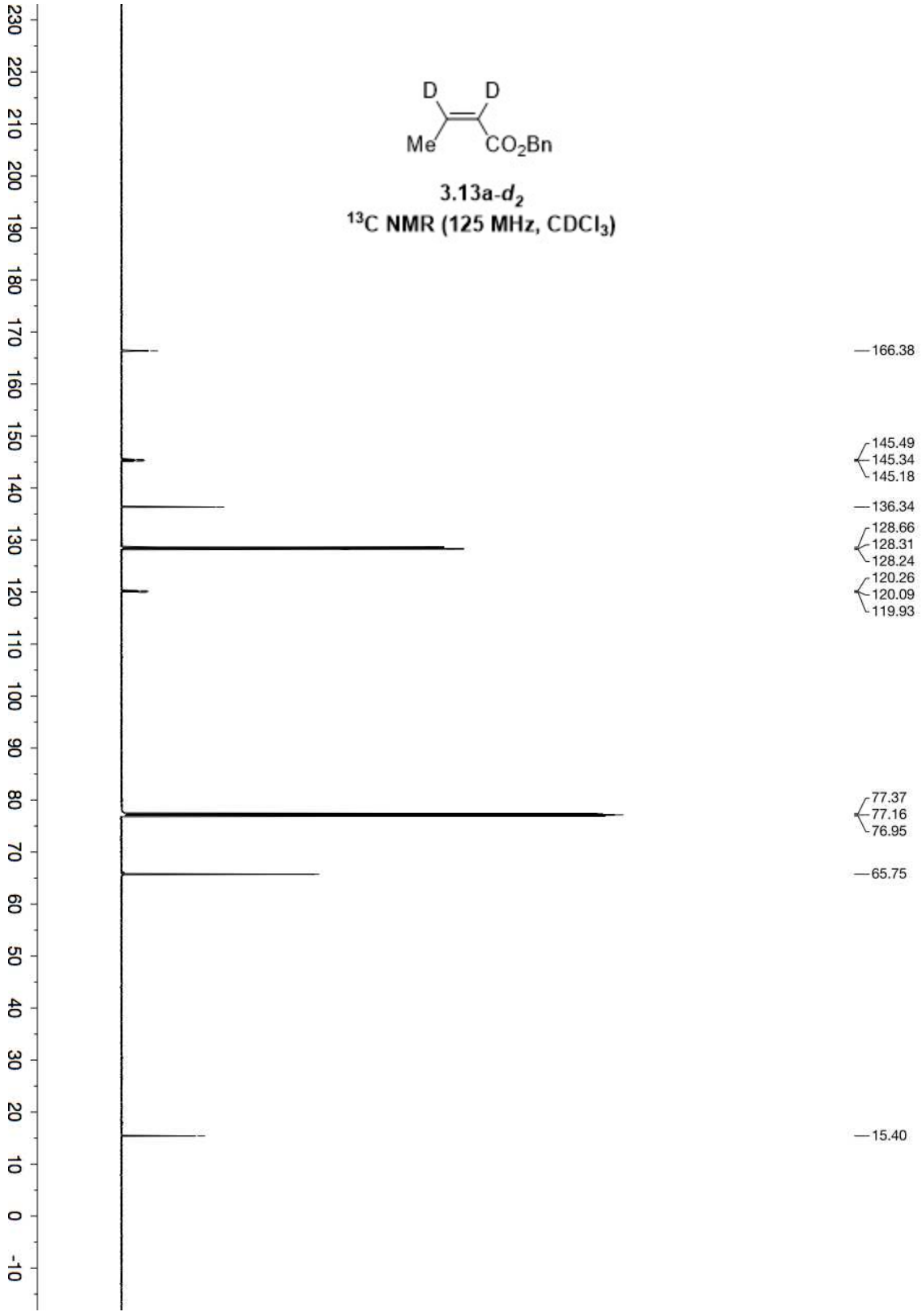
^{1}H NMR (400 MHz, $CDCl_3$)

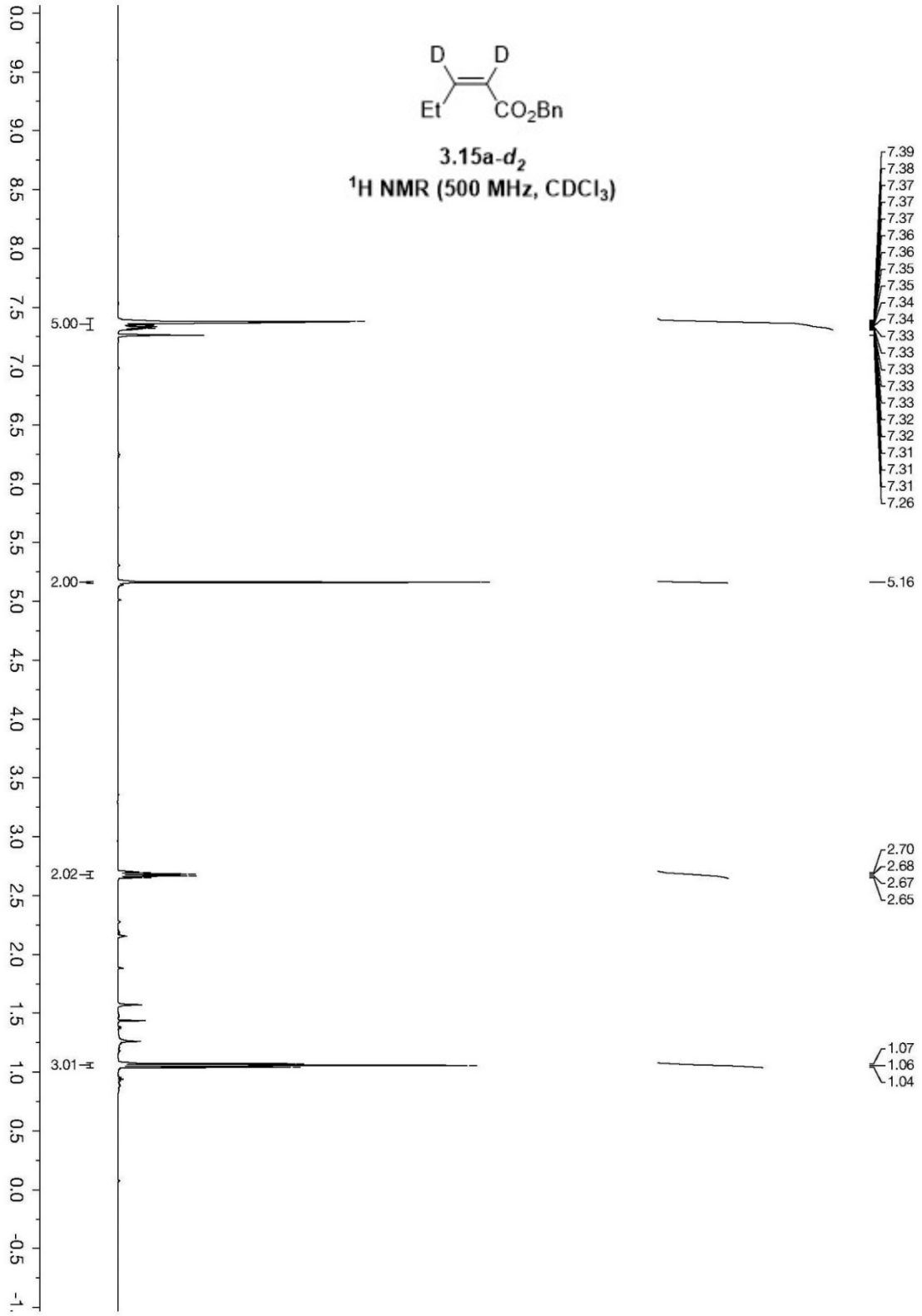


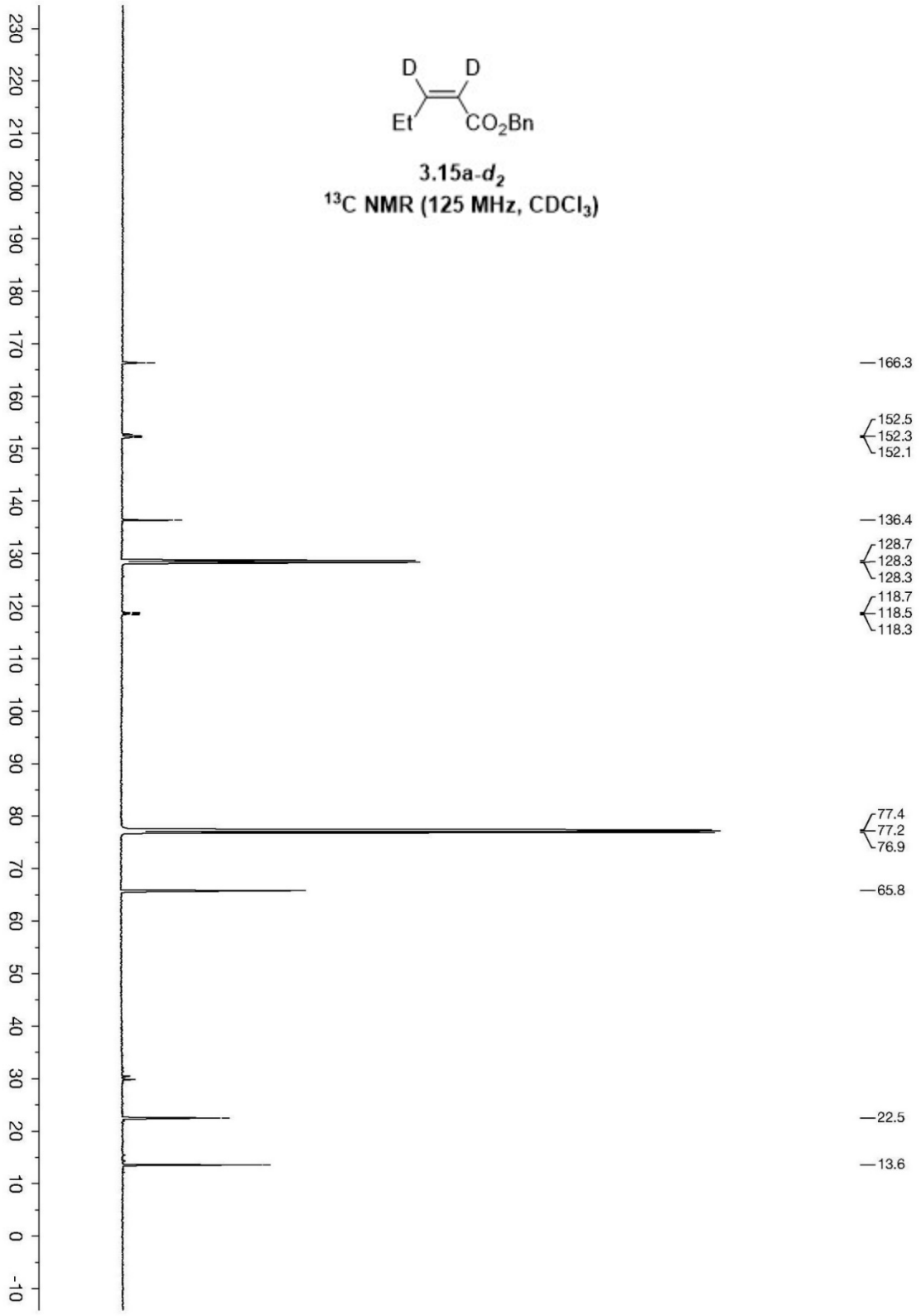
S4

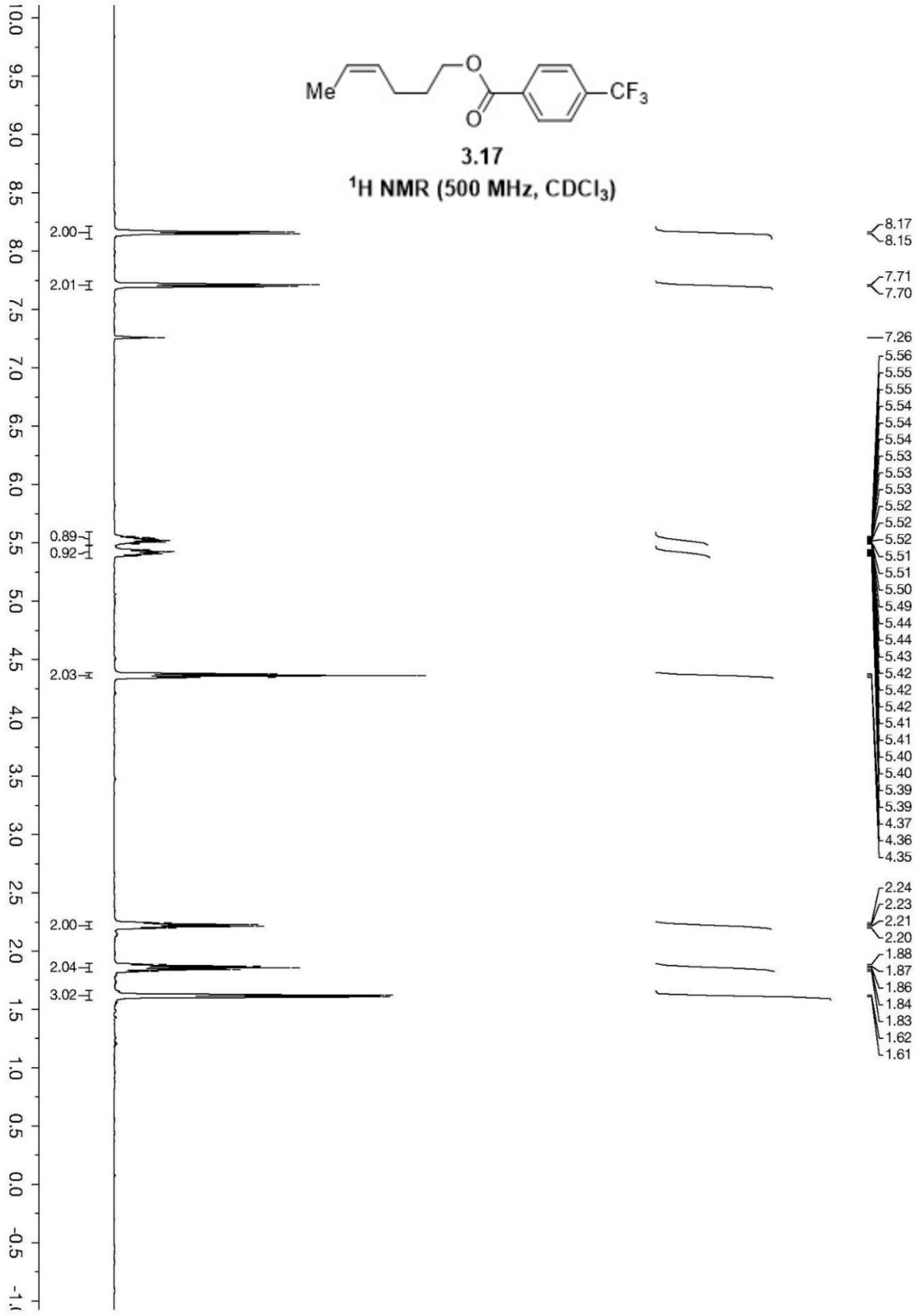
^{13}C NMR (100 MHz, $CDCl_3$)

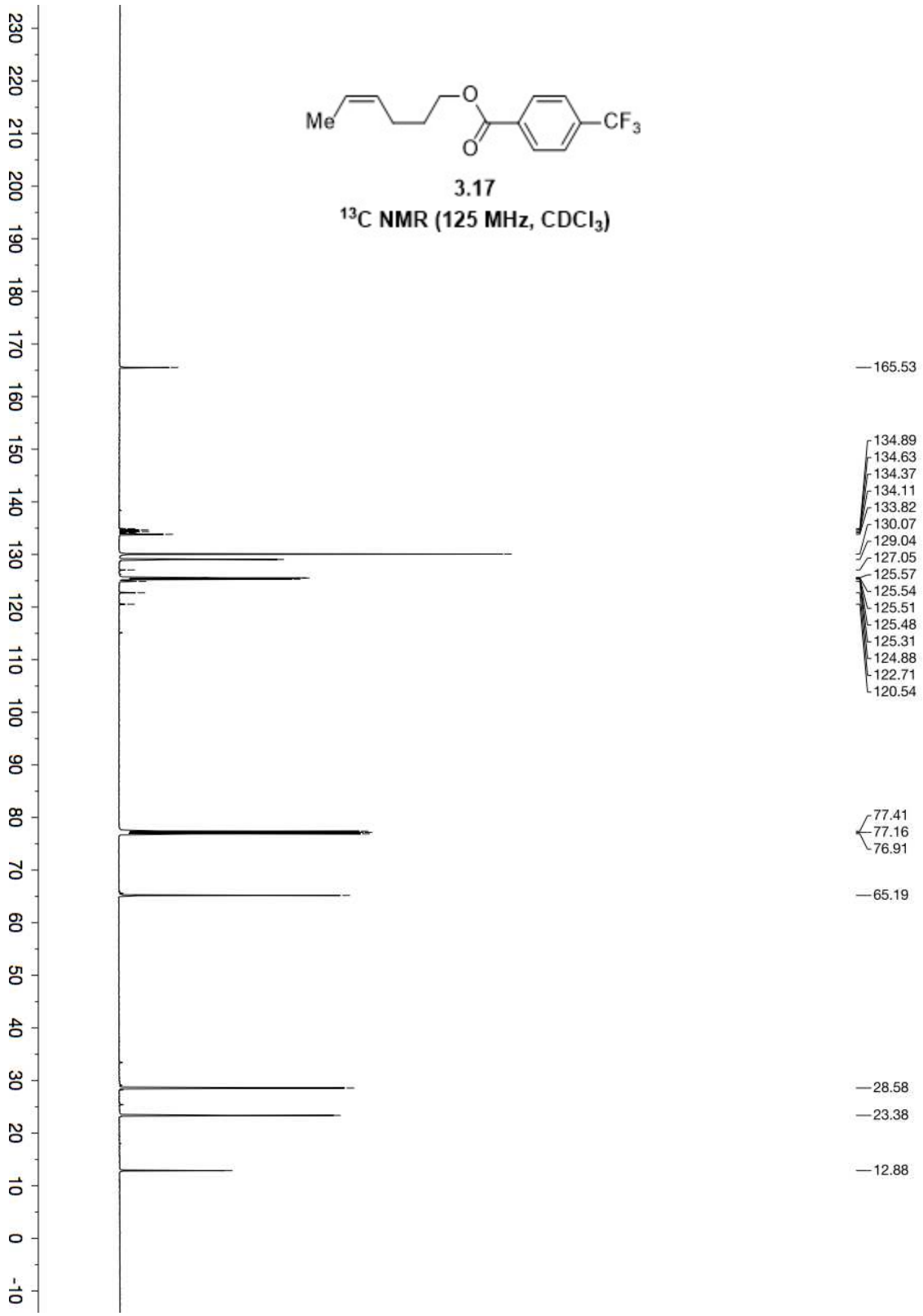

D
D
Me
CO2Bn
3.13a-d2
1H NMR (500 MHz, CDCl3)
7.40
7.39
7.38
7.37
7.37
7.36
7.36
7.34
7.34
7.33
7.33
7.33
7.32
7.32
7.32
7.31
7.26
5.00
2.00
3.02
5.17
2.16
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0

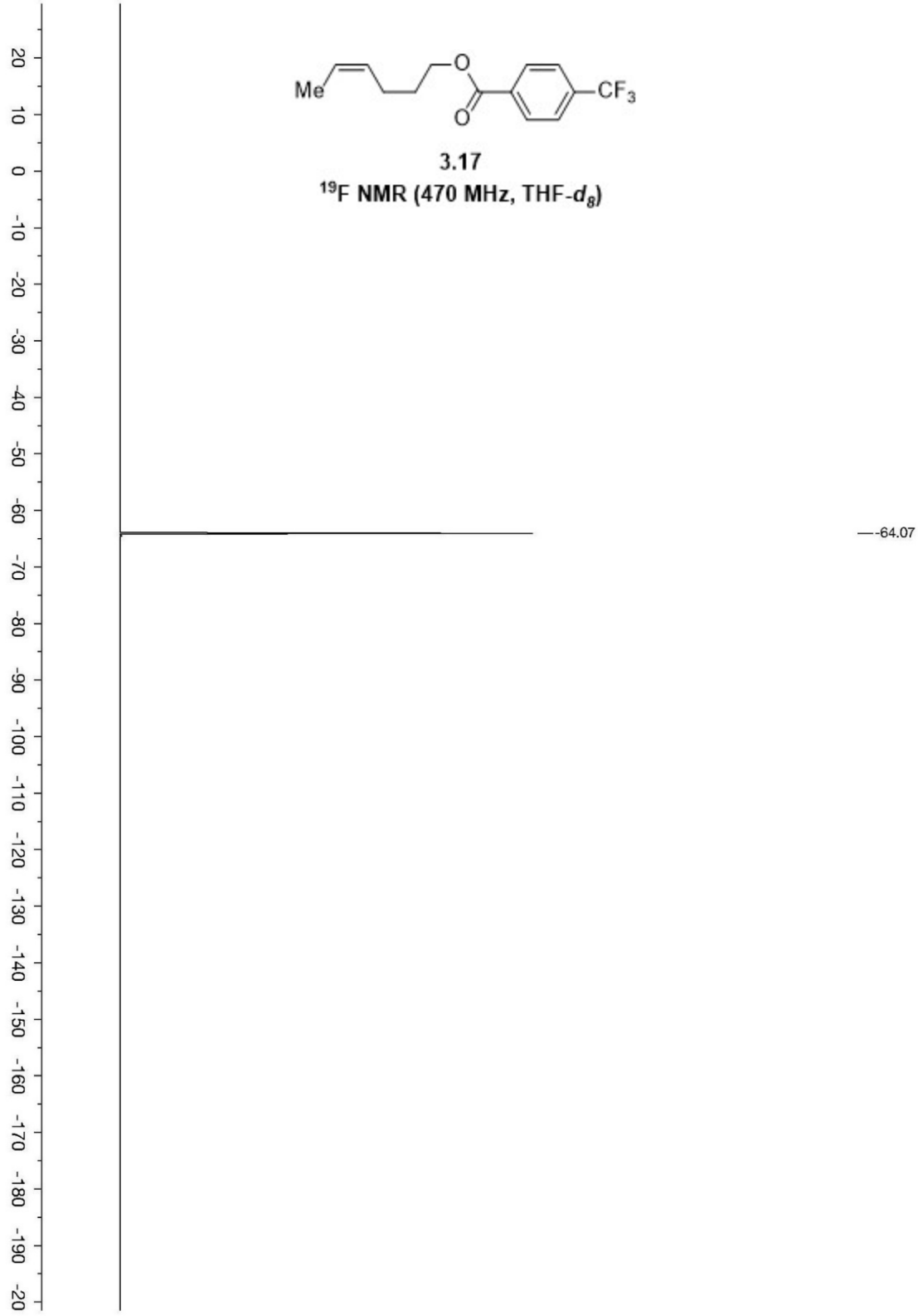

D
D
Me
CO2Bn
3.13a-d2
13C NMR (125 MHz, CDCl3)
166.38
145.49
145.34
145.18
136.34
128.66
128.31
128.24
120.26
120.09
119.93
77.37
77.16
76.95
65.75
15.40
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10


D
D
Et
CO2Bn
3.15a-d2
1H NMR (500 MHz, CDCl3)
7.39
7.38
7.37
7.37
7.37
7.36
7.36
7.35
7.35
7.34
7.34
7.33
7.33
7.33
7.33
7.33
7.32
7.32
7.31
7.31
7.31
7.26
5.16
2.70
2.68
2.67
2.65
1.07
1.06
1.04
5.00
2.00
2.02
3.01


D
D
Et
CO2Bn
3.15a-d2
13C NMR (125 MHz, CDCl3)
166.3
152.5
152.3
152.1
136.4
128.7
128.3
128.3
118.7
118.5
118.3
77.4
77.2
76.9
65.8
22.5
13.6

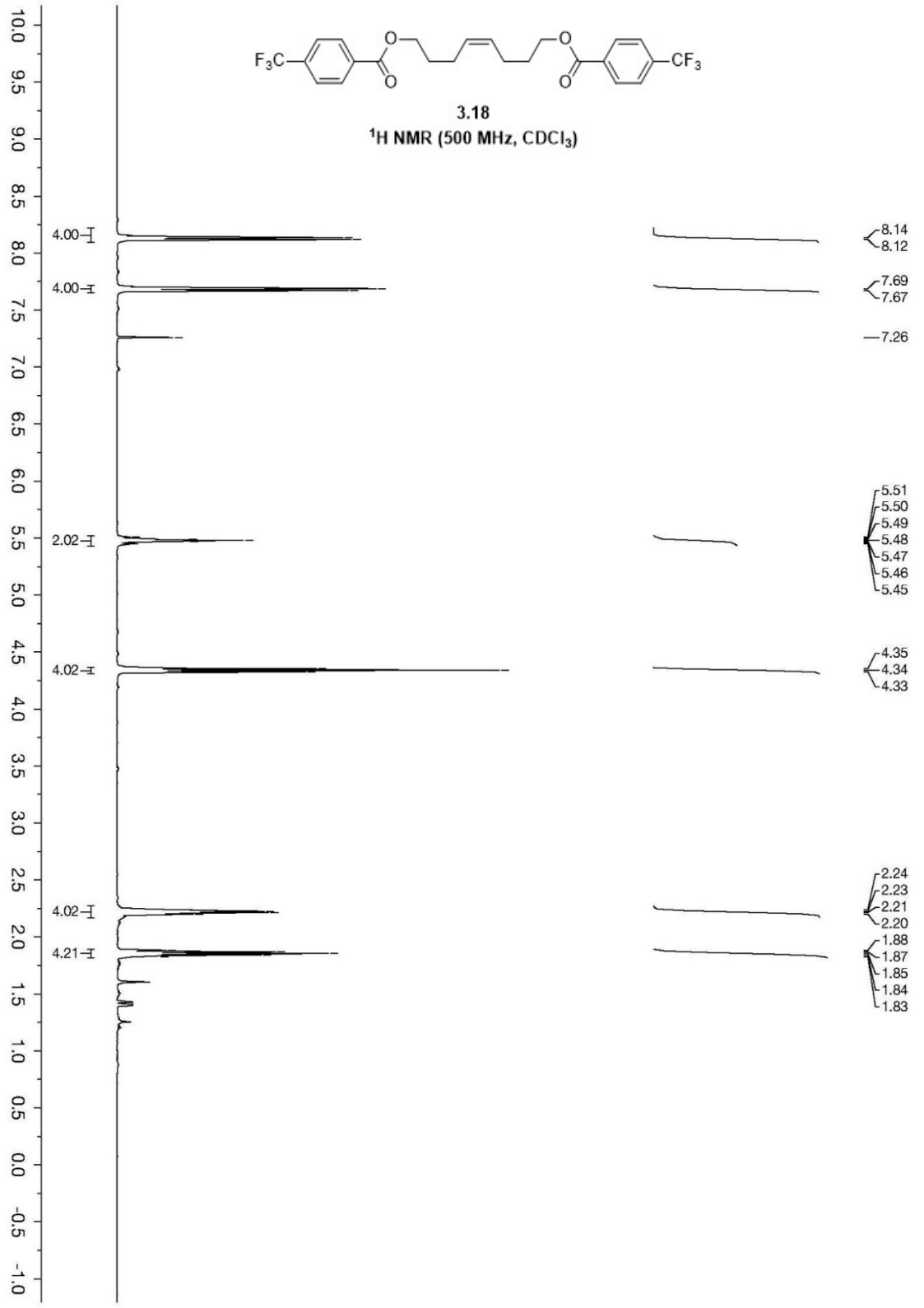

Me
O
O
CF3
3.17
1H NMR (500 MHz, CDCl3)
2.00
2.01
0.89
0.92
2.03
2.00
2.04
3.02
8.17
8.15
7.71
7.70
7.26
5.56
5.55
5.55
5.54
5.54
5.54
5.53
5.53
5.53
5.52
5.52
5.52
5.51
5.51
5.50
5.49
5.44
5.44
5.43
5.42
5.42
5.42
5.41
5.41
5.40
5.40
5.39
5.39
4.37
4.36
4.35
2.24
2.23
2.21
2.20
1.88
1.87
1.86
1.84
1.83
1.62
1.61

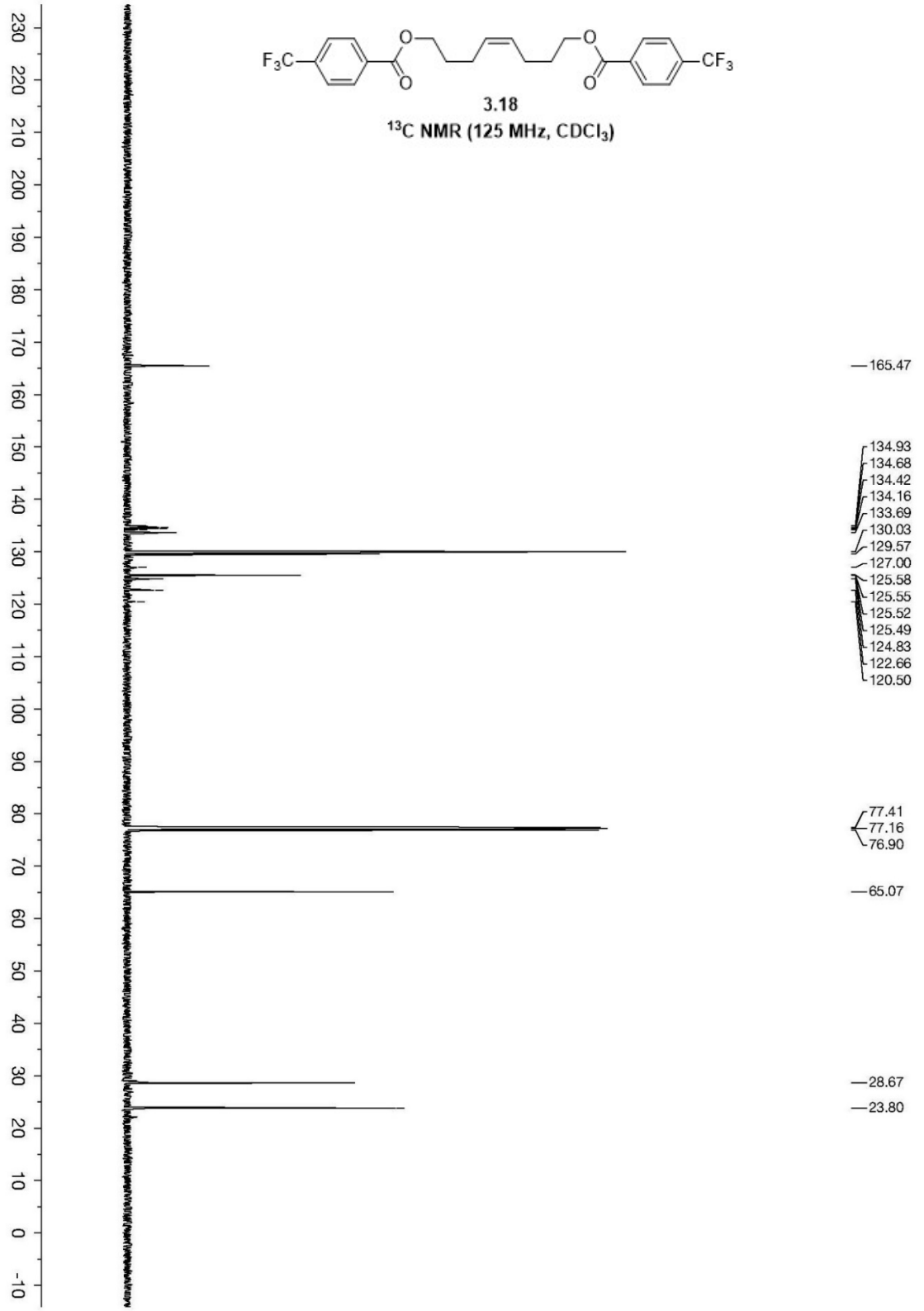

Me
O
O
CF3
3.17
13C NMR (125 MHz, CDCl3)
165.53
134.89
134.63
134.37
134.11
133.82
130.07
129.04
127.05
125.57
125.54
125.51
125.48
125.31
124.88
122.71
120.54
77.41
77.16
76.91
65.19
28.58
23.38
12.88

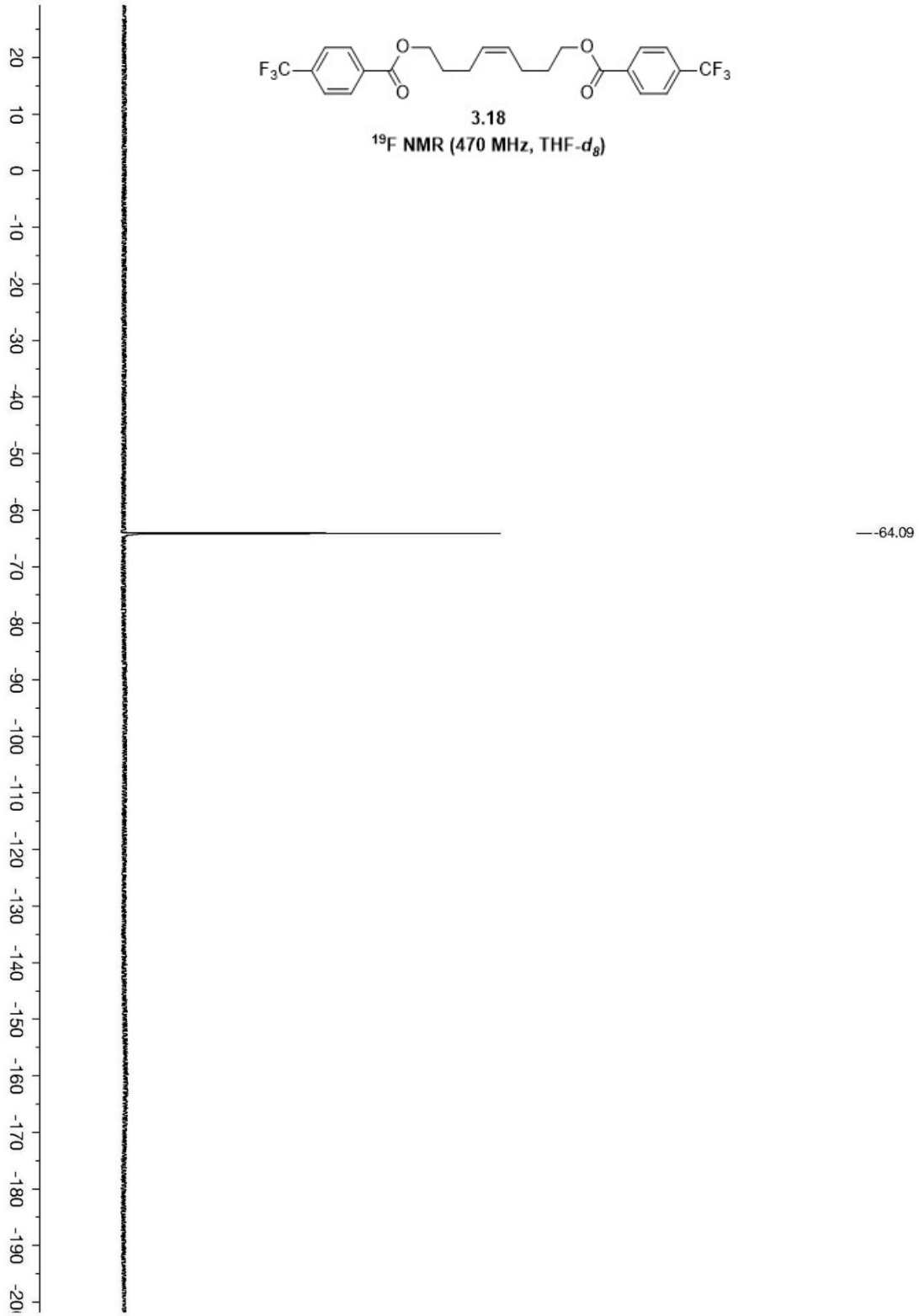


3.17

^{19}F NMR (470 MHz, THF-d_8)

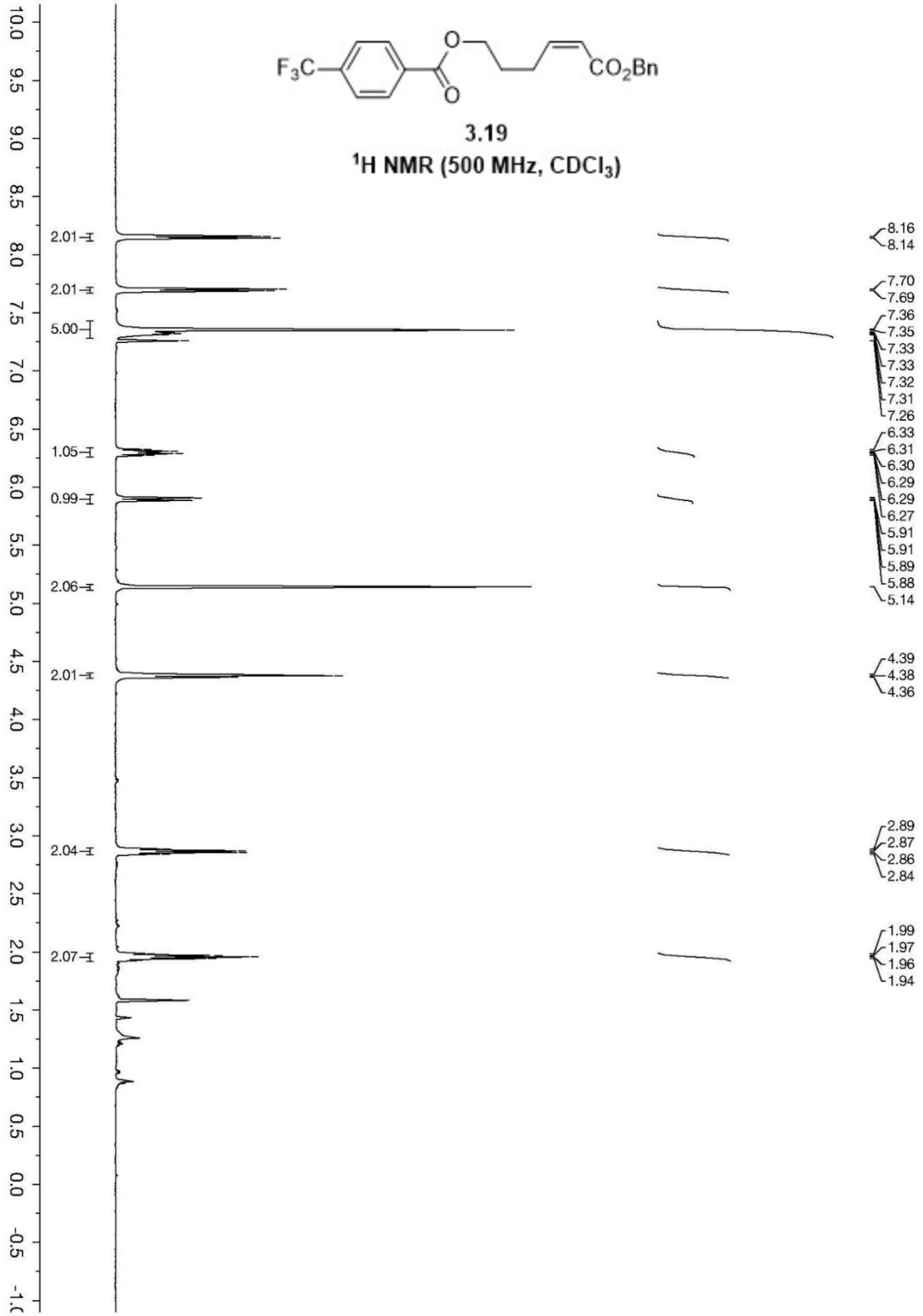

F3C
O
O
O
O
CF3
3.18
1H NMR (500 MHz, CDCl3)
4.00
4.00
2.02
4.02
4.02
4.21
8.14
8.12
7.69
7.67
7.26
5.51
5.50
5.49
5.48
5.47
5.46
5.45
4.35
4.34
4.33
2.24
2.23
2.21
2.20
1.88
1.87
1.85
1.84
1.83

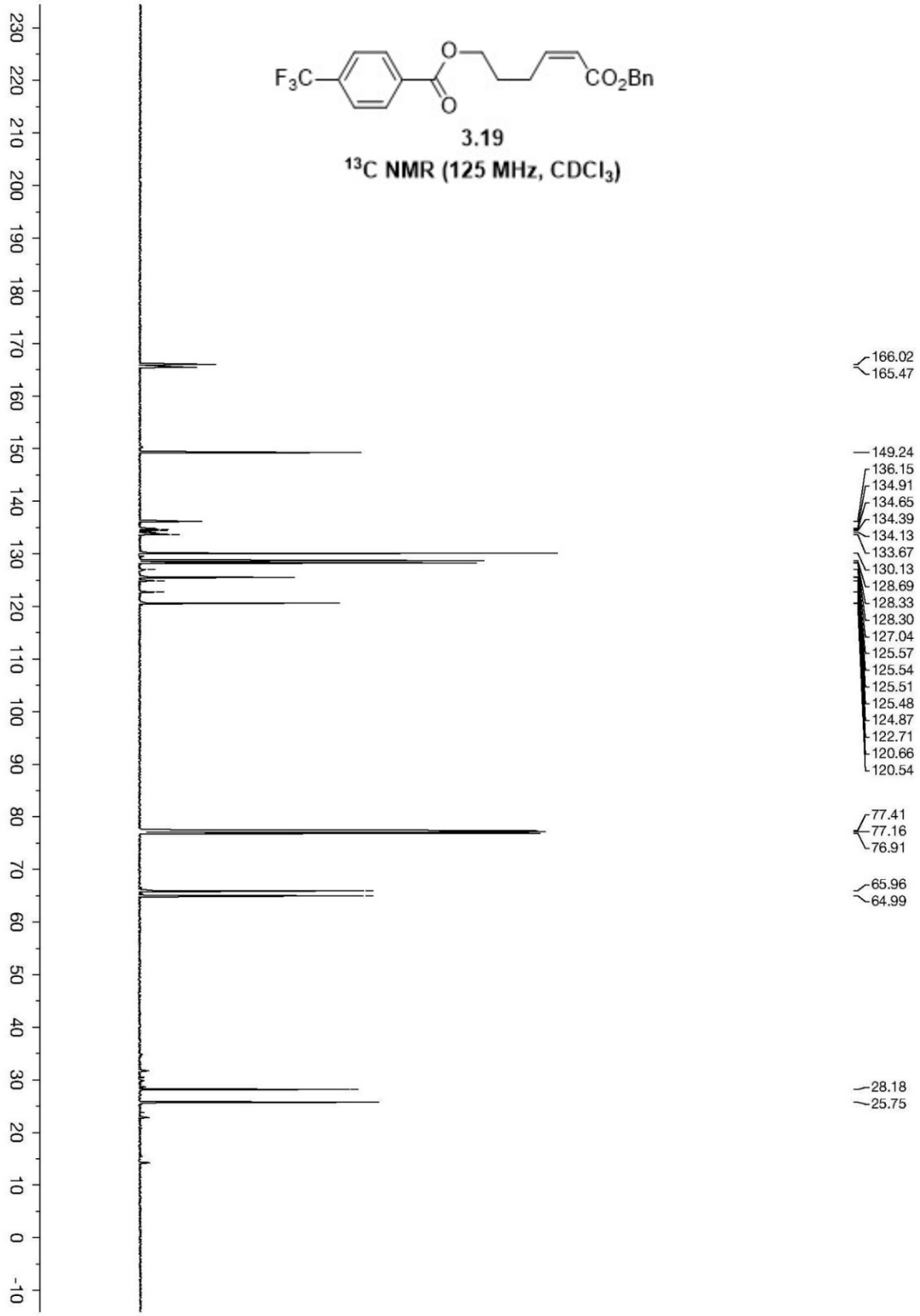

F3C
O
O
O
O
CF3
3.18
13C NMR (125 MHz, CDCl3)
165.47
134.93
134.68
134.42
134.16
133.69
130.03
129.57
127.00
125.58
125.55
125.52
125.49
124.83
122.66
120.50
77.41
77.16
76.90
65.07
28.67
23.80

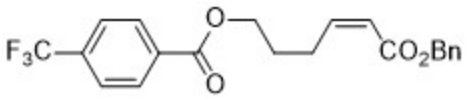


3.18

^{19}F NMR (470 MHz, THF-d_8)

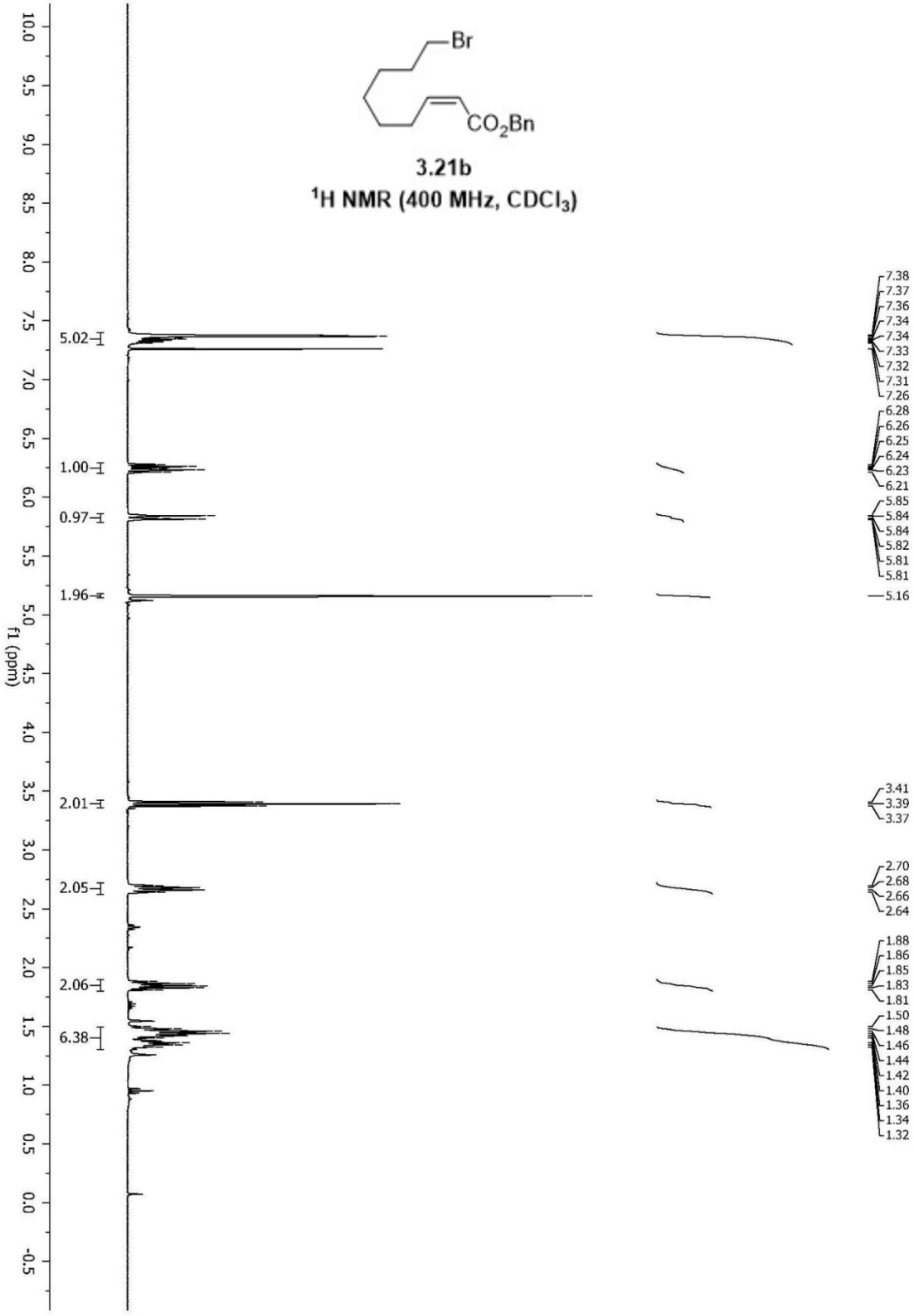

F3C
O
O
CO2Bn
3.19
1H NMR (500 MHz, CDCl3)
2.01
2.01
5.00
1.05
0.99
2.06
2.01
2.04
2.07
8.16
8.14
7.70
7.69
7.36
7.35
7.33
7.33
7.32
7.31
7.26
6.33
6.31
6.30
6.29
6.29
6.27
5.91
5.91
5.89
5.88
5.14
4.39
4.38
4.36
2.89
2.87
2.86
2.84
1.99
1.97
1.96
1.94

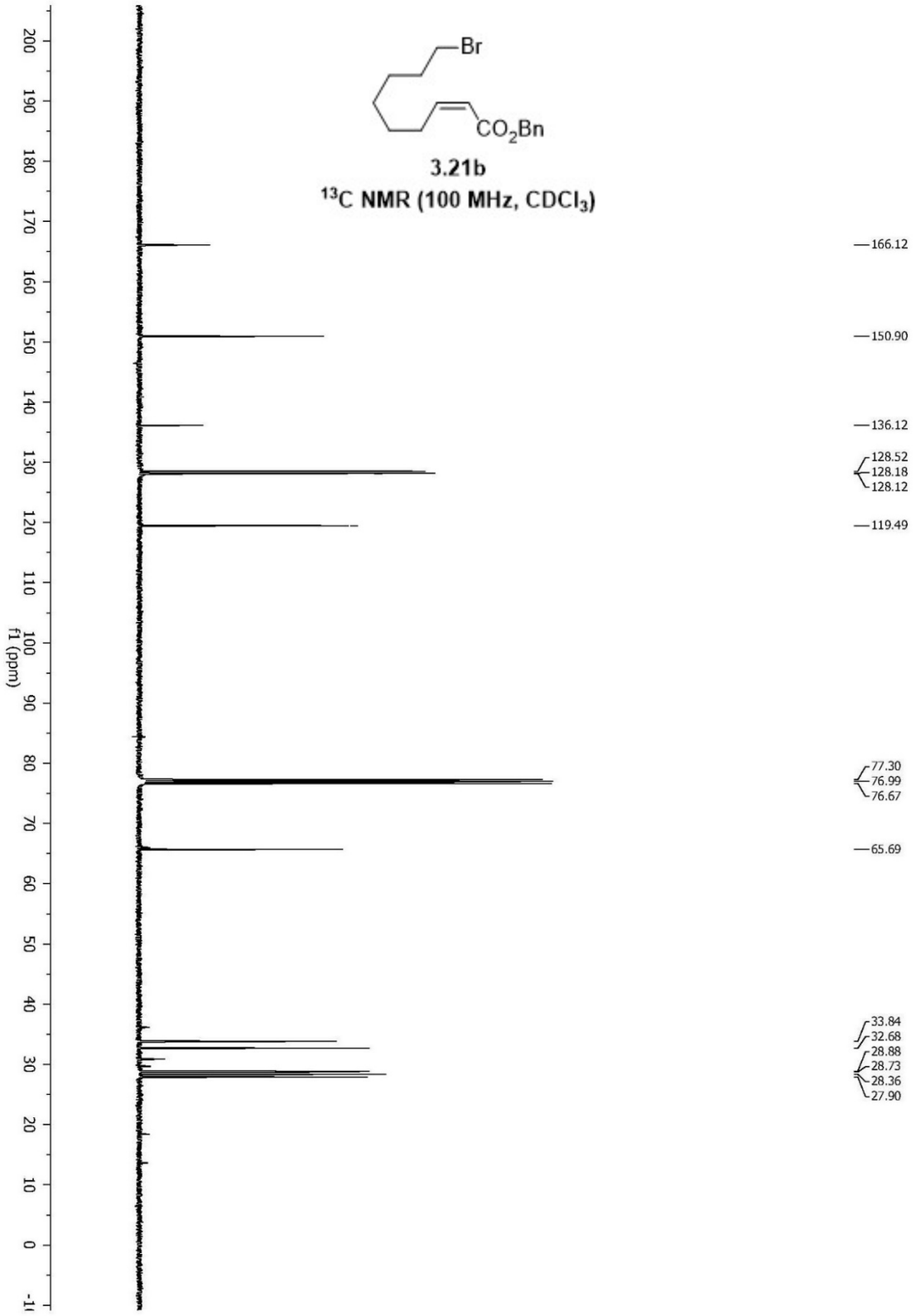

F3C
O
O
CO2Bn
3.19
13C NMR (125 MHz, CDCl3)
166.02
165.47
149.24
136.15
134.91
134.65
134.39
134.13
133.67
130.13
128.69
128.33
128.30
127.04
125.57
125.54
125.51
125.48
124.87
122.71
120.66
120.54
77.41
77.16
76.91
65.96
64.99
28.18
25.75

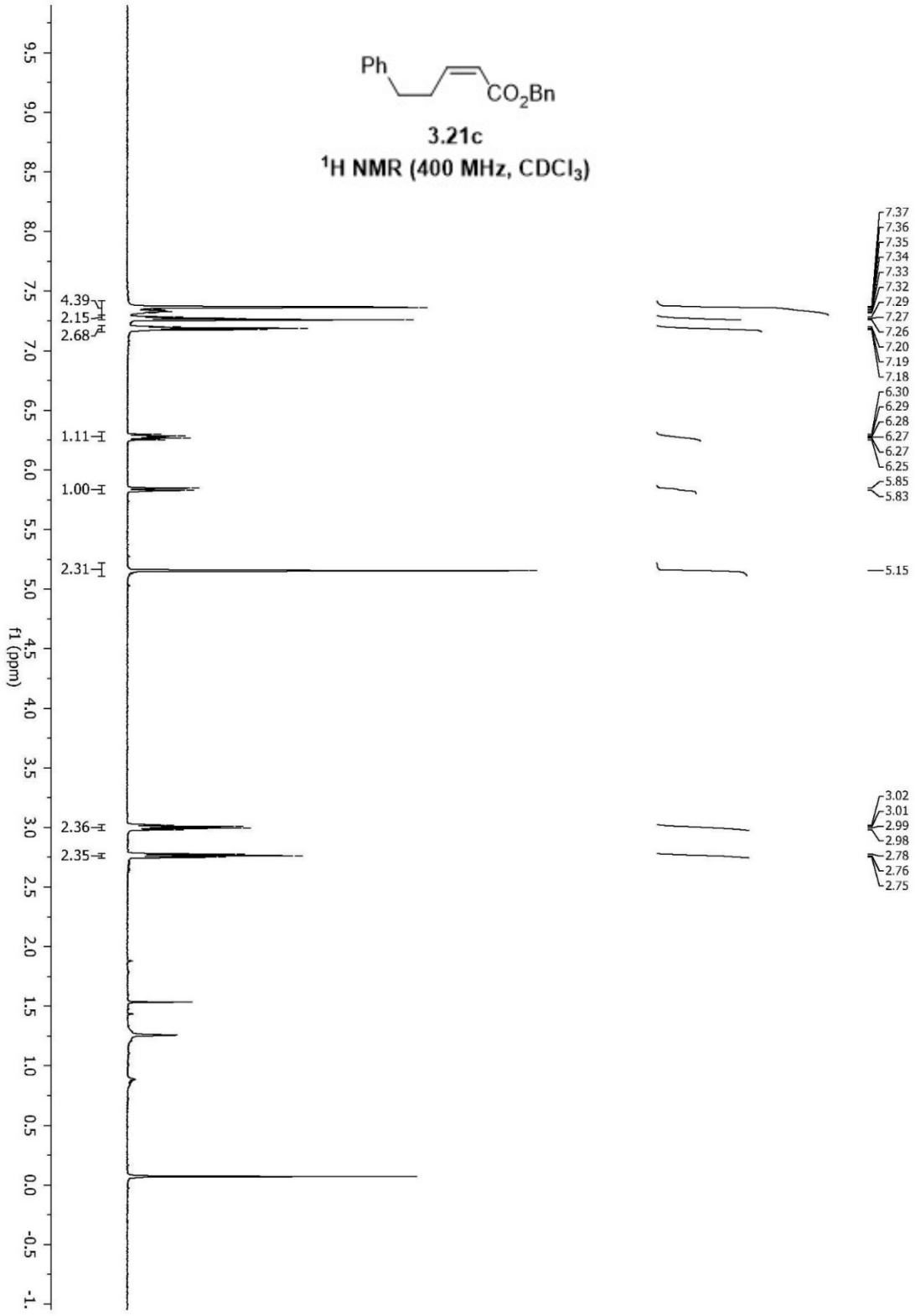


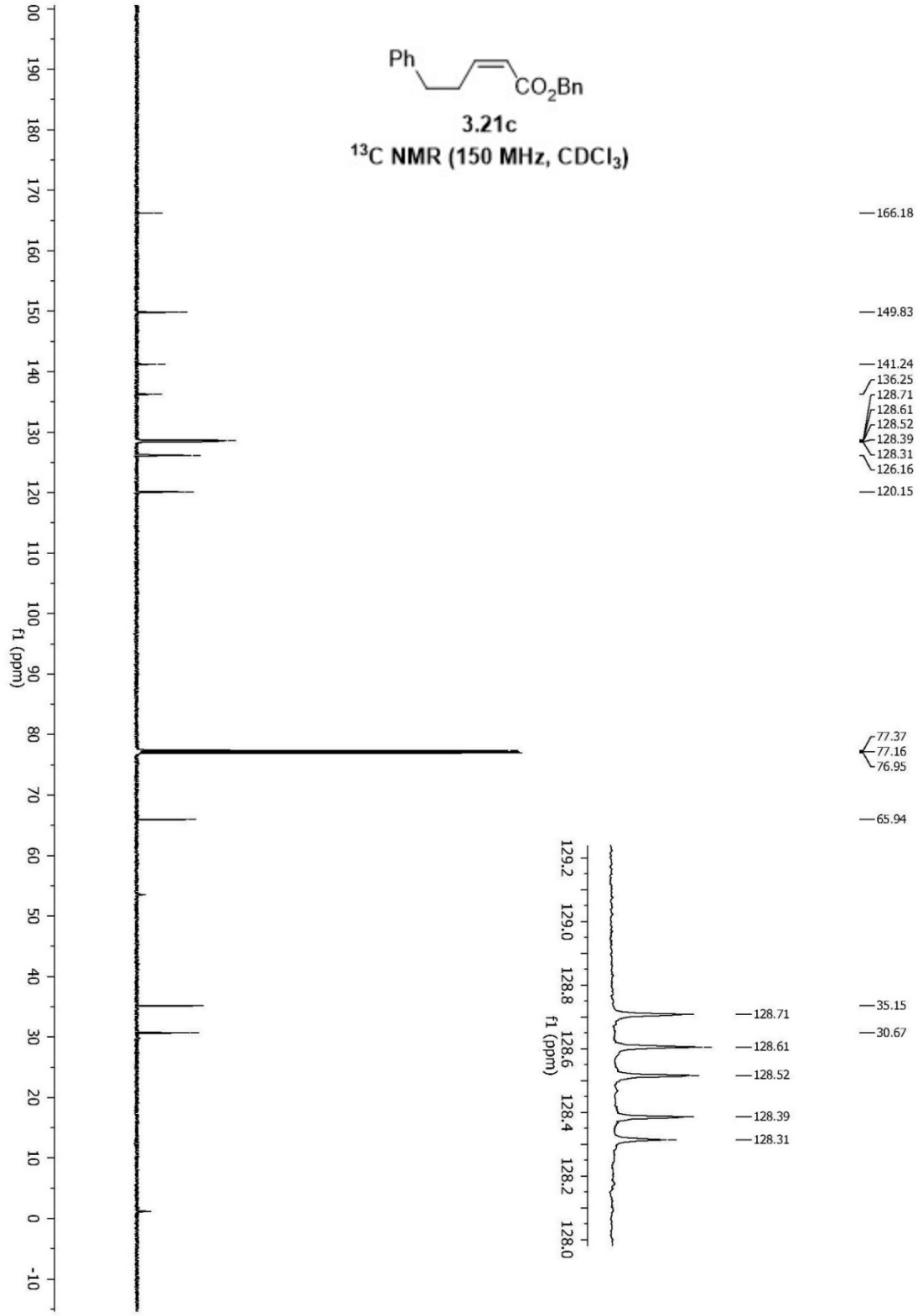
3.19

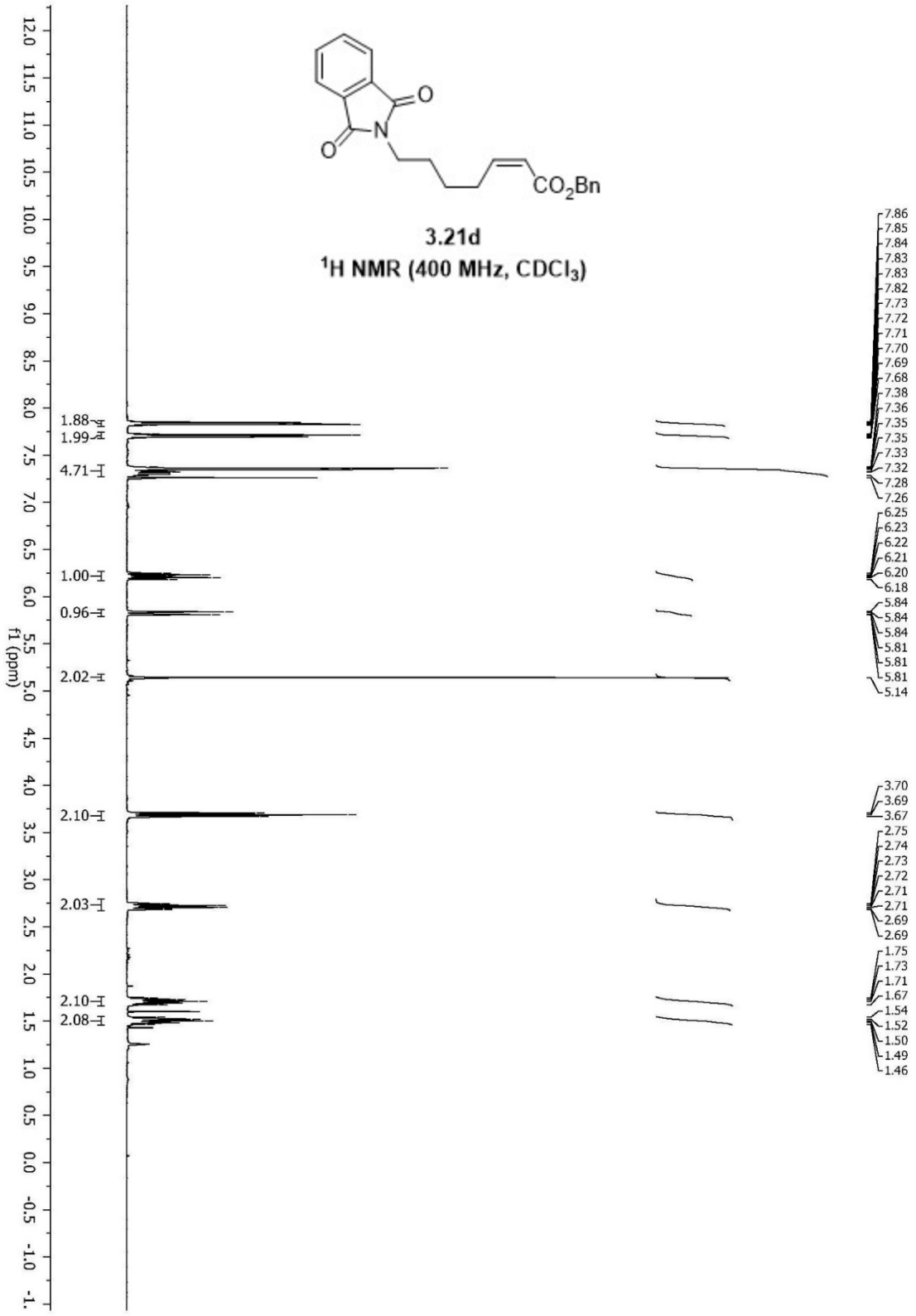
^{19}F NMR (470 MHz, THF-d_8)

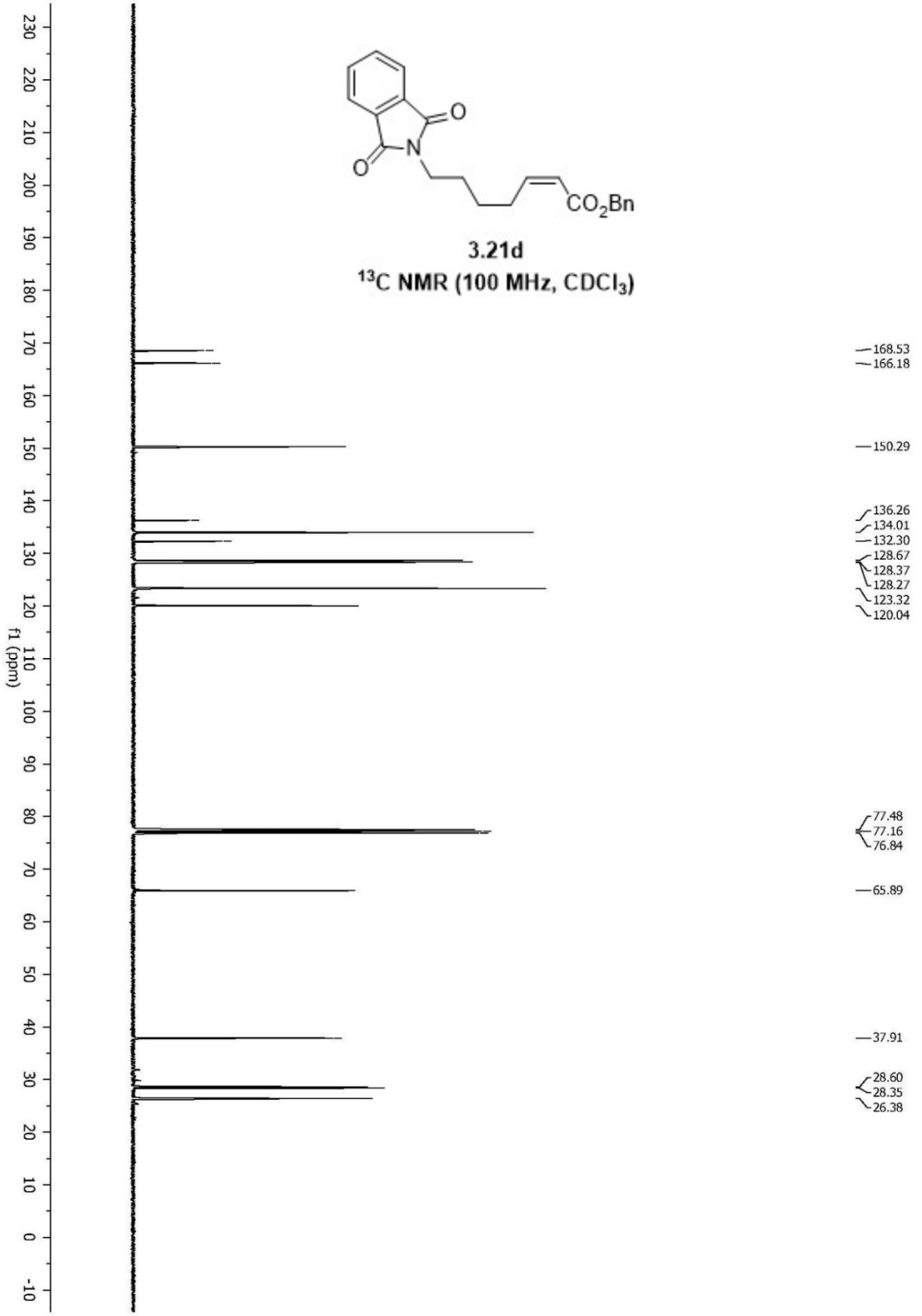

Br
CO2Bn
3.21b
1H NMR (400 MHz, CDCl3)
f1 (ppm)
5.02
1.00
0.97
1.96
2.01
2.05
2.06
6.38
7.38
7.37
7.36
7.34
7.34
7.33
7.32
7.31
7.26
6.28
6.26
6.25
6.24
6.23
6.21
5.85
5.84
5.84
5.82
5.81
5.81
5.16
3.41
3.39
3.37
2.70
2.68
2.66
2.64
1.88
1.86
1.85
1.83
1.81
1.50
1.48
1.46
1.44
1.42
1.40
1.36
1.34
1.32

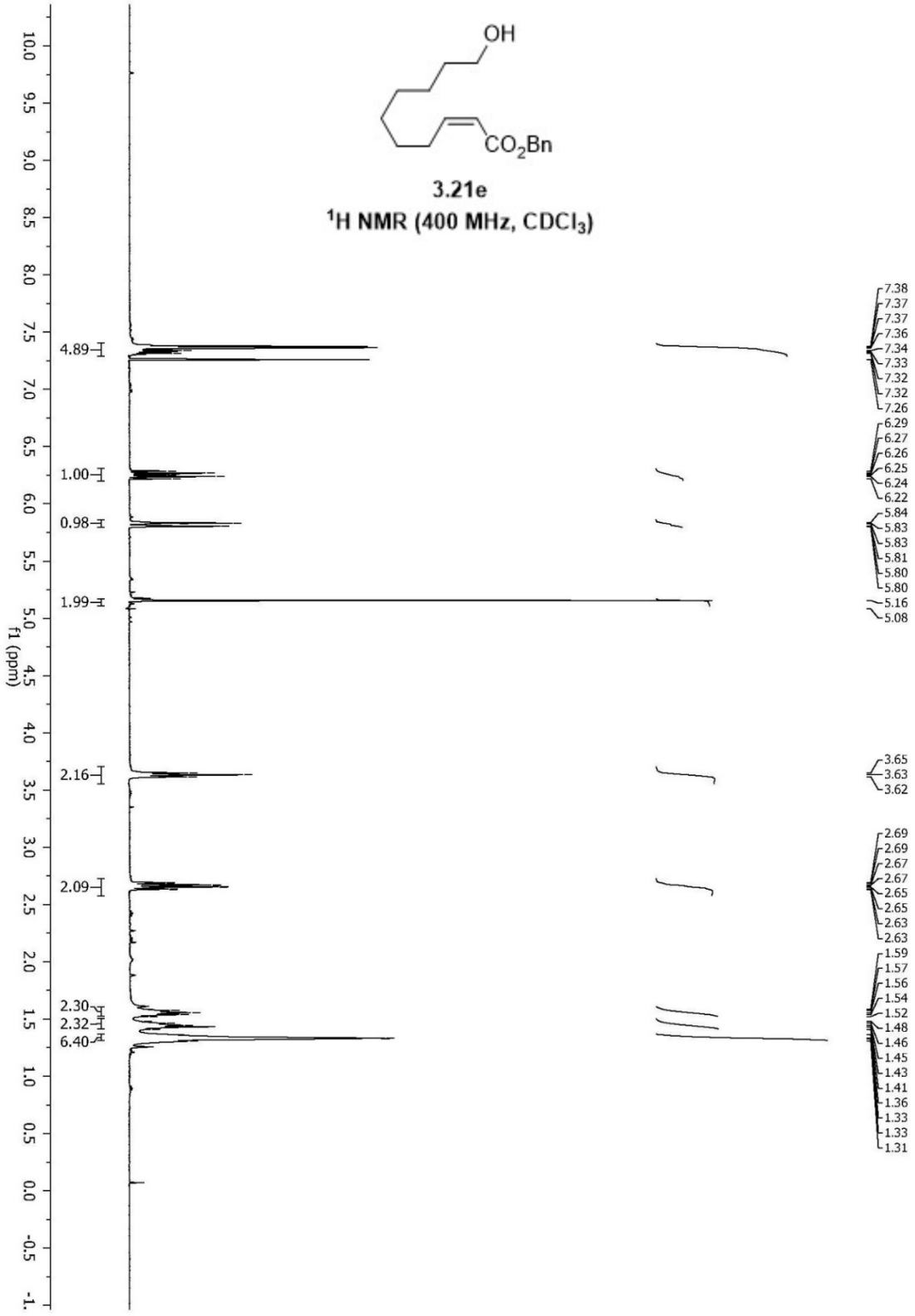

Br
CO2Bn
3.21b
13C NMR (100 MHz, CDCl3)
166.12
150.90
136.12
128.52
128.18
128.12
119.49
77.30
76.99
76.67
65.69
33.84
32.68
28.88
28.73
28.36
27.90
f1 (ppm)

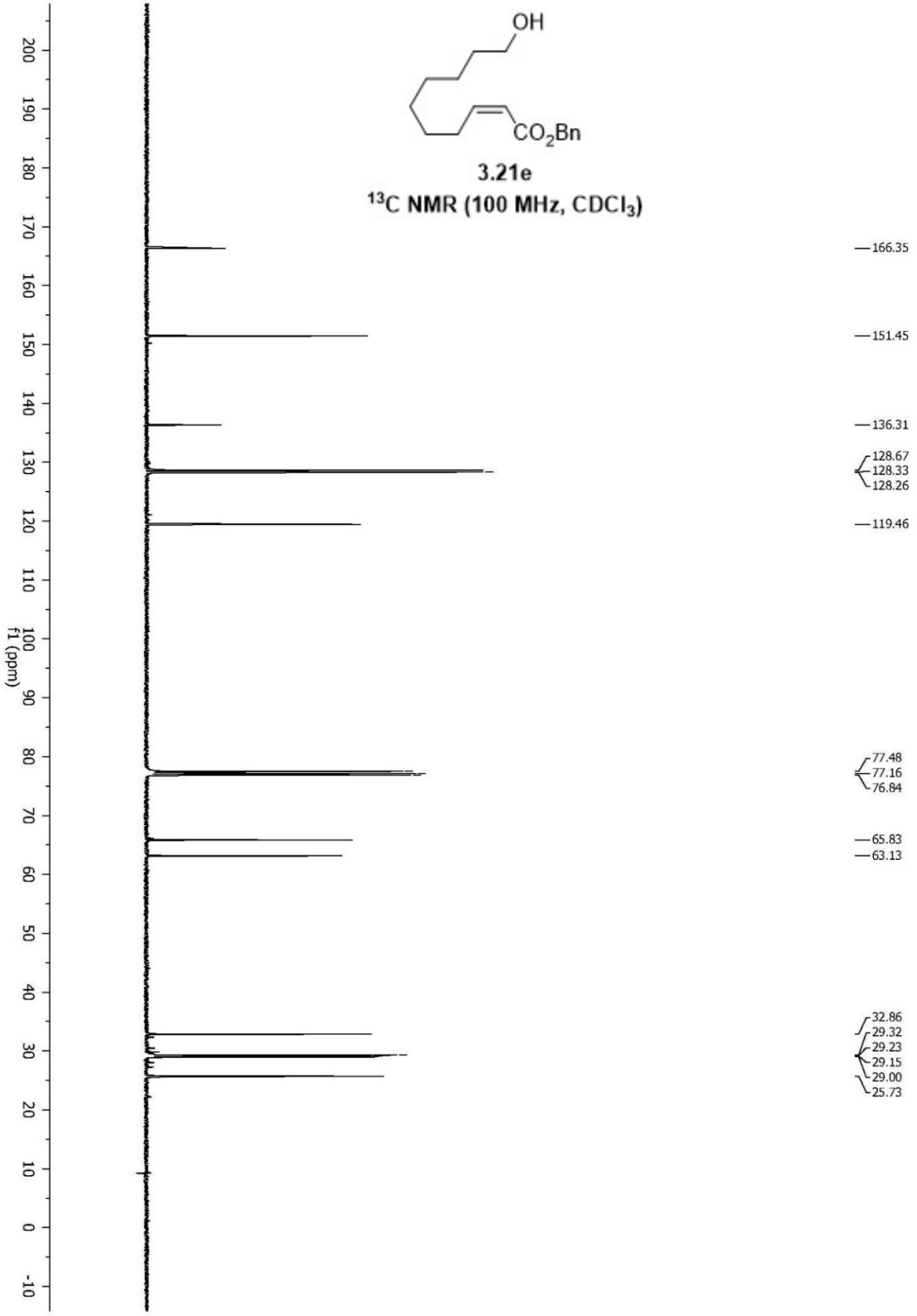

Ph
CO2Bn
3.21c
1H NMR (400 MHz, CDCl3)
f1 (ppm)
4.39
2.15
2.68
1.11
1.00
2.31
2.36
2.35
7.37
7.36
7.35
7.34
7.33
7.32
7.29
7.27
7.26
7.20
7.19
7.18
6.30
6.29
6.28
6.27
6.27
6.25
5.85
5.83
5.15
3.02
3.01
2.99
2.98
2.78
2.76
2.75

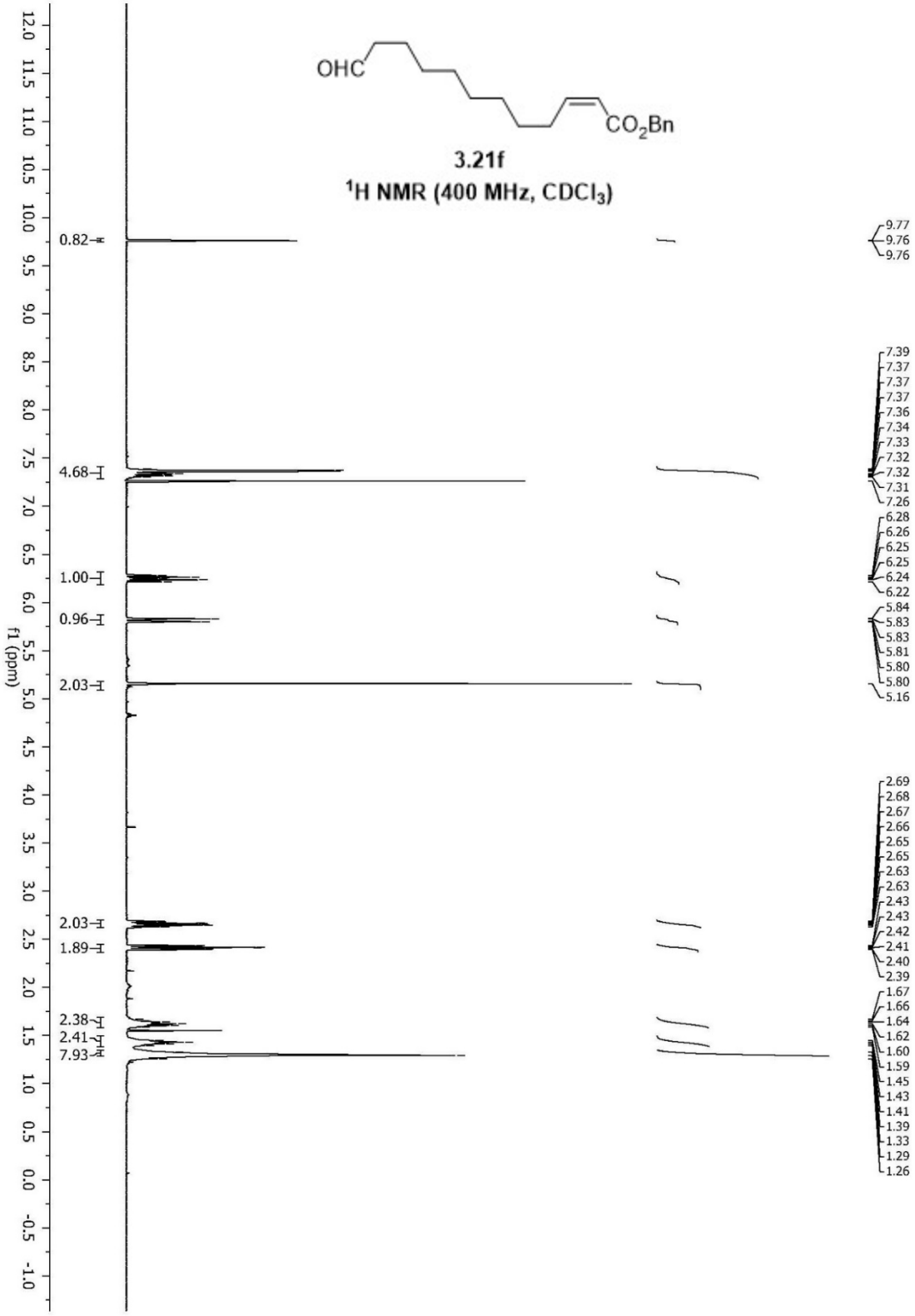

Ph
CO2Bn
3.21c
13C NMR (150 MHz, CDCl3)
166.18
149.83
141.24
136.25
128.71
128.61
128.52
128.39
128.31
126.16
120.15
77.37
77.16
76.95
65.94
35.15
30.67
f1 (ppm)
128.71
128.61
128.52
128.39
128.31

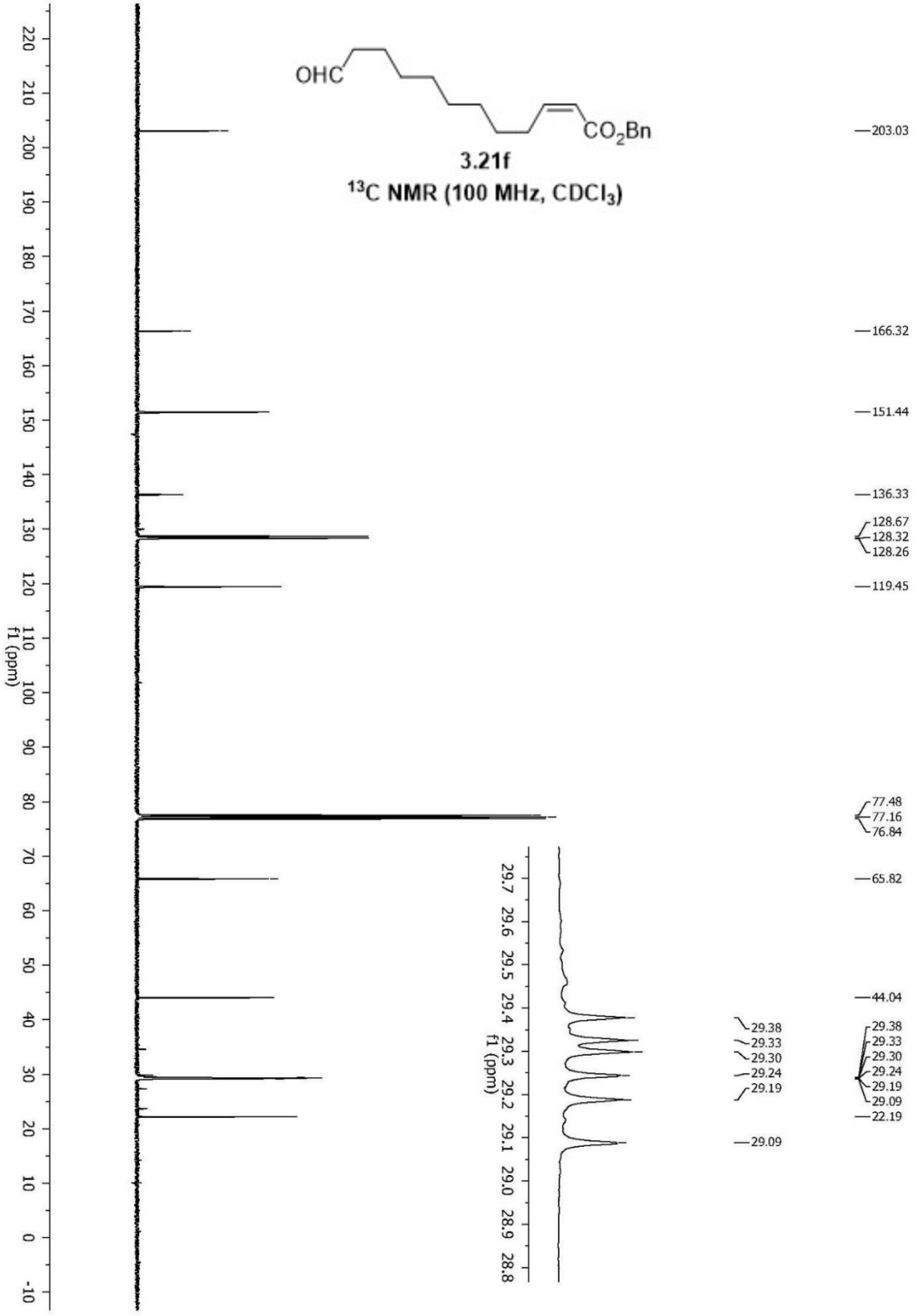

O
O
N
CO2Bn
3.21d
1H NMR (400 MHz, CDCl3)
f1 (ppm)
1.88
1.99
4.71
1.00
0.96
2.02
2.10
2.03
2.10
2.08
7.86
7.85
7.84
7.83
7.83
7.82
7.73
7.72
7.71
7.70
7.69
7.68
7.38
7.36
7.35
7.35
7.33
7.32
7.28
7.26
6.25
6.23
6.22
6.21
6.20
6.18
5.84
5.84
5.84
5.81
5.81
5.81
5.14
3.70
3.69
3.67
2.75
2.74
2.73
2.72
2.71
2.71
2.69
2.69
1.75
1.73
1.71
1.67
1.54
1.52
1.50
1.49
1.46

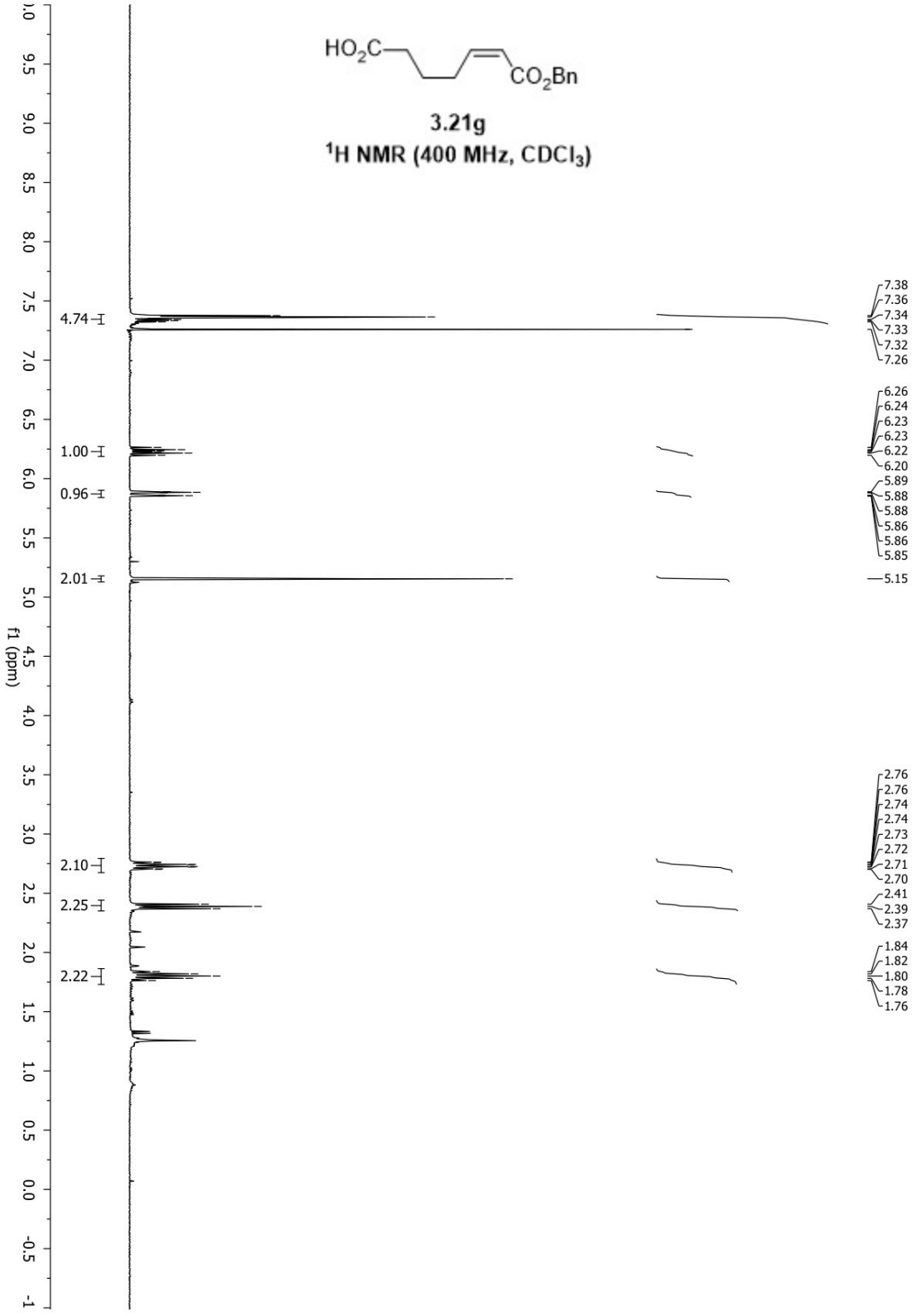

O
O
N
CO2Bn
3.21d
13C NMR (100 MHz, CDCl3)
168.53
166.18
150.29
136.26
134.01
132.30
128.67
128.37
128.27
123.32
120.04
77.48
77.16
76.84
65.89
37.91
28.60
28.35
26.38
f1 (ppm)

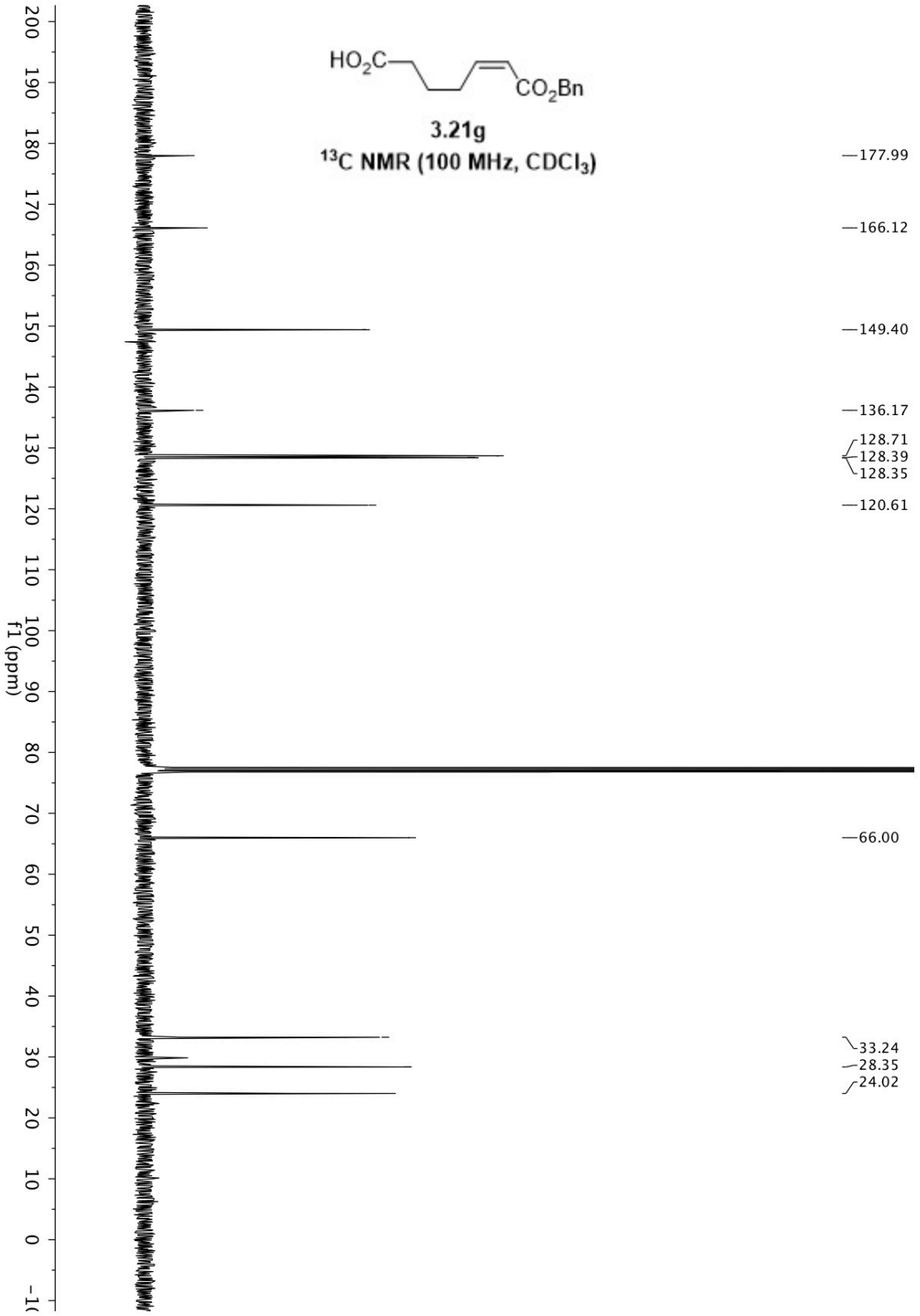

OH
CO2Bn
3.21e
1H NMR (400 MHz, CDCl3)
f1 (ppm)
4.89
1.00
0.98
1.99
2.16
2.09
2.30
2.32
6.40
7.38
7.37
7.37
7.36
7.34
7.33
7.32
7.32
7.26
6.29
6.27
6.26
6.25
6.24
6.22
5.84
5.83
5.83
5.81
5.80
5.80
5.16
5.08
3.65
3.63
3.62
2.69
2.69
2.67
2.67
2.65
2.65
2.63
2.63
1.59
1.57
1.56
1.54
1.52
1.48
1.46
1.45
1.43
1.41
1.36
1.33
1.33
1.31

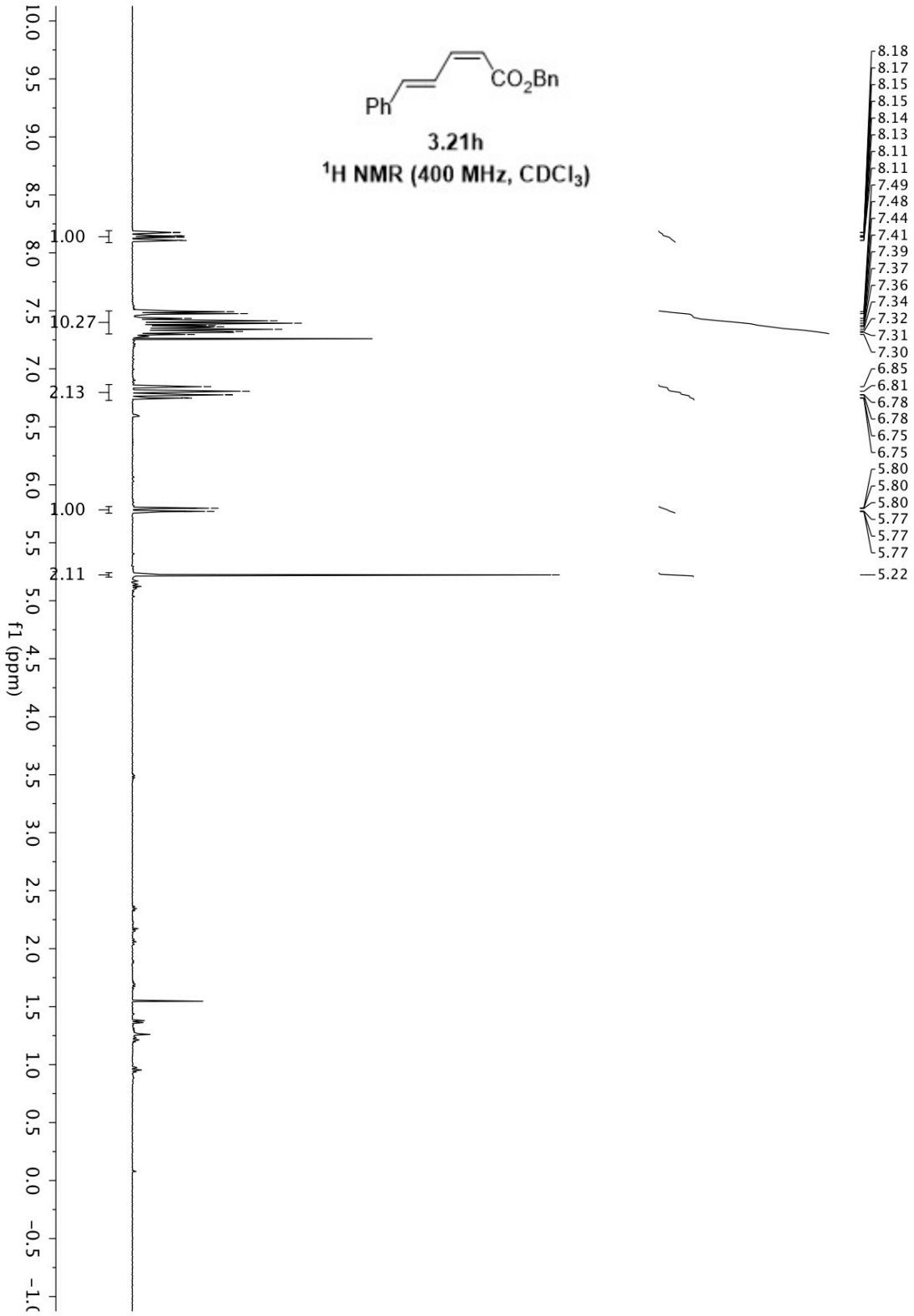

OH
CO2Bn
3.21e
13C NMR (100 MHz, CDCl3)
166.35
151.45
136.31
128.67
128.33
128.26
119.46
77.48
77.16
76.84
65.83
63.13
32.86
29.32
29.23
29.15
29.00
25.73
f1 (ppm)

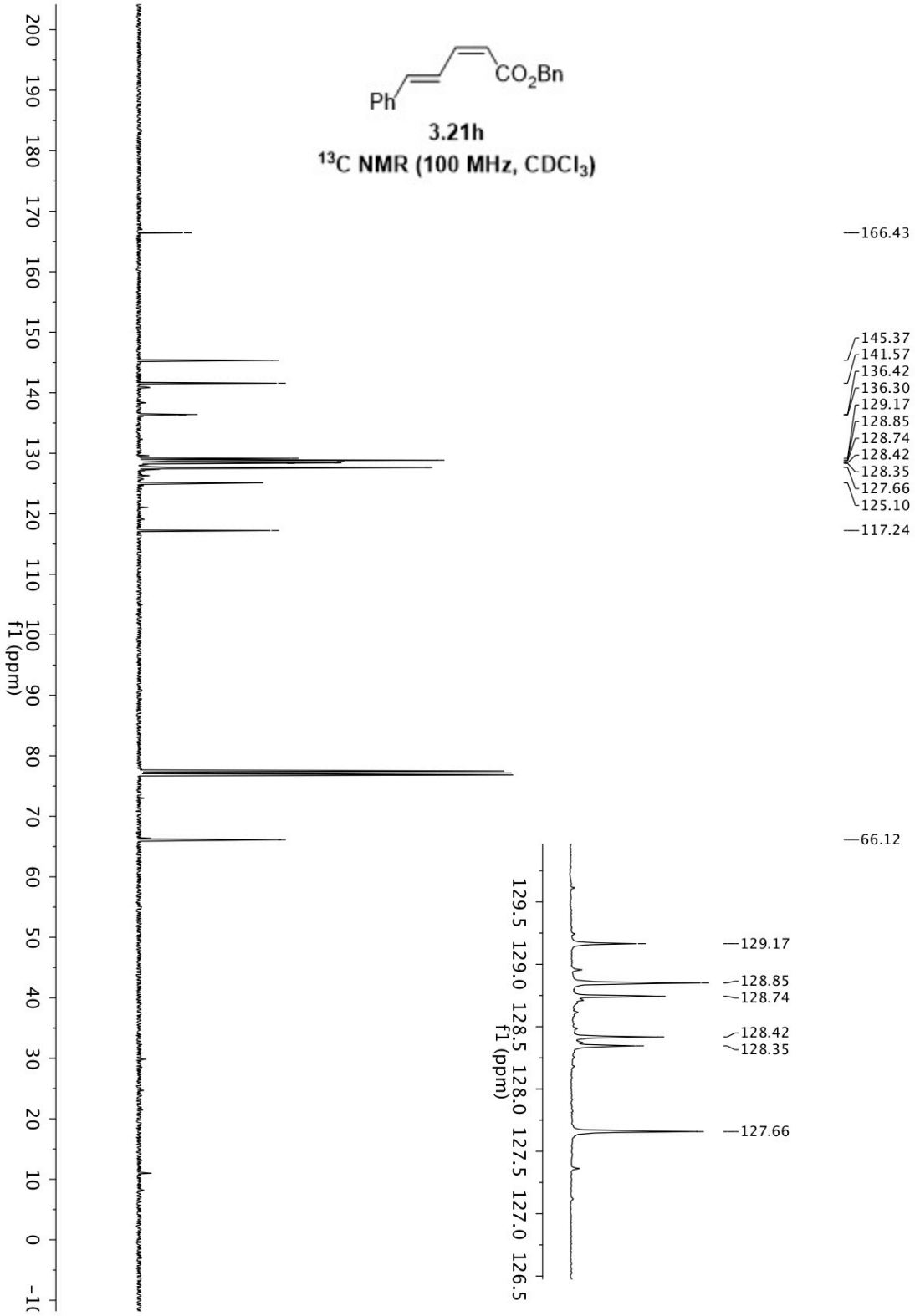

OHC
CO2Bn
3.21f
1H NMR (400 MHz, CDCl3)
f1 (ppm)
0.82
4.68
1.00
0.96
2.03
2.03
1.89
2.38
2.41
7.93
9.77
9.76
9.76
7.39
7.37
7.37
7.37
7.36
7.34
7.33
7.32
7.32
7.31
7.26
6.28
6.26
6.25
6.25
6.24
6.22
5.84
5.83
5.83
5.81
5.80
5.80
5.16
2.69
2.68
2.67
2.66
2.65
2.65
2.63
2.63
2.43
2.43
2.42
2.41
2.40
2.39
1.67
1.66
1.64
1.62
1.60
1.59
1.45
1.43
1.41
1.39
1.33
1.29
1.26

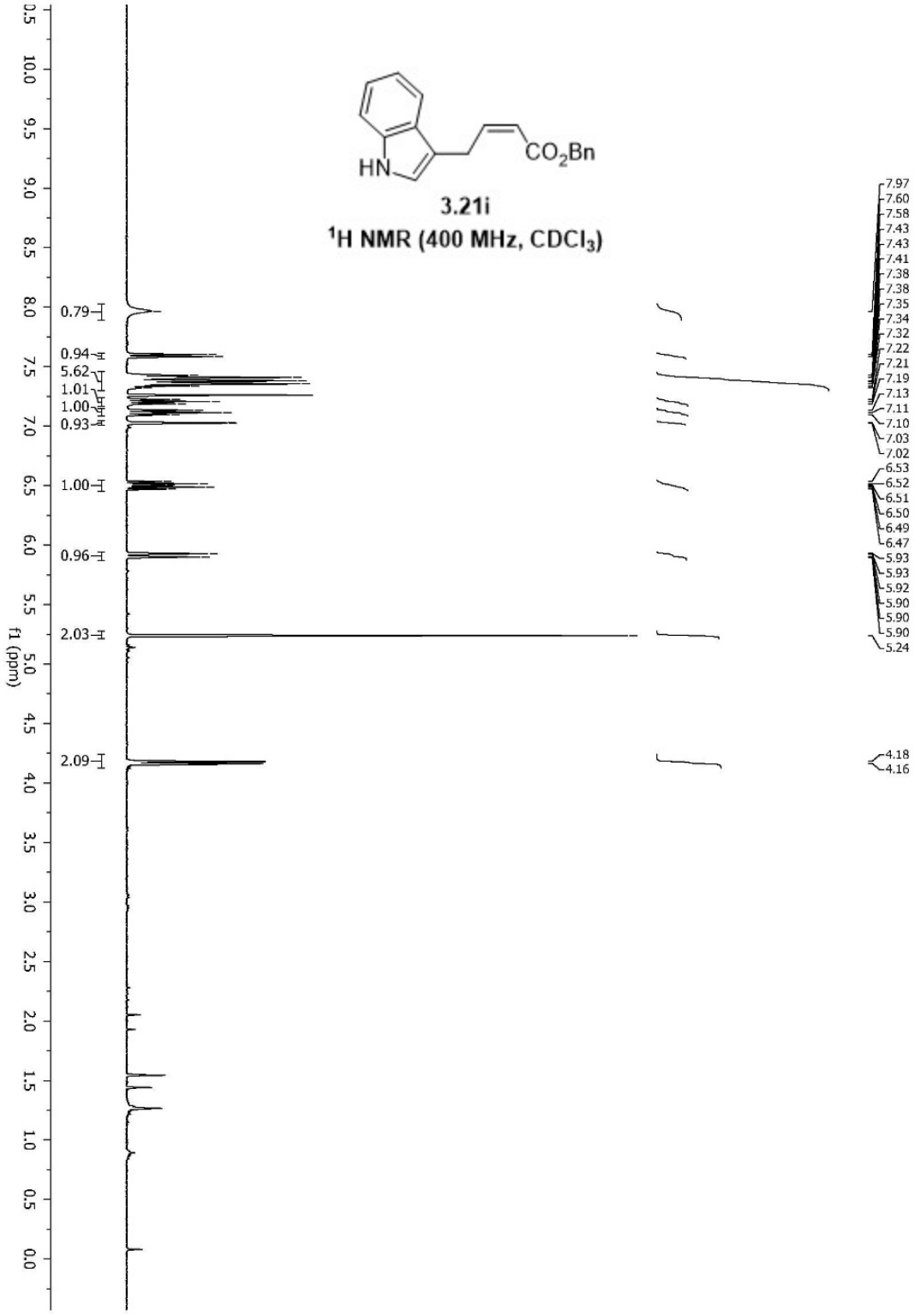

OHC
CO2Bn
3.21f
13C NMR (100 MHz, CDCl3)
f1 (ppm)
203.03
166.32
151.44
136.33
128.67
128.32
128.26
119.45
77.48
77.16
76.84
65.82
44.04
29.38
29.33
29.30
29.24
29.19
29.09
22.19

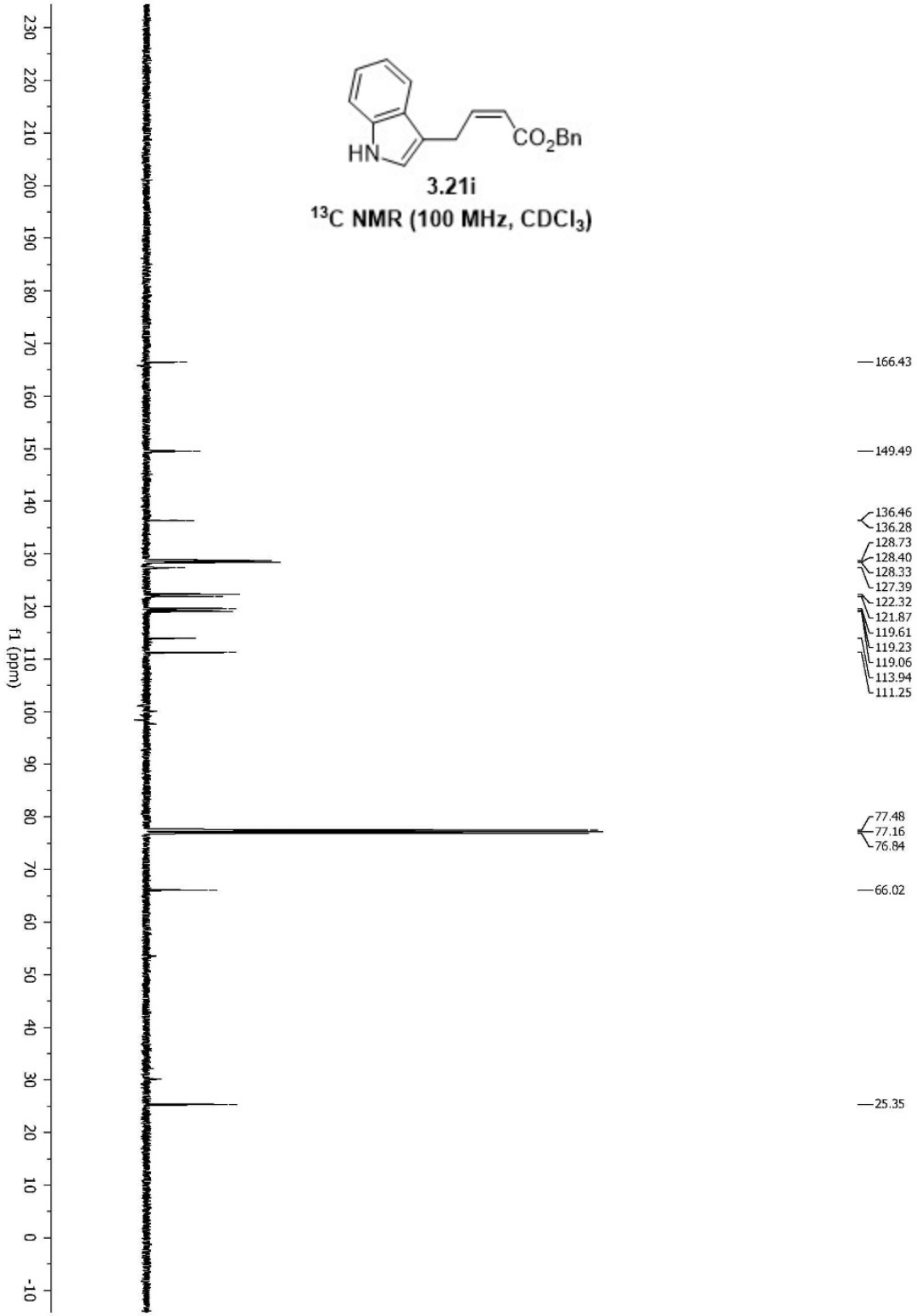

HO2C
CO2Bn
3.21g
1H NMR (400 MHz, CDCl3)
f1 (ppm)
4.74
1.00
0.96
2.01
2.10
2.25
2.22
7.38
7.36
7.34
7.33
7.32
7.26
6.26
6.24
6.23
6.23
6.22
6.20
5.89
5.88
5.88
5.86
5.86
5.85
5.15
2.76
2.76
2.74
2.74
2.73
2.72
2.71
2.70
2.41
2.39
2.37
1.84
1.82
1.80
1.78
1.76

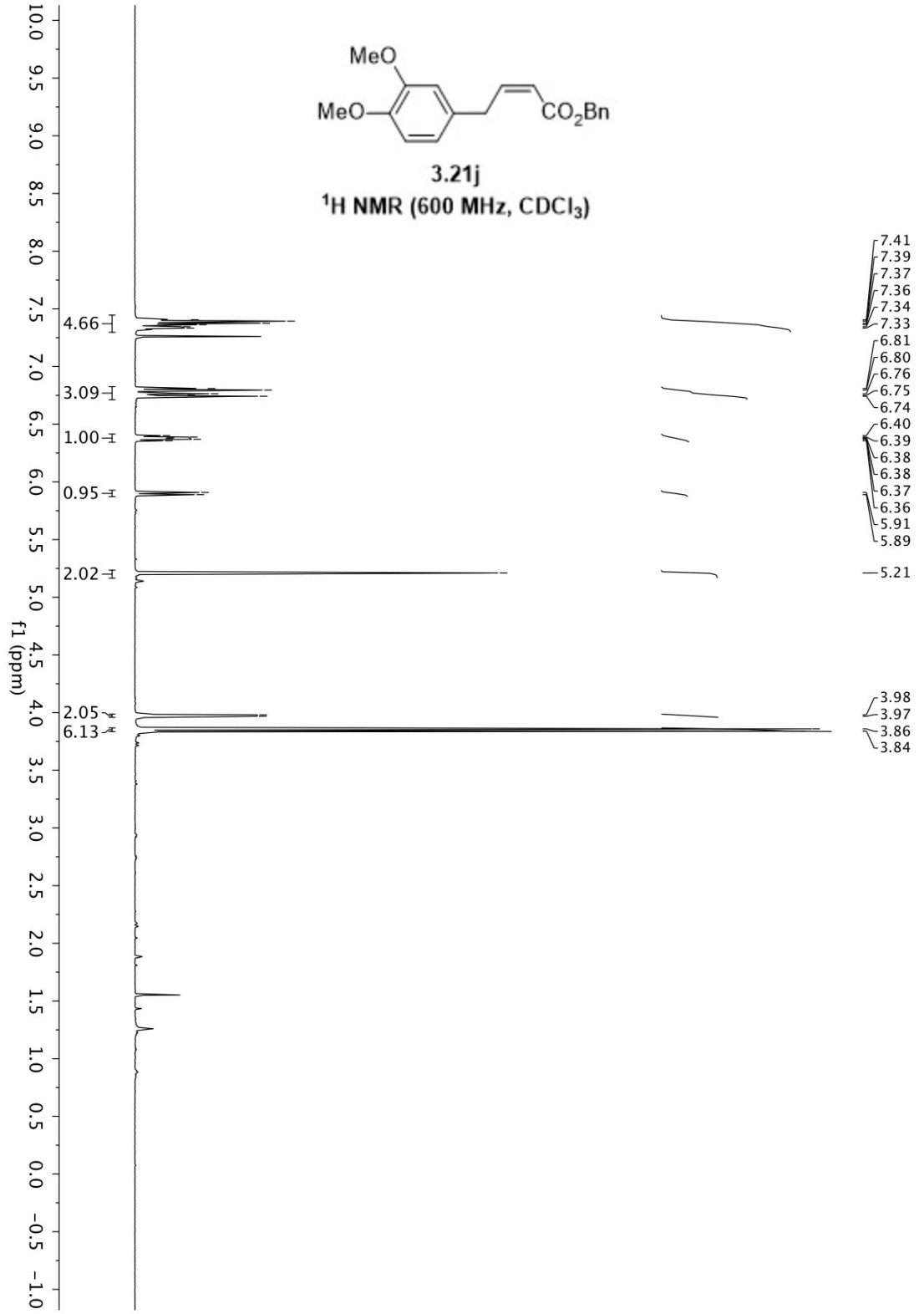

HO2C
CO2Bn
3.21g
13C NMR (100 MHz, CDCl3)
177.99
166.12
149.40
136.17
128.71
128.39
128.35
120.61
66.00
33.24
28.35
24.02
f1 (ppm)

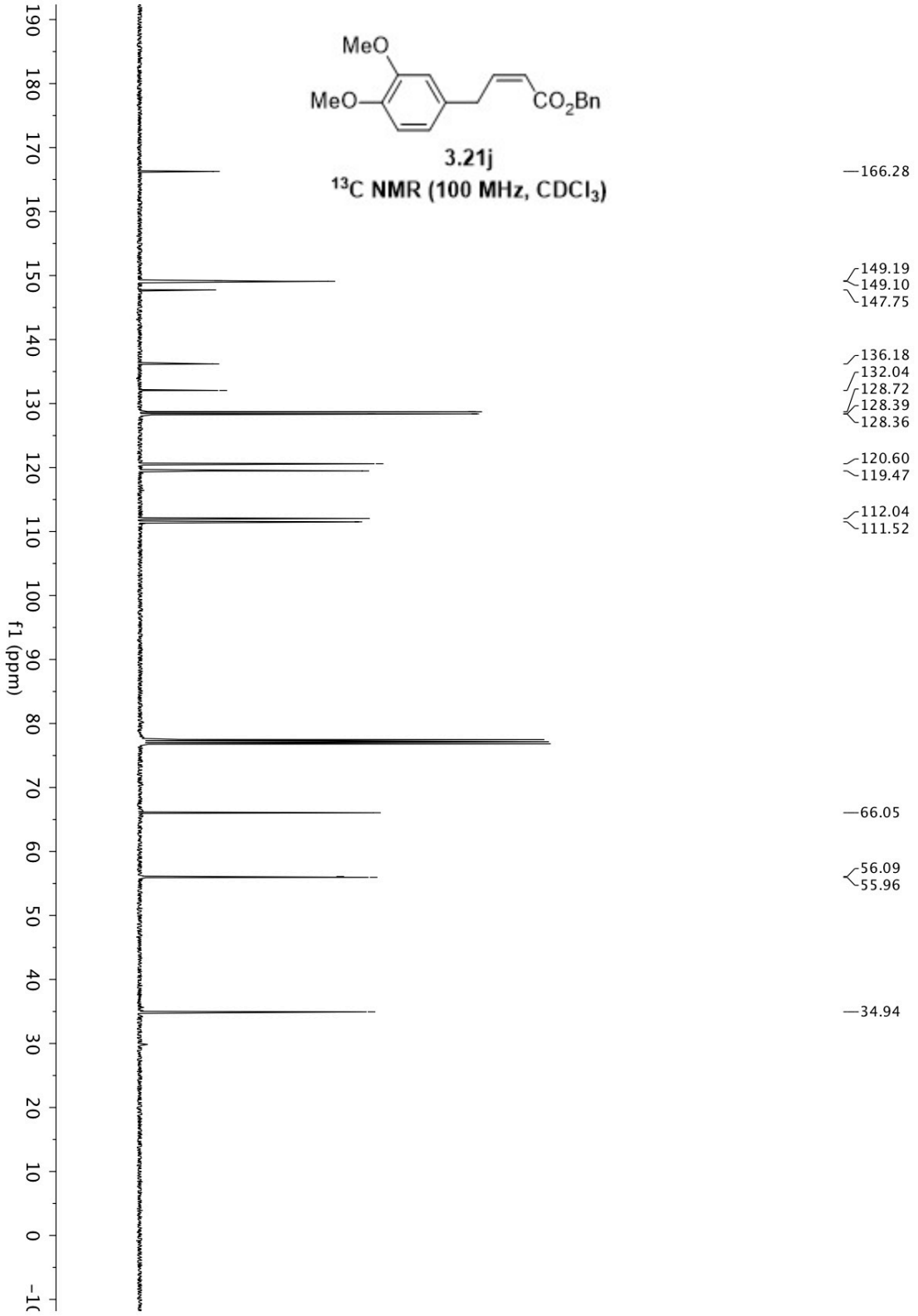

Ph
CO2Bn
3.21h
1H NMR (400 MHz, CDCl3)
1.00
10.27
2.13
1.00
2.11
8.18
8.17
8.15
8.15
8.14
8.13
8.11
8.11
7.49
7.48
7.44
7.41
7.39
7.37
7.36
7.34
7.32
7.31
7.30
6.85
6.81
6.78
6.78
6.75
6.75
5.80
5.80
5.80
5.77
5.77
5.77
5.22
f1 (ppm)

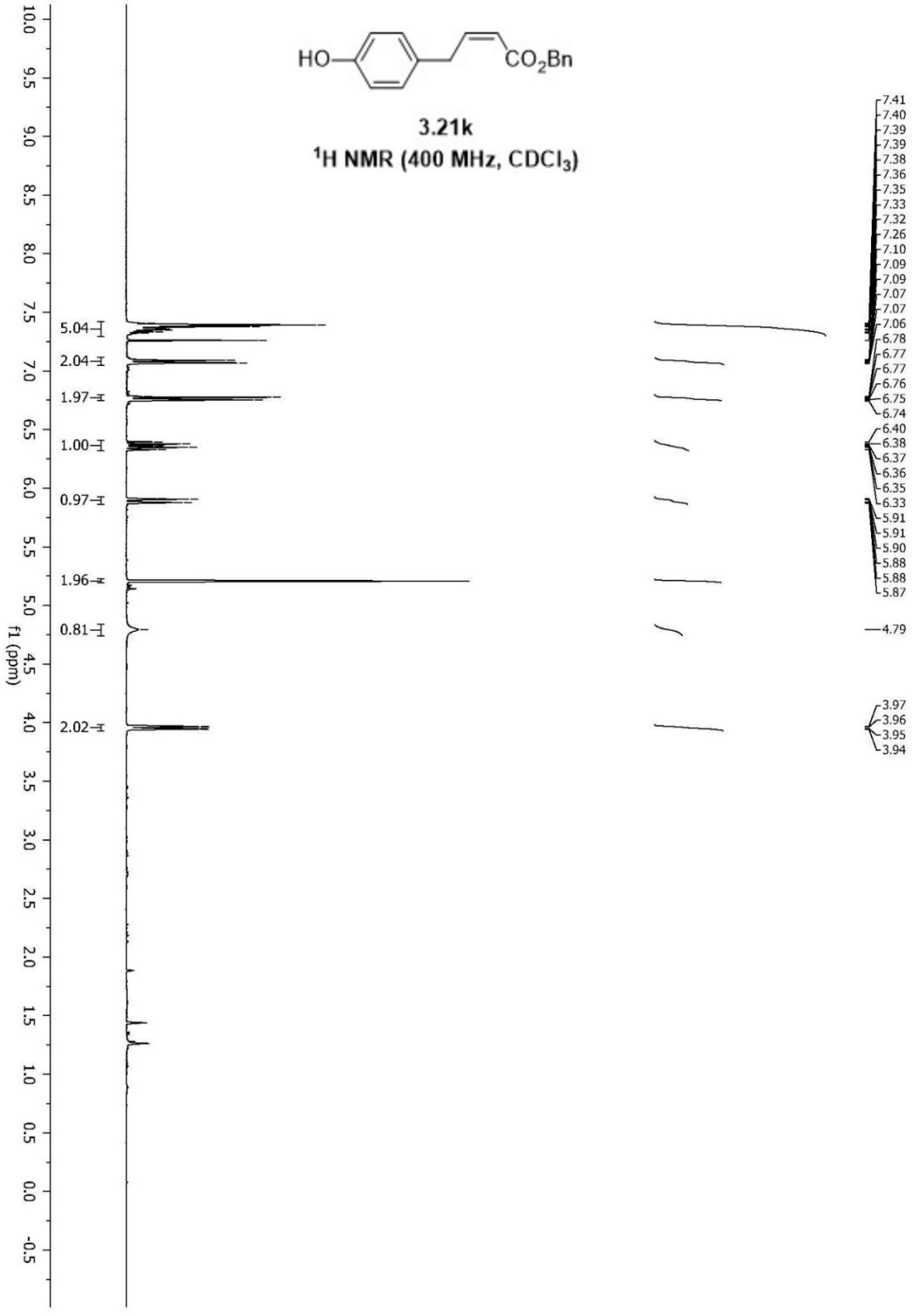

Ph
CO2Bn
3.21h
13C NMR (100 MHz, CDCl3)
166.43
145.37
141.57
136.42
136.30
129.17
128.85
128.74
128.42
128.35
127.66
125.10
117.24
66.12
129.17
128.85
128.74
128.42
128.35
127.66
f1 (ppm)
f1 (ppm)

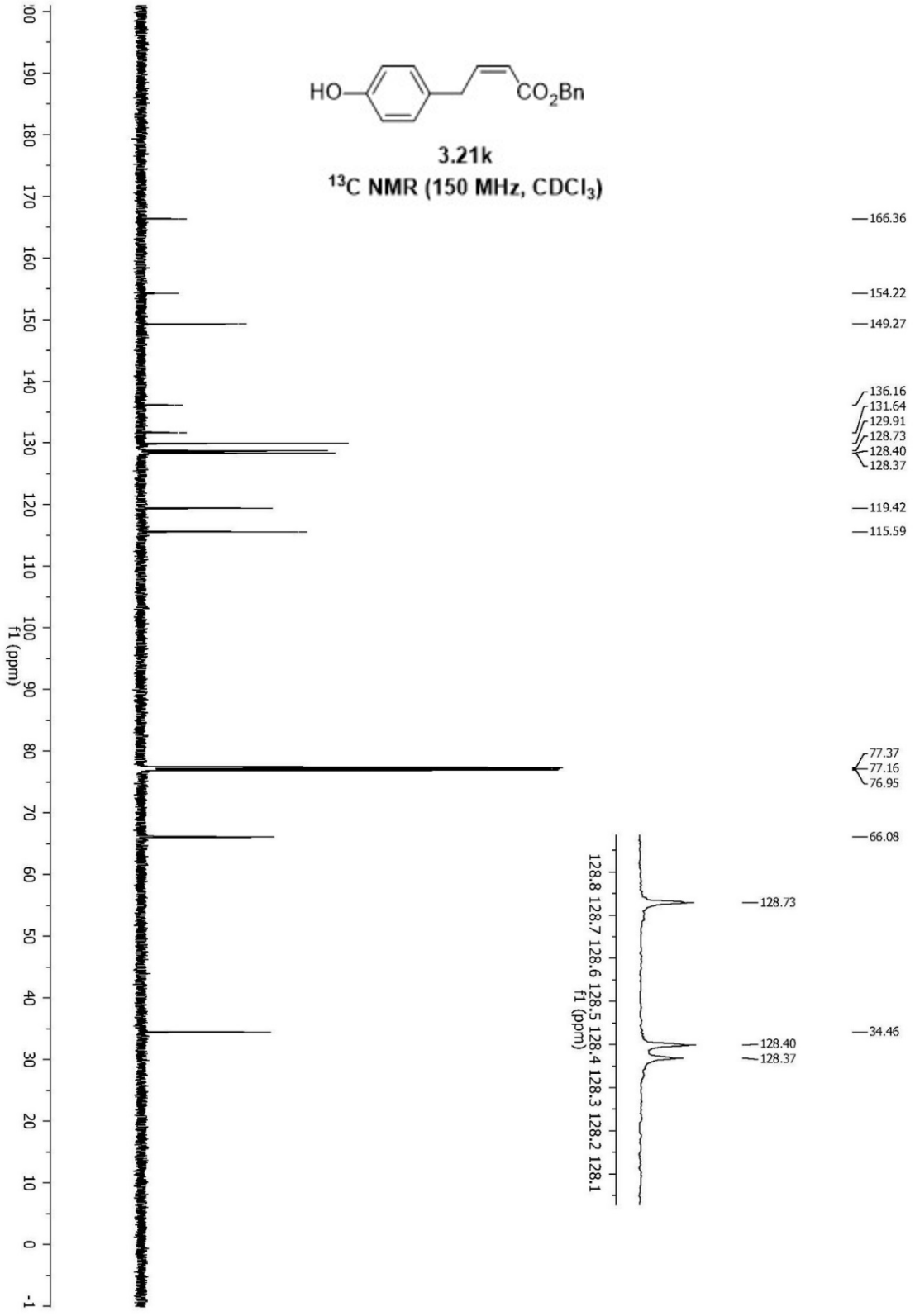

HN
CO2Bn
3.21i
1H NMR (400 MHz, CDCl3)
0.79
0.94
5.62
1.01
1.00
0.93
1.00
0.96
2.03
2.09
7.97
7.60
7.58
7.43
7.43
7.41
7.38
7.38
7.35
7.34
7.32
7.22
7.21
7.19
7.13
7.11
7.10
7.03
7.02
6.53
6.52
6.51
6.50
6.49
6.47
5.93
5.93
5.92
5.90
5.90
5.90
5.24
4.18
4.16
f1 (ppm)

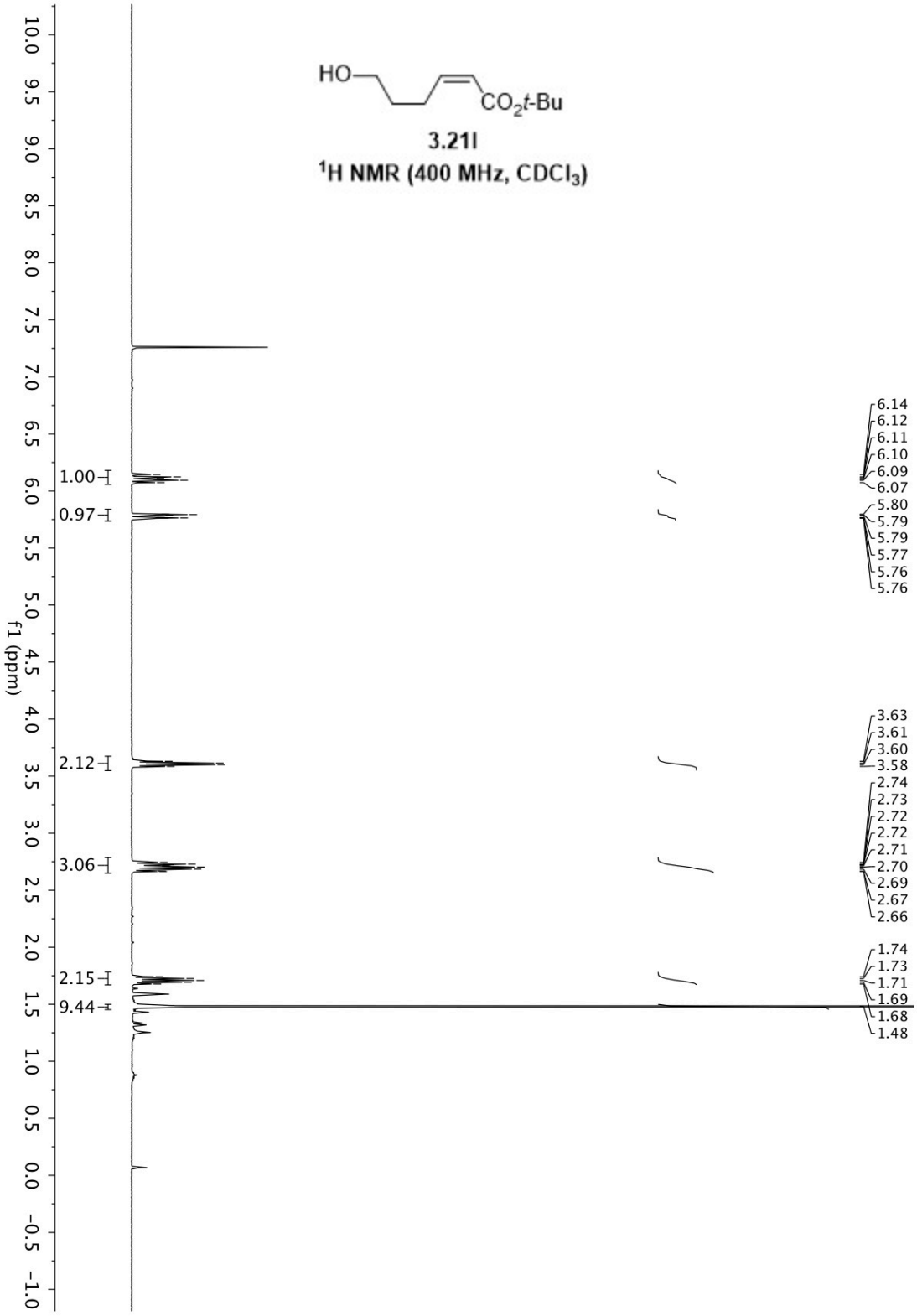

HN
CO2Bn
3.21i
13C NMR (100 MHz, CDCl3)
f1 (ppm)
166.43
149.49
136.46
136.28
128.73
128.40
128.33
127.39
122.32
121.87
119.61
119.23
119.06
113.94
111.25
77.48
77.16
76.84
66.02
25.35

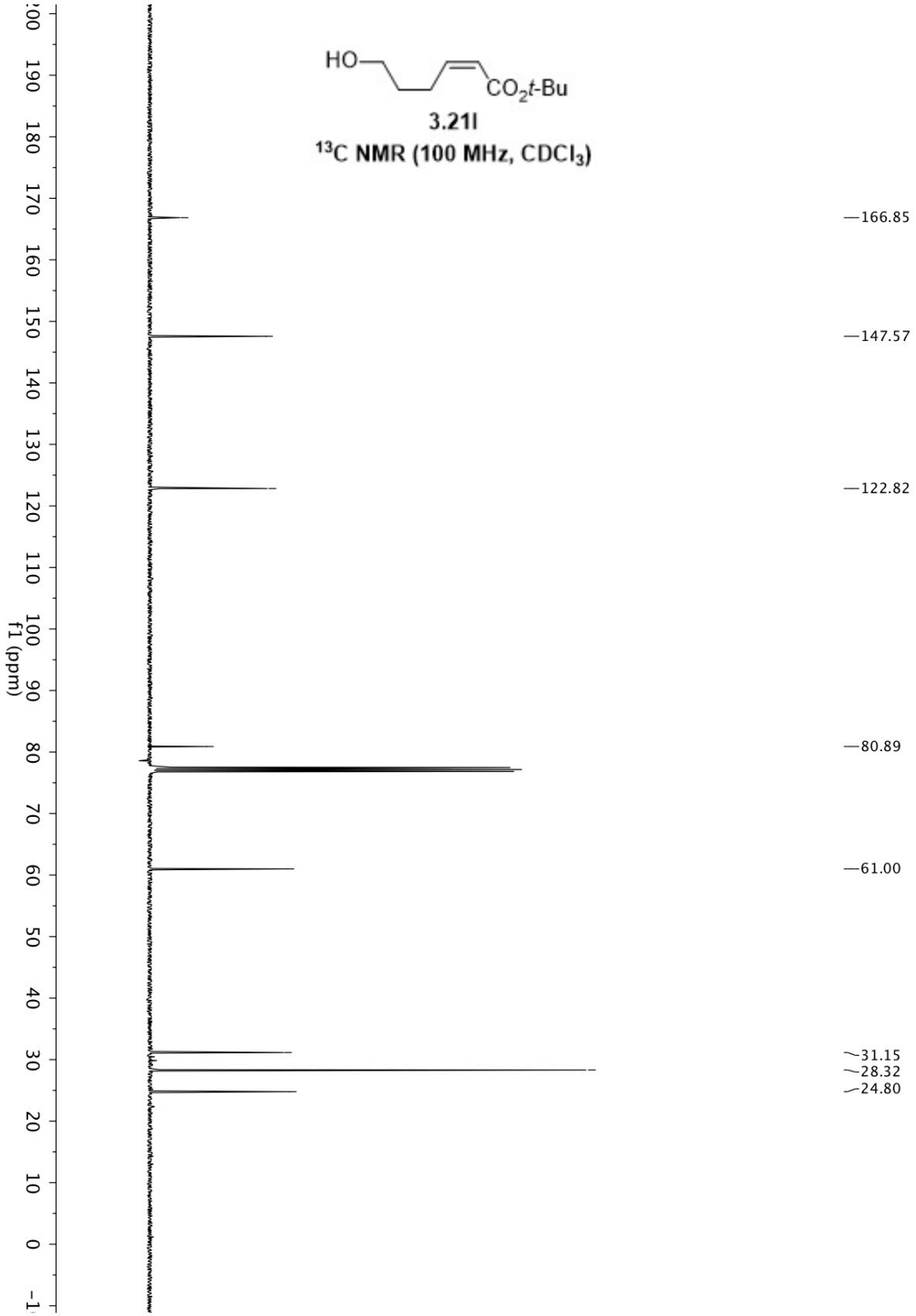

MeO
MeO
CO2Bn
3.21j
1H NMR (600 MHz, CDCl3)
f1 (ppm)
4.66
3.09
1.00
0.95
2.02
2.05
6.13
7.41
7.39
7.37
7.36
7.34
7.33
6.81
6.80
6.76
6.75
6.74
6.40
6.39
6.38
6.38
6.37
6.36
5.91
5.89
5.21
3.98
3.97
3.86
3.84

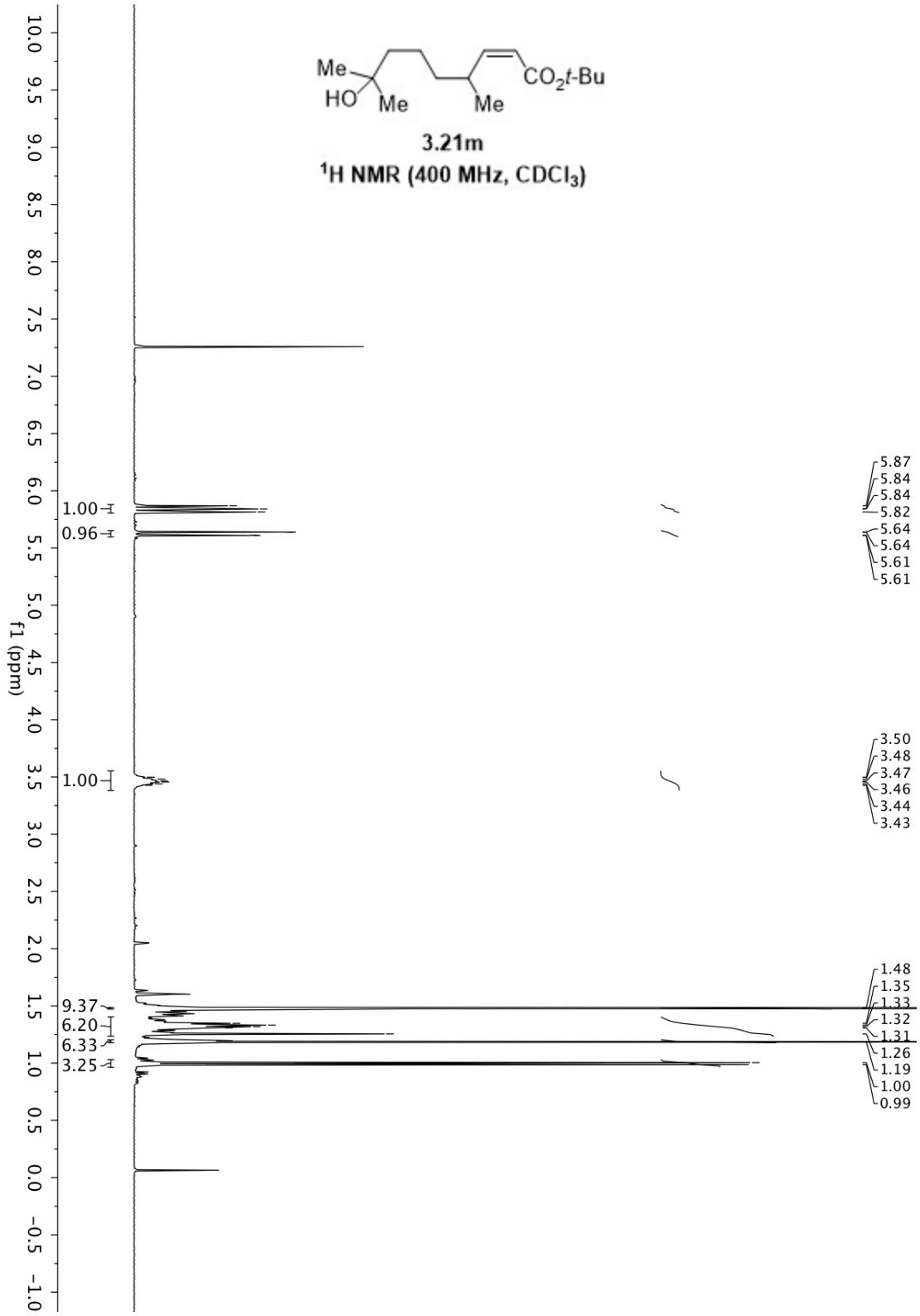

MeO
MeO
CO2Bn
3.21j
13C NMR (100 MHz, CDCl3)
166.28
149.19
149.10
147.75
136.18
132.04
128.72
128.39
128.36
120.60
119.47
112.04
111.52
66.05
56.09
55.96
34.94
f1 (ppm)

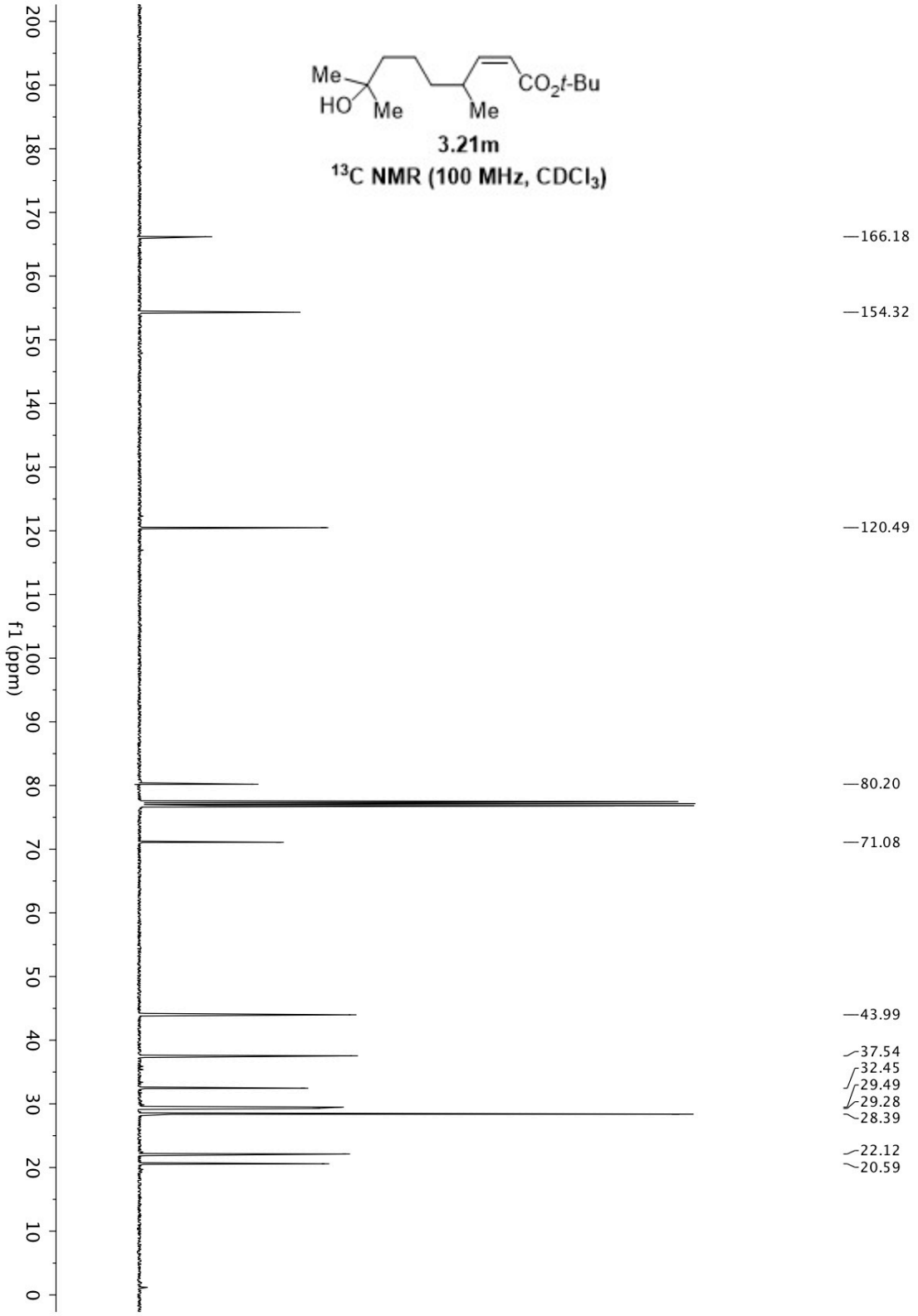

HO
CO2Bn
3.21k
1H NMR (400 MHz, CDCl3)
f1 (ppm)
5.04
2.04
1.97
1.00
0.97
1.96
0.81
2.02
7.41
7.40
7.39
7.39
7.38
7.36
7.35
7.33
7.32
7.26
7.10
7.09
7.09
7.07
7.07
7.06
6.78
6.77
6.77
6.76
6.75
6.74
6.40
6.38
6.37
6.36
6.35
6.33
5.91
5.91
5.90
5.88
5.88
5.87
4.79
3.97
3.96
3.95
3.94

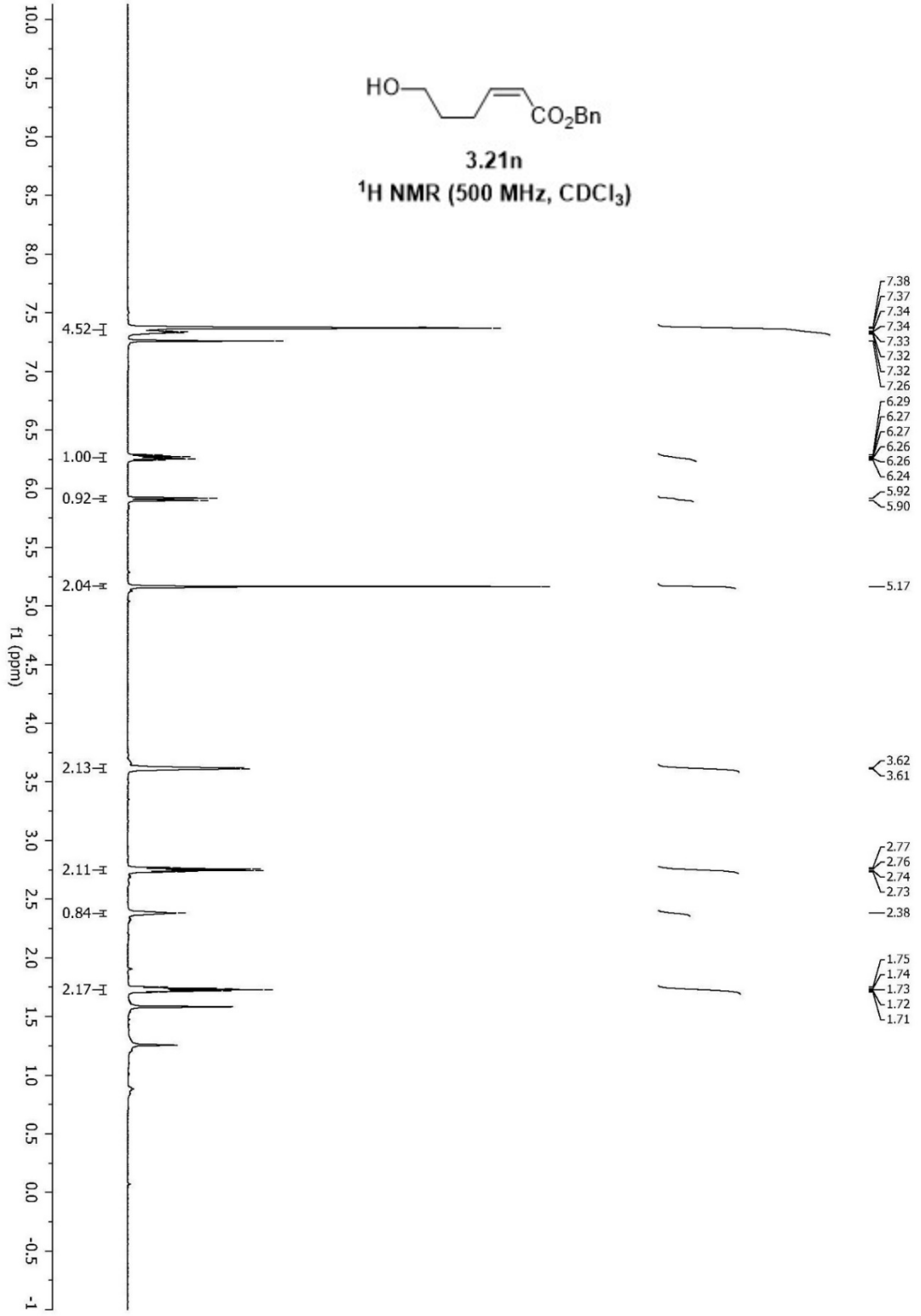

HO
CO2Bn
3.21k
13C NMR (150 MHz, CDCl3)
166.36
154.22
149.27
136.16
131.64
129.91
128.73
128.40
128.37
119.42
115.59
77.37
77.16
76.95
66.08
34.46
f1 (ppm)
128.8 128.7 128.6 128.5 128.4 128.3 128.2 128.1
128.73
128.40
128.37

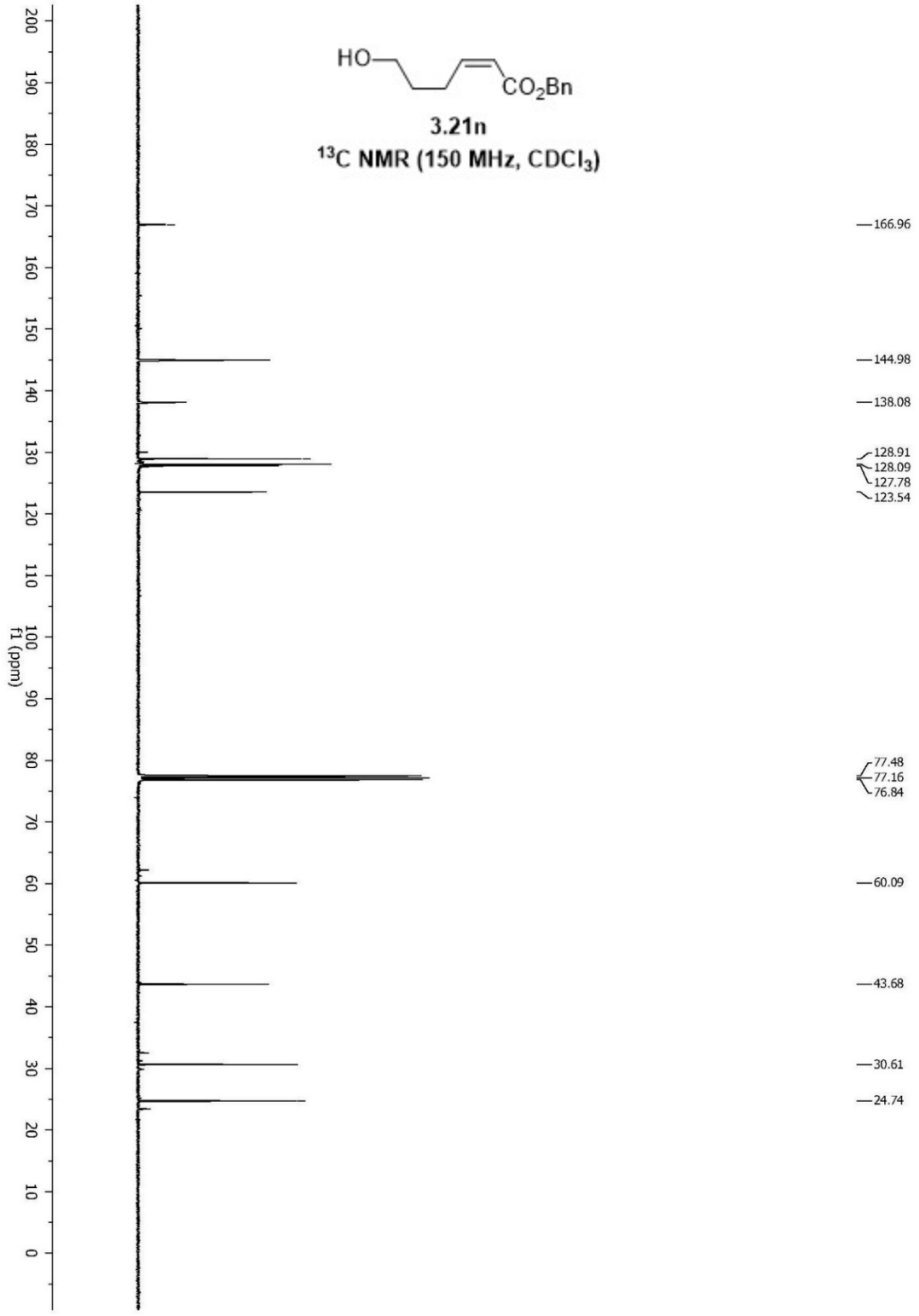

HO
CO2t-Bu
3.21l
1H NMR (400 MHz, CDCl3)
f1 (ppm)
1.00
0.97
2.12
3.06
2.15
9.44
6.14
6.12
6.11
6.10
6.09
6.07
5.80
5.79
5.79
5.77
5.76
5.76
3.63
3.61
3.60
3.58
2.74
2.73
2.72
2.72
2.71
2.70
2.69
2.67
2.66
1.74
1.73
1.71
1.69
1.68
1.48

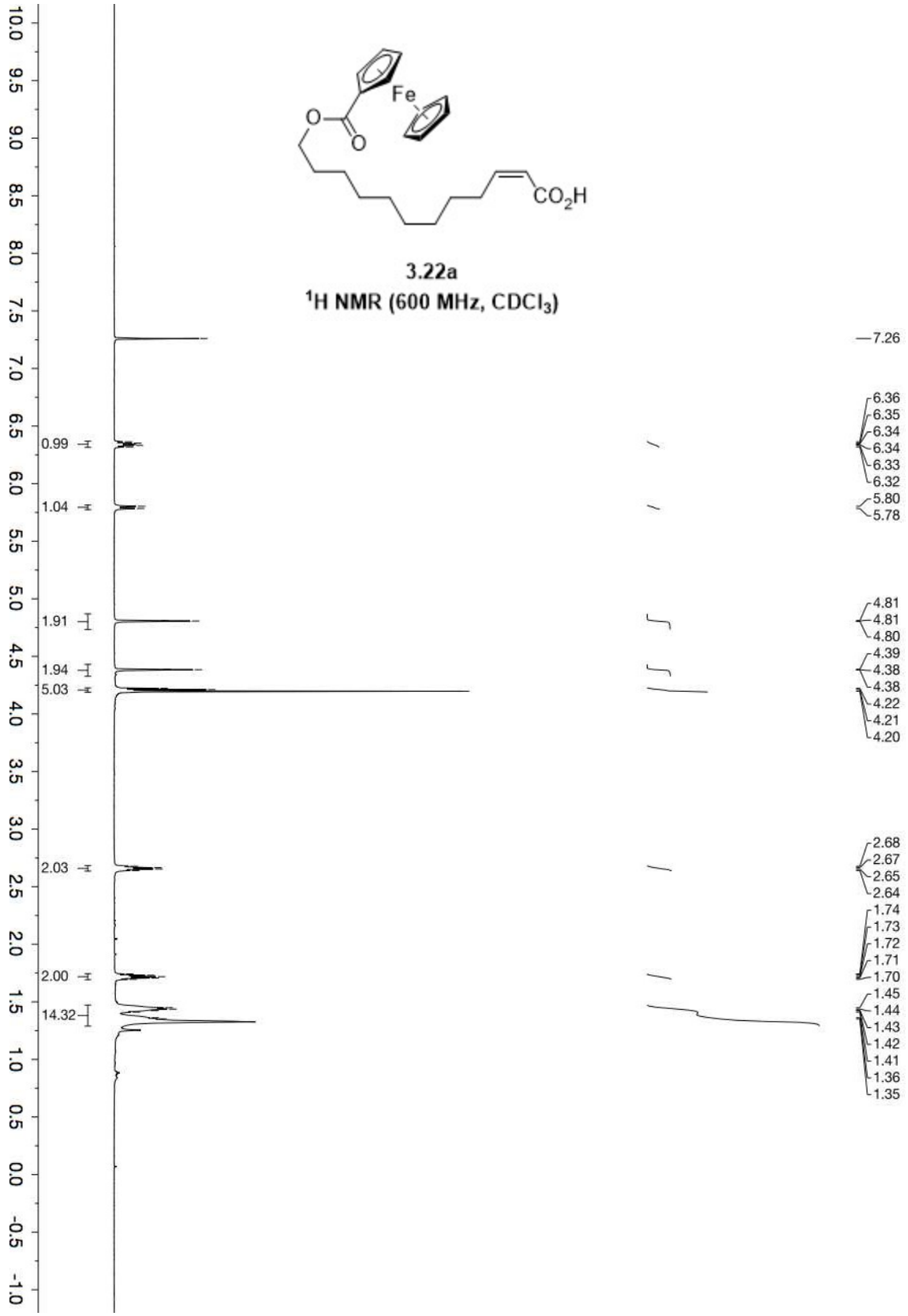

HO
CO2t-Bu
3.21l
13C NMR (100 MHz, CDCl3)
166.85
147.57
122.82
80.89
61.00
31.15
28.32
24.80
f1 (ppm)

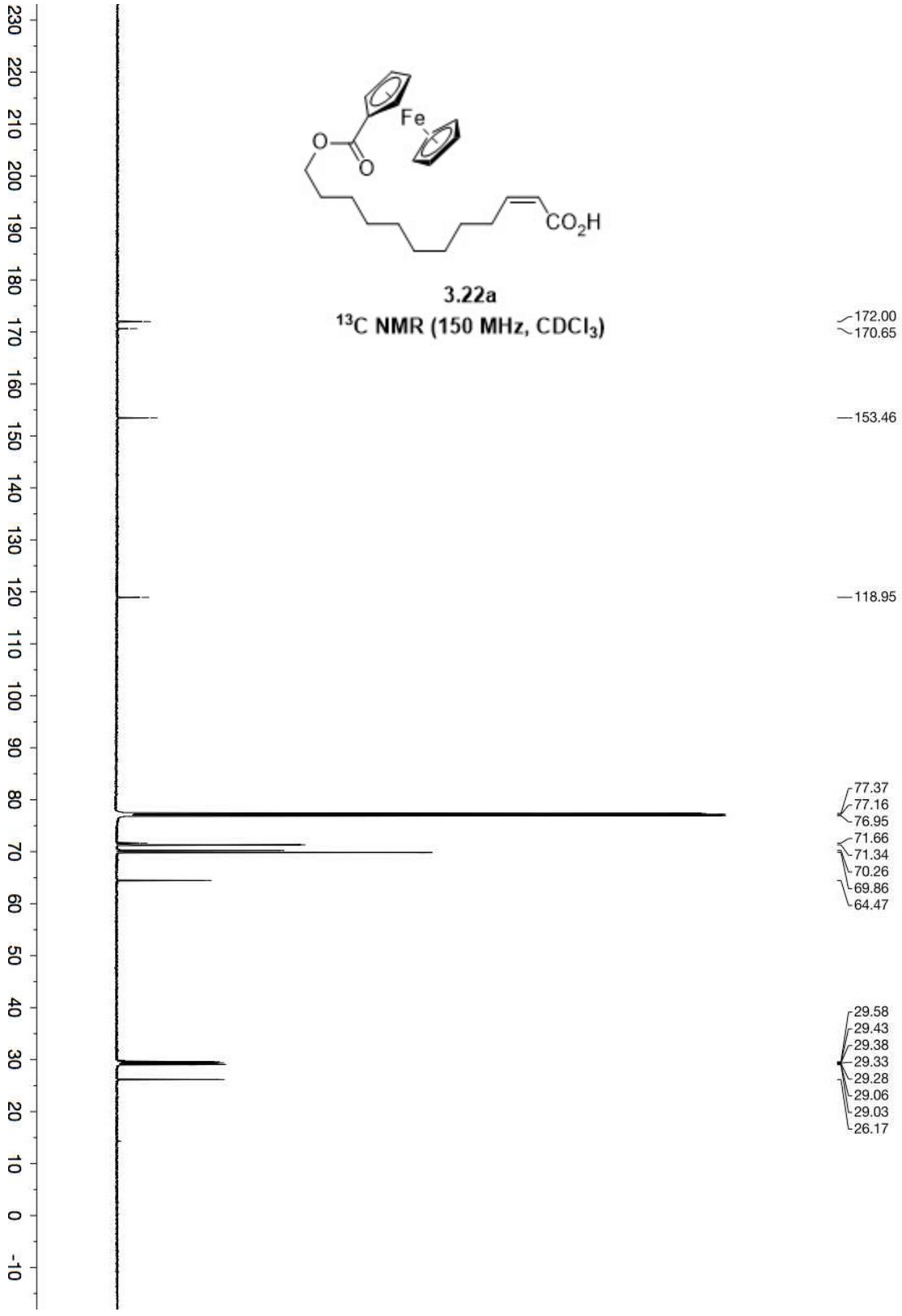

Me
HO
Me
Me
CO2t-Bu
3.21m
1H NMR (400 MHz, CDCl3)
f1 (ppm)
1.00
0.96
1.00
9.37
6.20
6.33
3.25
5.87
5.84
5.84
5.82
5.64
5.64
5.61
5.61
3.50
3.48
3.47
3.46
3.44
3.43
1.48
1.35
1.33
1.32
1.31
1.26
1.19
1.00
0.99

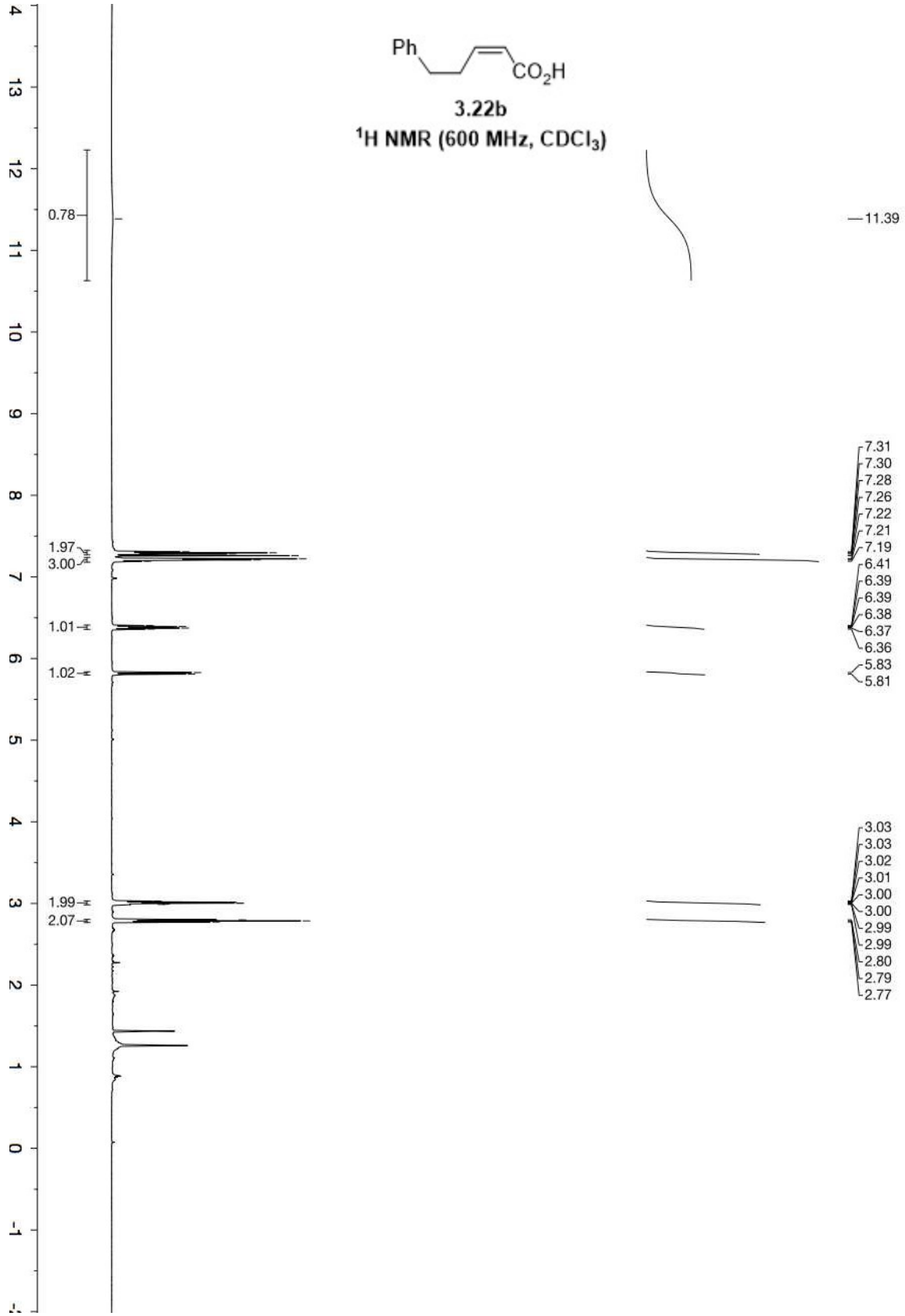

Me
HO
Me
Me
CO2t-Bu
3.21m
13C NMR (100 MHz, CDCl3)
166.18
154.32
120.49
80.20
71.08
43.99
37.54
32.45
29.49
29.28
28.39
22.12
20.59
f1 (ppm)
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0

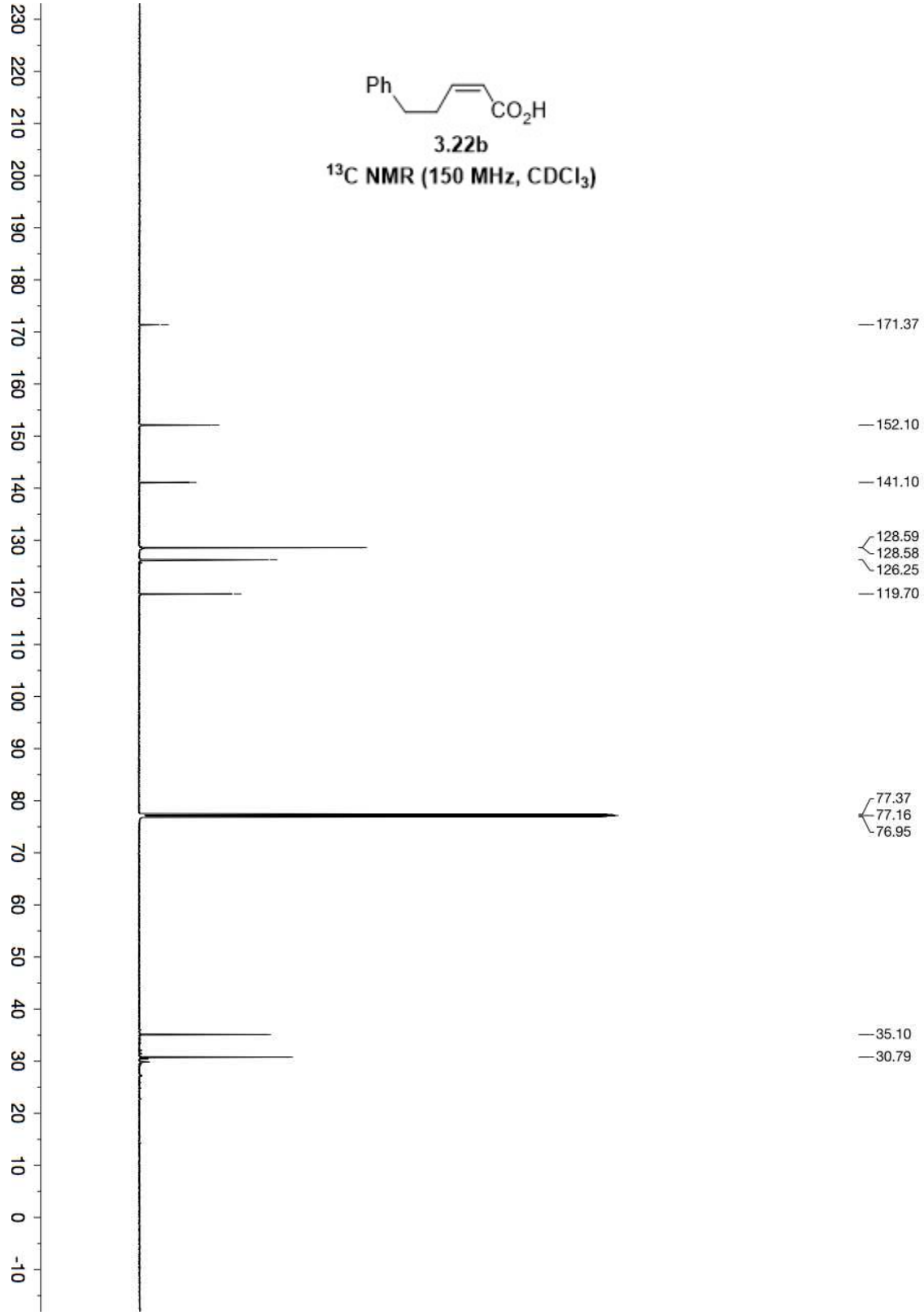

HO
CO2Bn
3.21n
1H NMR (500 MHz, CDCl3)
f1 (ppm)
4.52
1.00
0.92
2.04
2.13
2.11
0.84
2.17
7.38
7.37
7.34
7.34
7.33
7.32
7.32
7.26
6.29
6.27
6.27
6.26
6.26
6.24
5.92
5.90
5.17
3.62
3.61
2.77
2.76
2.74
2.73
2.38
1.75
1.74
1.73
1.72
1.71

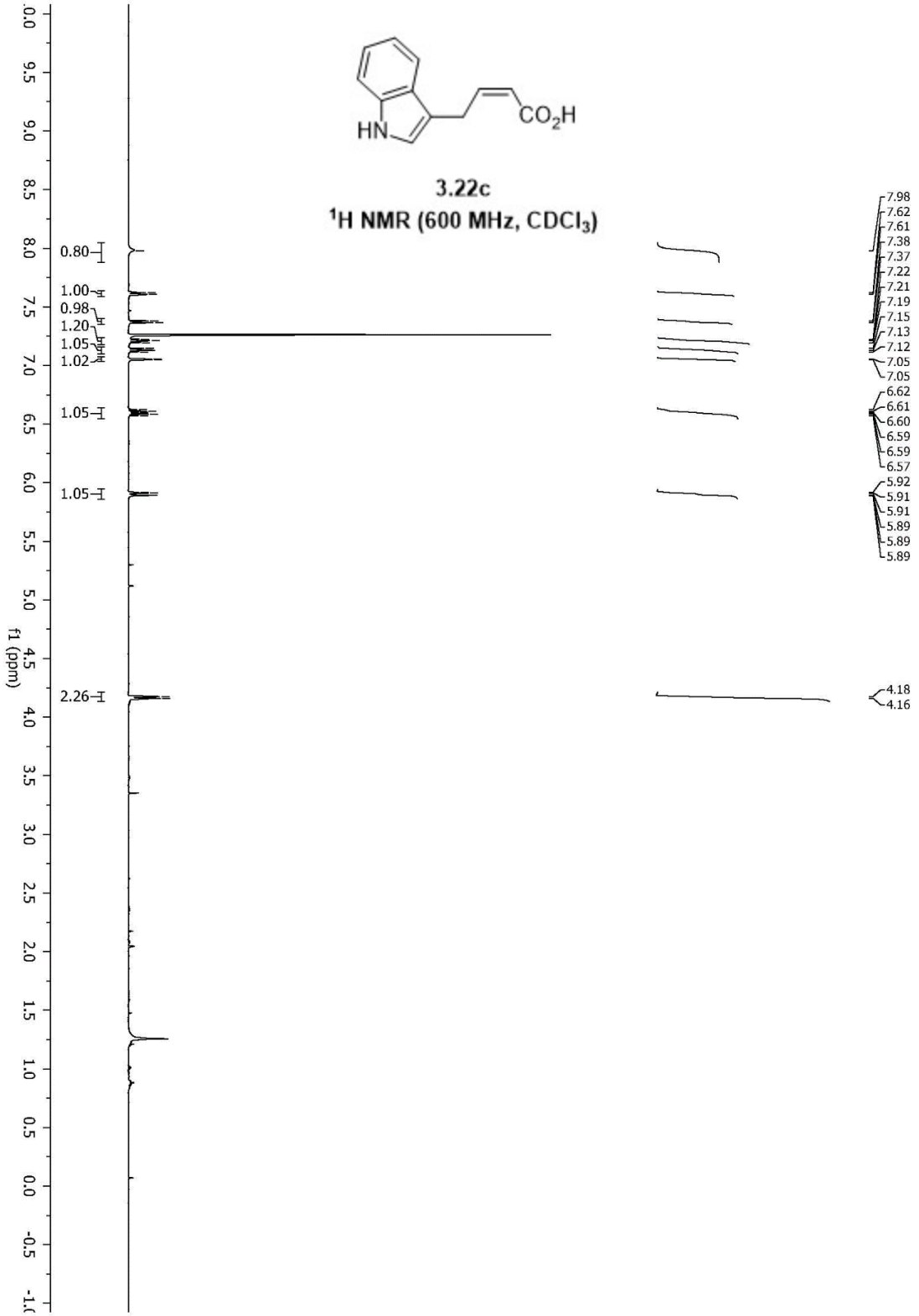

HO
CO2Bn
3.21n
13C NMR (150 MHz, CDCl3)
166.96
144.98
138.08
128.91
128.09
127.78
123.54
77.48
77.16
76.84
60.09
43.68
30.61
24.74
f1 (ppm)

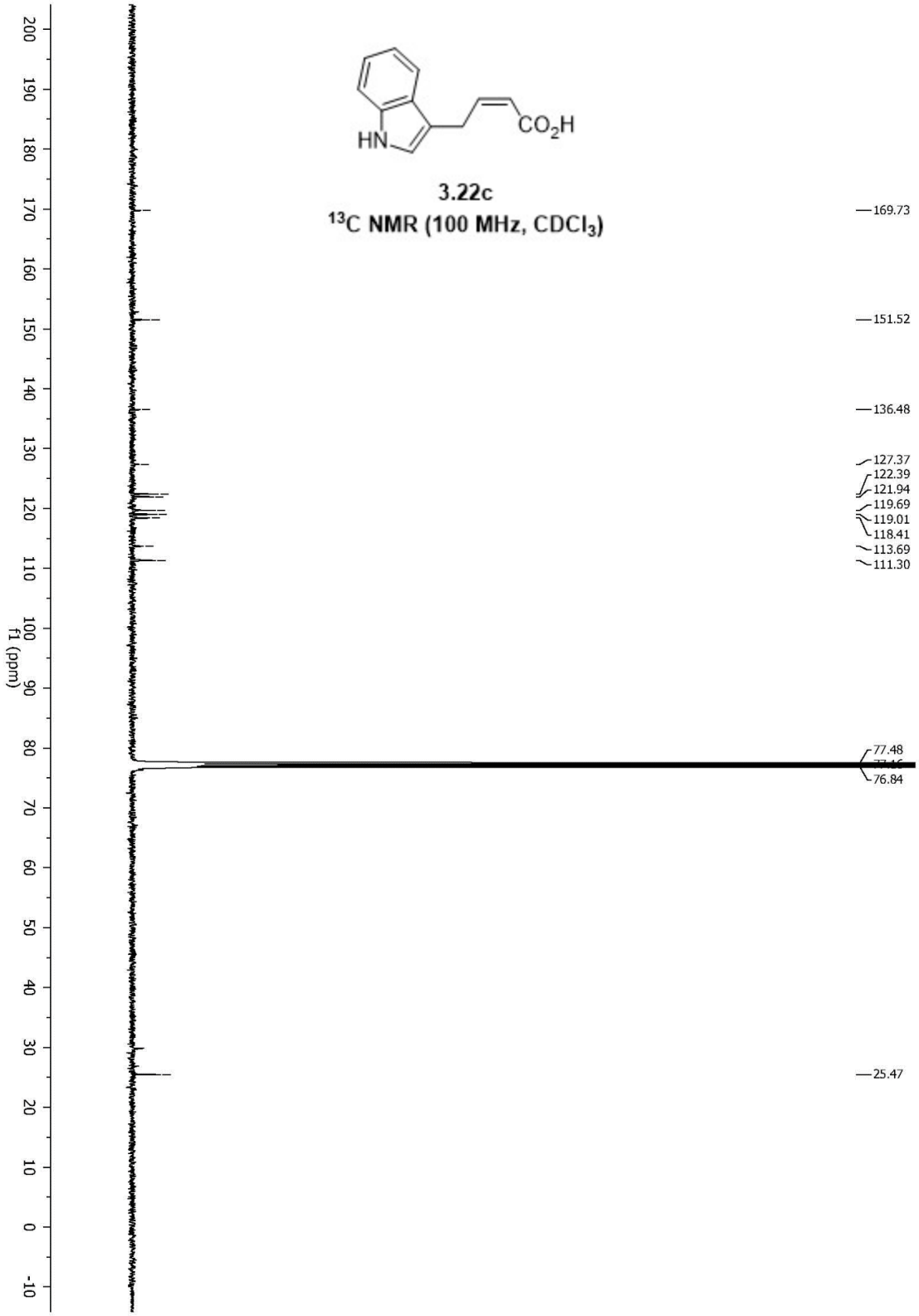

Fe
O
O
CO2H
3.22a
1H NMR (600 MHz, CDCl3)
7.26
6.36
6.35
6.34
6.34
6.33
6.32
5.80
5.78
4.81
4.81
4.80
4.39
4.38
4.38
4.22
4.21
4.20
2.68
2.67
2.65
2.64
1.74
1.73
1.72
1.71
1.70
1.45
1.44
1.43
1.42
1.41
1.36
1.35
0.99
1.04
1.91
1.94
5.03
2.03
2.00
14.32

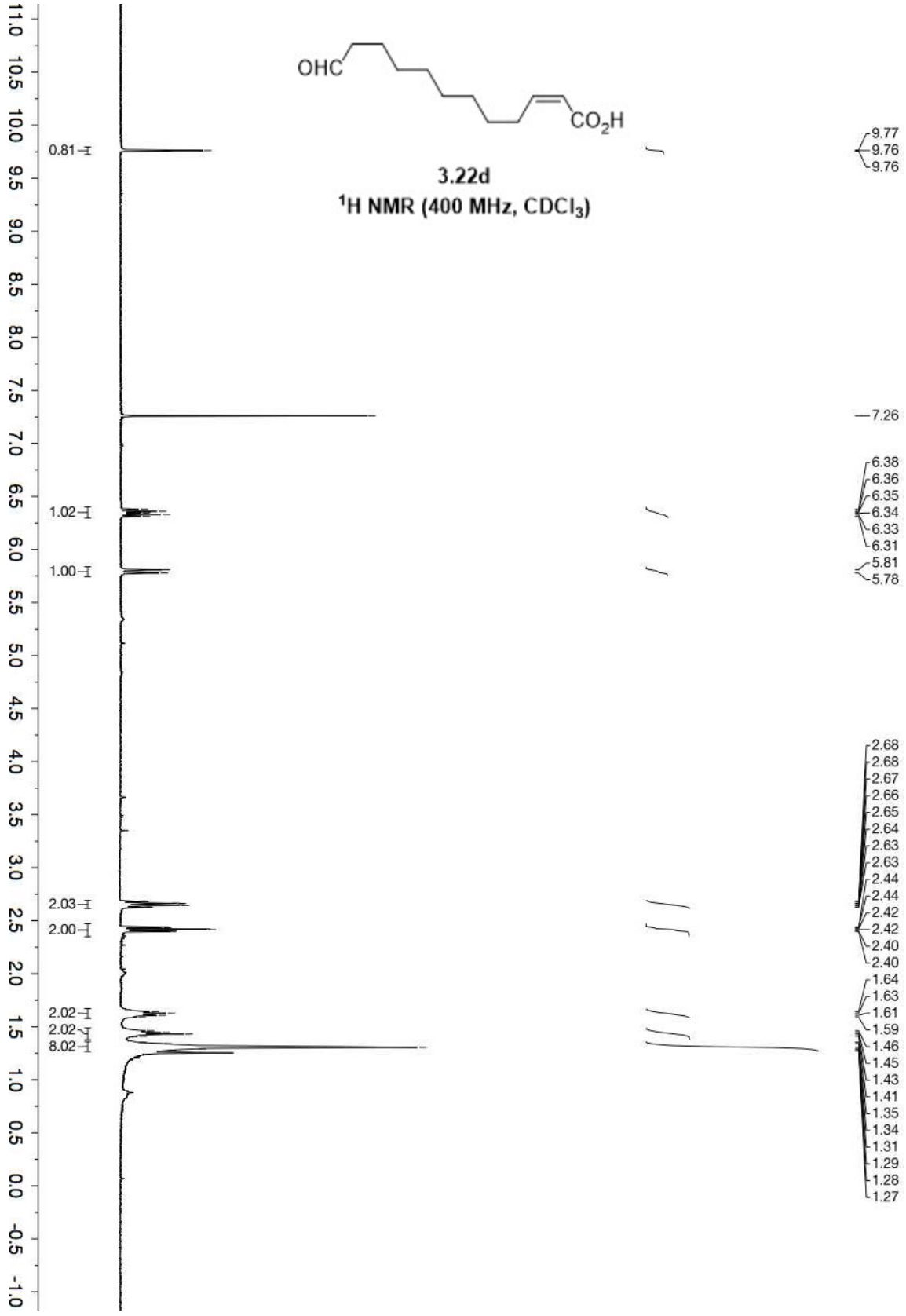

Fe
O
O
CO2H
3.22a
13C NMR (150 MHz, CDCl3)
172.00
170.65
153.46
118.95
77.37
77.16
76.95
71.66
71.34
70.26
69.86
64.47
29.58
29.43
29.38
29.33
29.28
29.06
29.03
26.17

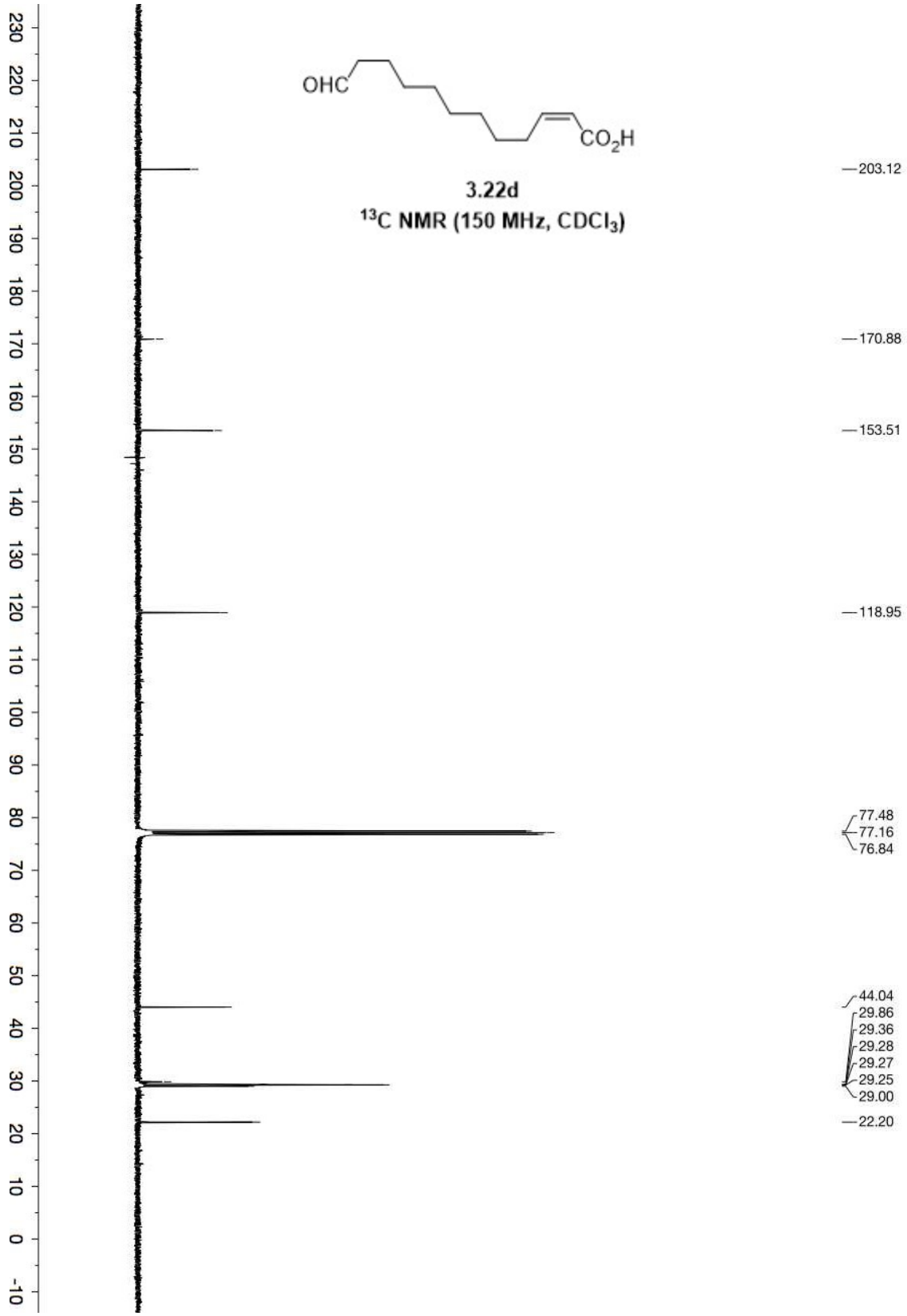

Ph
CO2H
3.22b
1H NMR (600 MHz, CDCl3)
0.78
11.39
1.97
3.00
1.01
1.02
1.99
2.07
7.31
7.30
7.28
7.26
7.22
7.21
7.19
6.41
6.39
6.39
6.38
6.37
6.36
5.83
5.81
3.03
3.03
3.02
3.01
3.00
3.00
2.99
2.99
2.80
2.79
2.77

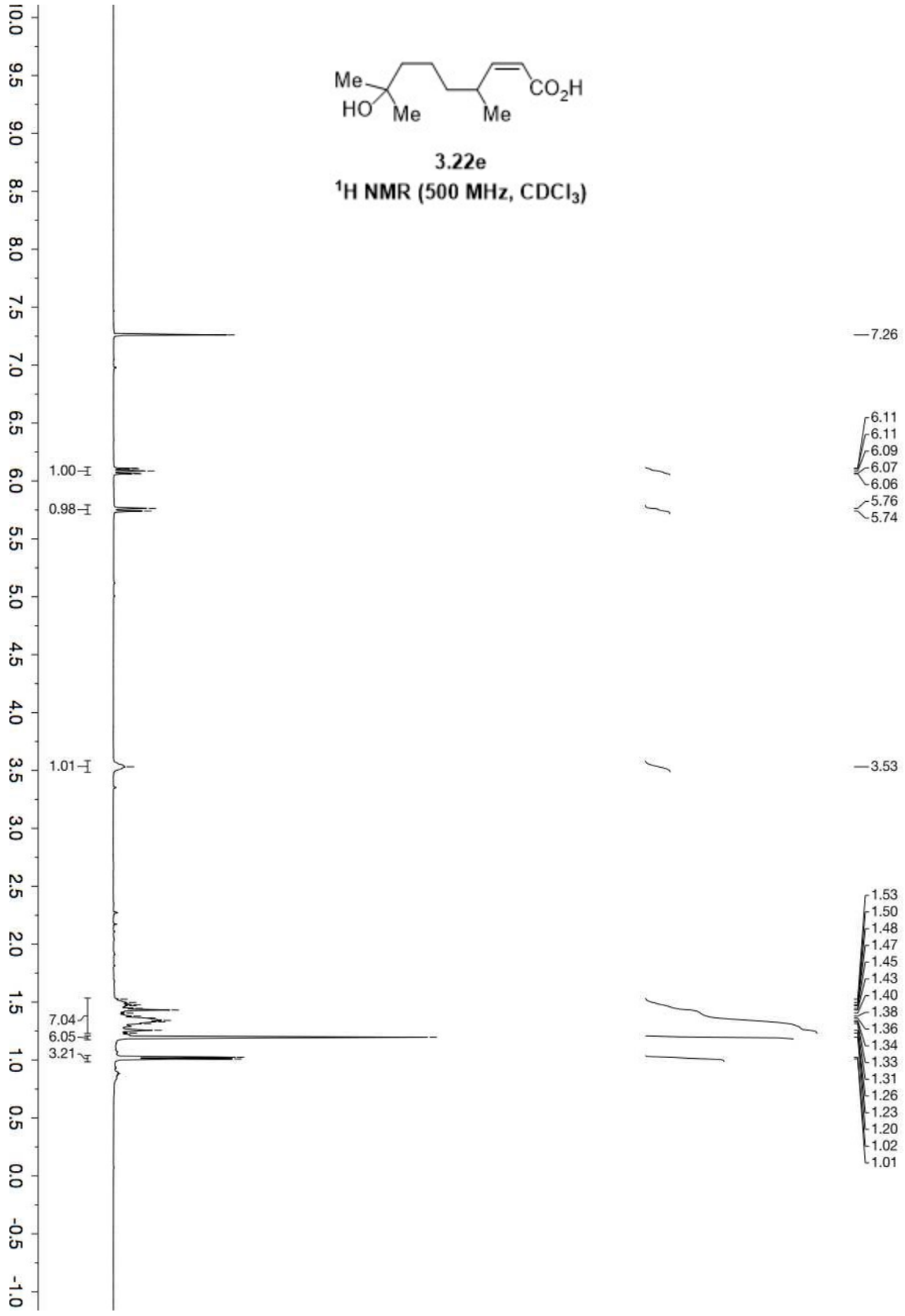

Ph
CO2H
3.22b
13C NMR (150 MHz, CDCl3)
171.37
152.10
141.10
128.59
128.58
126.25
119.70
77.37
77.16
76.95
35.10
30.79
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10

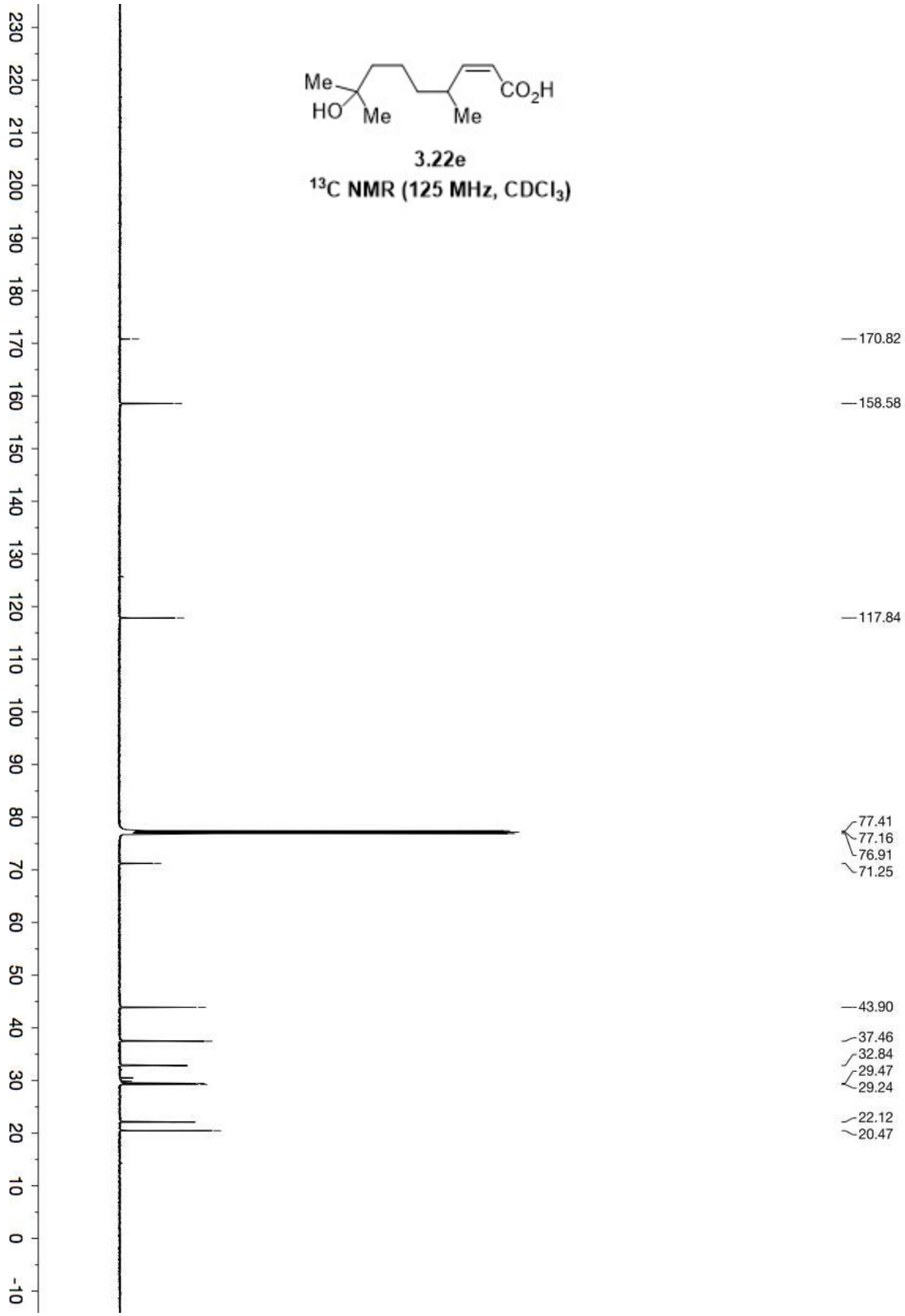

HN
CO2H
3.22c
1H NMR (600 MHz, CDCl3)
0.80
1.00
0.98
1.20
1.05
1.02
1.05
1.05
2.26
7.98
7.62
7.61
7.38
7.37
7.22
7.21
7.19
7.15
7.13
7.12
7.05
7.05
6.62
6.61
6.60
6.59
6.59
6.57
5.92
5.91
5.91
5.89
5.89
5.89
4.18
4.16
f1 (ppm)

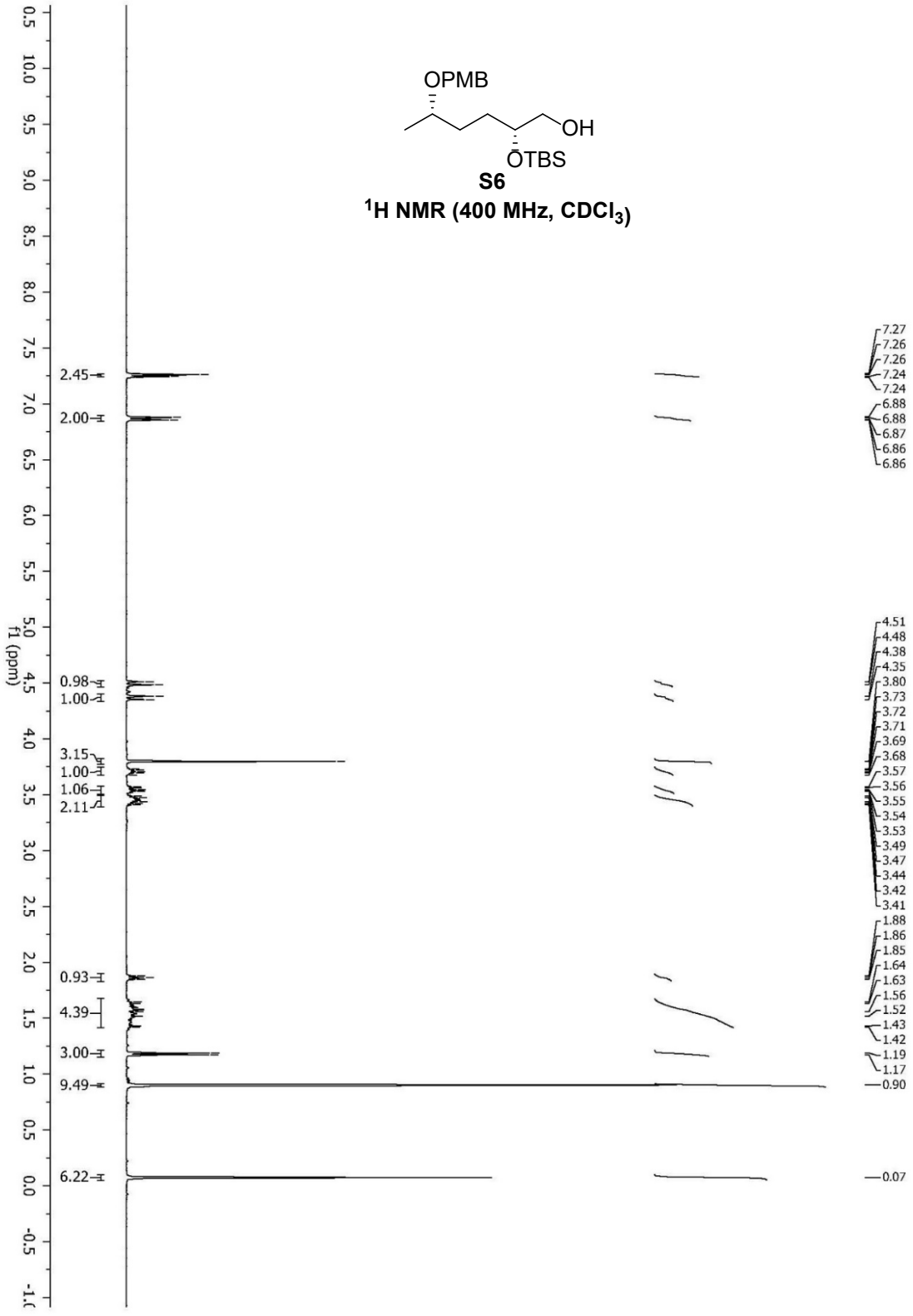

HN
CO2H
3.22c
13C NMR (100 MHz, CDCl3)
169.73
151.52
136.48
127.37
122.39
121.94
119.69
119.01
118.41
113.69
111.30
77.48
76.84
25.47
f1 (ppm)


OHC
CO2H
3.22d
1H NMR (400 MHz, CDCl3)
0.81
1.02
1.00
2.03
2.00
2.02
2.02
8.02
9.77
9.76
9.76
7.26
6.38
6.36
6.35
6.34
6.33
6.31
5.81
5.78
2.68
2.68
2.67
2.66
2.65
2.64
2.63
2.63
2.44
2.44
2.42
2.42
2.40
2.40
1.64
1.63
1.61
1.59
1.46
1.45
1.43
1.41
1.35
1.34
1.31
1.29
1.28
1.27


OHC
CO2H
3.22d
13C NMR (150 MHz, CDCl3)
203.12
170.88
153.51
118.95
77.48
77.16
76.84
44.04
29.86
29.36
29.28
29.27
29.25
29.00
22.20
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10

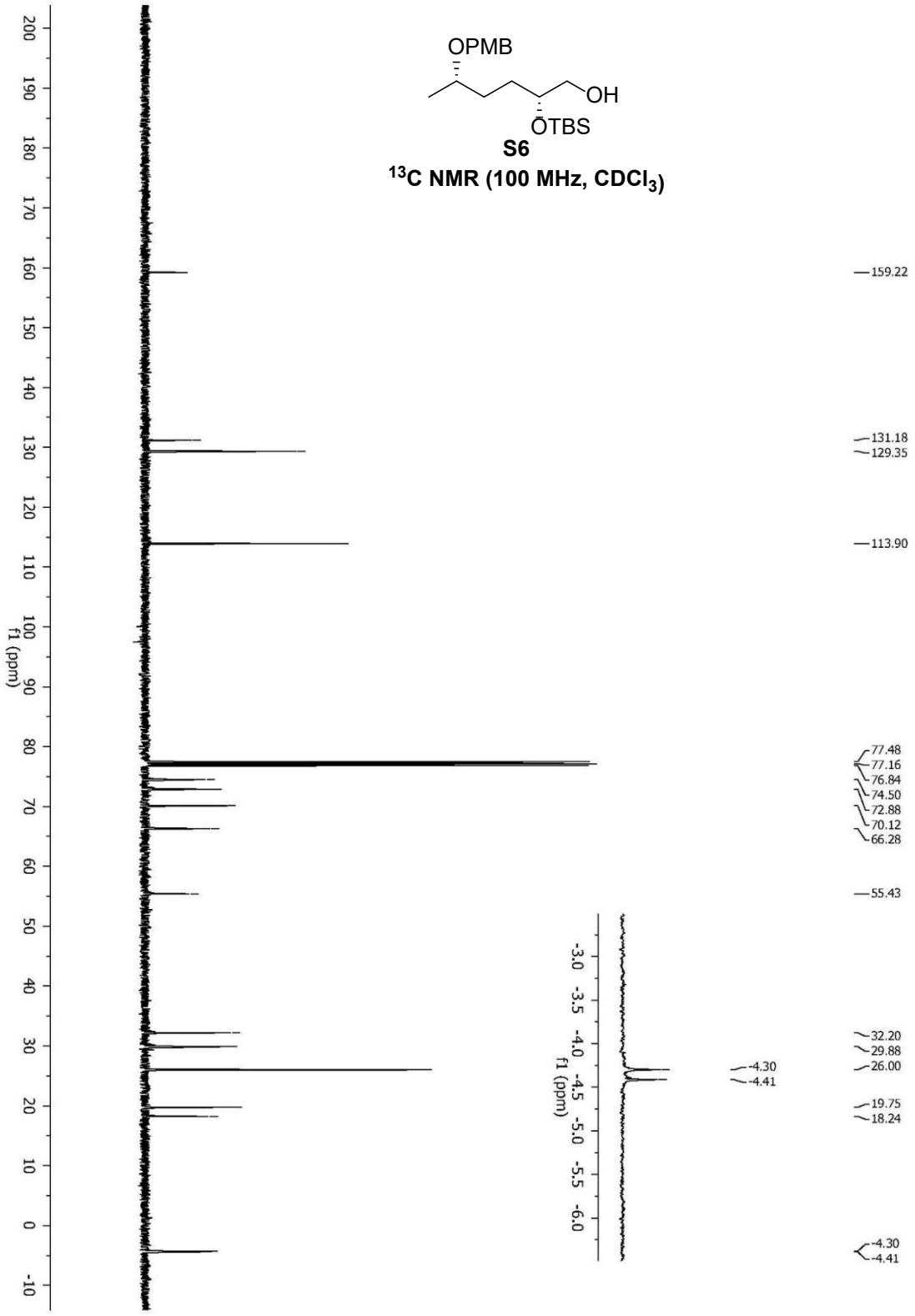

Me
HO
Me
Me
CO2H
3.22e
1H NMR (500 MHz, CDCl3)
7.26
6.11
6.11
6.09
6.07
6.06
5.76
5.74
3.53
1.53
1.50
1.48
1.47
1.45
1.43
1.40
1.38
1.36
1.34
1.33
1.31
1.26
1.23
1.20
1.02
1.01
1.00
0.98
1.01
7.04
6.05
3.21


Me
HO
Me
Me
CO2H
3.22e
13C NMR (125 MHz, CDCl3)
170.82
158.58
117.84
77.41
77.16
76.91
71.25
43.90
37.46
32.84
29.47
29.24
22.12
20.47



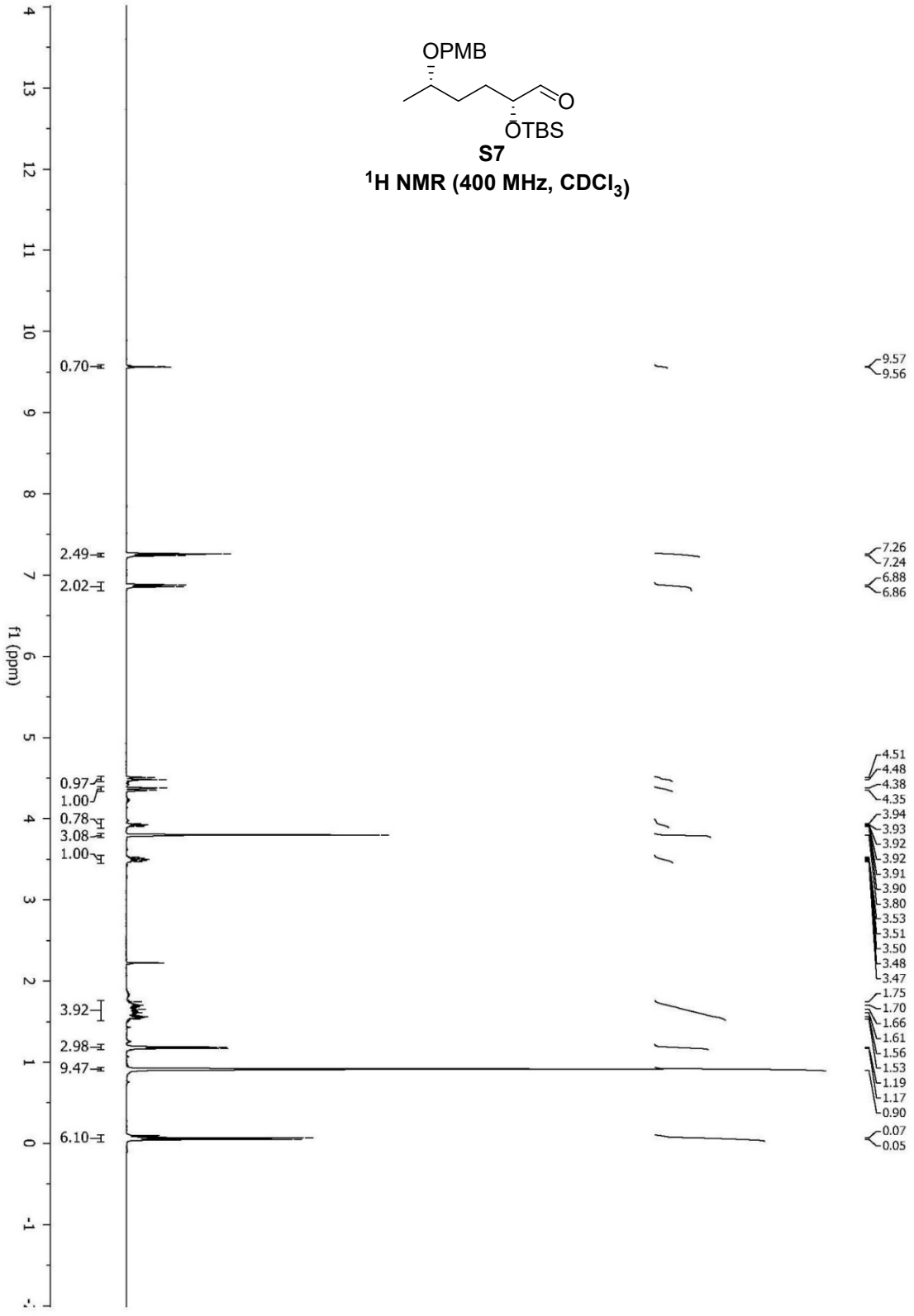
S6

^{1}H NMR (400 MHz, $CDCl_3$)



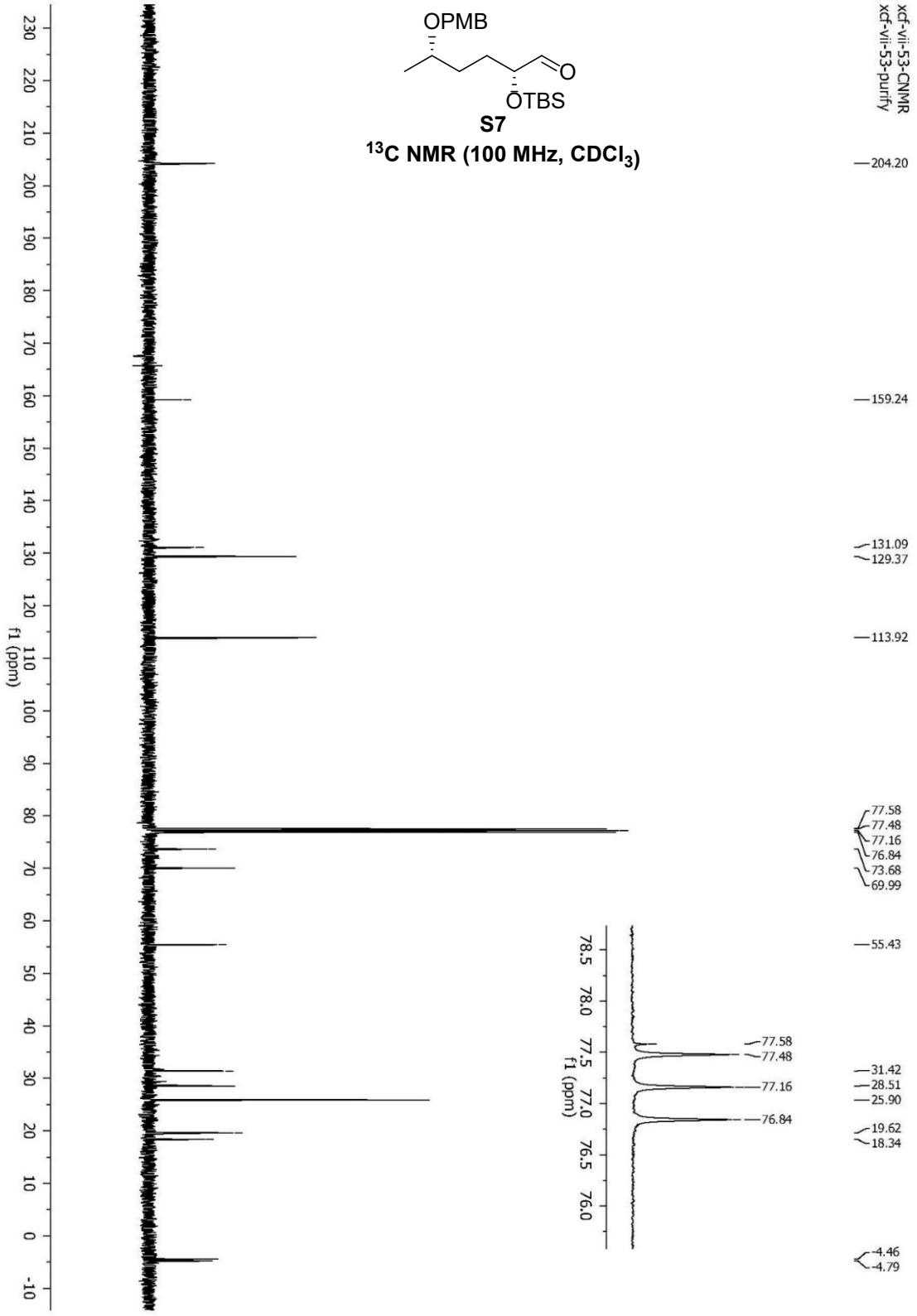
S6

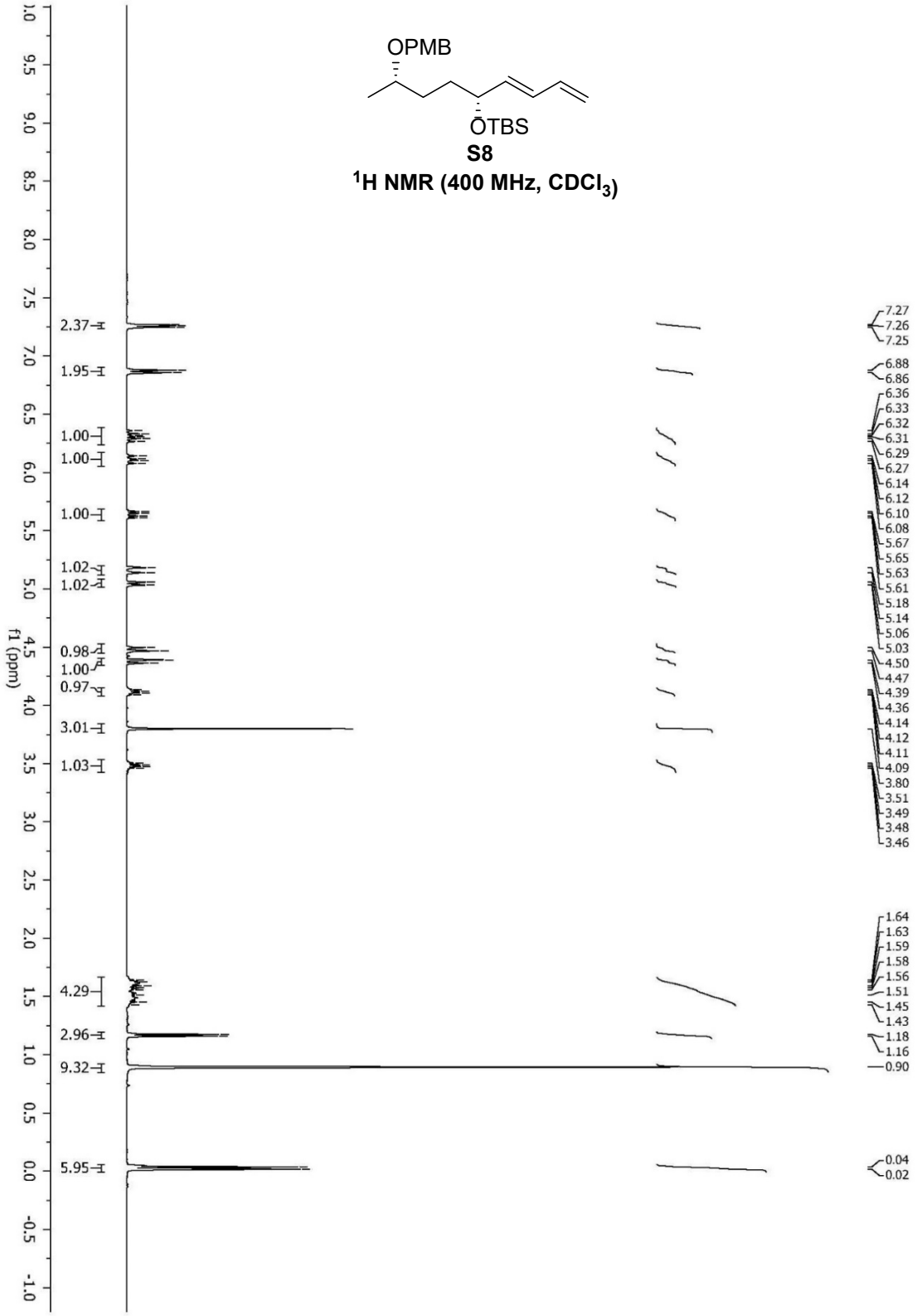
^{13}C NMR (100 MHz, $CDCl_3$)



S7

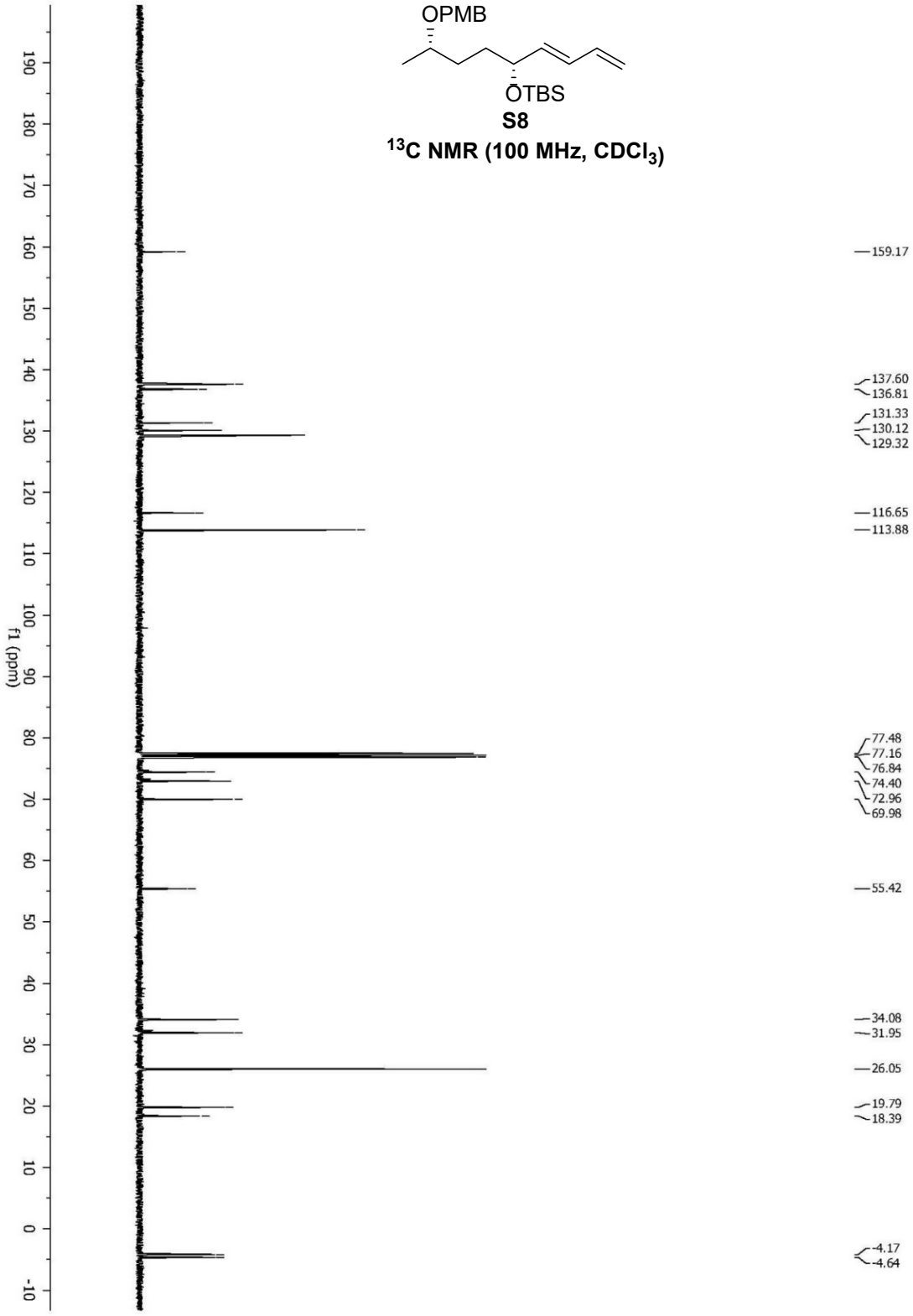
^{1}H NMR (400 MHz, $CDCl_3$)

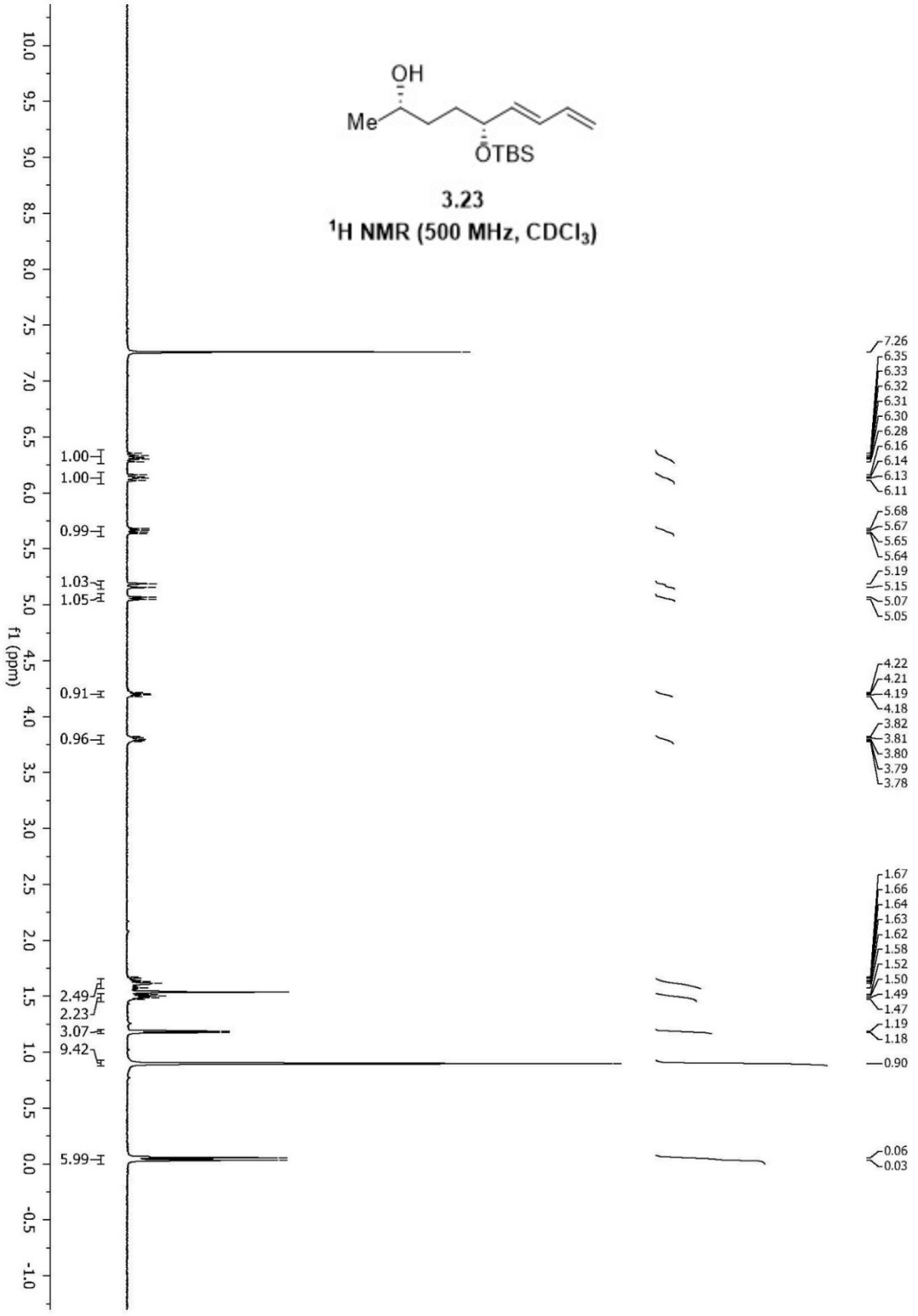

OPMB
O
OTBS
S7
^{13}C NMR (100 MHz, CDCl$_3$)
xcf-vii-53-CNMR
xcf-vii-53-purify
204.20
159.24
131.09
129.37
113.92
77.58
77.48
77.16
76.84
73.68
69.99
55.43
31.42
28.51
25.90
19.62
18.34
-4.46
-4.79
f1 (ppm)

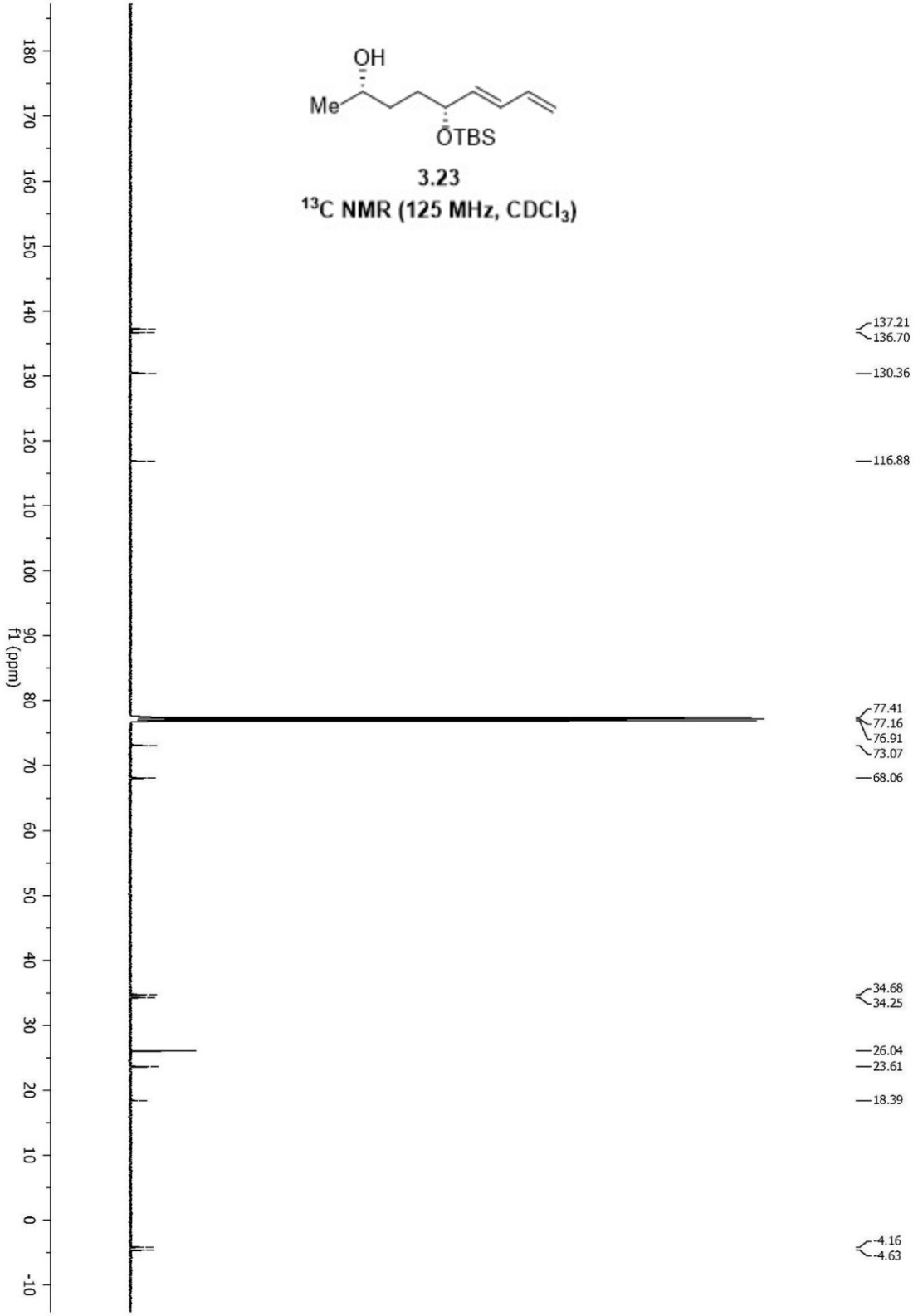


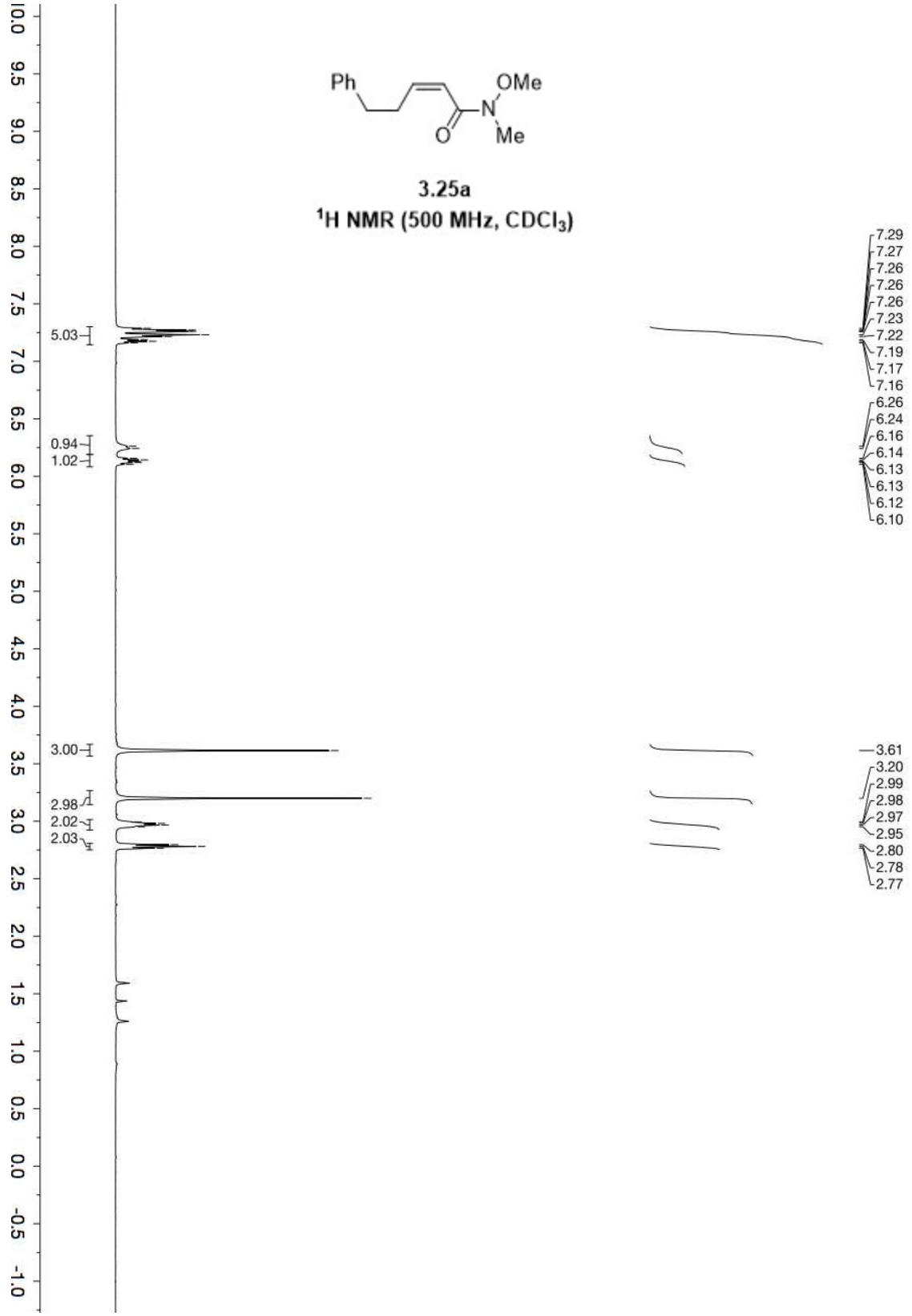
S8

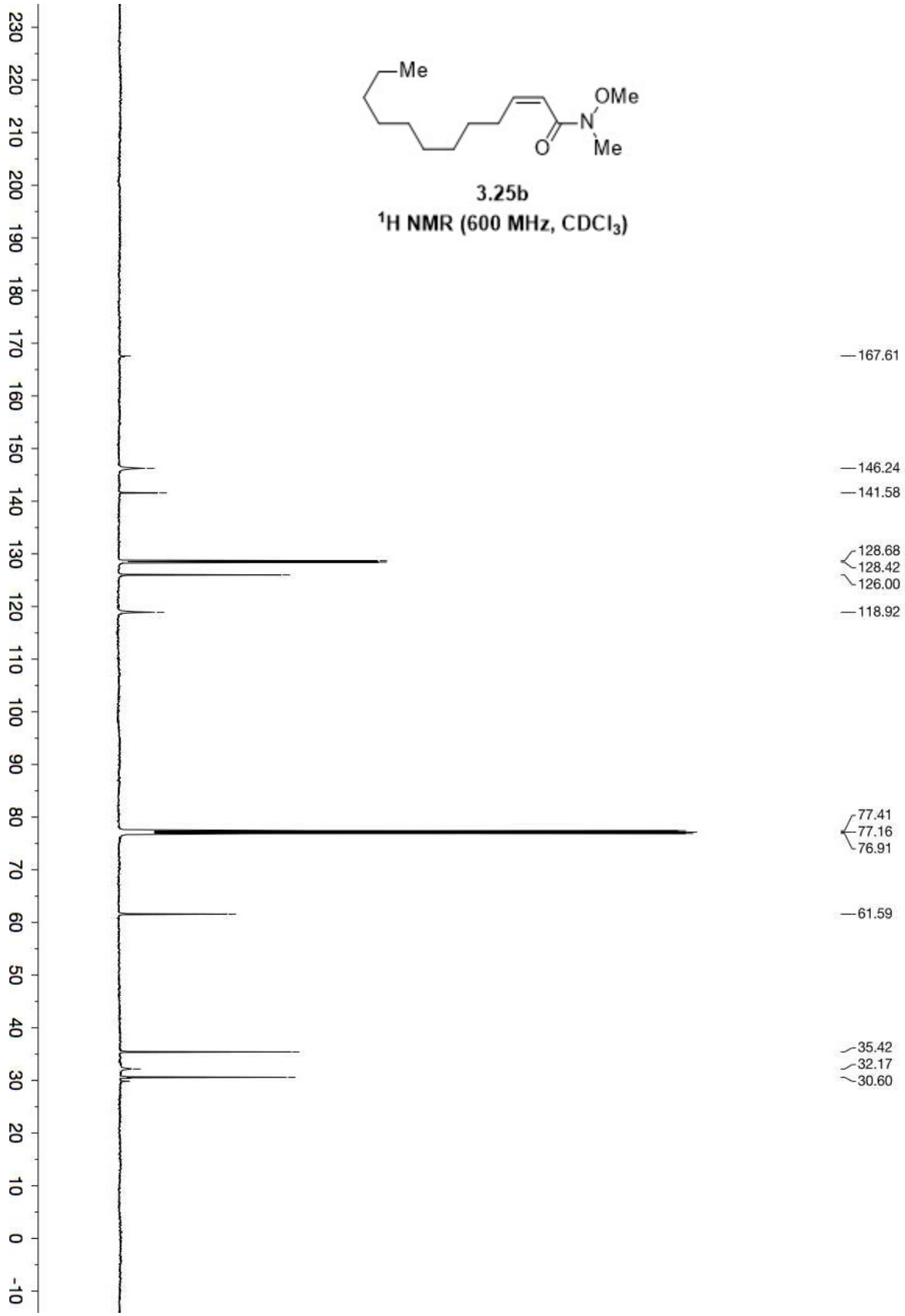
^{1}H NMR (400 MHz, $CDCl_3$)

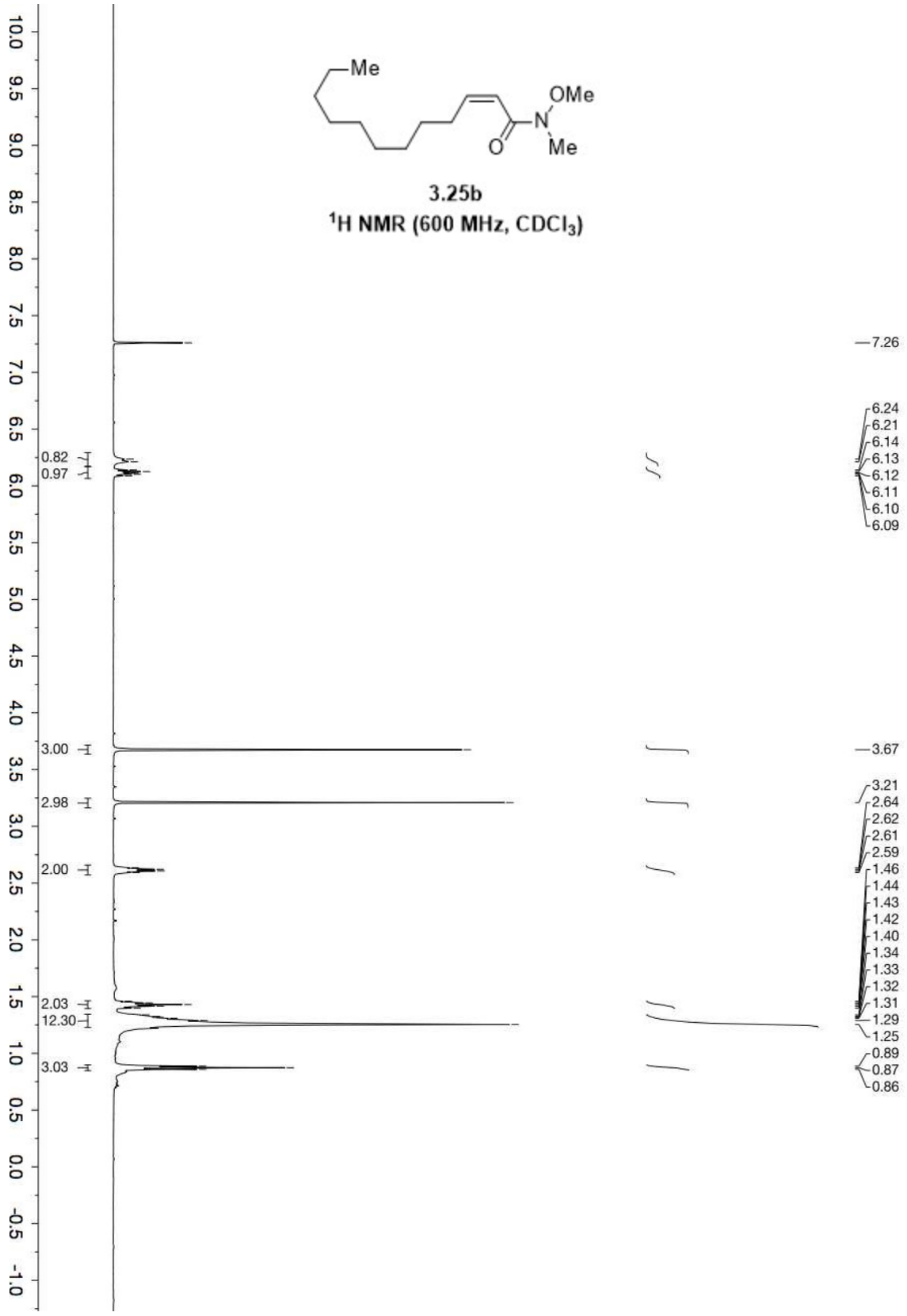

OPMB
OTBS
S8
^{13}C NMR (100 MHz, CDCl$_3$)
f1 (ppm)
159.17
137.60
136.81
131.33
130.12
129.32
116.65
113.88
77.48
77.16
76.84
74.40
72.96
69.98
55.42
34.08
31.95
26.05
19.79
18.39
-4.17
-4.64

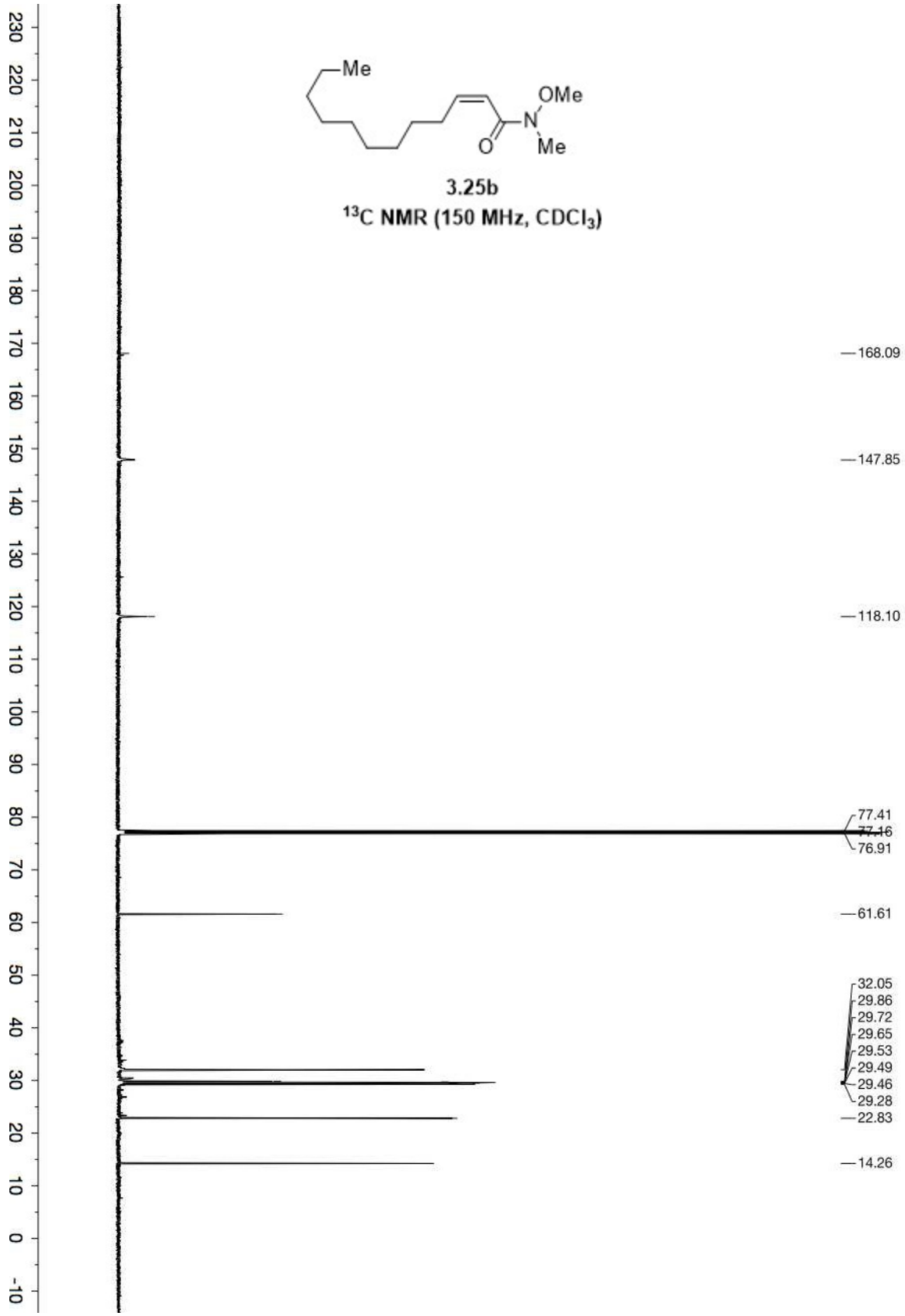

OH
Me
OTBS
3.23
¹H NMR (500 MHz, CDCl₃)
f1 (ppm)
1.00
1.00
0.99
1.03
1.05
0.91
0.96
2.49
2.23
3.07
9.42
5.99
7.26
6.35
6.33
6.32
6.31
6.30
6.28
6.16
6.14
6.13
6.11
5.68
5.67
5.65
5.64
5.19
5.15
5.07
5.05
4.22
4.21
4.19
4.18
3.82
3.81
3.80
3.79
3.78
1.67
1.66
1.64
1.63
1.62
1.58
1.52
1.50
1.49
1.47
1.19
1.18
0.90
0.06
0.03

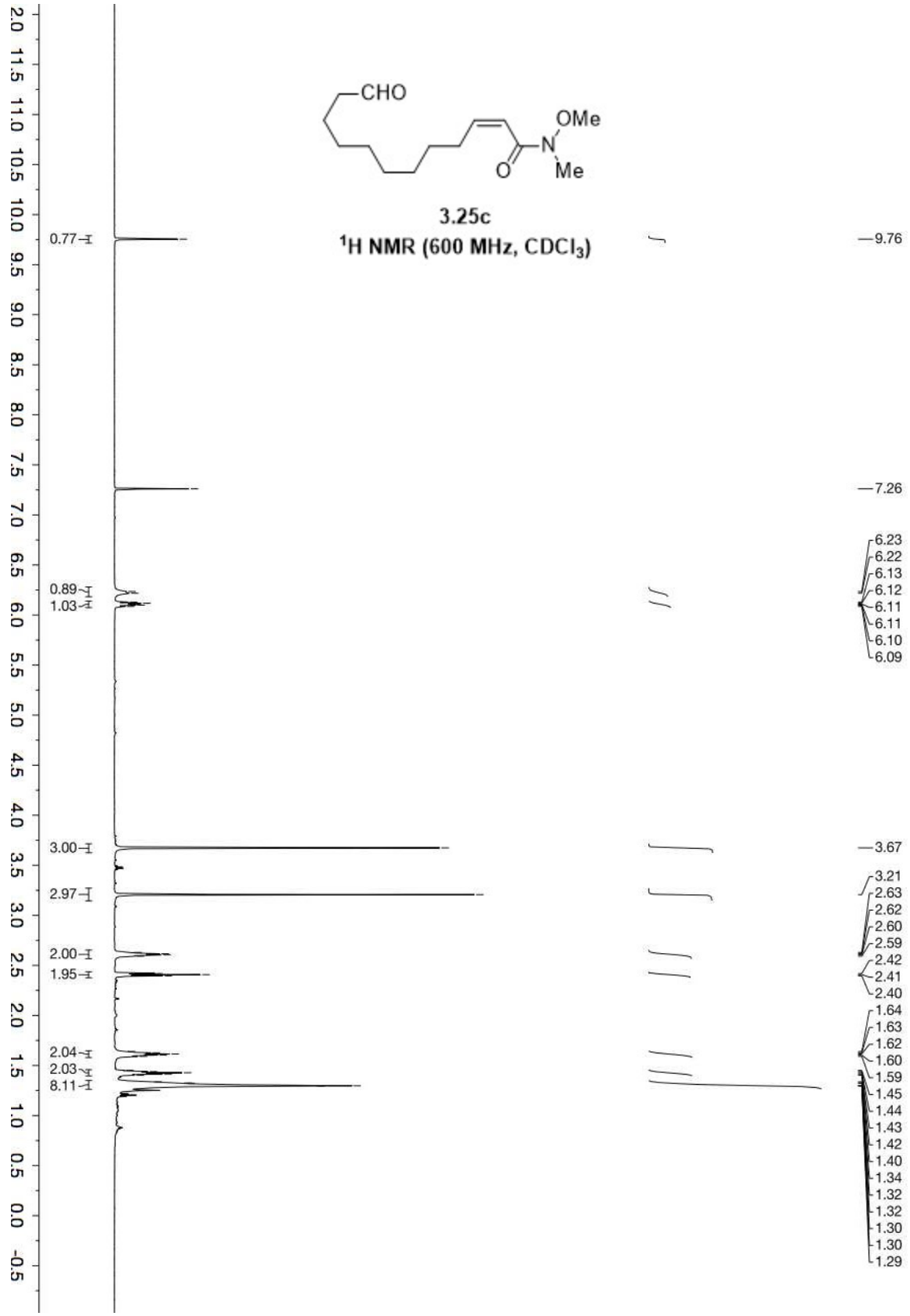

OH
Me
OTBS
3.23
^{13}C NMR (125 MHz, $CDCl_3$)
f1 (ppm)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
137.21
136.70
130.36
116.88
77.41
77.16
76.91
73.07
68.06
34.68
34.25
26.04
23.61
18.39
-4.16
-4.63

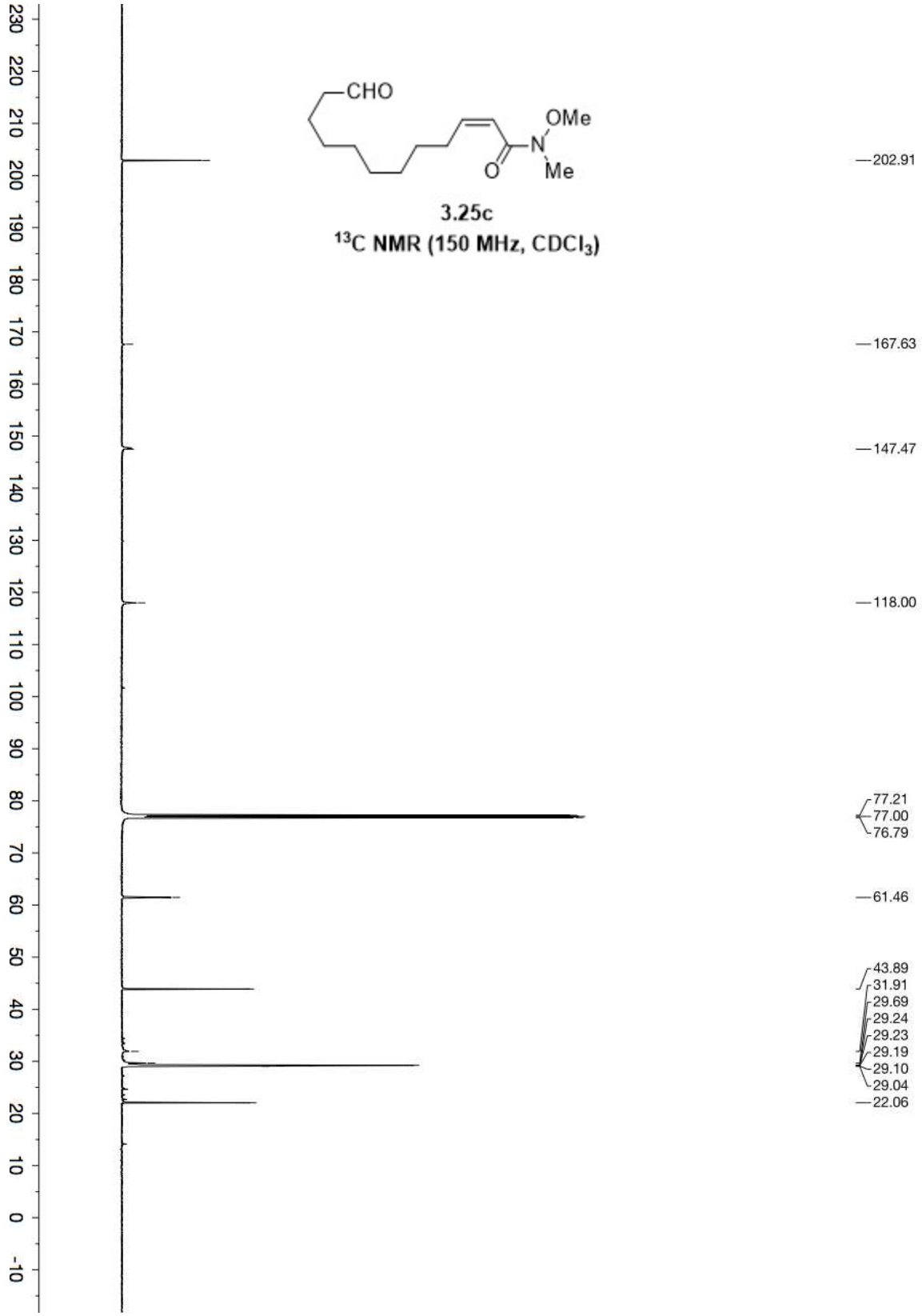

Ph
OMe
N
Me
O
3.25a
^{1}H NMR (500 MHz, $CDCl_3$)
5.03
0.94
1.02
3.00
2.98
2.02
2.03
7.29
7.27
7.26
7.26
7.26
7.23
7.22
7.19
7.17
7.16
6.26
6.24
6.16
6.14
6.13
6.13
6.12
6.10
3.61
3.20
2.99
2.98
2.97
2.95
2.80
2.78
2.77

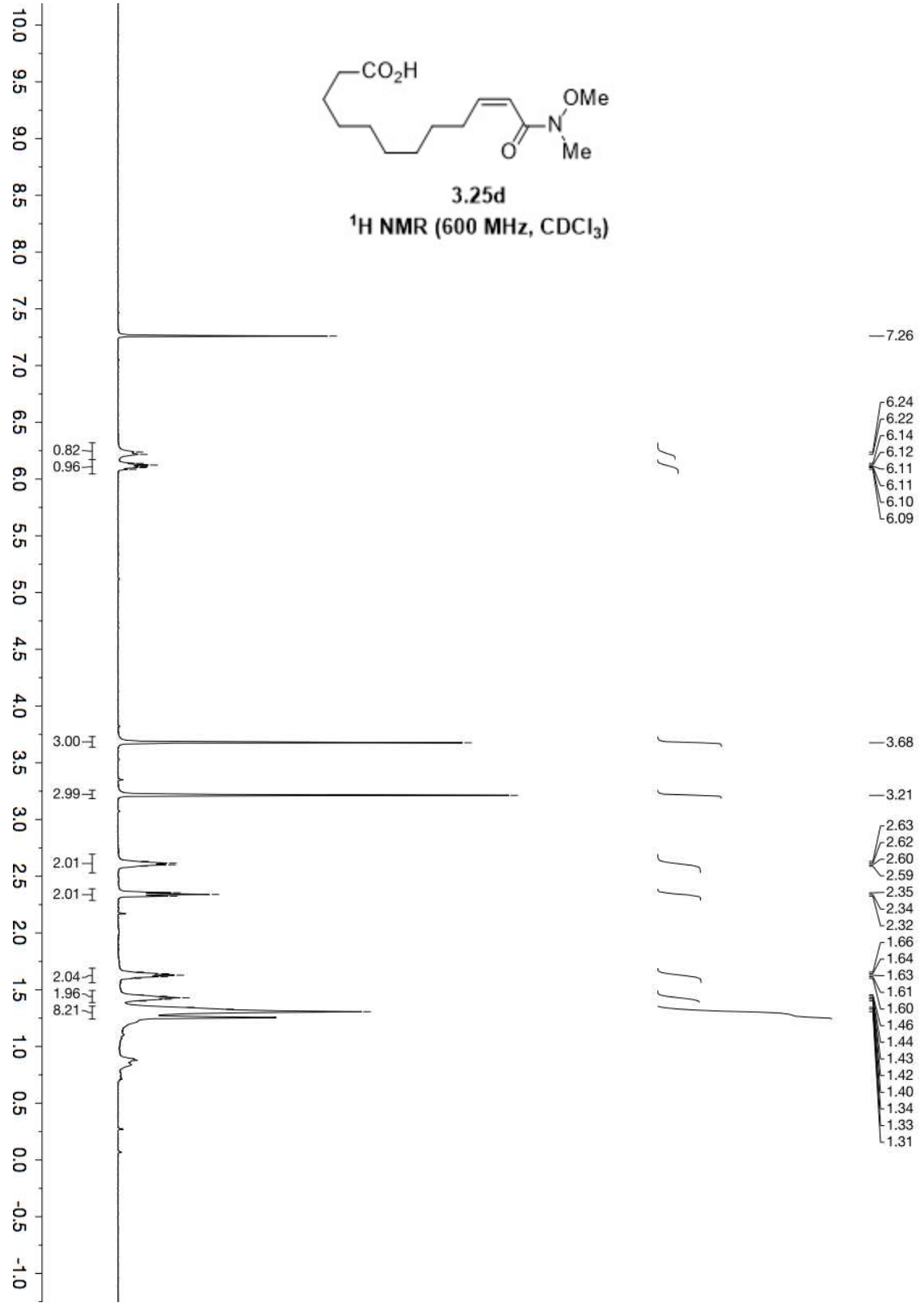

Me
OMe
N
O
Me
3.25b
^{1}H NMR (600 MHz, $CDCl_3$)
167.61
146.24
141.58
128.68
128.42
126.00
118.92
77.41
77.16
76.91
61.59
35.42
32.17
30.60

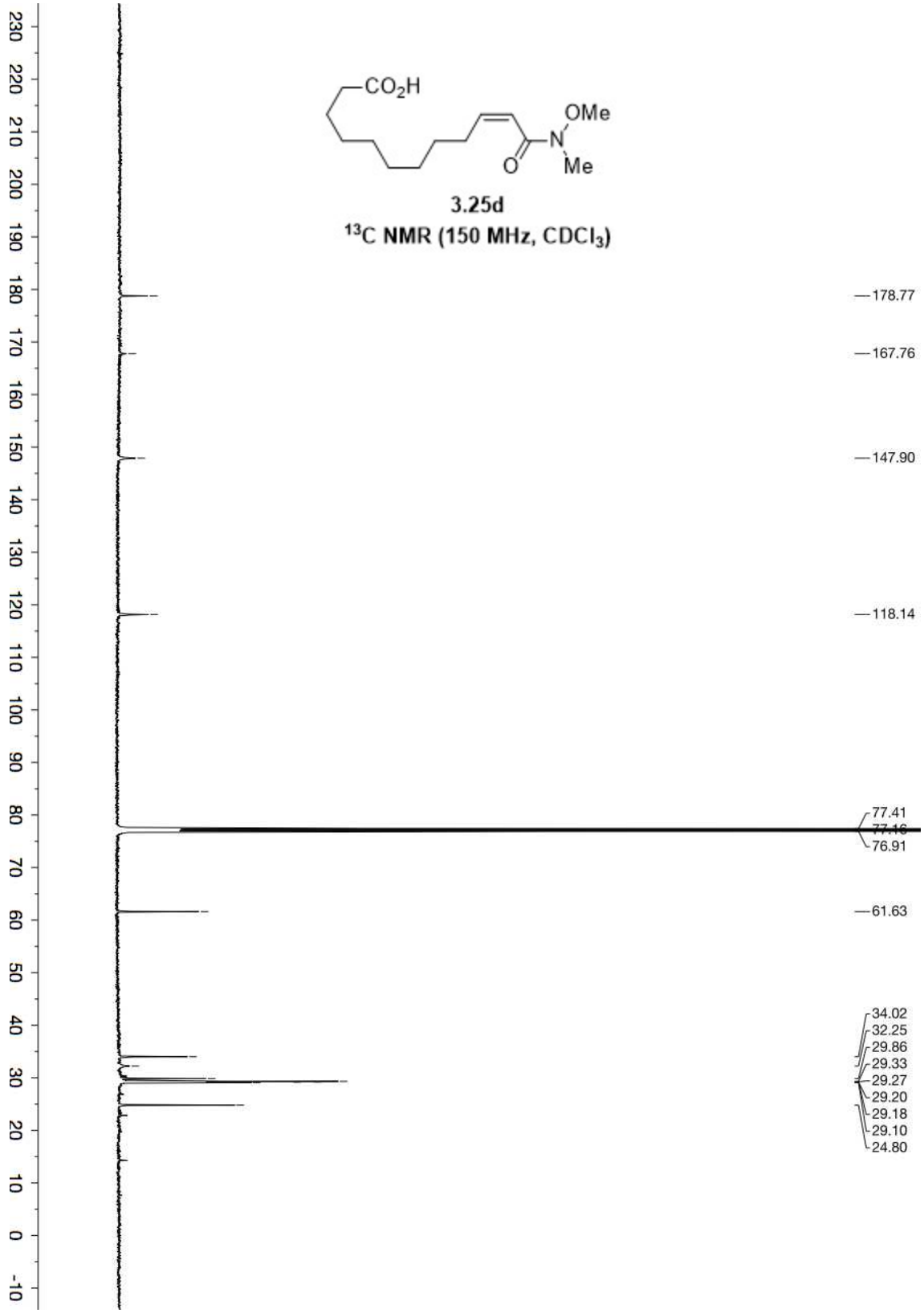

Me
OMe
N
Me
O
3.25b
^{1}H NMR (600 MHz, $CDCl_3$)
7.26
6.24
6.21
6.14
6.13
6.12
6.11
6.10
6.09
0.82
0.97
3.00
2.98
2.00
2.03
12.30
3.03
3.67
3.21
2.64
2.62
2.61
2.59
1.46
1.44
1.43
1.42
1.40
1.34
1.33
1.32
1.31
1.29
1.25
0.89
0.87
0.86

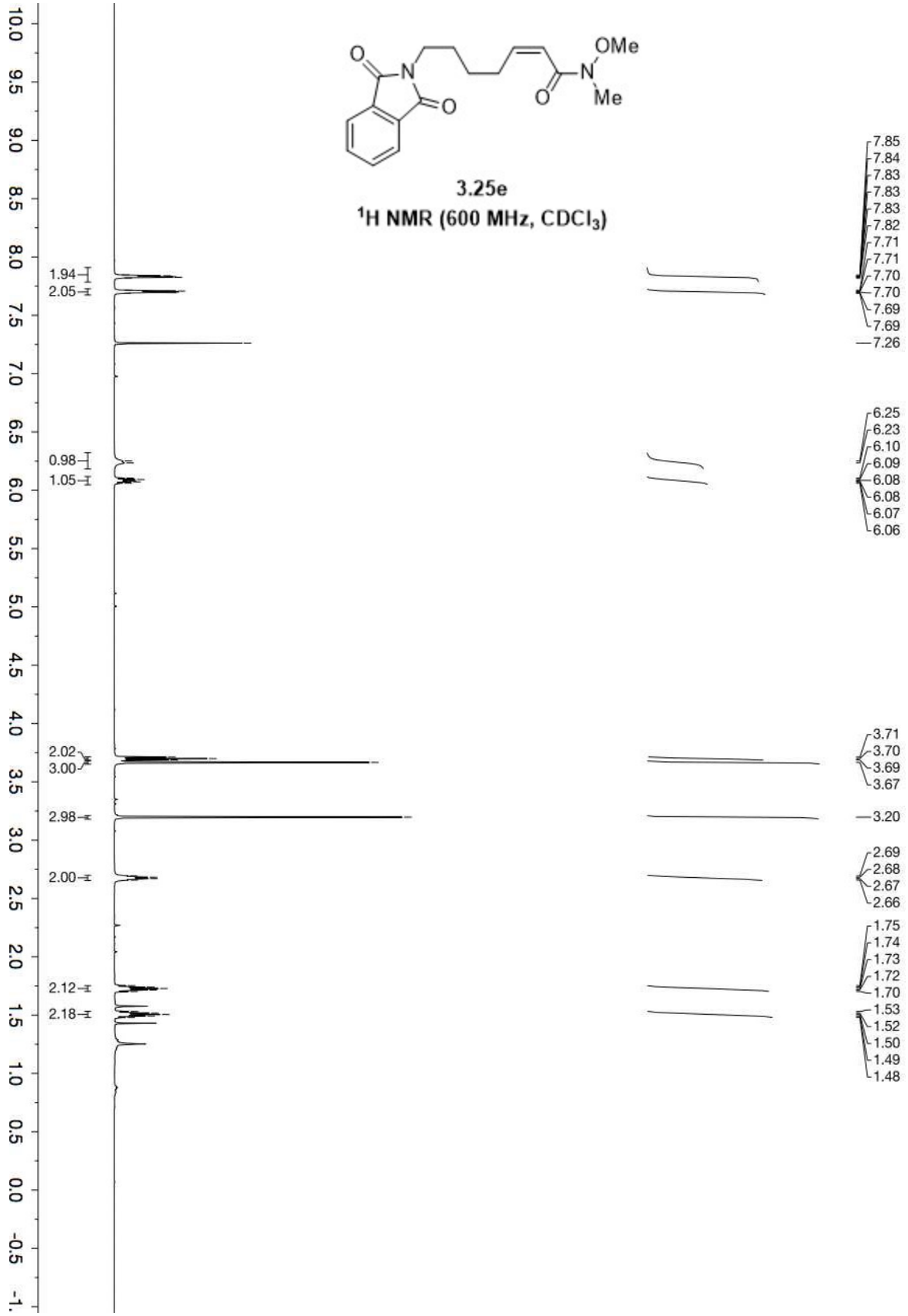

Me
OMe
N
Me
O
3.25b
^{13}C NMR (150 MHz, $CDCl_3$)
168.09
147.85
118.10
77.41
77.16
76.91
61.61
32.05
29.86
29.72
29.65
29.53
29.49
29.46
29.28
22.83
14.26

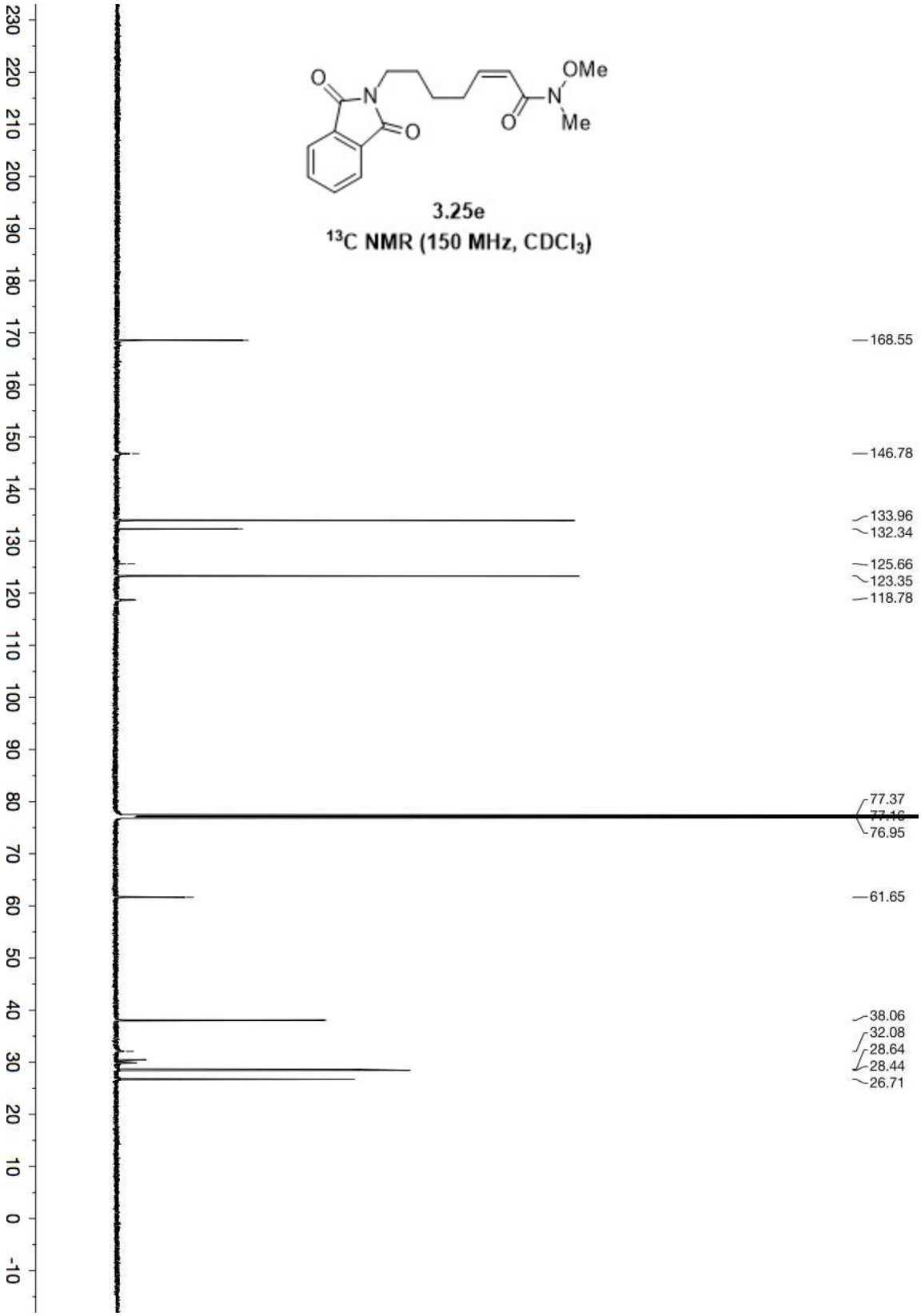

CHO
OMe
N
Me
O
3.25c
^{1}H NMR (600 MHz, $CDCl_3$)
0.77
0.89
1.03
3.00
2.97
2.00
1.95
2.04
2.03
8.11
9.76
7.26
6.23
6.22
6.13
6.12
6.11
6.11
6.10
6.09
3.67
3.21
2.63
2.62
2.60
2.59
2.42
2.41
2.40
1.64
1.63
1.62
1.60
1.59
1.45
1.44
1.43
1.42
1.40
1.34
1.32
1.32
1.30
1.30
1.29

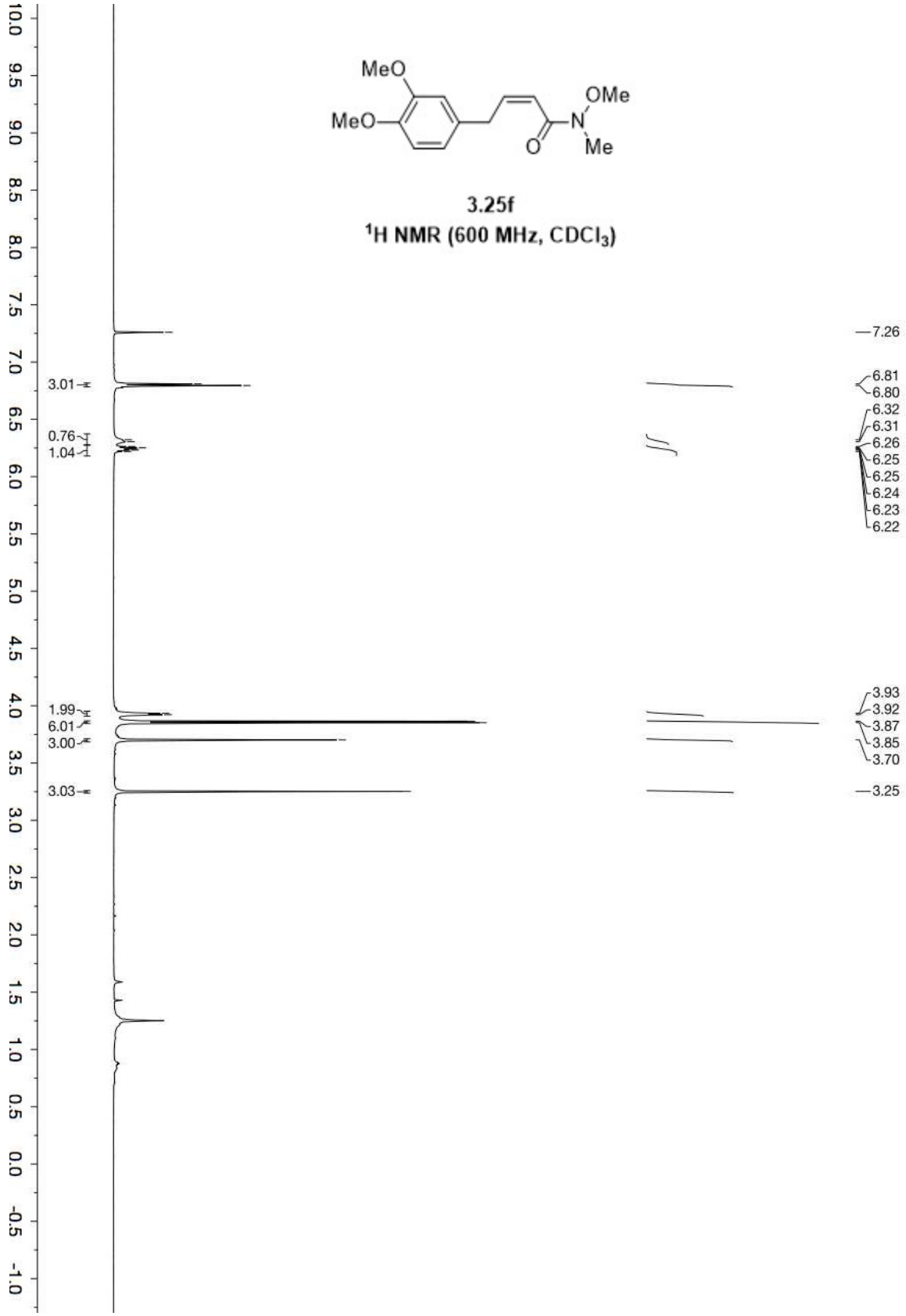

CHO
OMe
N
Me
O
3.25c
^{13}C NMR (150 MHz, $CDCl_3$)
202.91
167.63
147.47
118.00
77.21
77.00
76.79
61.46
43.89
31.91
29.69
29.24
29.23
29.19
29.10
29.04
22.06
230 220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10

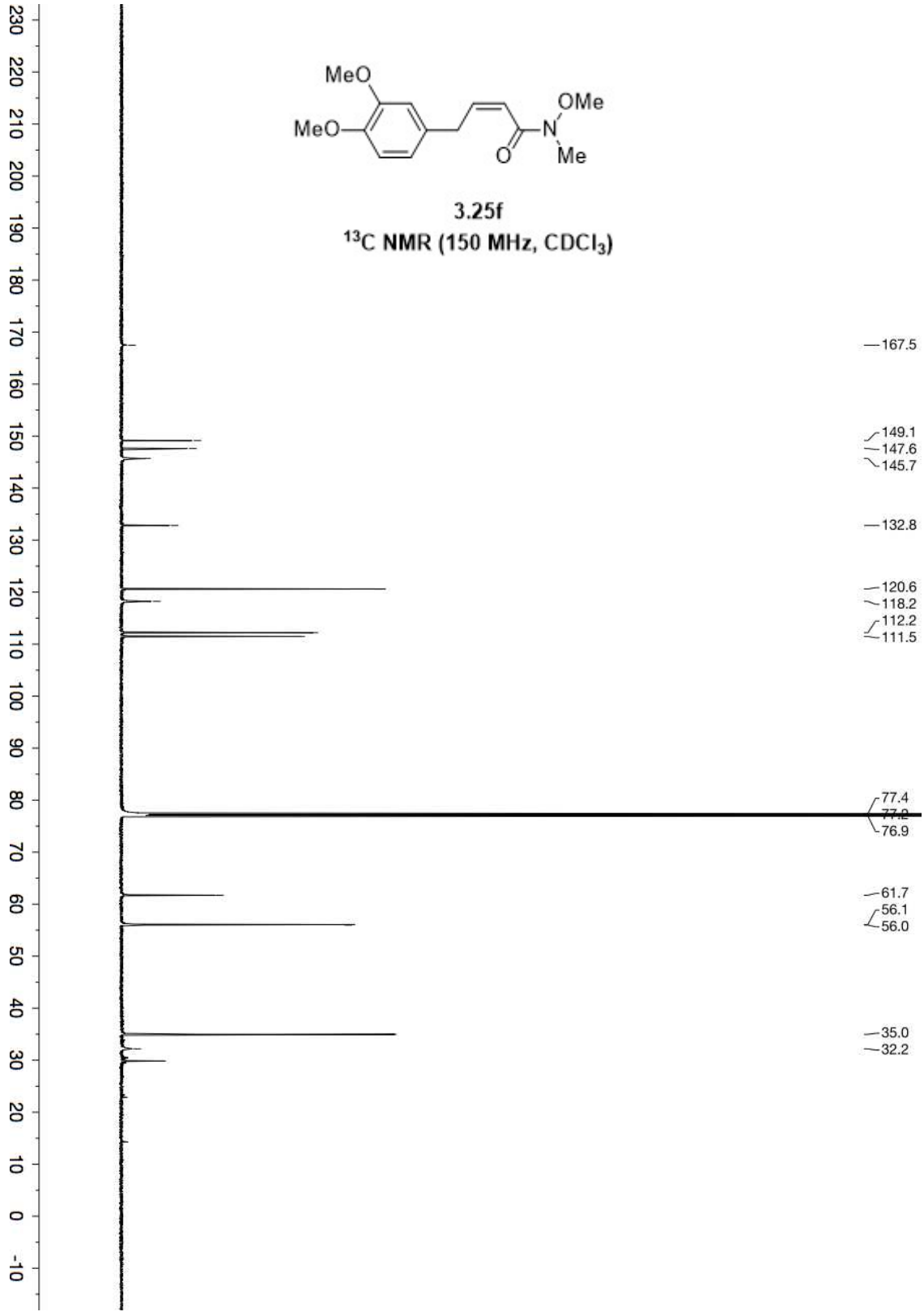

CO2H
OMe
N
Me
O
3.25d
1H NMR (600 MHz, CDCl3)
7.26
6.24
6.22
6.14
6.12
6.11
6.11
6.10
6.09
3.68
3.21
2.63
2.62
2.60
2.59
2.35
2.34
2.32
1.66
1.64
1.63
1.61
1.60
1.46
1.44
1.43
1.42
1.40
1.34
1.33
1.31
0.82
0.96
3.00
2.99
2.01
2.01
2.04
1.96
8.21

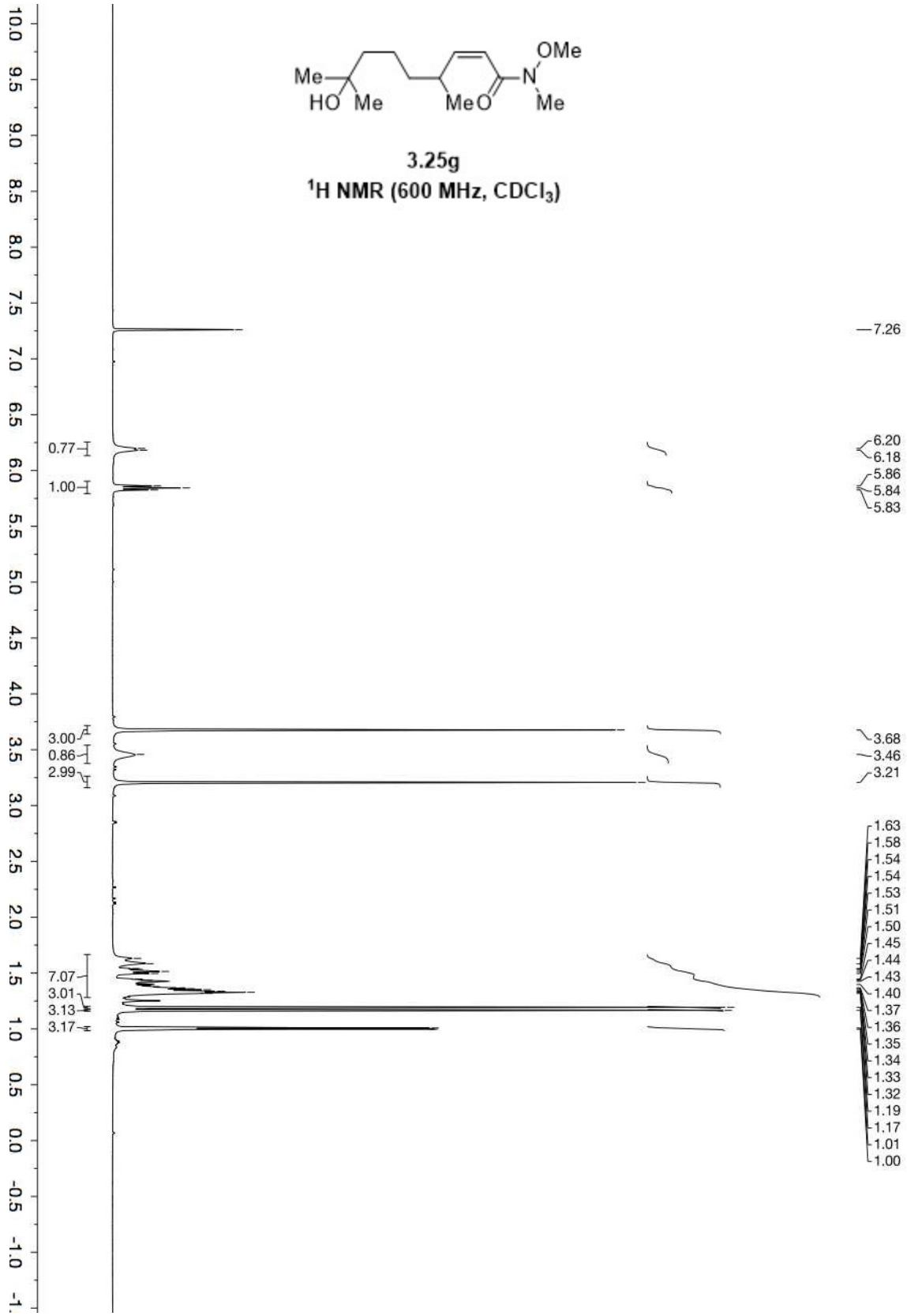

CO2H
OMe
N
Me
O
3.25d
13C NMR (150 MHz, CDCl3)
178.77
167.76
147.90
118.14
77.41
77.16
76.91
61.63
34.02
32.25
29.86
29.33
29.27
29.20
29.18
29.10
24.80

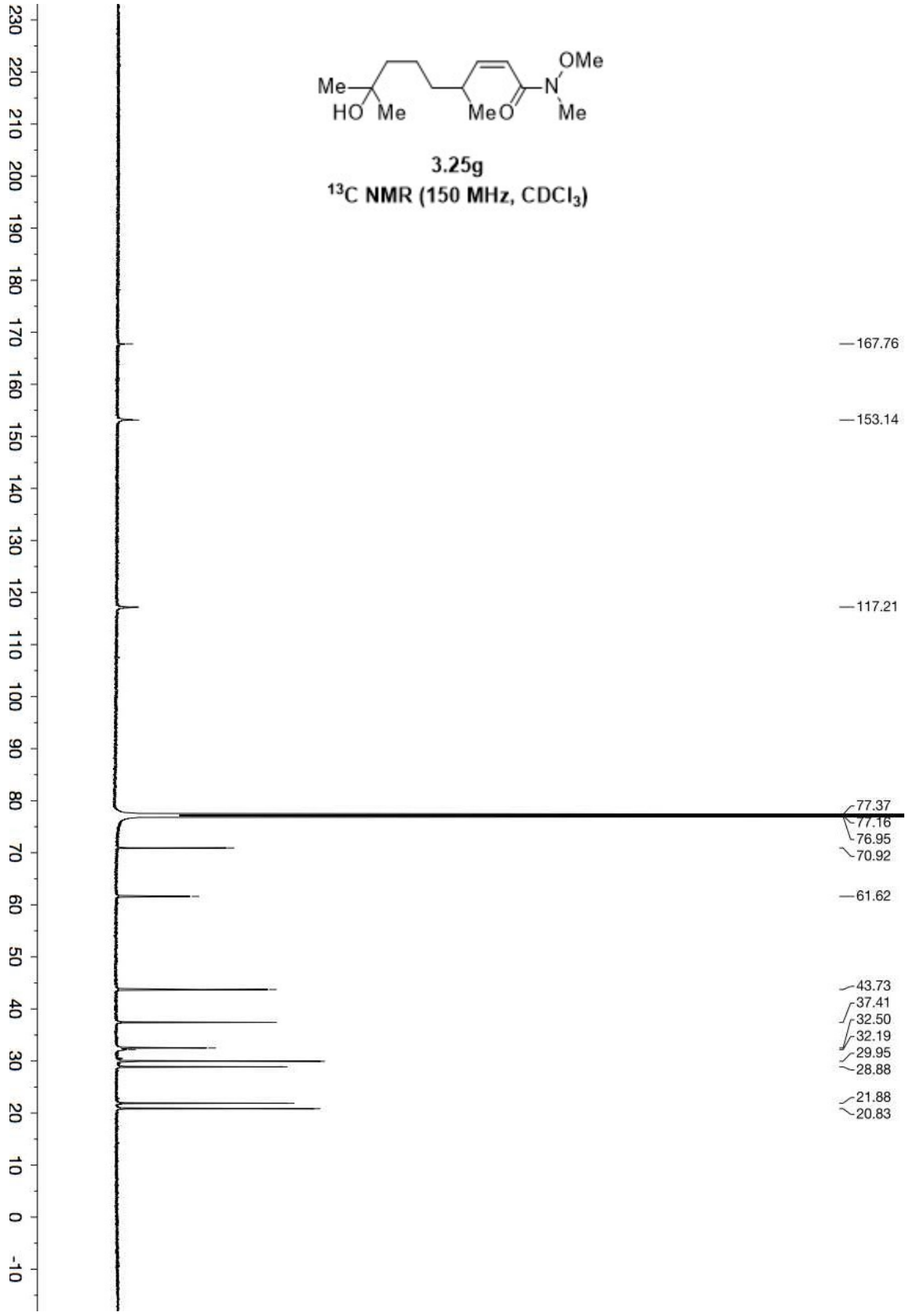

3.25e
^{1}H NMR (600 MHz, $CDCl_3$)
1.94
2.05
0.98
1.05
2.02
3.00
2.98
2.00
2.12
2.18
7.85
7.84
7.83
7.83
7.83
7.82
7.71
7.71
7.70
7.70
7.69
7.69
7.26
6.25
6.23
6.10
6.09
6.08
6.08
6.07
6.06
3.71
3.70
3.69
3.67
3.20
2.69
2.68
2.67
2.66
1.75
1.74
1.73
1.72
1.70
1.53
1.52
1.50
1.49
1.48

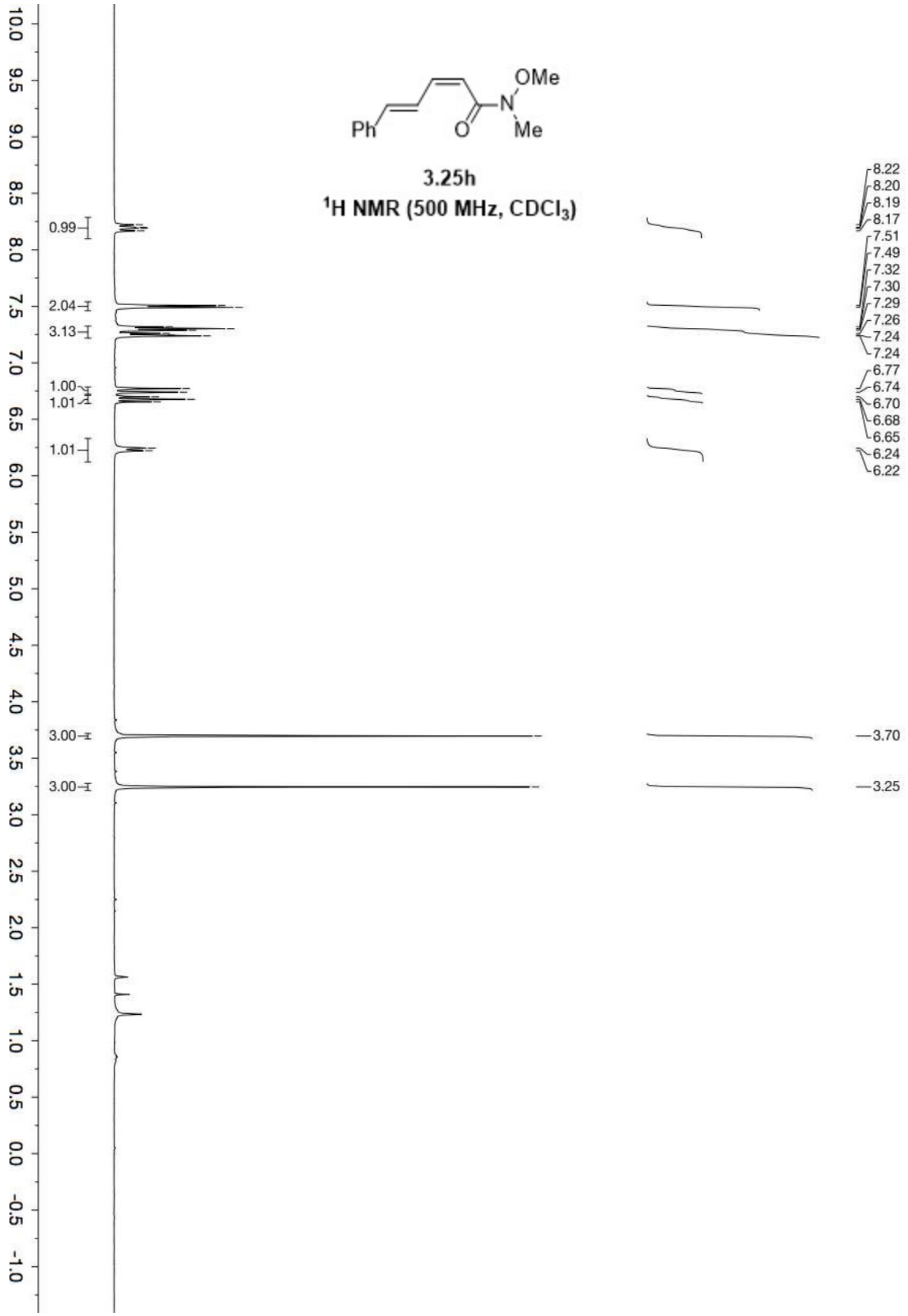

3.25e
^{13}C NMR (150 MHz, $CDCl_3$)
168.55
146.78
133.96
132.34
125.66
123.35
118.78
77.37
77.16
76.95
61.65
38.06
32.08
28.64
28.44
26.71

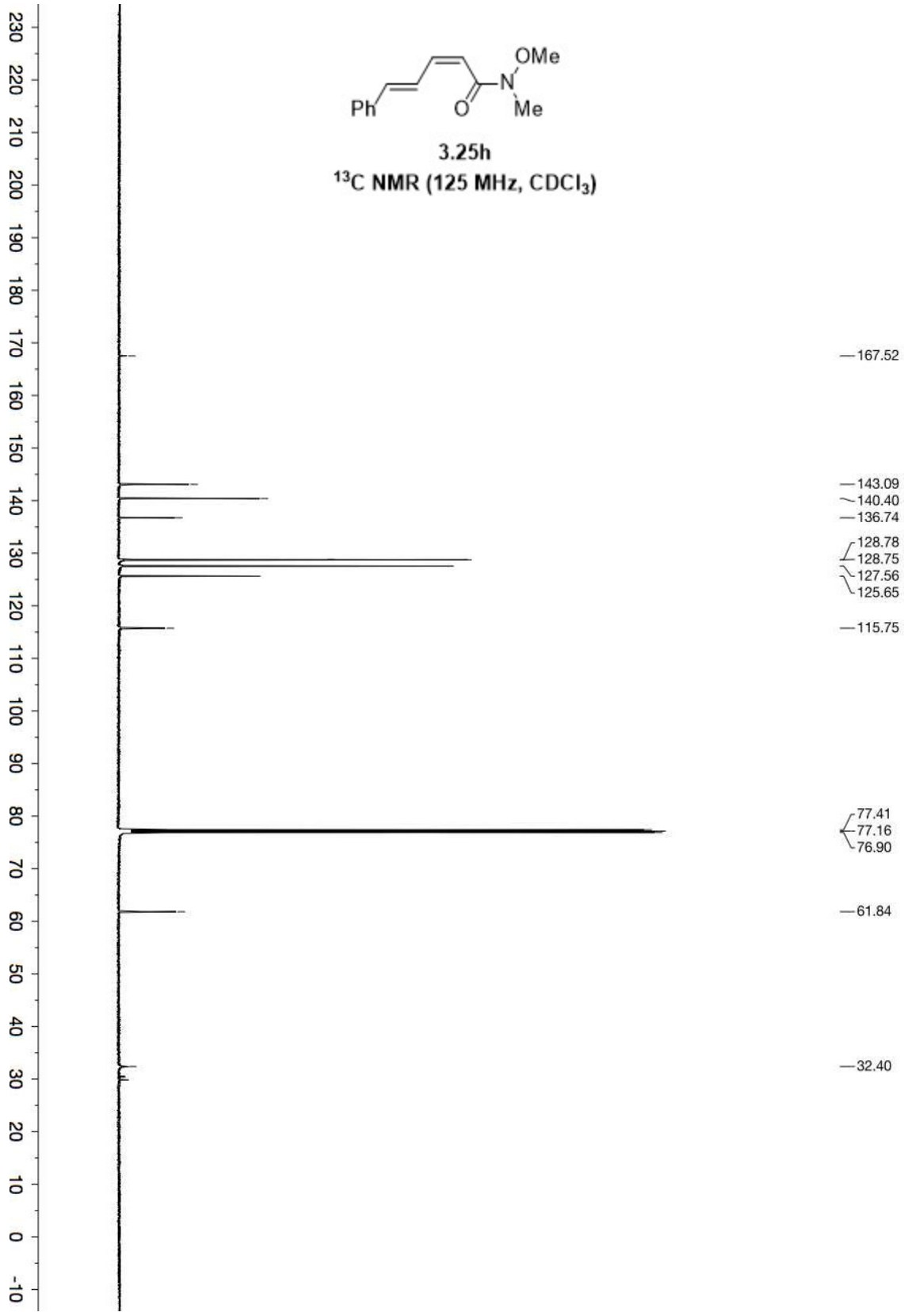

MeO
MeO
OMe
N
Me
O
3.25f
1H NMR (600 MHz, CDCl3)
7.26
6.81
6.80
6.32
6.31
6.26
6.25
6.25
6.24
6.23
6.22
3.93
3.92
3.87
3.85
3.70
3.25
3.01
0.76
1.04
1.99
6.01
3.00
3.03

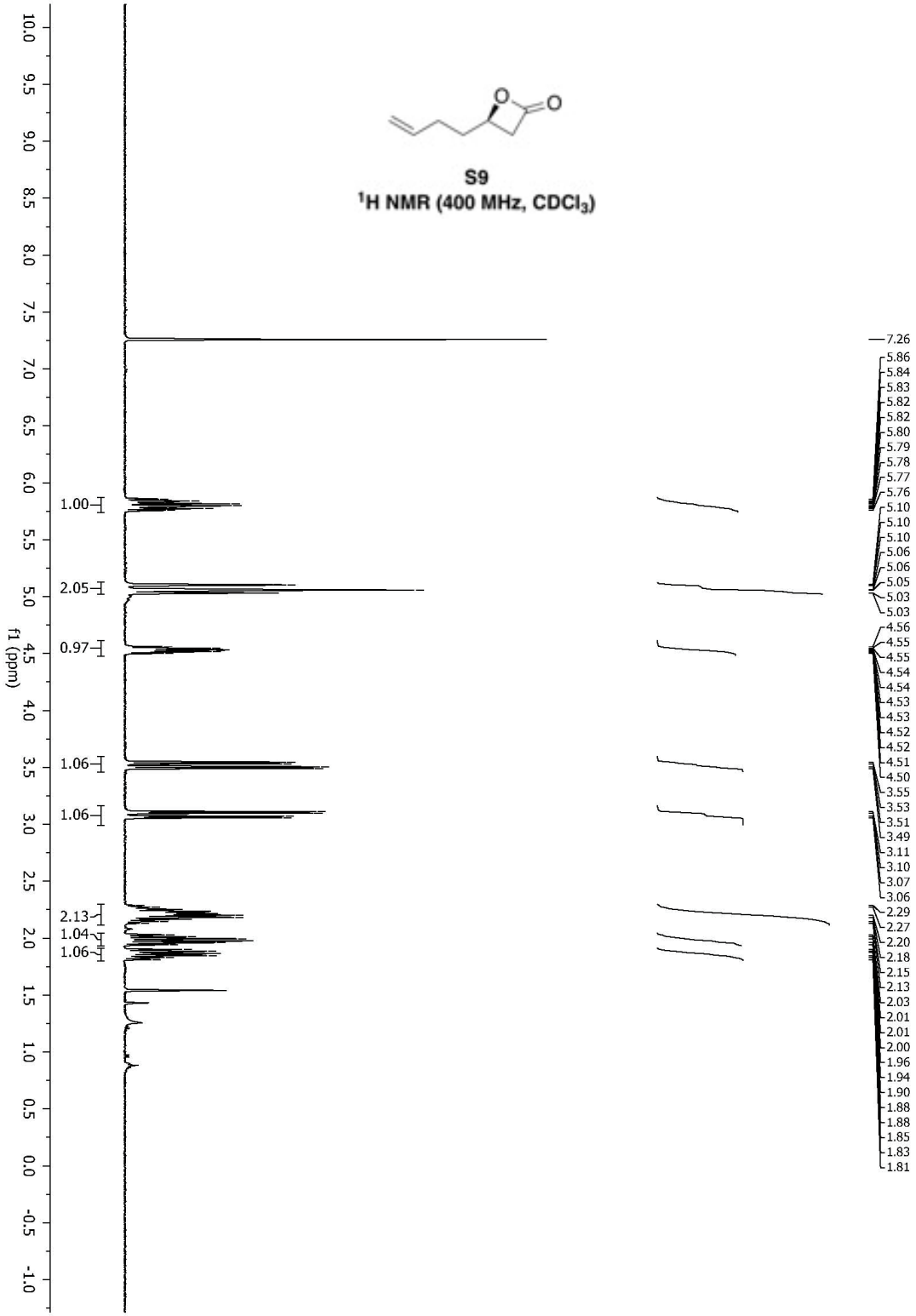

MeO
MeO
OMe
N
Me
O
3.25f
^{13}C NMR (150 MHz, $CDCl_3$)
167.5
149.1
147.6
145.7
132.8
120.6
118.2
112.2
111.5
77.4
76.9
61.7
56.1
56.0
35.0
32.2

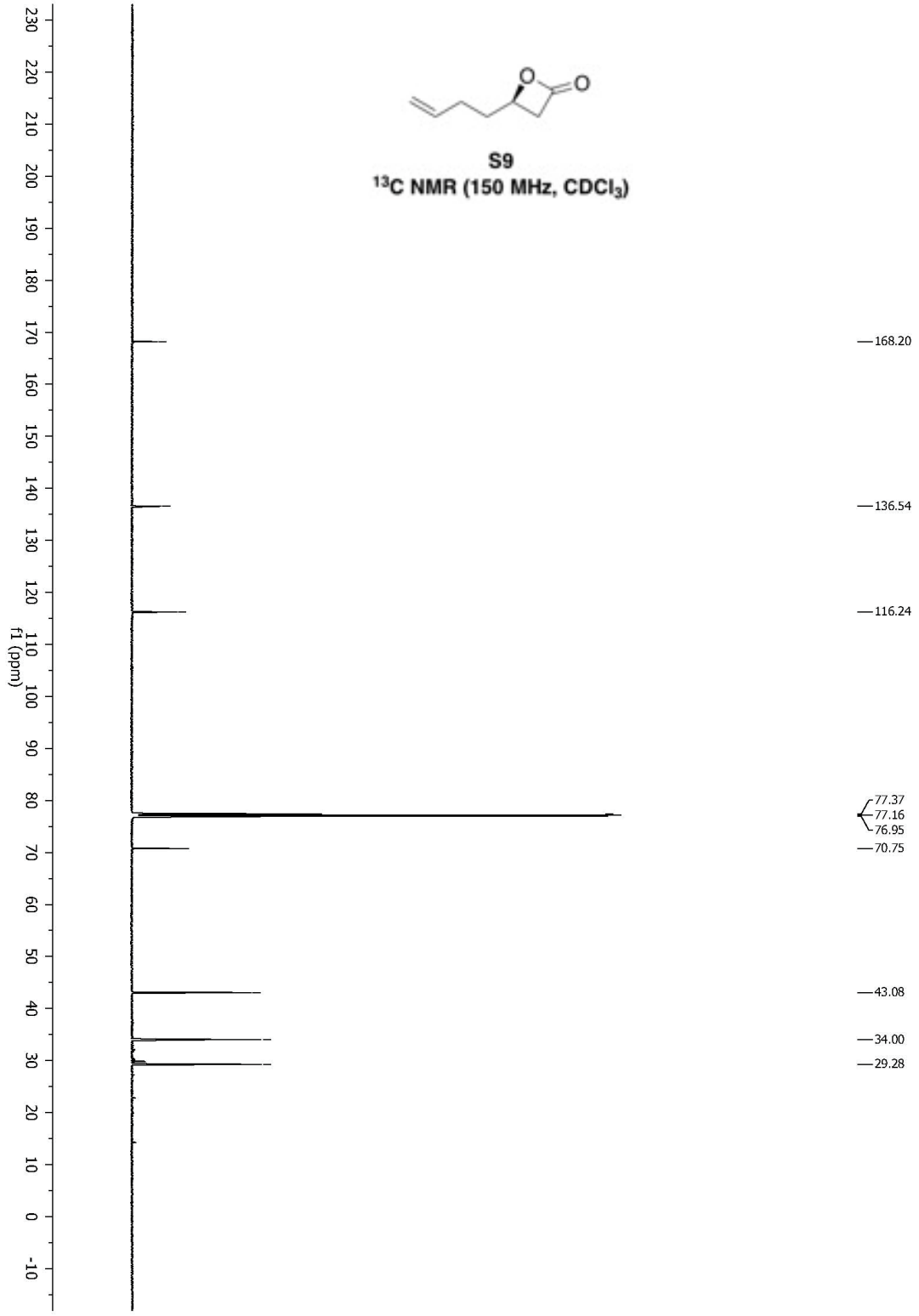

Me
HO
Me
Me
O
OMe
N
Me
3.25g
¹H NMR (600 MHz, CDCl₃)
7.26
6.20
6.18
5.86
5.84
5.83
3.68
3.46
3.21
1.63
1.58
1.54
1.54
1.53
1.51
1.50
1.45
1.44
1.43
1.40
1.37
1.36
1.35
1.34
1.33
1.32
1.19
1.17
1.01
1.00
0.77
1.00
3.00
0.86
2.99
7.07
3.01
3.13
3.17

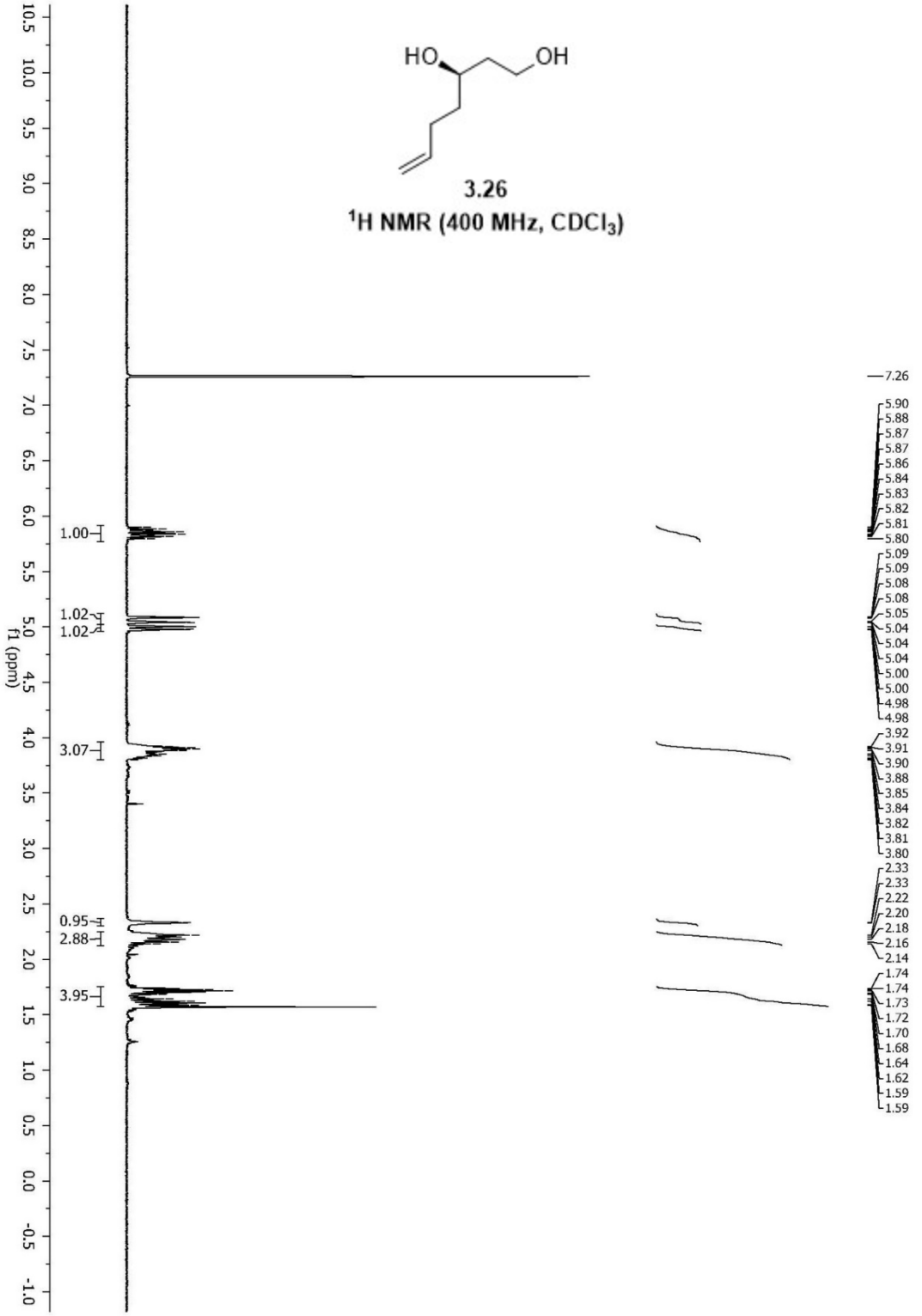

OMe
Me
N
HO Me
MeO
Me
3.25g
13C NMR (150 MHz, CDCl3)
167.76
153.14
117.21
77.37
77.16
76.95
70.92
61.62
43.73
37.41
32.50
32.19
29.95
28.88
21.88
20.83

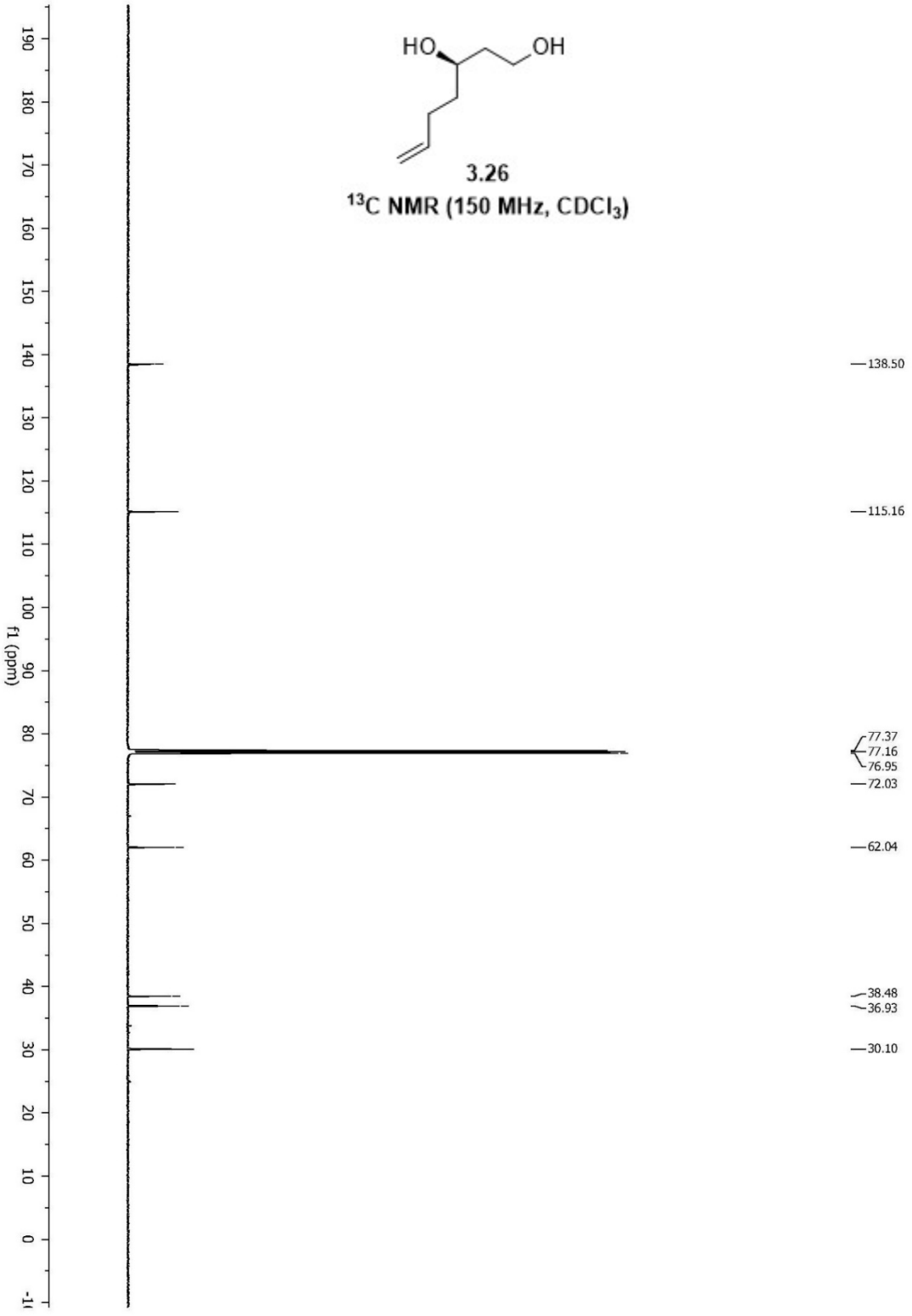

OMe
N
Ph
O
Me
3.25h
^{1}H NMR (500 MHz, $CDCl_3$)
0.99
2.04
3.13
1.00
1.01
1.01
3.00
3.00
8.22
8.20
8.19
8.17
7.51
7.49
7.32
7.30
7.29
7.26
7.24
7.24
6.77
6.74
6.70
6.68
6.65
6.24
6.22
3.70
3.25

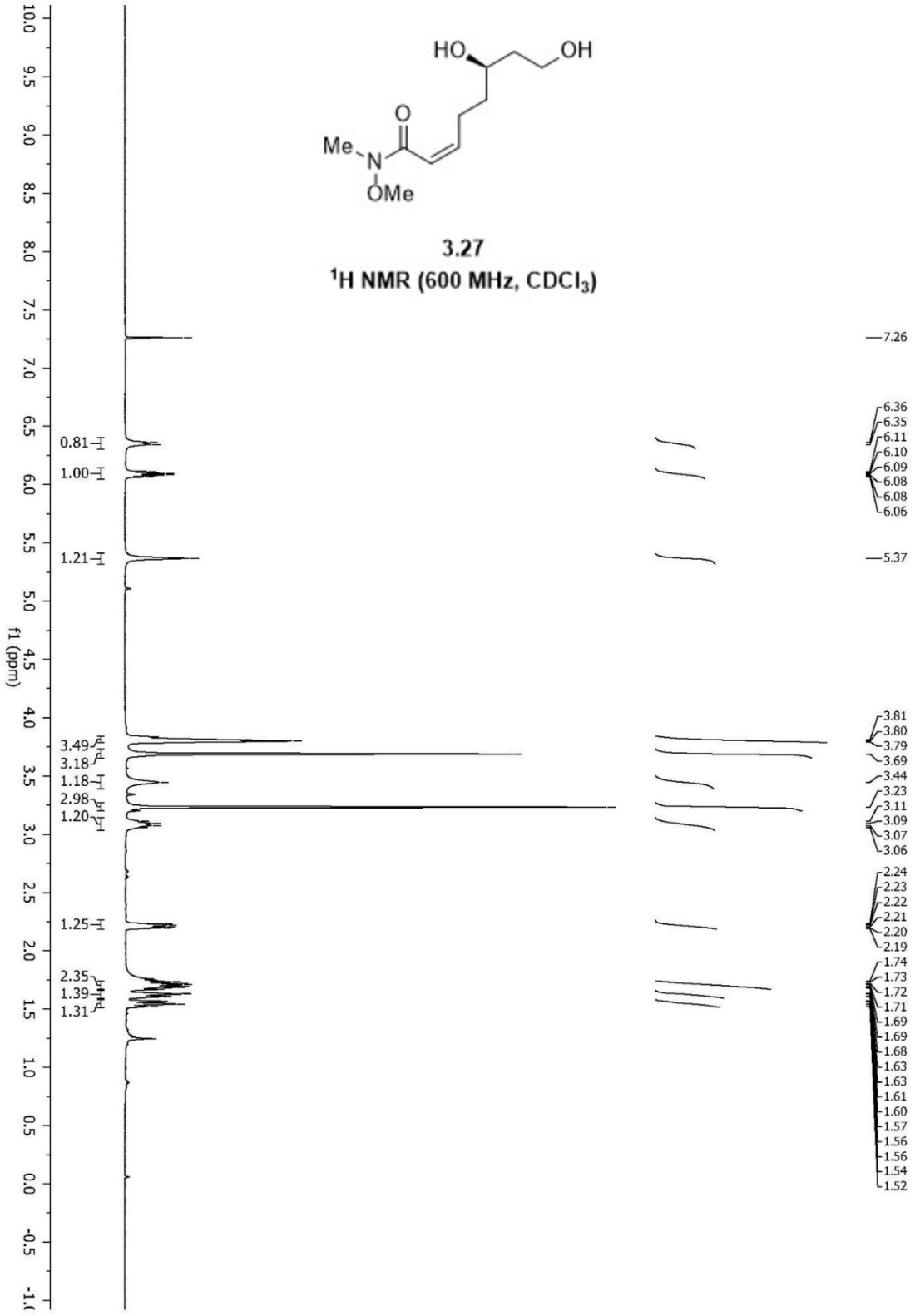

OMe
N
Ph
O
Me
3.25h
^{13}C NMR (125 MHz, $CDCl_3$)
167.52
143.09
140.40
136.74
128.78
128.75
127.56
125.65
115.75
77.41
77.16
76.90
61.84
32.40

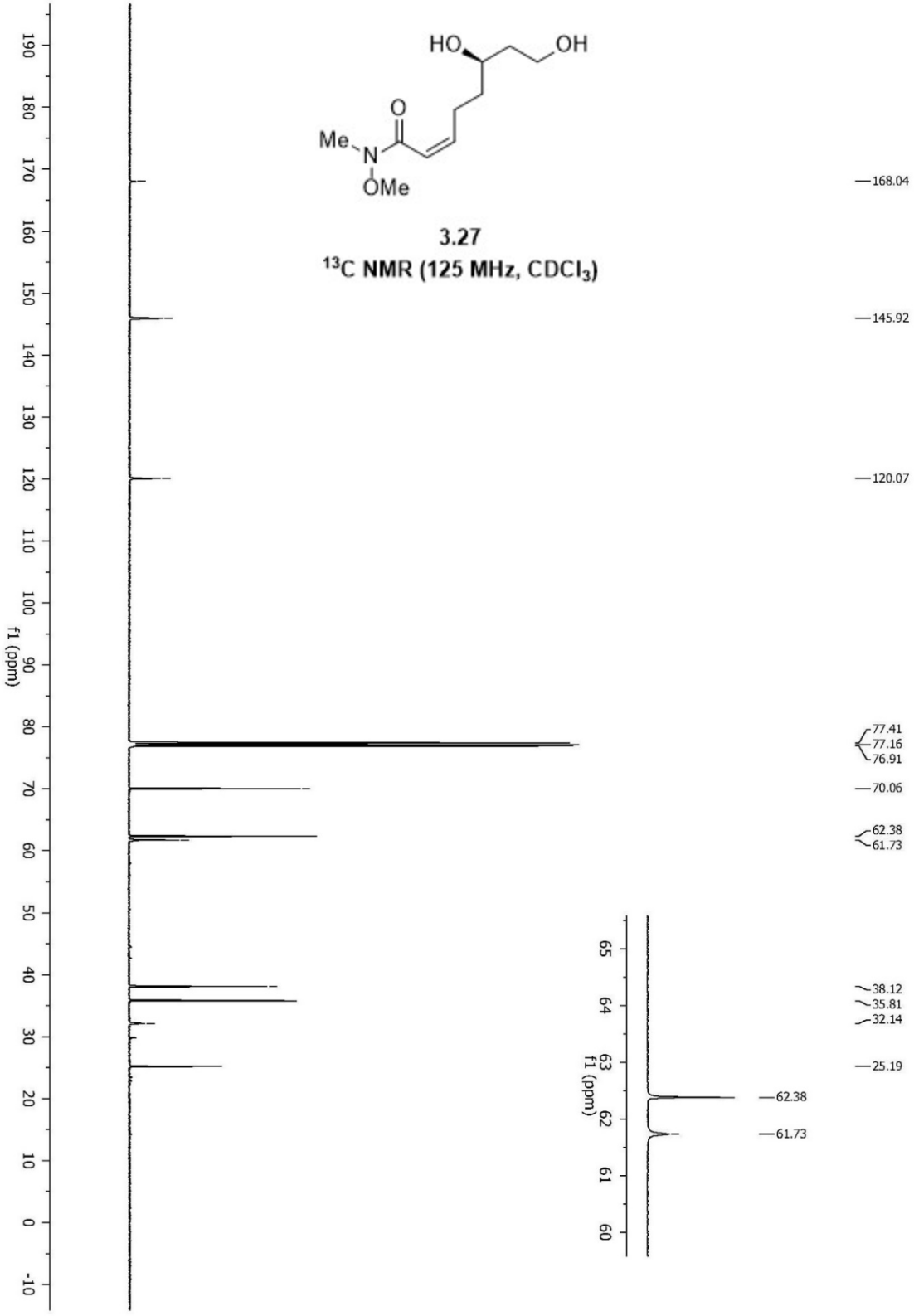

S9
^{1}H NMR (400 MHz, $CDCl_3$)
f1 (ppm)
1.00
2.05
0.97
1.06
1.06
2.13
1.04
1.06
7.26
5.86
5.84
5.83
5.82
5.82
5.80
5.79
5.78
5.77
5.76
5.10
5.10
5.10
5.06
5.06
5.05
5.03
5.03
4.56
4.55
4.55
4.54
4.54
4.53
4.53
4.52
4.52
4.51
4.50
3.55
3.53
3.51
3.49
3.11
3.10
3.07
3.06
2.29
2.27
2.20
2.18
2.15
2.13
2.03
2.01
2.01
2.00
1.96
1.94
1.90
1.88
1.88
1.85
1.83
1.81

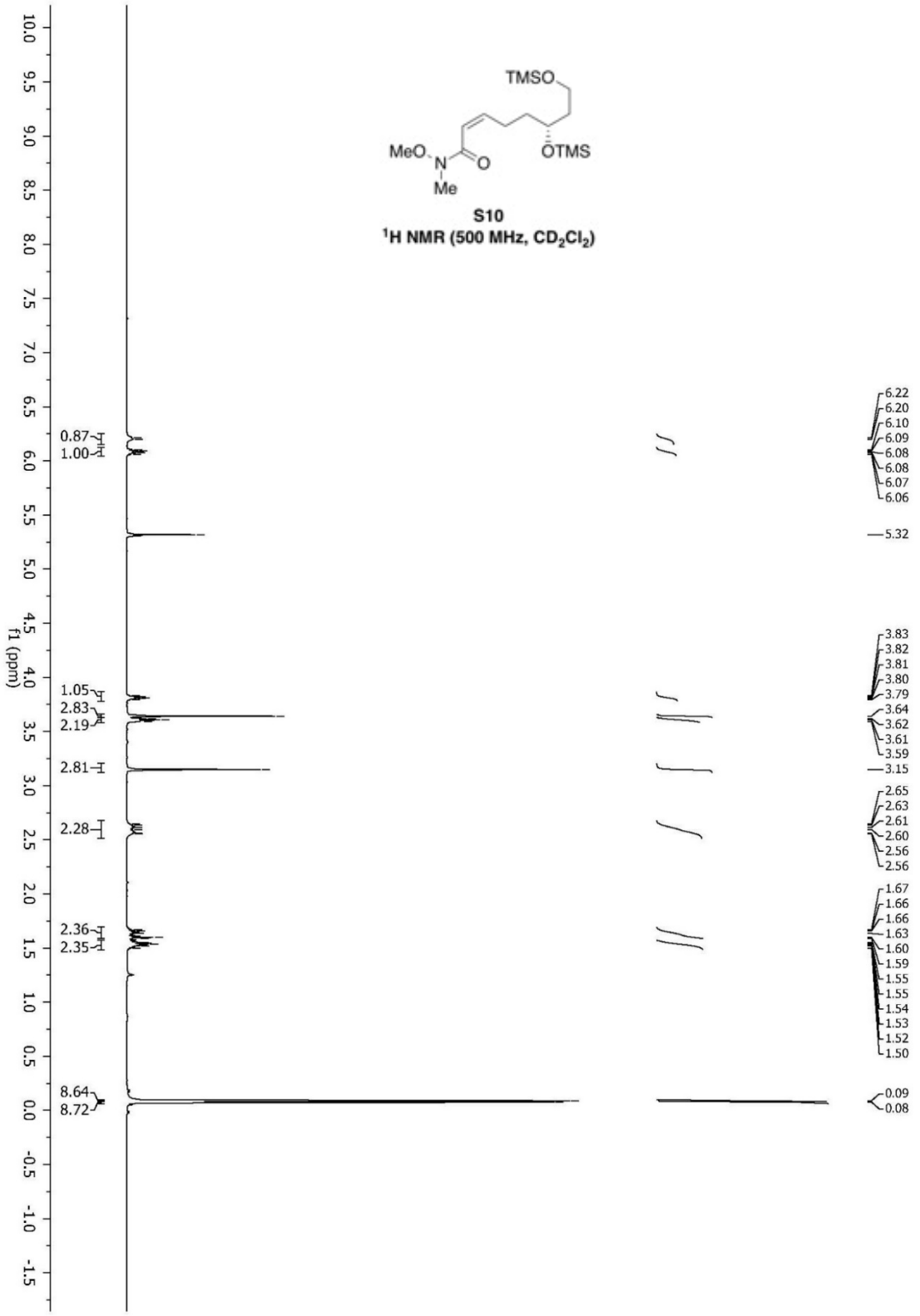

S9
^{13}C NMR (150 MHz, $CDCl_3$)
168.20
136.54
116.24
77.37
77.16
76.95
70.75
43.08
34.00
29.28
f1 (ppm)

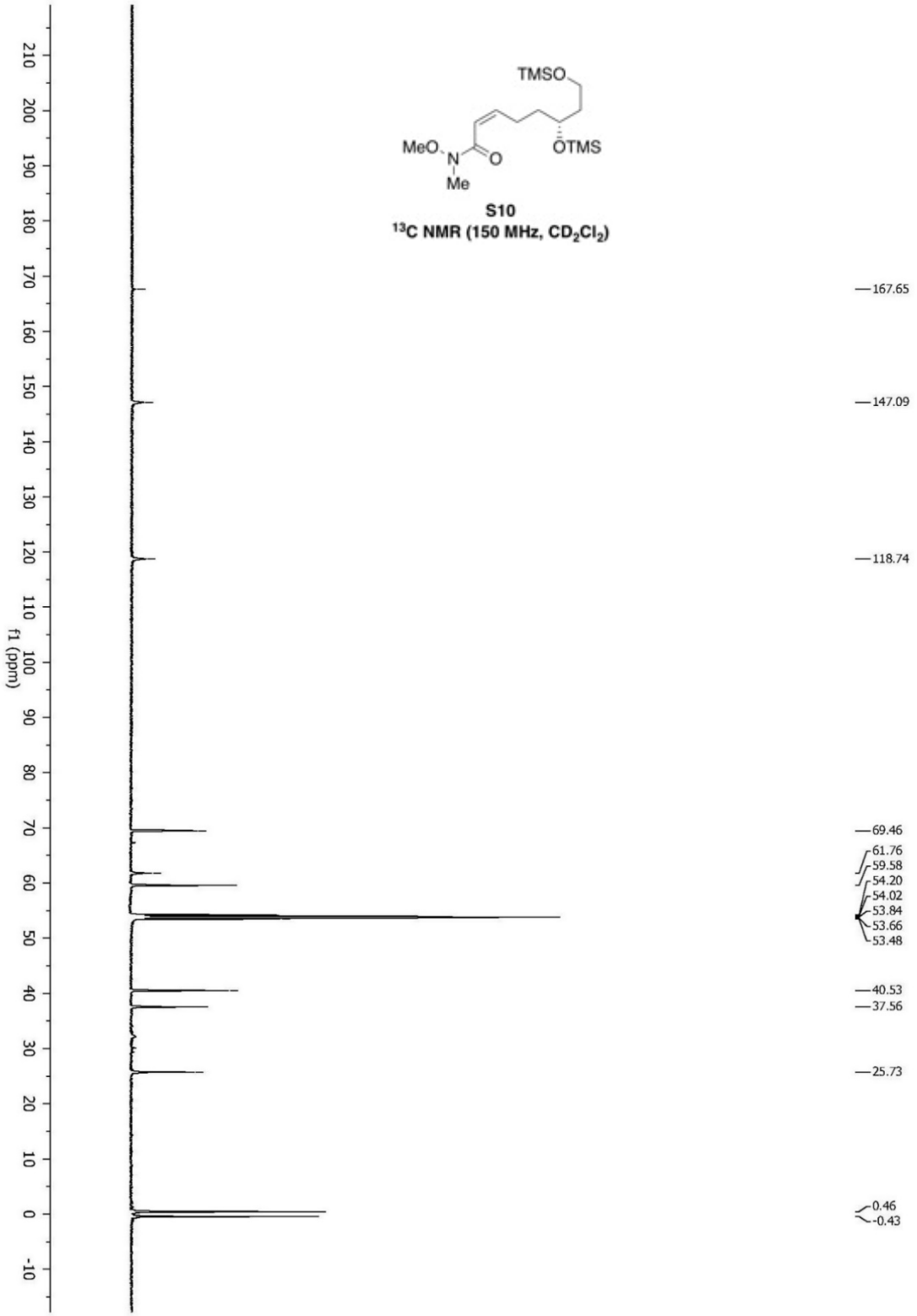

HO
OH
3.26
¹H NMR (400 MHz, CDCl₃)
f1 (ppm)
1.00
1.02
1.02
3.07
0.95
2.88
3.95
7.26
5.90
5.88
5.87
5.87
5.86
5.84
5.83
5.82
5.81
5.80
5.09
5.09
5.08
5.08
5.05
5.04
5.04
5.04
5.00
5.00
4.98
4.98
3.92
3.91
3.90
3.88
3.85
3.84
3.82
3.81
3.80
2.33
2.33
2.22
2.20
2.18
2.16
2.14
1.74
1.74
1.73
1.72
1.70
1.68
1.64
1.62
1.59
1.59

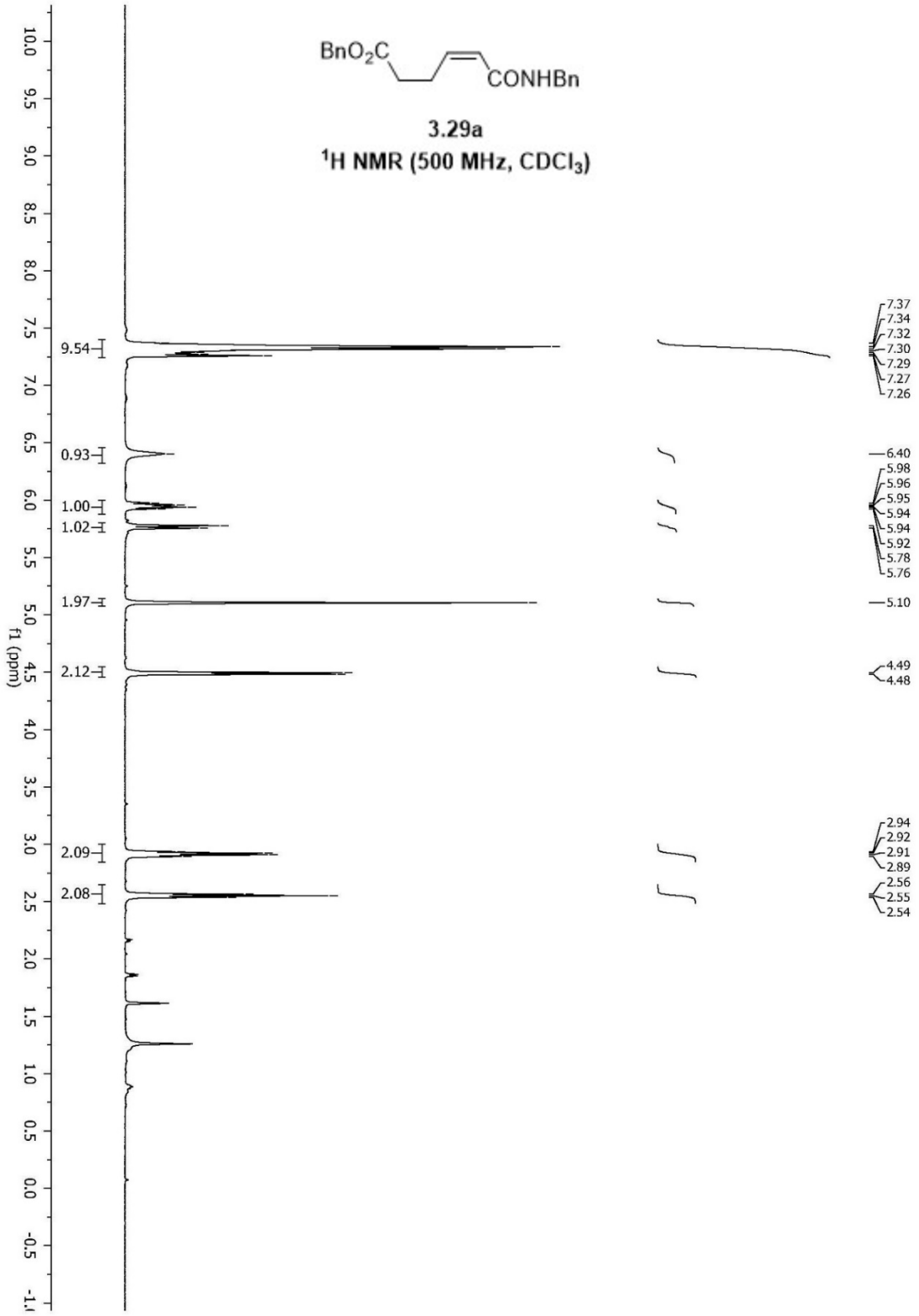

HO
OH
3.26
^{13}C NMR (150 MHz, $CDCl_3$)
f1 (ppm)
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-1
138.50
115.16
77.37
77.16
76.95
72.03
62.04
38.48
36.93
30.10

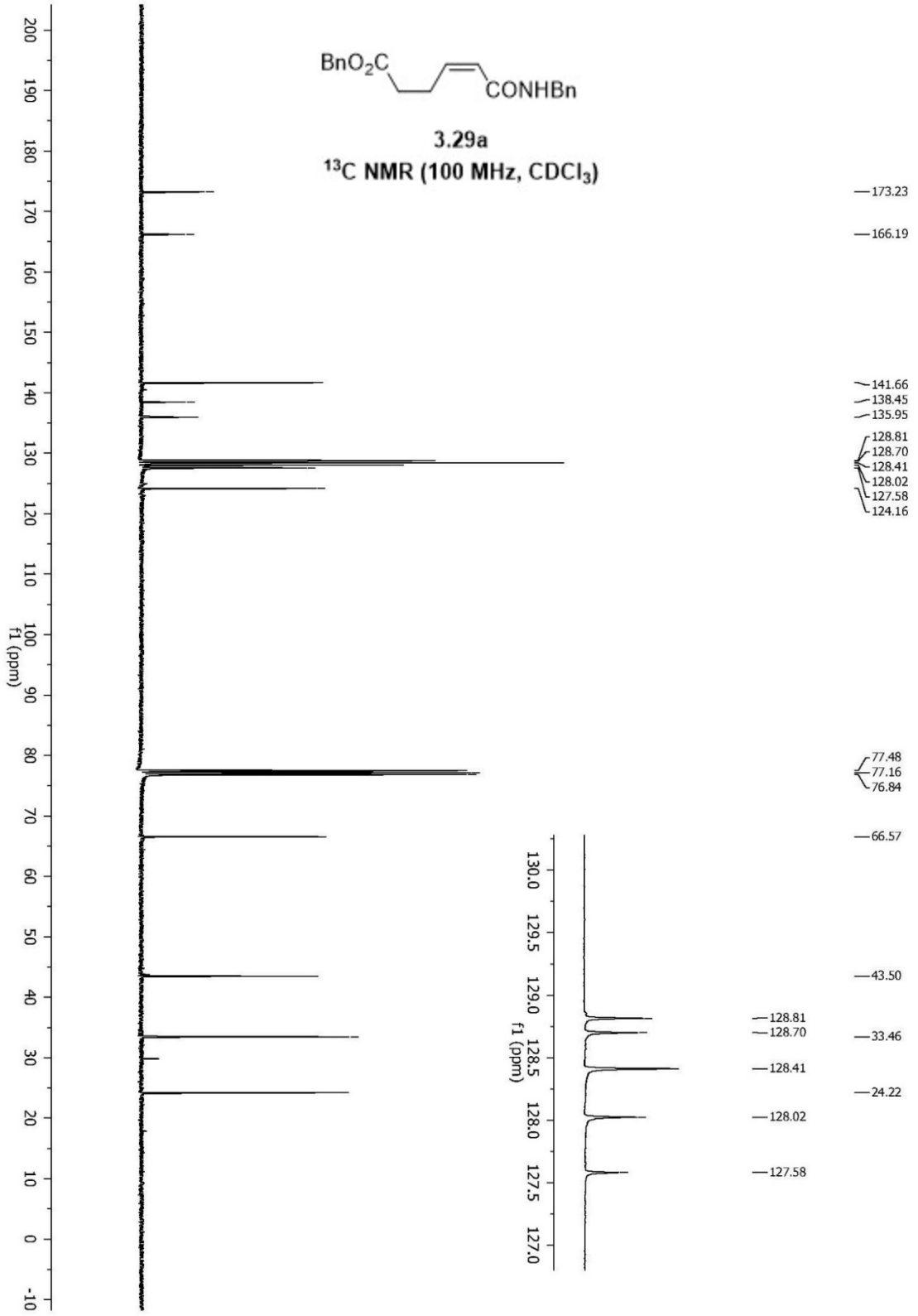

HO
OH
O
Me
N
OMe
3.27
^{1}H NMR (600 MHz, $CDCl_3$)
f1 (ppm)
0.81
1.00
1.21
3.49
3.18
1.18
2.98
1.20
1.25
2.35
1.39
1.31
7.26
6.36
6.35
6.11
6.10
6.09
6.08
6.08
6.06
5.37
3.81
3.80
3.79
3.69
3.44
3.23
3.11
3.09
3.07
3.06
2.24
2.23
2.22
2.21
2.20
2.19
1.74
1.73
1.72
1.71
1.69
1.69
1.68
1.63
1.63
1.61
1.60
1.57
1.56
1.56
1.54
1.52

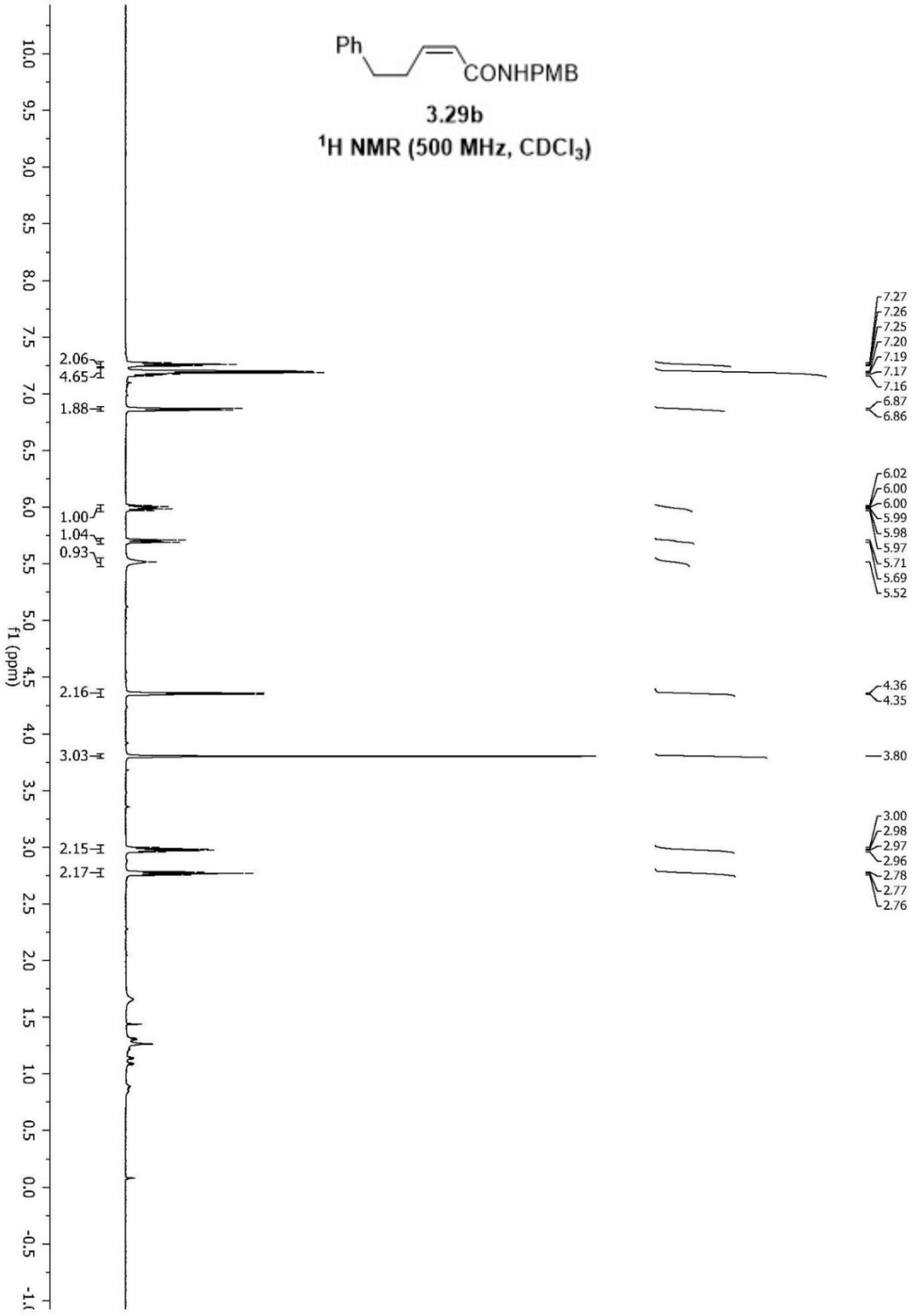

HO
OH
O
Me
N
OMe
3.27
^{13}C NMR (125 MHz, $CDCl_3$)
168.04
145.92
120.07
77.41
77.16
76.91
70.06
62.38
61.73
38.12
35.81
32.14
25.19
f1 (ppm)

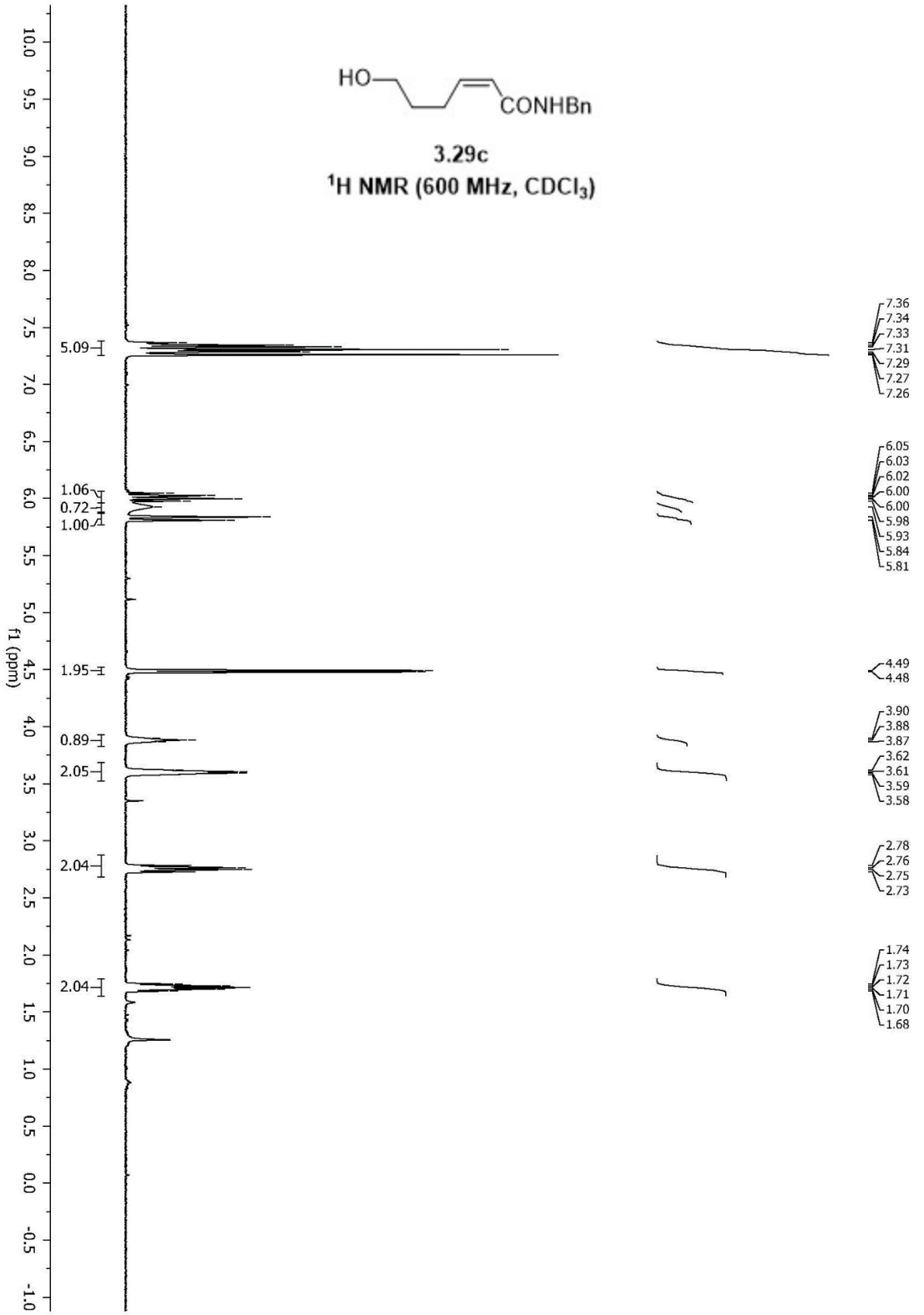

TMSO
MeO
N
Me
O
OTMS
S10
¹H NMR (500 MHz, CD₂Cl₂)
f1 (ppm)
0.87
1.00
1.05
2.83
2.19
2.81
2.28
2.36
2.35
8.64
8.72
6.22
6.20
6.10
6.09
6.08
6.08
6.07
6.06
5.32
3.83
3.82
3.81
3.80
3.79
3.64
3.62
3.61
3.59
3.15
2.65
2.63
2.61
2.60
2.56
2.56
1.67
1.66
1.66
1.63
1.60
1.59
1.55
1.55
1.54
1.53
1.52
1.50
0.09
0.08

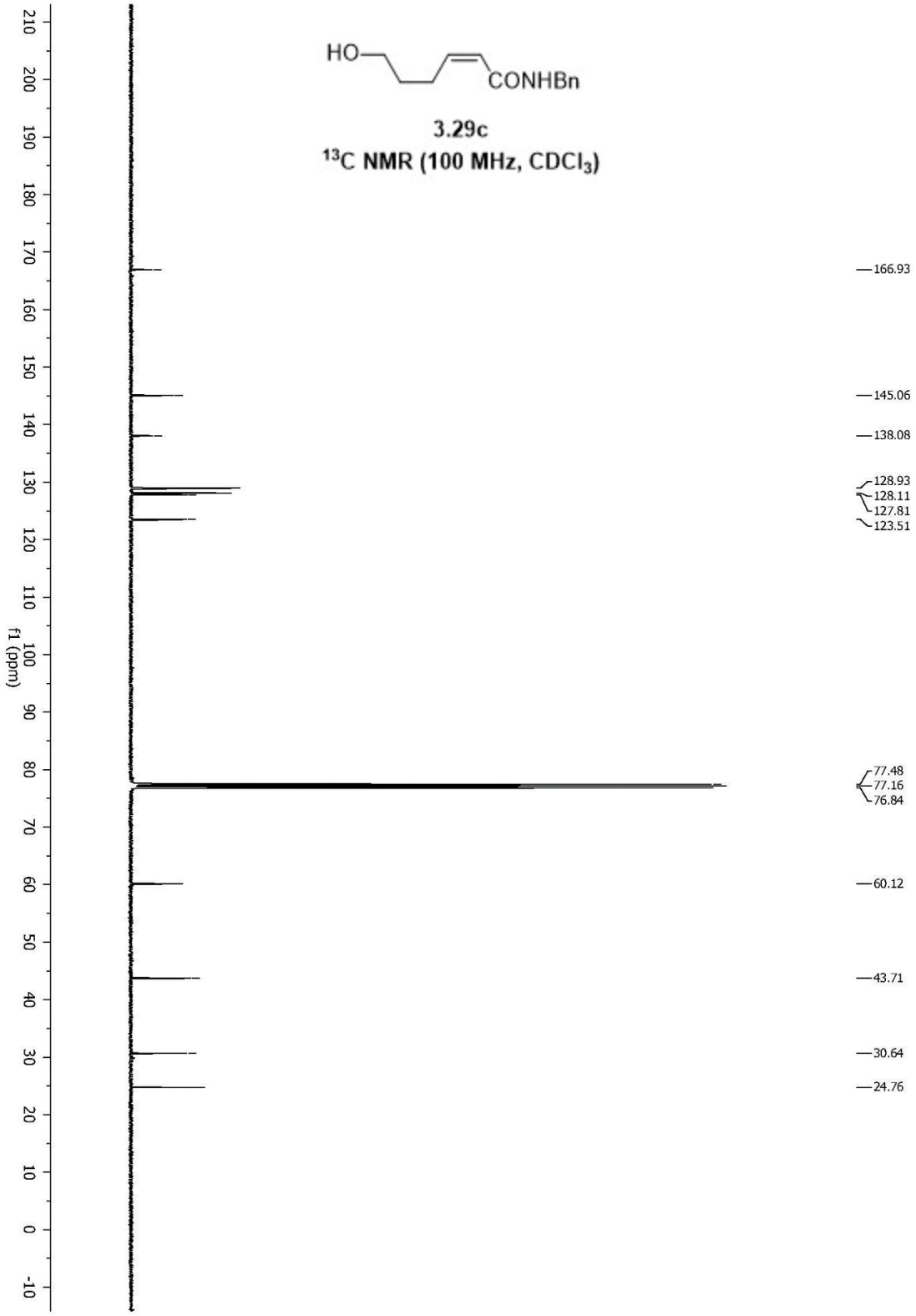

TMSO
MeO
N
Me
O
OTMS
S10
^{13}C NMR (150 MHz, CD_2Cl_2)
f1 (ppm)
167.65
147.09
118.74
69.46
61.76
59.58
54.20
54.02
53.84
53.66
53.48
40.53
37.56
25.73
0.46
-0.43

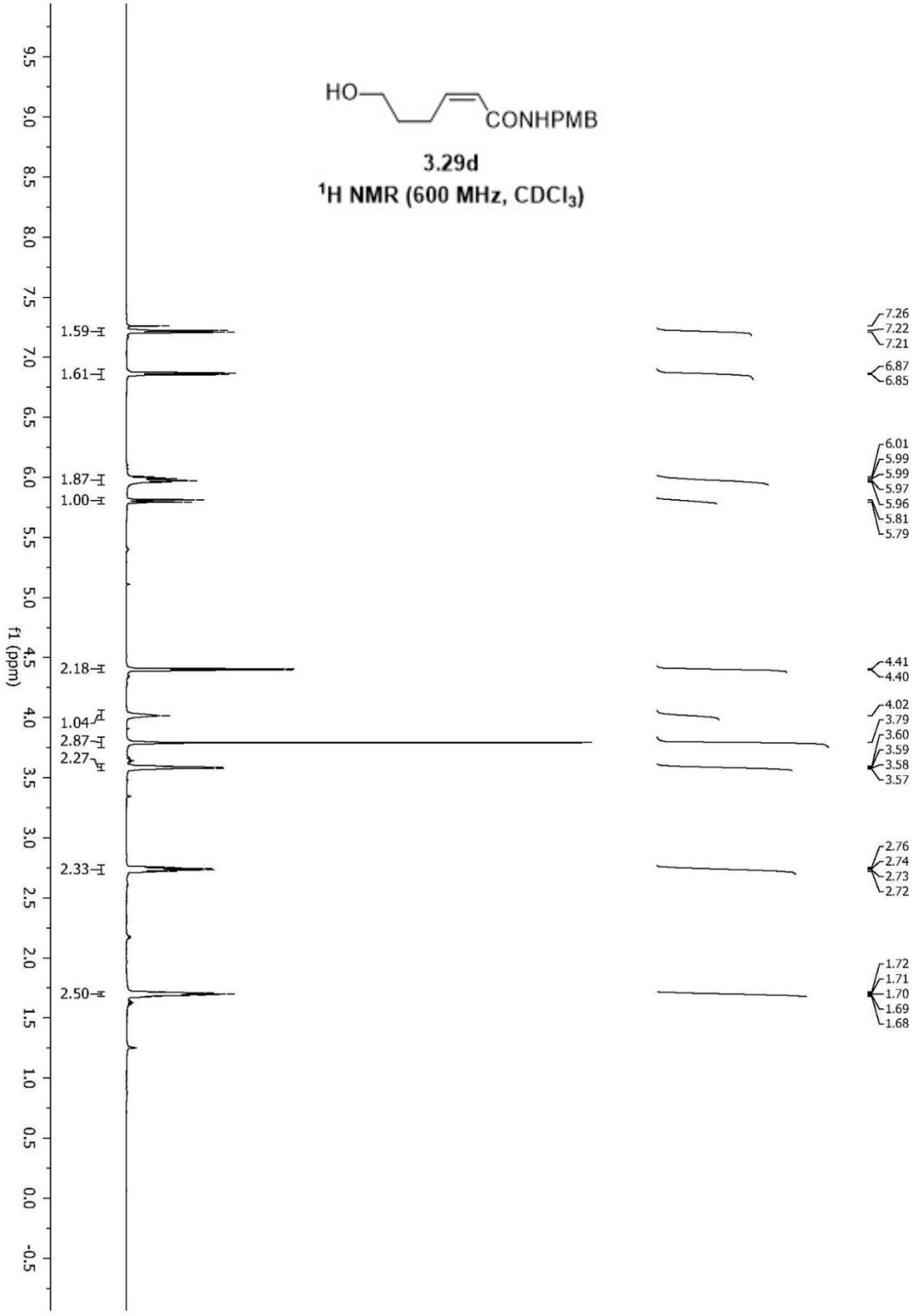

BnO2C
CONHBn
3.29a
1H NMR (500 MHz, CDCl3)
9.54
0.93
1.00
1.02
1.97
2.12
2.09
2.08
7.37
7.34
7.32
7.30
7.29
7.27
7.26
6.40
5.98
5.96
5.95
5.94
5.94
5.92
5.78
5.76
5.10
4.49
4.48
2.94
2.92
2.91
2.89
2.56
2.55
2.54
f1 (ppm)

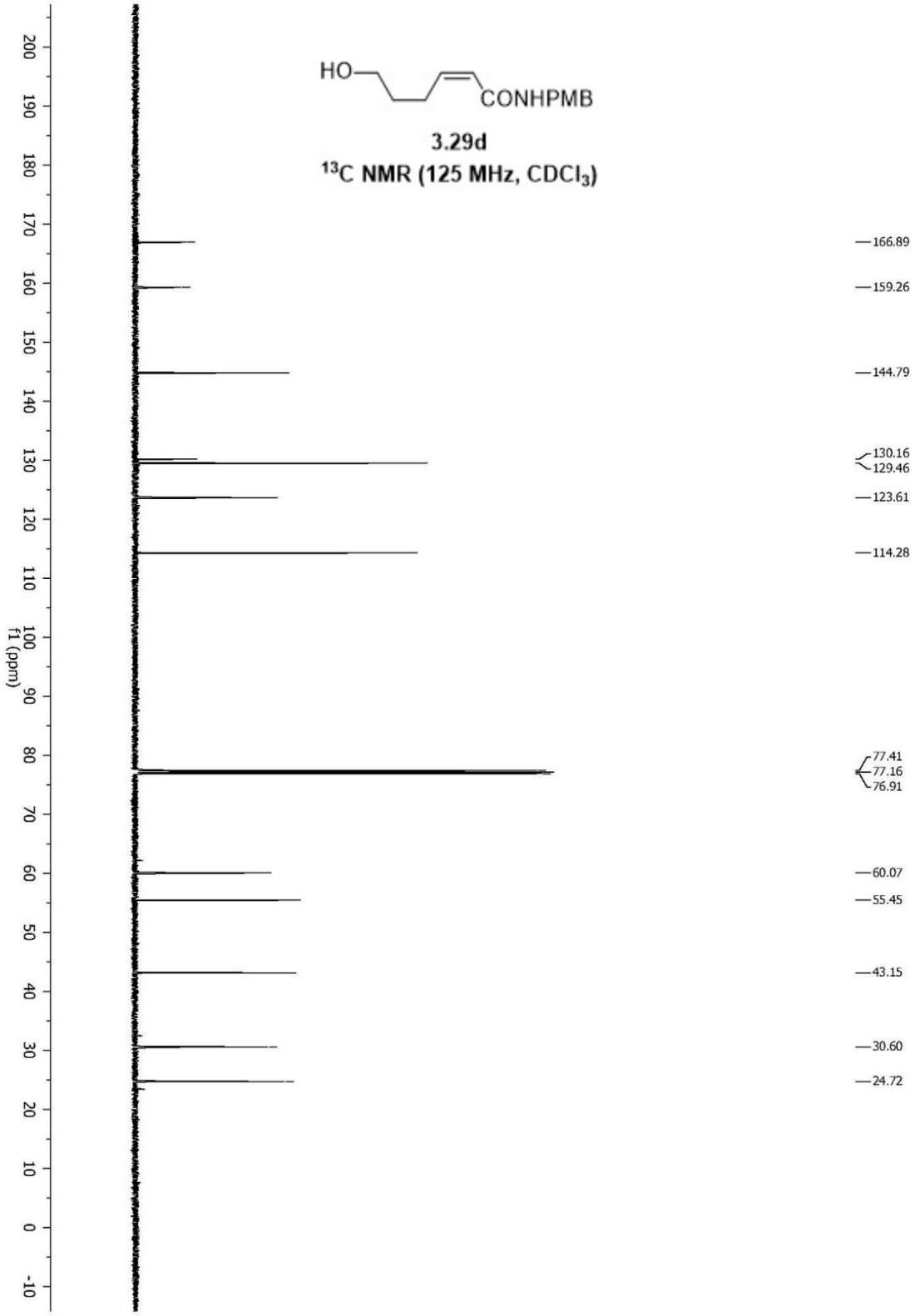

BnO2C
CONHBn
3.29a
13C NMR (100 MHz, CDCl3)
173.23
166.19
141.66
138.45
135.95
128.81
128.70
128.41
128.02
127.58
124.16
77.48
77.16
76.84
66.57
43.50
33.46
24.22
f1 (ppm)

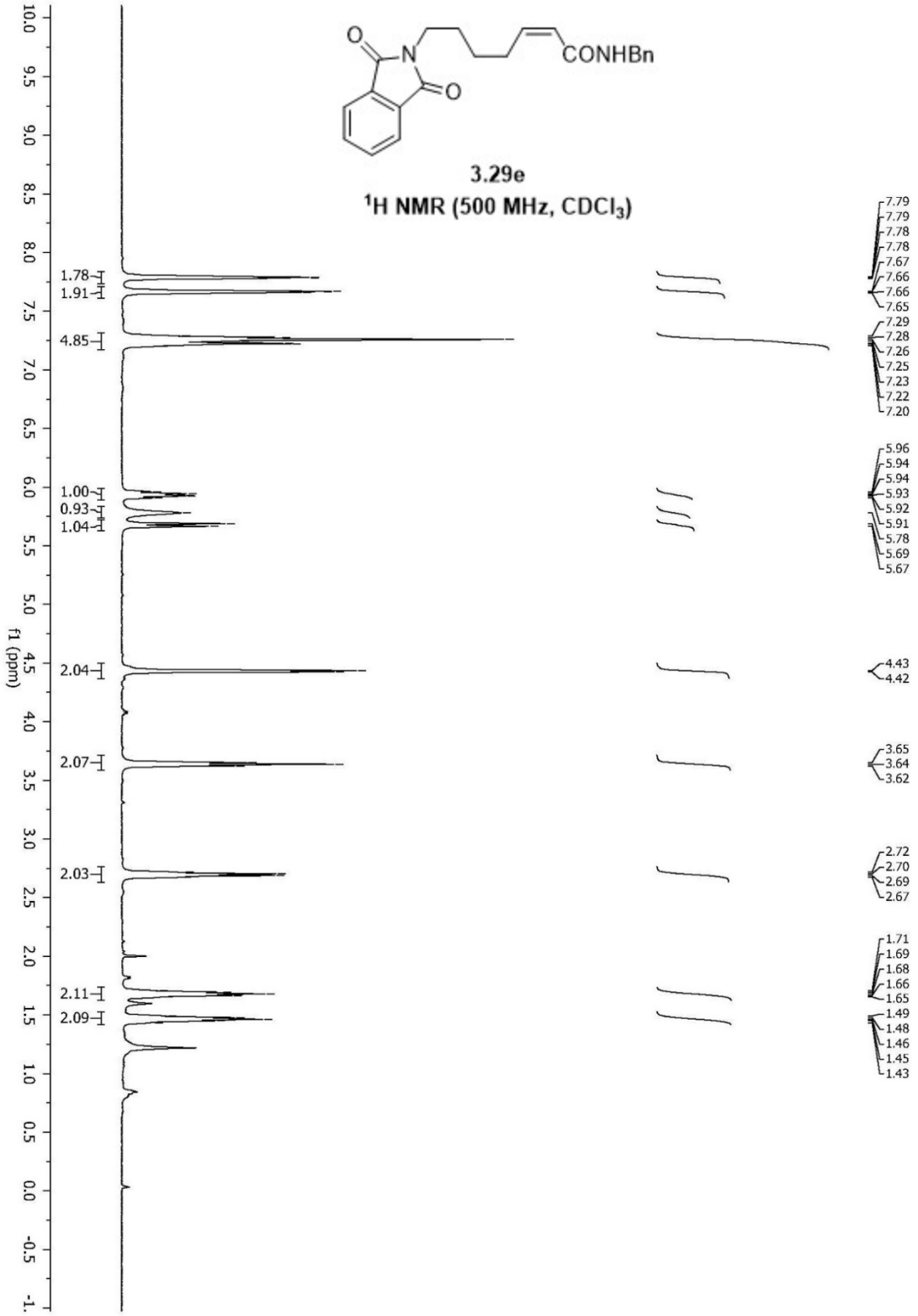

Ph
CONHPMB
3.29b
¹H NMR (500 MHz, CDCl₃)
f1 (ppm)
2.06
4.65
1.88
1.00
1.04
0.93
2.16
3.03
2.15
2.17
7.27
7.26
7.25
7.20
7.19
7.17
7.16
6.87
6.86
6.02
6.00
6.00
5.99
5.98
5.97
5.71
5.69
5.52
4.36
4.35
3.80
3.00
2.98
2.97
2.96
2.78
2.77
2.76

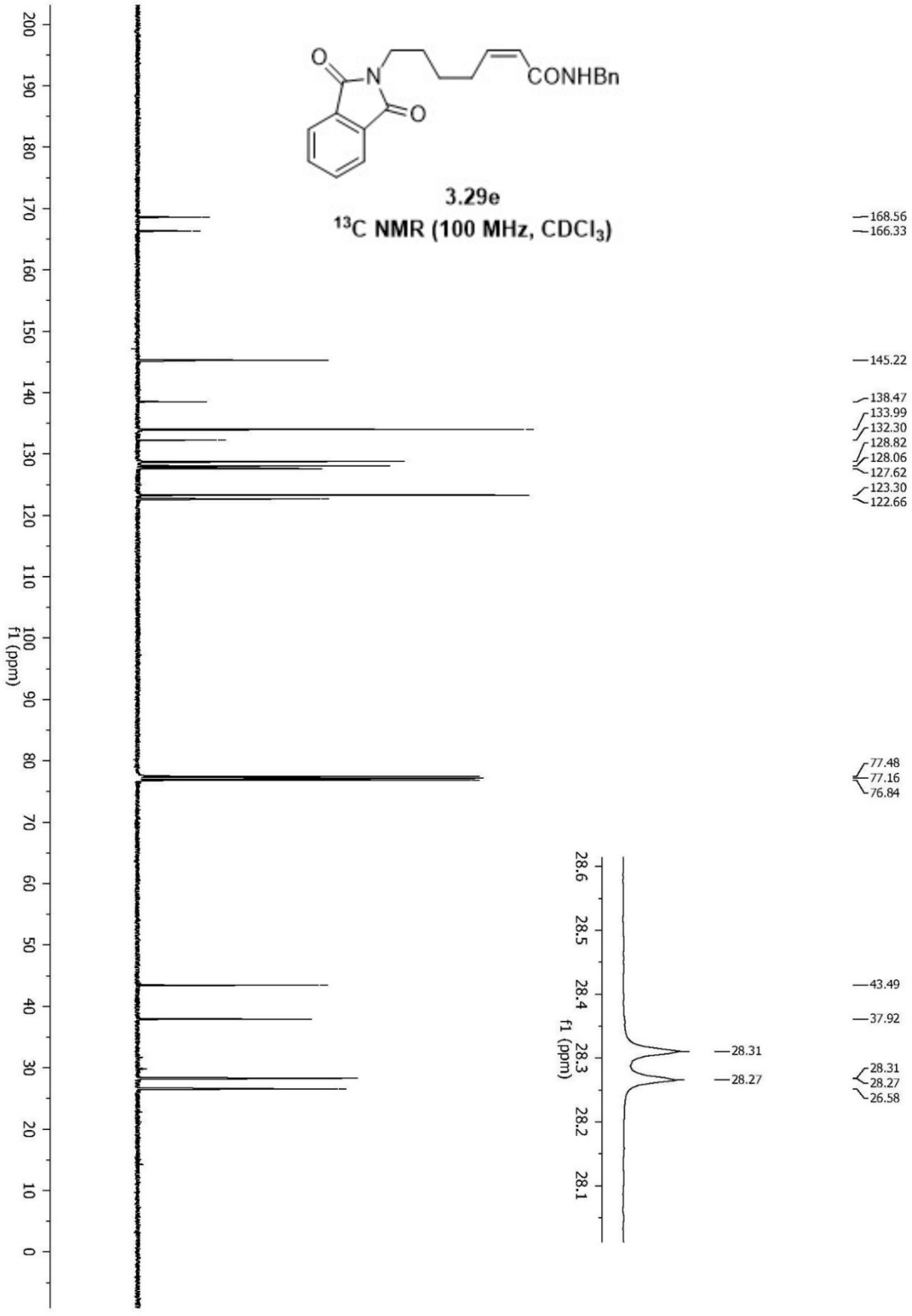

HO
CONHBn
3.29c
¹H NMR (600 MHz, CDCl₃)
f1 (ppm)
5.09
1.06
0.72
1.00
1.95
0.89
2.05
2.04
2.04
7.36
7.34
7.33
7.31
7.29
7.27
7.26
6.05
6.03
6.02
6.00
6.00
5.98
5.93
5.84
5.81
4.49
4.48
3.90
3.88
3.87
3.62
3.61
3.59
3.58
2.78
2.76
2.75
2.73
1.74
1.73
1.72
1.71
1.70
1.68

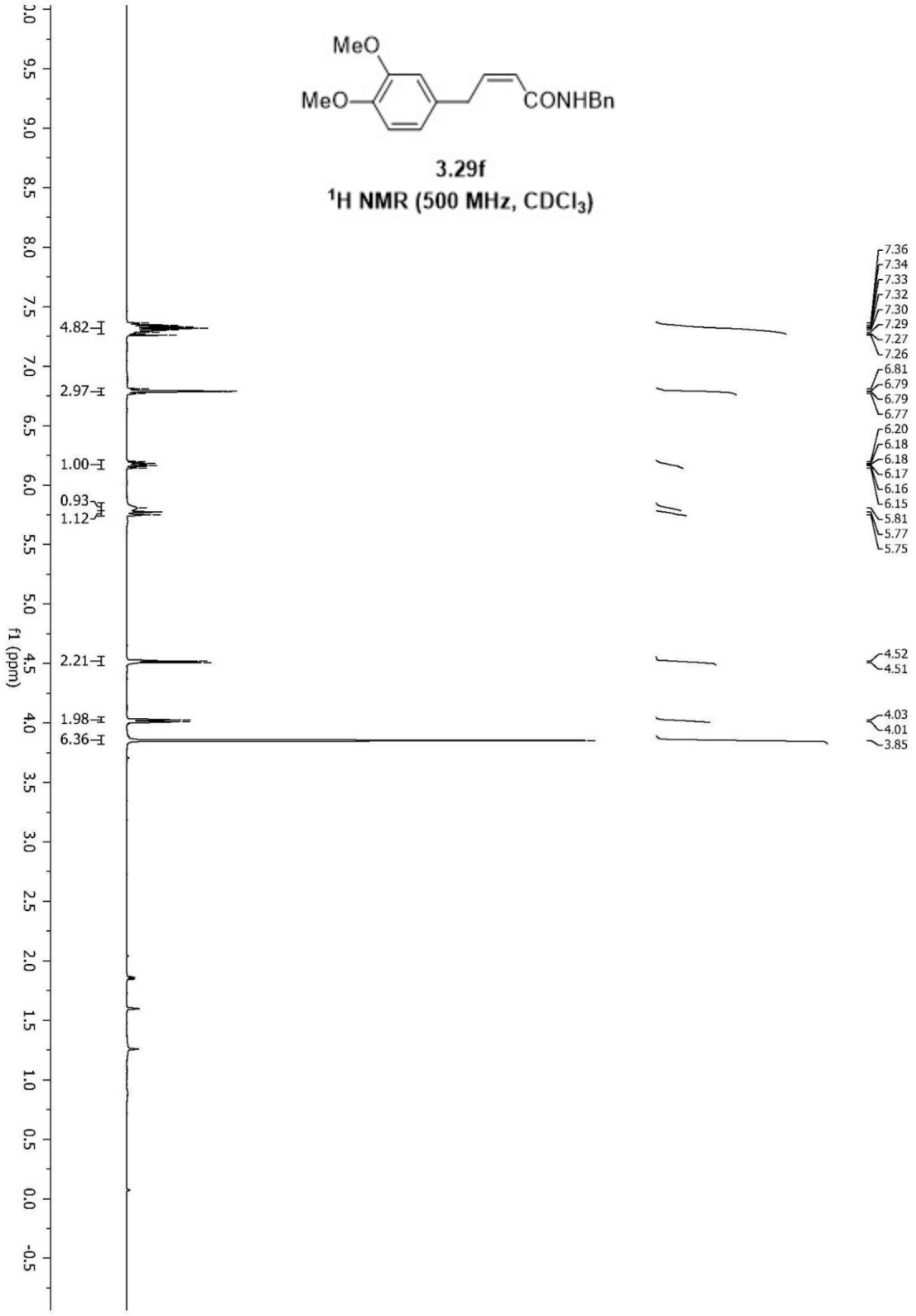

HO
CONHBn
3.29c
^{13}C NMR (100 MHz, $CDCl_3$)
166.93
145.06
138.08
128.93
128.11
127.81
123.51
77.48
77.16
76.84
60.12
43.71
30.64
24.76
f1 (ppm)

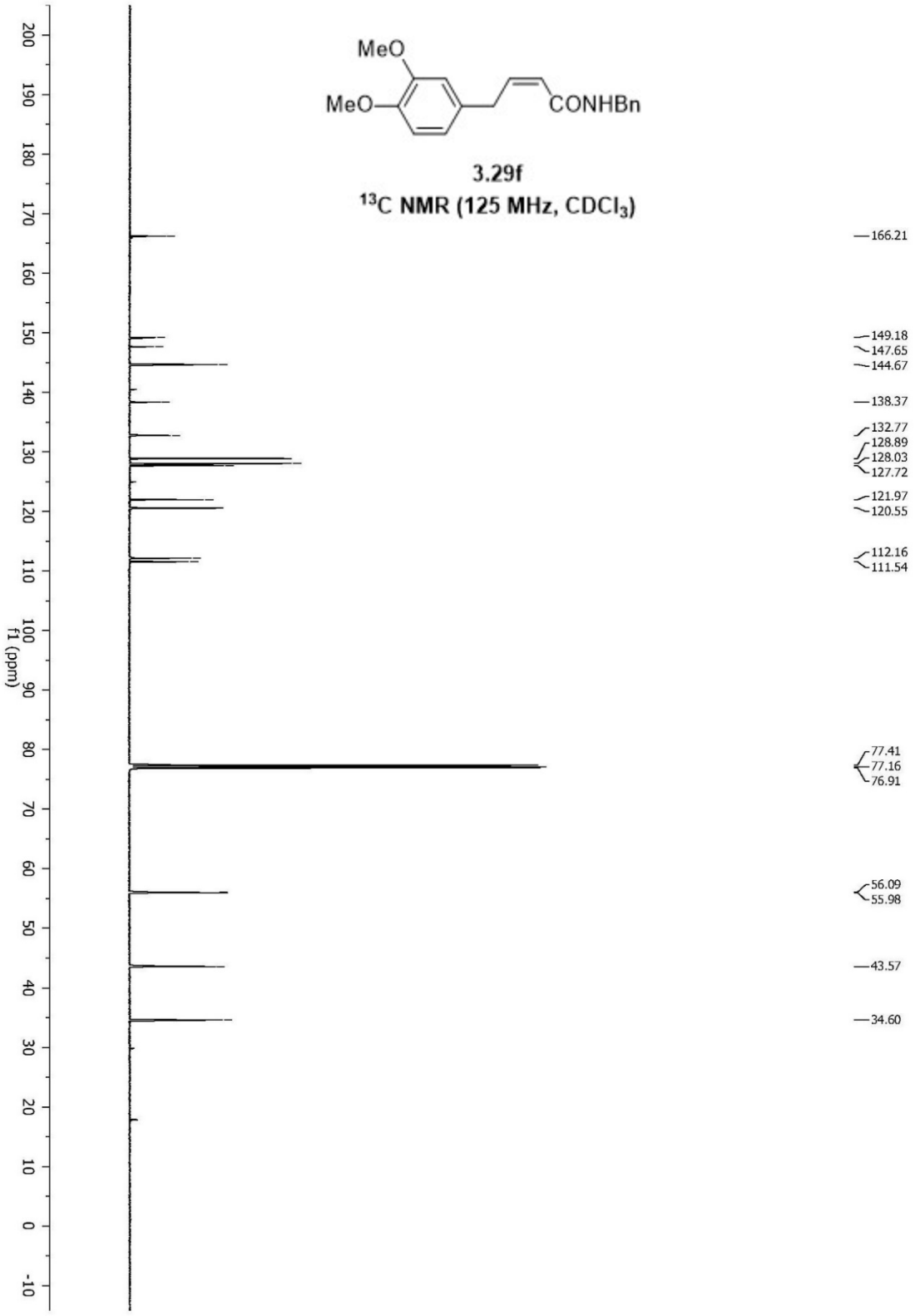

HO
CONHPMB
3.29d
¹H NMR (600 MHz, CDCl₃)
f1 (ppm)
1.59
1.61
1.87
1.00
2.18
1.04
2.87
2.27
2.33
2.50
7.26
7.22
7.21
6.87
6.85
6.01
5.99
5.99
5.97
5.96
5.81
5.79
4.41
4.40
4.02
3.79
3.60
3.59
3.58
3.57
2.76
2.74
2.73
2.72
1.72
1.71
1.70
1.69
1.68

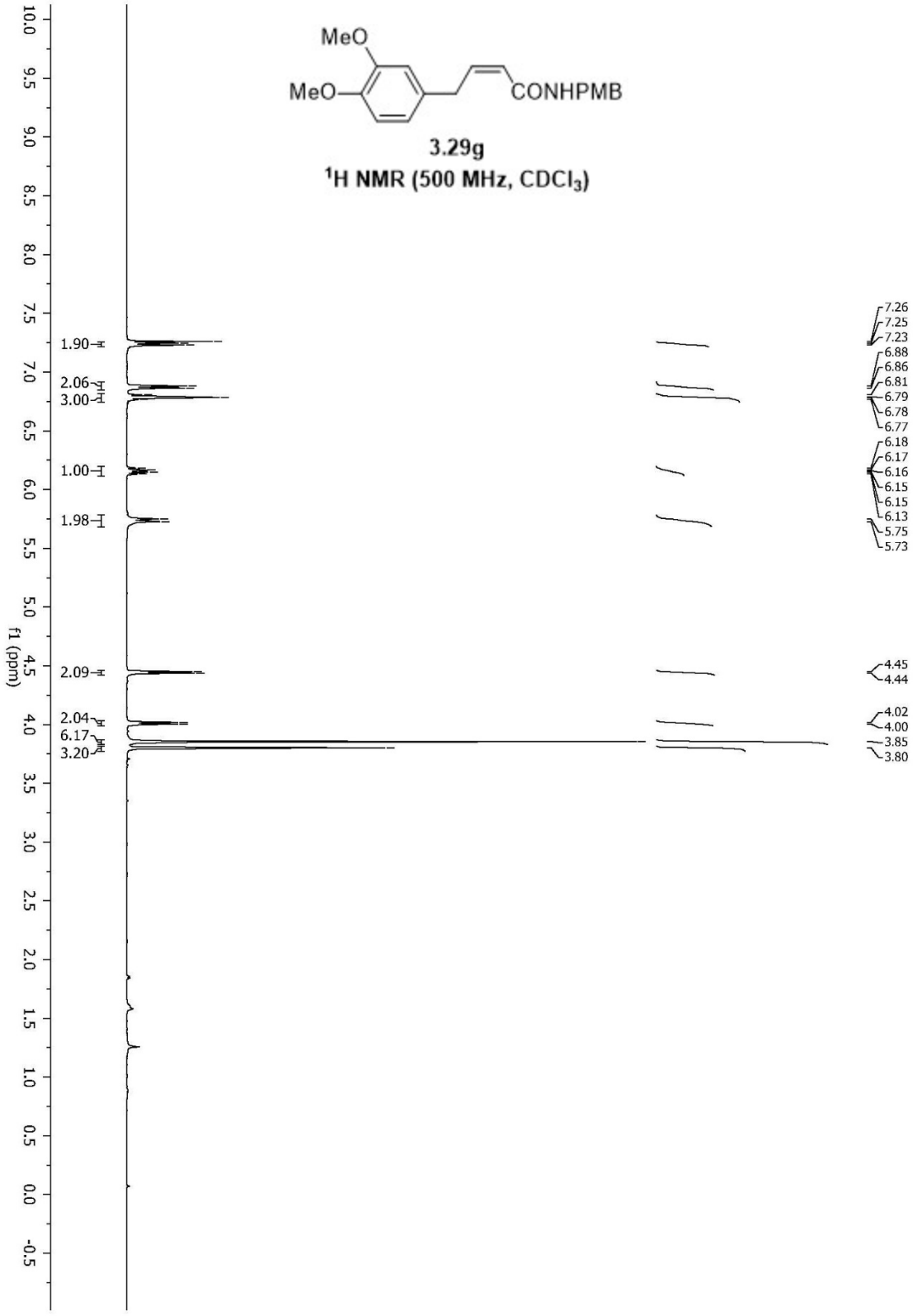

HO
CONHPMB
3.29d
13C NMR (125 MHz, CDCl3)
166.89
159.26
144.79
130.16
129.46
123.61
114.28
77.41
77.16
76.91
60.07
55.45
43.15
30.60
24.72
f1 (ppm)

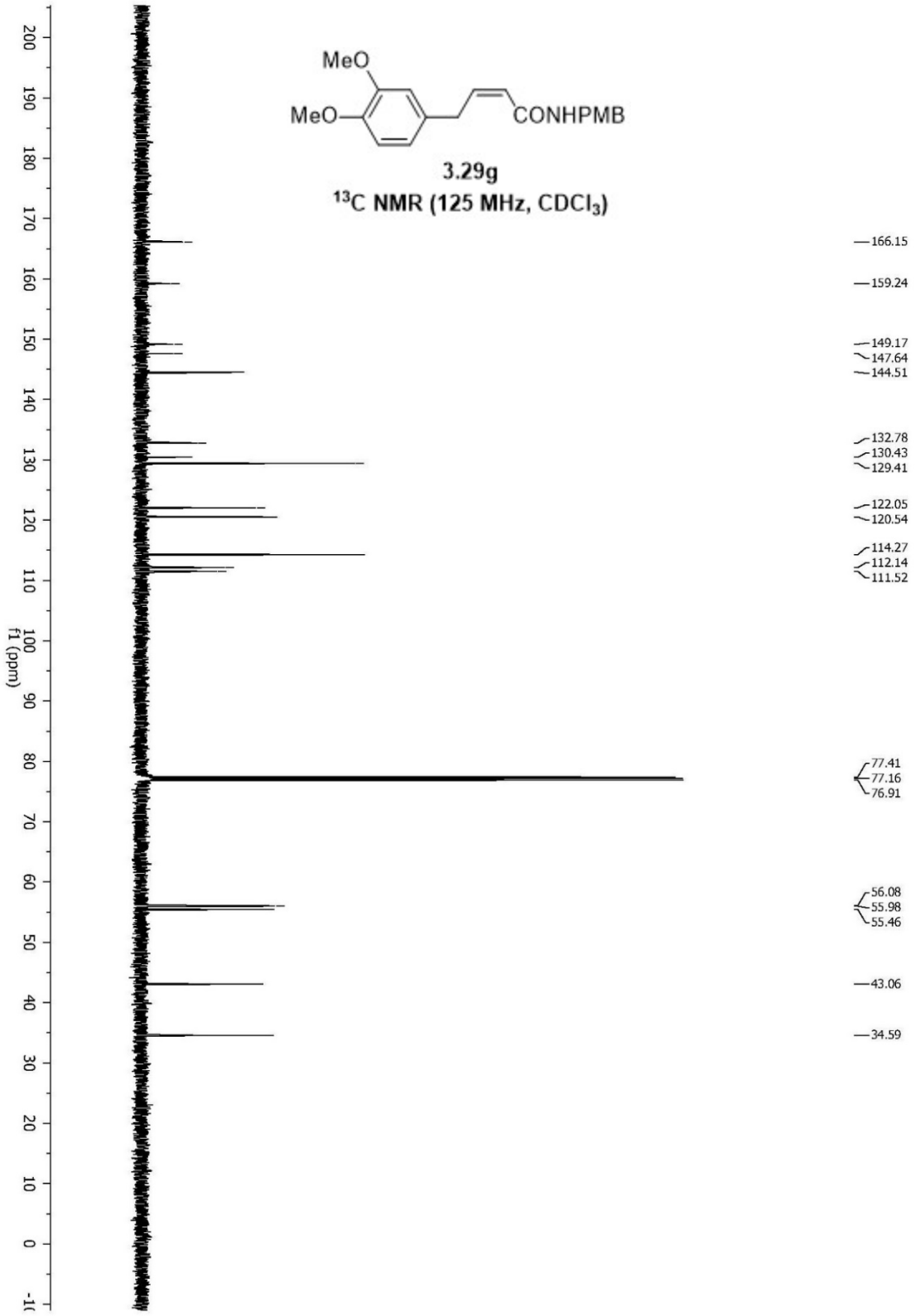

CONHBn
3.29e
¹H NMR (500 MHz, CDCl₃)
f1 (ppm)
1.78
1.91
4.85
1.00
0.93
1.04
2.04
2.07
2.03
2.11
2.09
7.79
7.79
7.78
7.78
7.67
7.66
7.66
7.65
7.29
7.28
7.26
7.25
7.23
7.22
7.20
5.96
5.94
5.94
5.93
5.92
5.91
5.78
5.69
5.67
4.43
4.42
3.65
3.64
3.62
2.72
2.70
2.69
2.67
1.71
1.69
1.68
1.66
1.65
1.49
1.48
1.46
1.45
1.43

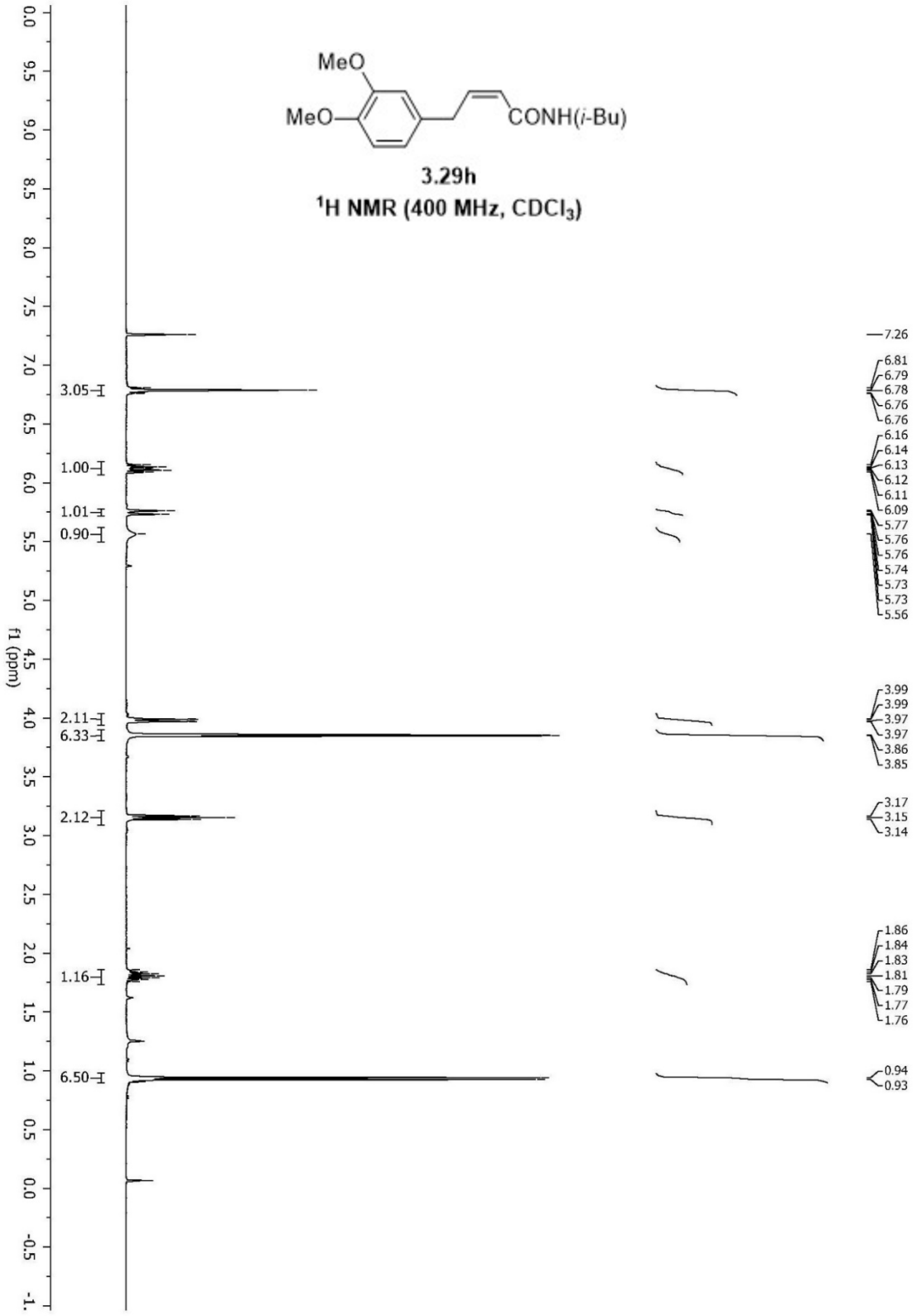

CONHBn
3.29e
^{13}C NMR (100 MHz, $CDCl_3$)
f1 (ppm)
168.56
166.33
145.22
138.47
133.99
132.30
128.82
128.06
127.62
123.30
122.66
77.48
77.16
76.84
43.49
37.92
28.31
28.27
26.58

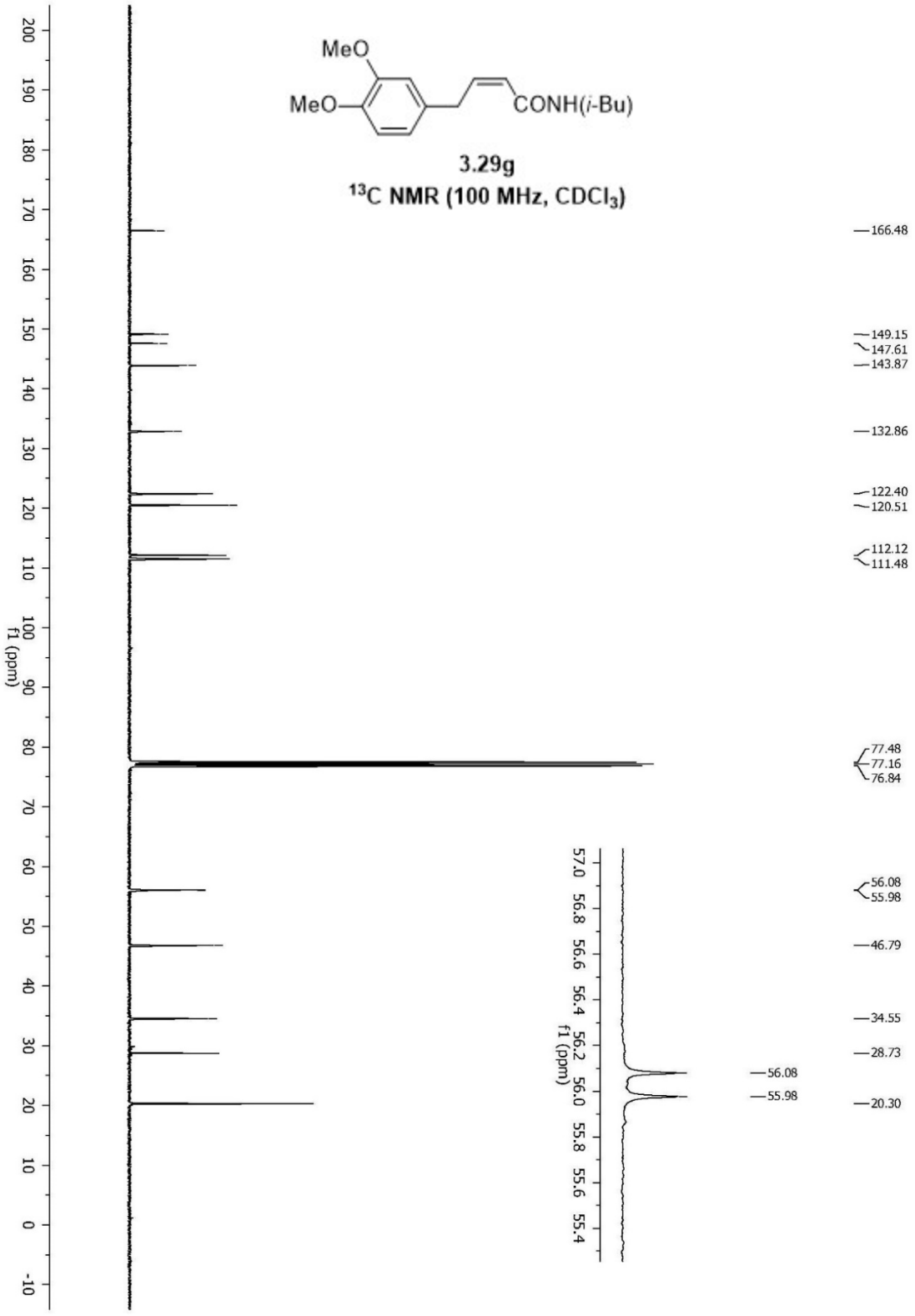

MeO
MeO
CONHBn
3.29f
¹H NMR (500 MHz, CDCl₃)
f1 (ppm)
4.82
2.97
1.00
0.93
1.12
2.21
1.98
6.36
7.36
7.34
7.33
7.32
7.30
7.29
7.27
7.26
6.81
6.79
6.79
6.77
6.20
6.18
6.18
6.17
6.16
6.15
5.81
5.77
5.75
4.52
4.51
4.03
4.01
3.85

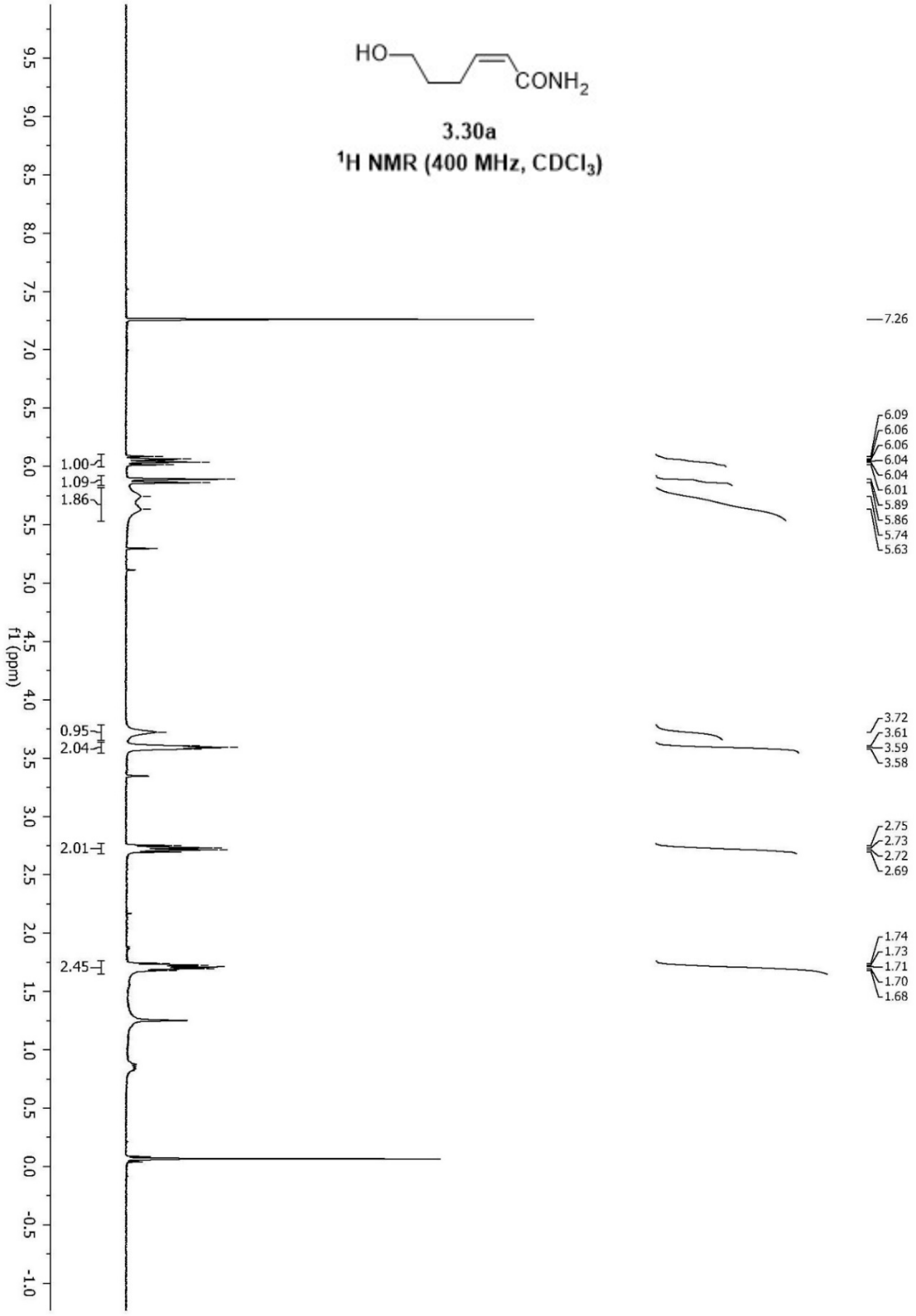

MeO
MeO
CONHBn
3.29f
^{13}C NMR (125 MHz, $CDCl_3$)
166.21
149.18
147.65
144.67
138.37
132.77
128.89
128.03
127.72
121.97
120.55
112.16
111.54
77.41
77.16
76.91
56.09
55.98
43.57
34.60
f1 (ppm)

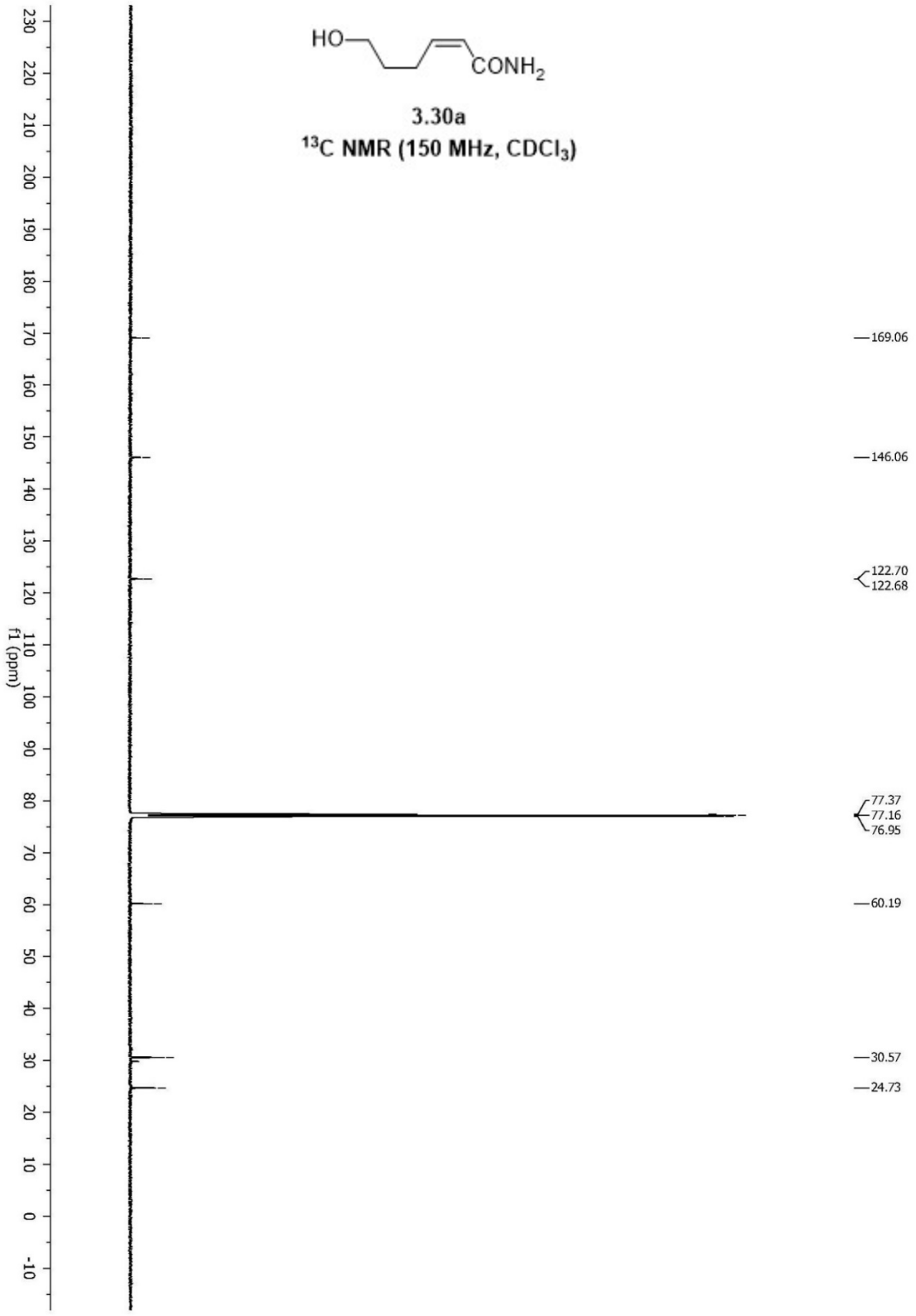

MeO
MeO
CONHPMB
3.29g
¹H NMR (500 MHz, CDCl₃)
f1 (ppm)
1.90
2.06
3.00
1.00
1.98
2.09
2.04
6.17
3.20
7.26
7.25
7.23
6.88
6.86
6.81
6.79
6.78
6.77
6.18
6.17
6.16
6.15
6.15
6.13
5.75
5.73
4.45
4.44
4.02
4.00
3.85
3.80

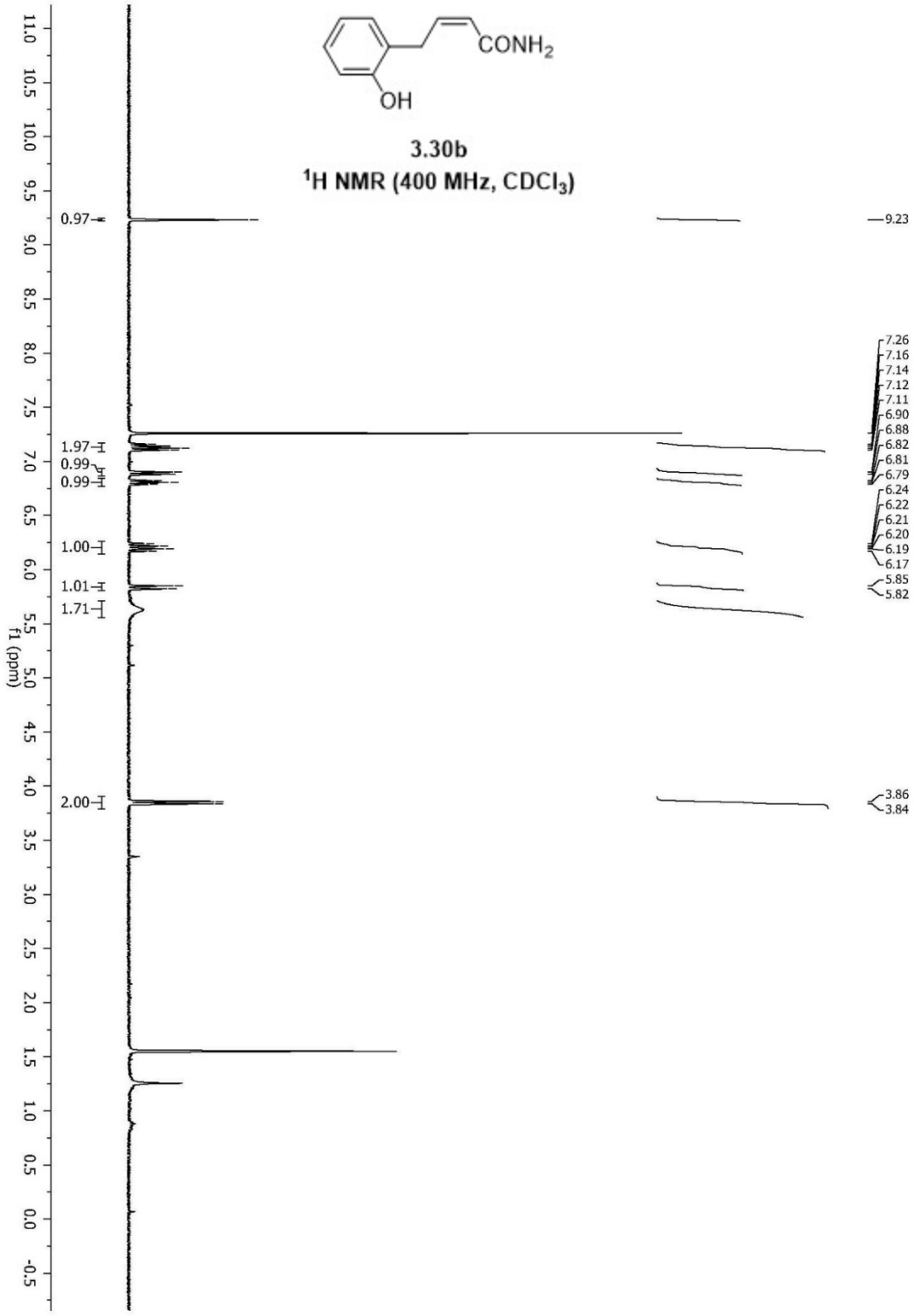

MeO
MeO
CONHPMB
3.29g
^{13}C NMR (125 MHz, $CDCl_3$)
166.15
159.24
149.17
147.64
144.51
132.78
130.43
129.41
122.05
120.54
114.27
112.14
111.52
77.41
77.16
76.91
56.08
55.98
55.46
43.06
34.59
f1 (ppm)

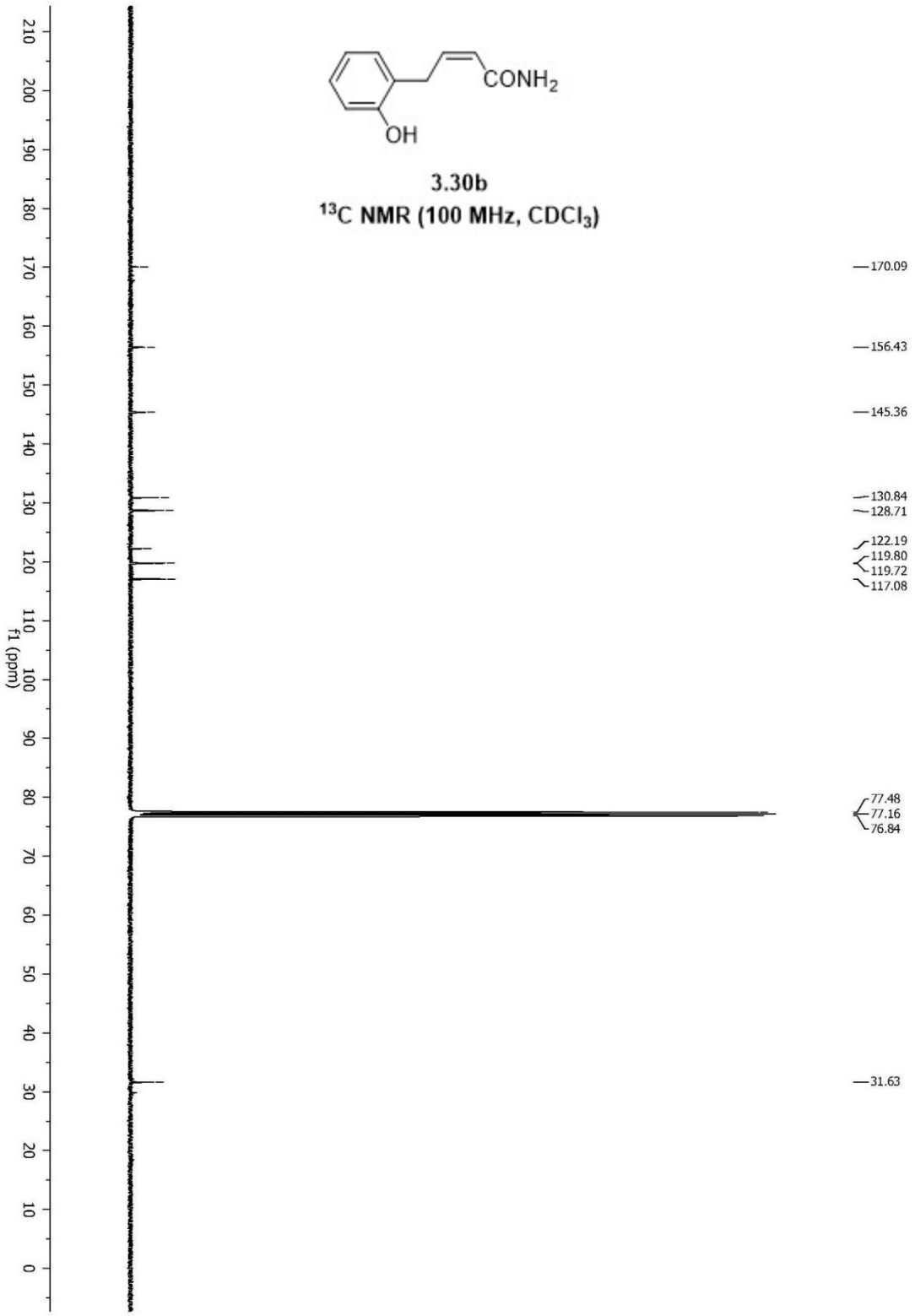

MeO
MeO
CONH(*i*-Bu)
3.29h
^{1}H NMR (400 MHz, $CDCl_3$)
f1 (ppm)
3.05
1.00
1.01
0.90
2.11
6.33
2.12
1.16
6.50
7.26
6.81
6.79
6.78
6.76
6.76
6.16
6.14
6.13
6.12
6.11
6.09
5.77
5.76
5.76
5.74
5.73
5.73
5.56
3.99
3.99
3.97
3.97
3.86
3.85
3.17
3.15
3.14
1.86
1.84
1.83
1.81
1.79
1.77
1.76
0.94
0.93

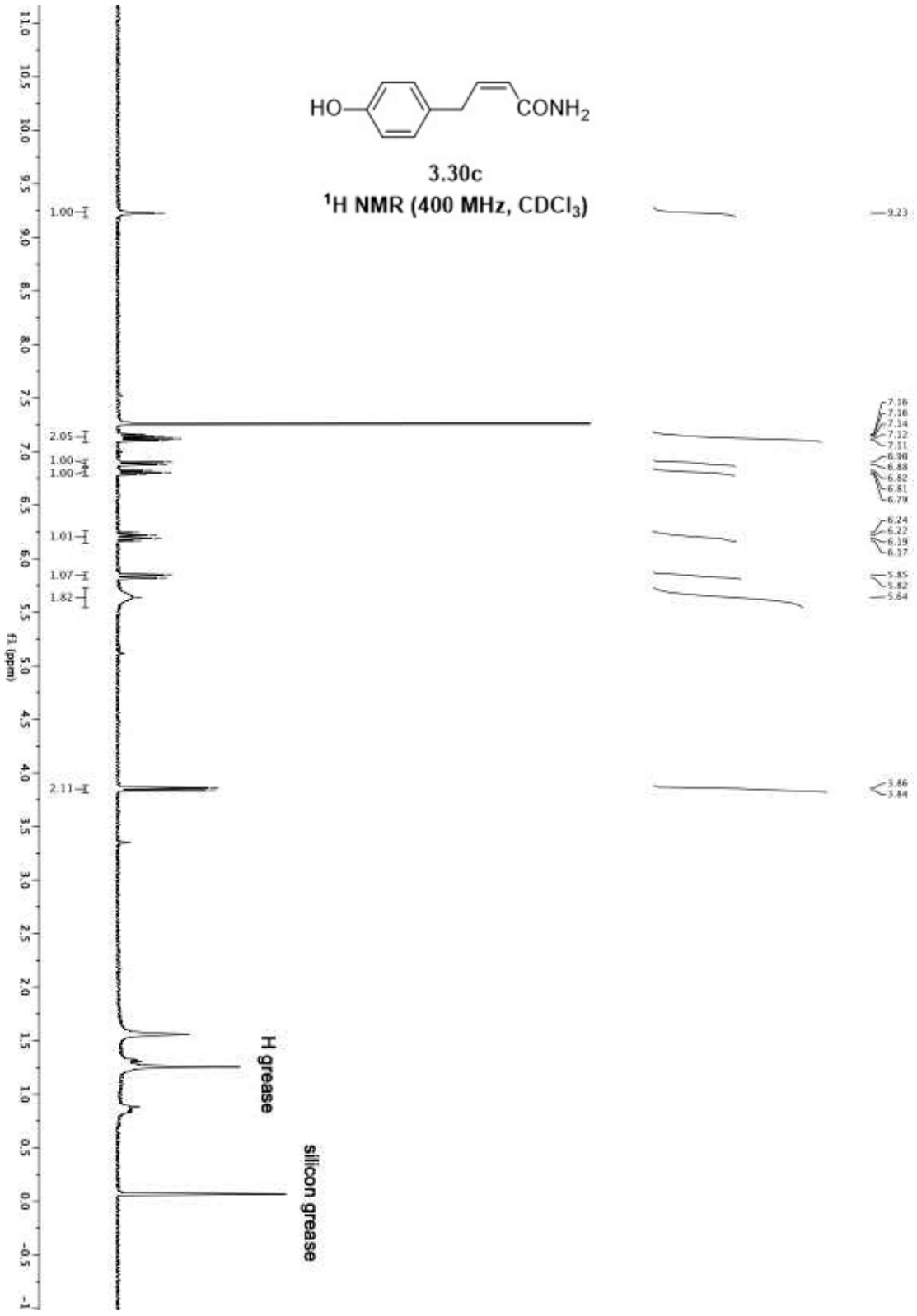

MeO
MeO
CONH(*i*-Bu)
3.29g
^{13}C NMR (100 MHz, $CDCl_3$)
166.48
149.15
147.61
143.87
132.86
122.40
120.51
112.12
111.48
77.48
77.16
76.84
56.08
55.98
46.79
34.55
28.73
20.30
f1 (ppm)

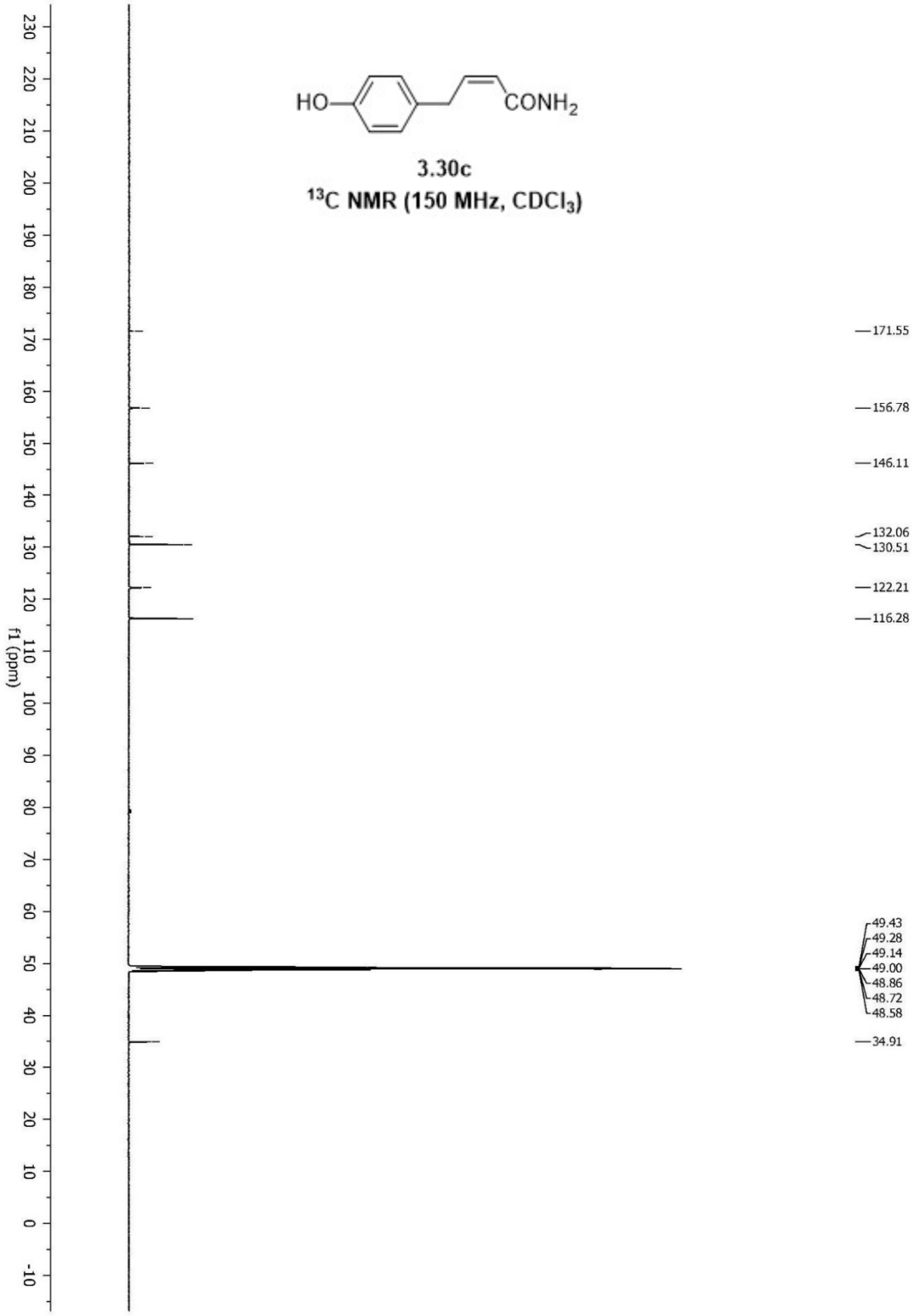

HO
CONH2
3.30a
1H NMR (400 MHz, CDCl3)
f1 (ppm)
1.00
1.09
1.86
0.95
2.04
2.01
2.45
7.26
6.09
6.06
6.06
6.04
6.04
6.01
5.89
5.86
5.74
5.63
3.72
3.61
3.59
3.58
2.75
2.73
2.72
2.69
1.74
1.73
1.71
1.70
1.68

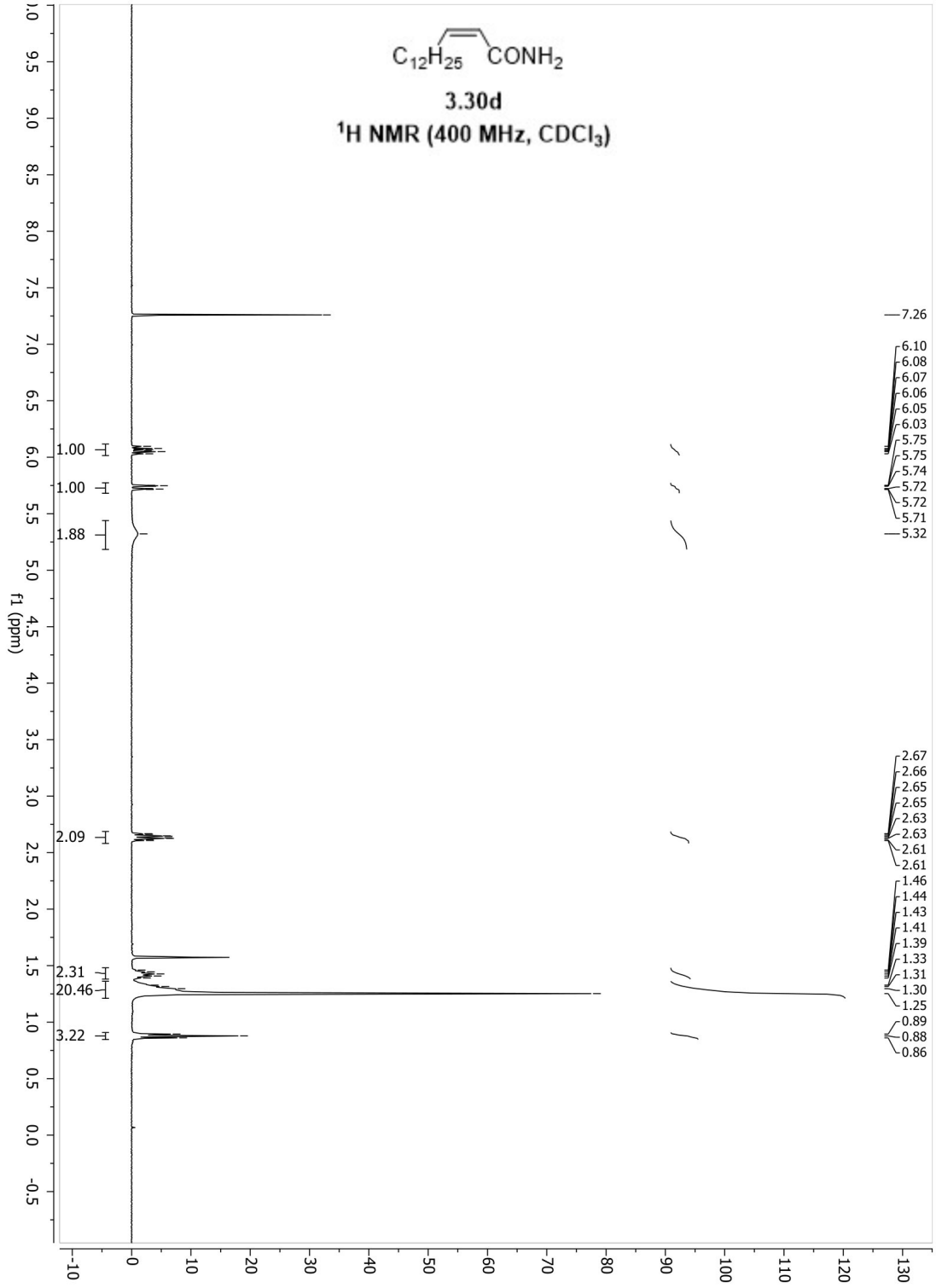

HO
CONH2
3.30a
13C NMR (150 MHz, CDCl3)
169.06
146.06
122.70
122.68
77.37
77.16
76.95
60.19
30.57
24.73
f1 (ppm)

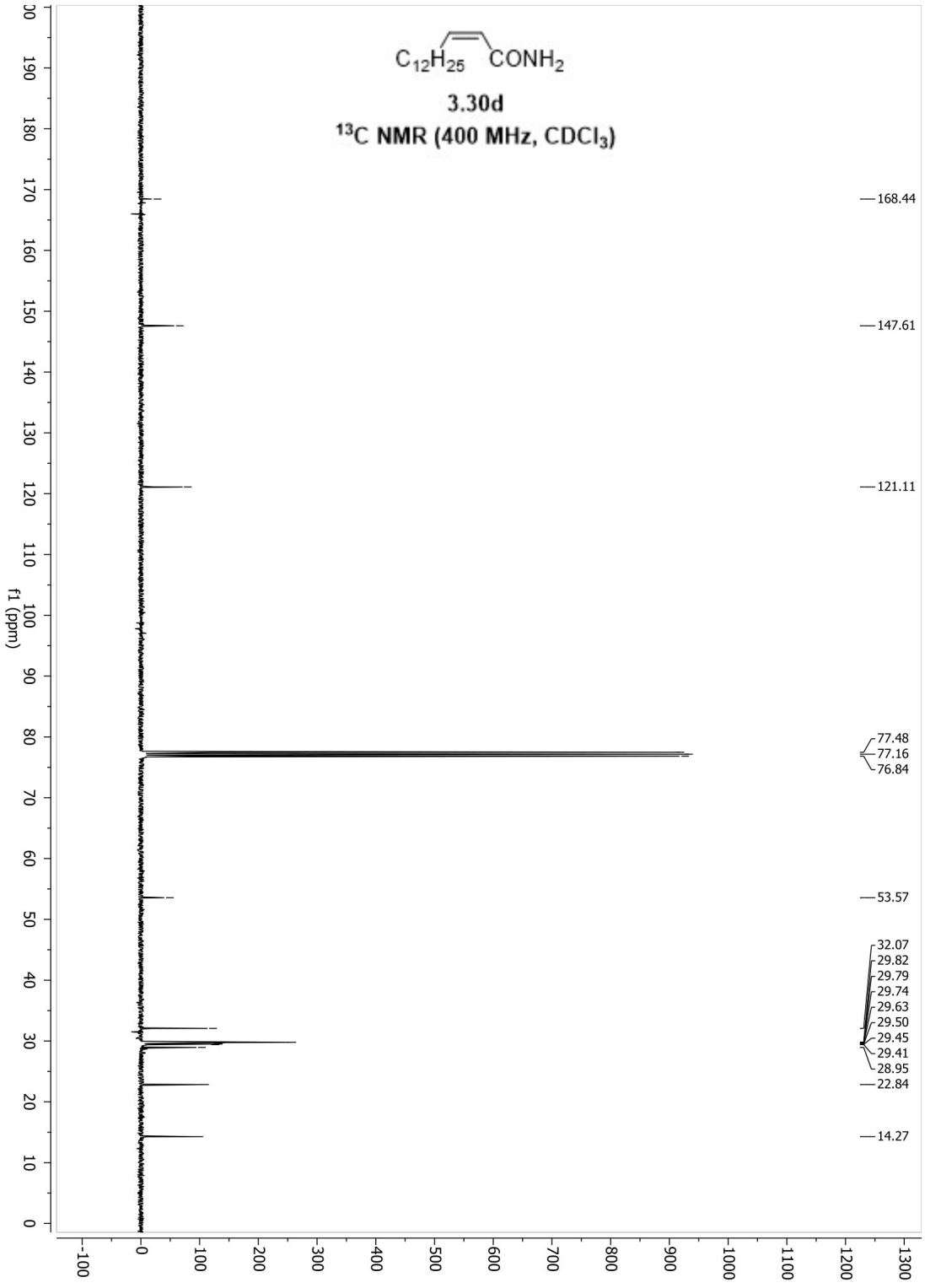

CONH2
OH
3.30b
1H NMR (400 MHz, CDCl3)
f1 (ppm)
0.97
1.97
0.99
0.99
1.00
1.01
1.71
2.00
9.23
7.26
7.16
7.14
7.12
7.11
6.90
6.88
6.82
6.81
6.79
6.24
6.22
6.21
6.20
6.19
6.17
5.85
5.82
3.86
3.84


CONH2
OH
3.30b
13C NMR (100 MHz, CDCl3)
170.09
156.43
145.36
130.84
128.71
122.19
119.80
119.72
117.08
77.48
77.16
76.84
31.63
f1 (ppm)


HO
CONH2
3.30c
1H NMR (400 MHz, CDCl3)
f1 (ppm)
H grease
silicon grease


HO
CONH2
3.30c
13C NMR (150 MHz, CDCl3)
f1 (ppm)
171.55
156.78
146.11
132.06
130.51
122.21
116.28
49.43
49.28
49.14
49.00
48.86
48.72
48.58
34.91


C12H25
CONH2
3.30d
1H NMR (400 MHz, CDCl3)
f1 (ppm)
1.00
1.00
1.88
2.09
2.31
20.46
3.22
7.26
6.10
6.08
6.07
6.06
6.05
6.03
5.75
5.75
5.74
5.72
5.72
5.71
5.32
2.67
2.66
2.65
2.65
2.63
2.63
2.61
2.61
1.46
1.44
1.43
1.41
1.39
1.33
1.31
1.30
1.25
0.89
0.88
0.86


C12H25
CONH2
3.30d
13C NMR (400 MHz, CDCl3)
168.44
147.61
121.11
77.48
77.16
76.84
53.57
32.07
29.82
29.79
29.74
29.63
29.50
29.45
29.41
28.95
22.84
14.27
f1 (ppm)

3.6.7 X-ray Structure of Ru-10

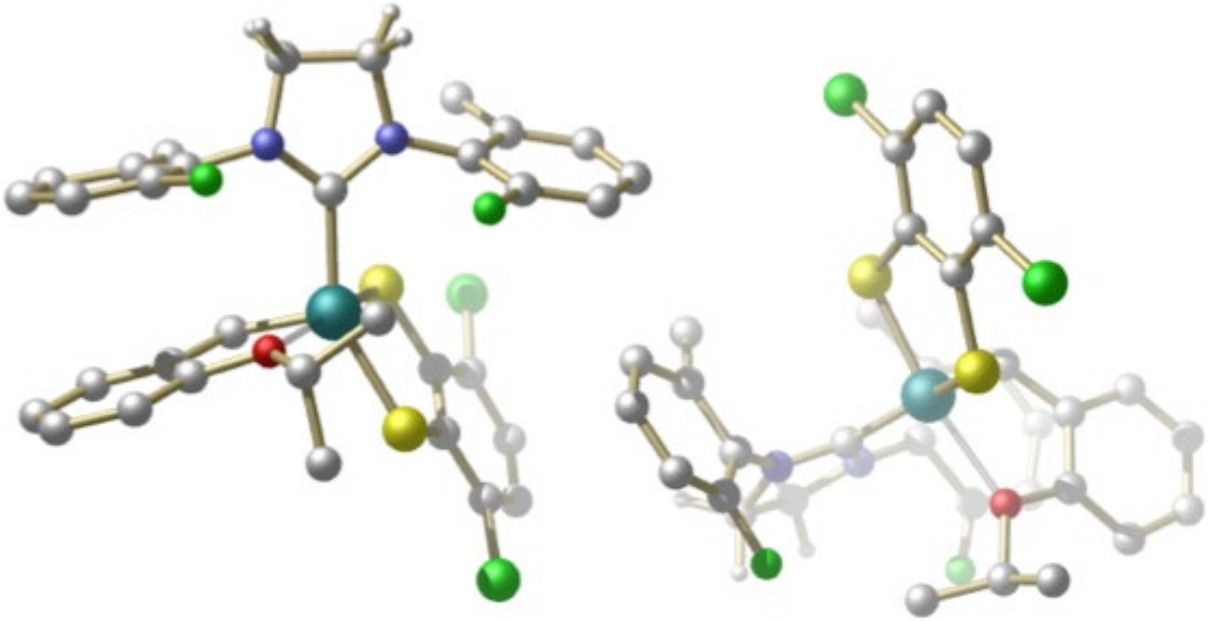


Table 1. Crystal data and structure refinement for $3(C_{33}H_{30}Cl_2F_2N_2ORuS_2)CH_2Cl_2$ (**Ru-10**).

Identification code	3(C33H30Cl2F2N2ORuS2)CH2Cl2	
Empirical formula	C100 H92 Cl8 F6 N6 O3 Ru3 S6	
Formula weight	2318.96	
Temperature	100(2) K	
Wavelength	1.54178 Å	
Crystal system	Monoclinic	
Space group	$P2_1/n$	
Unit cell dimensions	a = 12.6425(3) Å	a= 90°.
	b = 20.1905(4) Å	b= 93.2110(10)°.
	c = 38.4232(7) Å	g = 90°.
Volume	9792.4(4) $Å^3$	
Z	4	
Density (calculated)	1.573 Mg/m^3	
Absorption coefficient	7.444 mm^{-1}	
F(000)	4704	
Crystal size	0.320 x 0.180 x 0.150 mm^3	
Theta range for data collection	2.303 to 66.704°.	
Index ranges	-15<=h<=15, -21<=k<=23, -44<=l<=45	
Reflections collected	63548	
Independent reflections	17210 [R(int) = 0.0497]	
Completeness to theta = 66.704°	99.3 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.7533 and 0.5593	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	17210 / 1253 / 1231	
Goodness-of-fit on F^2	1.131	
Final R indices [I>2sigma(I)]	R1 = 0.0662, wR2 = 0.1724	

R indices (all data)	R1 = 0.0742, wR2 = 0.1776
Extinction coefficient	n/a
Largest diff. peak and hole	2.229 and -1.140 e.Å^{-3}

Table 2. Atomic coordinates (x10^4) and equivalent isotropic displacement parameters (Å^{2}x 10^3) for 3($C_{33}H_{30}Cl_2F_2N_2ORuS_2$)$CH_2Cl_2$ (**Ru-10**). U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
Ru(1)	6819(1)	3872(1)	8314(1)	27(1)
Cl(1)	2912(2)	4134(1)	7706(1)	51(1)
Cl(2)	6388(2)	6302(1)	7741(1)	61(1)
S(1)	5141(1)	3815(1)	8081(1)	31(1)
S(2)	6869(2)	4953(1)	8142(1)	37(1)
F(1)	8934(4)	2709(3)	9023(1)	53(1)
F(2)	6253(3)	4336(2)	9205(1)	45(1)
O(1)	8618(4)	3906(2)	8476(1)	36(1)
N(1)	6887(4)	2599(3)	8760(1)	26(1)
N(2)	5543(4)	3211(3)	8875(1)	27(1)
C(1)	6397(5)	3175(3)	8677(2)	27(1)
C(2)	6312(6)	2185(3)	8997(2)	34(2)
C(3)	5543(5)	2671(3)	9138(2)	29(1)
C(4)	7722(6)	2284(3)	8584(2)	32(1)
C(5)	8739(6)	2314(4)	8735(2)	39(2)
C(6)	9584(7)	1985(5)	8608(2)	54(2)
C(7)	9361(8)	1585(5)	8323(2)	59(2)
C(8)	8389(8)	1522(4)	8168(2)	53(2)
C(9)	7496(7)	1887(4)	8292(2)	41(2)
C(10)	6401(7)	1854(4)	8133(2)	49(2)
C(11)	4846(5)	3751(3)	8919(2)	30(1)
C(12)	3767(6)	3701(4)	8826(2)	35(1)
C(13)	3110(6)	4224(4)	8914(2)	47(2)
C(14)	3500(7)	4776(4)	9081(2)	49(2)
C(15)	4566(7)	4825(4)	9181(2)	46(2)
C(16)	5218(6)	4311(3)	9098(2)	35(1)
C(17)	3333(6)	3106(4)	8631(2)	45(2)
C(18)	7401(5)	3348(3)	7987(2)	29(1)
C(19)	8533(5)	3274(3)	7972(2)	31(1)
C(20)	9184(6)	3579(4)	8230(2)	35(1)
C(21)	10279(6)	3538(5)	8231(2)	48(2)
C(22)	10723(6)	3165(5)	7971(2)	52(2)
C(23)	10102(6)	2856(4)	7714(2)	46(2)
C(24)	9015(6)	2906(4)	7713(2)	38(2)
C(25)	9204(7)	4327(4)	8732(2)	46(2)
C(26)	9546(8)	4957(4)	8553(2)	54(2)
C(27)	8477(7)	4456(5)	9016(2)	53(2)
C(28)	4894(6)	4579(4)	7879(2)	35(1)
C(29)	3924(7)	4711(4)	7701(2)	42(2)
C(30)	3737(7)	5316(4)	7523(2)	51(2)

C(31)	4509(8)	5783(4)	7536(2)	51(2)
C(32)	5446(8)	5675(4)	7719(2)	46(2)
C(33)	5672(7)	5075(4)	7895(2)	40(2)
Ru(2)	3658(1)	2668(1)	6251(1)	24(1)
Cl(3)	4354(2)	424(1)	5557(1)	40(1)
Cl(4)	2150(1)	2931(1)	4916(1)	37(1)
S(3)	3848(1)	1619(1)	6056(1)	27(1)
S(4)	2843(1)	2919(1)	5722(1)	26(1)
F(3)	4753(5)	3787(3)	7179(1)	65(1)
O(2)	3664(4)	3773(3)	6388(1)	42(1)
N(3)	4363(5)	2518(3)	7031(1)	36(1)
N(4)	2791(5)	2132(3)	6920(2)	40(1)
C(34)	3625(5)	2391(3)	6776(2)	29(1)
C(35)	4032(7)	2312(5)	7378(2)	48(2)
C(36)	2876(8)	2139(6)	7306(2)	65(3)
C(37)	5425(6)	2720(4)	6992(2)	46(2)
C(38)	5594(7)	3425(5)	7092(2)	55(2)
C(39)	6531(8)	3694(5)	7090(2)	61(2)
C(40)	7350(7)	3289(5)	6981(2)	56(2)
C(41)	7259(9)	2633(6)	6888(3)	72(3)
C(42)	6205(7)	2326(5)	6896(3)	62(2)
C(43)	5935(10)	1629(5)	6801(3)	78(3)
C(44)	1863(6)	1866(5)	6750(2)	47(2)
C(45)	1637(15)	1226(8)	6645(9)	52(3)
C(46)	647(15)	1100(12)	6506(5)	59(3)
C(47)	-122(18)	1584(15)	6469(7)	69(4)
C(48)	40(12)	2216(12)	6569(5)	65(3)
C(49)	1076(13)	2366(10)	6717(7)	58(3)
C(50)	2478(16)	731(9)	6704(6)	55(4)
F(4)	1246(11)	3016(7)	6841(4)	71(3)
C(45X)	1948(17)	1162(8)	6685(10)	52(3)
C(46X)	1091(16)	794(12)	6546(5)	59(3)
C(47X)	146(17)	1109(14)	6456(6)	69(4)
C(48X)	17(19)	1760(15)	6508(8)	65(3)
C(49X)	867(12)	2115(12)	6672(7)	58(3)
C(50X)	2929(17)	770(12)	6777(7)	55(4)
F(4X)	823(13)	2766(9)	6765(5)	74(4)
C(51)	5047(5)	2881(4)	6217(2)	31(1)
C(52)	5407(6)	3557(4)	6252(2)	36(1)
C(53)	6441(7)	3751(5)	6201(2)	50(2)
C(54)	6765(9)	4386(5)	6252(2)	63(2)
C(55)	6054(9)	4843(5)	6352(2)	63(2)
C(56)	4980(8)	4686(4)	6407(2)	54(2)
C(57)	4674(6)	4035(4)	6349(2)	38(2)
C(58)	2796(8)	4232(5)	6449(2)	65(2)
C(59)	2636(14)	4318(8)	6811(3)	54(3)
C(60)	1862(12)	4082(8)	6226(4)	56(3)
C(58X)	2796(8)	4232(5)	6449(2)	65(2)
C(59X)	2120(16)	3871(9)	6669(5)	54(3)

C(60X)	2440(17)	4567(10)	6147(4)	56(3)
C(61)	3517(5)	1658(3)	5608(2)	25(1)
C(62)	3723(5)	1125(3)	5383(2)	29(1)
C(63)	3463(5)	1146(4)	5031(2)	33(1)
C(64)	2970(6)	1701(4)	4886(2)	33(1)
C(65)	2775(5)	2232(3)	5101(2)	28(1)
C(66)	3050(5)	2227(3)	5459(2)	23(1)
Ru(3)	8359(1)	3186(1)	4779(1)	28(1)
Cl(5)	7051(2)	3439(1)	3415(1)	63(1)
Cl(6)	11199(2)	4608(1)	4087(1)	61(1)
S(5)	7512(1)	3269(1)	4243(1)	33(1)
S(6)	9656(1)	3860(1)	4576(1)	37(1)
F(5)	7600(4)	2071(2)	5775(1)	46(1)
F(6)	7462(3)	4321(2)	5420(1)	42(1)
O(3)	9407(4)	3005(2)	5283(1)	34(1)
N(5)	6574(4)	2498(3)	5176(1)	28(1)
N(6)	6187(4)	3503(3)	5023(1)	28(1)
C(67)	6931(5)	3032(3)	5012(2)	26(1)
C(68)	5480(5)	2580(3)	5282(2)	31(1)
C(69)	5316(5)	3323(3)	5246(2)	31(1)
C(70)	7003(5)	1846(3)	5194(2)	28(1)
C(71)	7491(5)	1626(3)	5502(2)	33(1)
C(72)	7872(6)	1000(4)	5554(2)	40(2)
C(73)	7734(6)	560(4)	5279(2)	43(2)
C(74)	7252(5)	757(4)	4961(2)	38(2)
C(75)	6843(5)	1398(3)	4915(2)	30(1)
C(76)	6277(6)	1611(4)	4587(2)	35(2)
C(77)	6331(5)	4173(3)	4919(2)	31(1)
C(78)	5770(6)	4440(4)	4634(2)	40(2)
C(79)	5985(7)	5099(4)	4544(2)	48(2)
C(80)	6710(7)	5466(4)	4740(2)	48(2)
C(81)	7234(6)	5215(4)	5032(2)	43(2)
C(82)	7004(6)	4580(4)	5120(2)	35(1)
C(83)	4975(7)	4030(4)	4421(2)	49(2)
C(84)	8742(5)	2316(3)	4732(2)	28(1)
C(85)	9462(5)	2004(3)	4991(2)	30(1)
C(86)	9859(5)	1362(3)	4950(2)	32(1)
C(87)	10535(5)	1086(4)	5206(2)	40(2)
C(88)	10803(5)	1436(4)	5503(2)	39(2)
C(89)	10417(5)	2078(4)	5553(2)	36(2)
C(90)	9794(5)	2364(3)	5286(2)	31(1)
C(91)	9875(6)	3453(4)	5559(2)	44(2)
C(92)	9171(6)	3434(4)	5865(2)	43(2)
C(93)	10056(6)	4119(4)	5415(2)	47(2)
C(94)	8389(6)	3693(3)	3980(2)	36(1)
C(95)	8199(6)	3771(4)	3621(2)	43(2)
C(96)	8881(7)	4111(4)	3411(2)	50(2)
C(97)	9792(7)	4383(4)	3564(2)	51(2)
C(98)	10004(6)	4305(4)	3914(2)	44(2)

C(99)	9329(6)	3959(3)	4133(2)	38(2)
C(1S)	9064(11)	4867(7)	7532(3)	93(4)
Cl(1S)	8332(3)	5016(2)	7137(1)	91(1)
Cl(2S)	10289(3)	5266(3)	7537(1)	121(2)

Table 3. Bond lengths (Å) and angles (°])for 3($C_{33}H_{30}Cl_2F_2N_2ORuS_2$)$CH_2Cl_2$ (**Ru-10**).

Ru(1)-C(18)	1.830(7)
Ru(1)-C(1)	2.072(6)
Ru(1)-S(1)	2.2591(18)
Ru(1)-S(2)	2.2829(17)
Ru(1)-O(1)	2.325(5)
Cl(1)-C(29)	1.731(9)
Cl(2)-C(32)	1.737(9)
S(1)-C(28)	1.747(7)
S(2)-C(33)	1.757(8)
F(1)-C(5)	1.376(9)
F(2)-C(16)	1.350(9)
O(1)-C(20)	1.384(9)
O(1)-C(25)	1.469(8)
N(1)-C(1)	1.348(8)
N(1)-C(4)	1.434(9)
N(1)-C(2)	1.462(8)
N(2)-C(1)	1.357(8)
N(2)-C(11)	1.418(8)
N(2)-C(3)	1.487(8)
C(2)-C(3)	1.503(9)
C(2)-H(2A)	0.9900
C(2)-H(2B)	0.9900
C(3)-H(3A)	0.9900
C(3)-H(3B)	0.9900
C(4)-C(5)	1.382(11)
C(4)-C(9)	1.394(10)
C(5)-C(6)	1.369(11)
C(6)-C(7)	1.378(13)
C(6)-H(6)	0.9500
C(7)-C(8)	1.342(14)
C(7)-H(7)	0.9500
C(8)-C(9)	1.451(12)
C(8)-H(8)	0.9500
C(9)-C(10)	1.483(12)
C(10)-H(10A)	0.9800
C(10)-H(10B)	0.9800
C(10)-H(10C)	0.9800
C(11)-C(16)	1.390(10)
C(11)-C(12)	1.395(10)
C(12)-C(13)	1.397(11)
C(12)-C(17)	1.503(11)
C(13)-C(14)	1.365(13)

C(13)-H(13)	0.9500
C(14)-C(15)	1.383(12)
C(14)-H(14)	0.9500
C(15)-C(16)	1.374(11)
C(15)-H(15)	0.9500
C(17)-H(17A)	0.9800
C(17)-H(17B)	0.9800
C(17)-H(17C)	0.9800
C(18)-C(19)	1.444(9)
C(18)-H(18)	0.9500
C(19)-C(20)	1.396(10)
C(19)-C(24)	1.407(10)
C(20)-C(21)	1.387(11)
C(21)-C(22)	1.393(12)
C(21)-H(21)	0.9500
C(22)-C(23)	1.377(12)
C(22)-H(22)	0.9500
C(23)-C(24)	1.378(11)
C(23)-H(23)	0.9500
C(24)-H(24)	0.9500
C(25)-C(27)	1.490(11)
C(25)-C(26)	1.522(11)
C(25)-H(25)	1.0000
C(26)-H(26A)	0.9800
C(26)-H(26B)	0.9800
C(26)-H(26C)	0.9800
C(27)-H(27A)	0.9800
C(27)-H(27B)	0.9800
C(27)-H(27C)	0.9800
C(28)-C(29)	1.396(11)
C(28)-C(33)	1.403(11)
C(29)-C(30)	1.413(11)
C(30)-C(31)	1.356(13)
C(30)-H(30)	0.9500
C(31)-C(32)	1.362(13)
C(31)-H(31)	0.9500
C(32)-C(33)	1.409(11)
Ru(2)-C(51)	1.820(7)
Ru(2)-C(34)	2.096(6)
Ru(2)-S(3)	2.2639(16)
Ru(2)-S(4)	2.2831(15)
Ru(2)-O(2)	2.293(5)
Cl(3)-C(62)	1.739(7)
Cl(4)-C(65)	1.750(7)
S(3)-C(61)	1.750(6)
S(4)-C(66)	1.754(6)
F(3)-C(38)	1.348(11)
O(2)-C(57)	1.397(9)
O(2)-C(58)	1.465(10)

N(3)-C(34)	1.339(9)
N(3)-C(37)	1.419(10)
N(3)-C(35)	1.479(9)
N(4)-C(34)	1.326(9)
N(4)-C(44)	1.416(10)
N(4)-C(36)	1.479(9)
C(35)-C(36)	1.513(12)
C(35)-H(35A)	0.9900
C(35)-H(35B)	0.9900
C(36)-H(36A)	0.9900
C(36)-H(36B)	0.9900
C(37)-C(42)	1.335(13)
C(37)-C(38)	1.486(13)
C(38)-C(39)	1.303(13)
C(39)-C(40)	1.402(14)
C(39)-H(39)	0.9500
C(40)-C(41)	1.374(15)
C(40)-H(40)	0.9500
C(41)-C(42)	1.472(14)
C(41)-H(41)	0.9500
C(42)-C(43)	1.490(15)
C(43)-H(43A)	0.9800
C(43)-H(43B)	0.9800
C(43)-H(43C)	0.9800
C(44)-C(45)	1.380(17)
C(44)-C(49)	1.417(17)
C(45)-C(46)	1.357(19)
C(45)-C(50)	1.47(2)
C(46)-C(47)	1.38(3)
C(46)-H(46)	0.9500
C(47)-C(48)	1.34(3)
C(47)-H(47)	0.9500
C(48)-C(49)	1.43(2)
C(48)-H(48)	0.9500
C(49)-F(4)	1.41(2)
C(50)-H(50A)	0.9800
C(50)-H(50B)	0.9800
C(50)-H(50C)	0.9800
C(51)-C(52)	1.443(10)
C(51)-H(51)	0.9500
C(52)-C(53)	1.388(11)
C(52)-C(57)	1.404(11)
C(53)-C(54)	1.357(13)
C(53)-H(53)	0.9500
C(54)-C(55)	1.359(15)
C(54)-H(54)	0.9500
C(55)-C(56)	1.422(14)
C(55)-H(55)	0.9500
C(56)-C(57)	1.384(11)

C(56)-H(56)	0.9500
C(58)-C(59)	1.430(15)
C(58)-C(60)	1.452(16)
C(58)-H(58)	1.0000
C(59)-H(59A)	0.9800
C(59)-H(59B)	0.9800
C(59)-H(59C)	0.9800
C(60)-H(60A)	0.9800
C(60)-H(60B)	0.9800
C(60)-H(60C)	0.9800
C(61)-C(66)	1.399(9)
C(61)-C(62)	1.414(9)
C(62)-C(63)	1.374(9)
C(63)-C(64)	1.384(10)
C(63)-H(63)	0.9500
C(64)-C(65)	1.384(10)
C(64)-H(64)	0.9500
C(65)-C(66)	1.400(9)
Ru(3)-C(84)	1.834(7)
Ru(3)-C(67)	2.083(6)
Ru(3)-S(5)	2.2738(19)
Ru(3)-S(6)	2.2994(16)
Ru(3)-O(3)	2.312(5)
Cl(5)-C(95)	1.749(9)
Cl(6)-C(98)	1.728(9)
S(5)-C(94)	1.763(7)
S(6)-C(99)	1.741(8)
F(5)-C(71)	1.382(8)
F(6)-C(82)	1.366(8)
O(3)-C(90)	1.382(8)
O(3)-C(91)	1.493(9)
N(5)-C(67)	1.340(8)
N(5)-C(70)	1.424(8)
N(5)-C(68)	1.473(8)
N(6)-C(67)	1.341(8)
N(6)-C(77)	1.423(9)
N(6)-C(69)	1.479(8)
C(68)-C(69)	1.519(9)
C(68)-H(68A)	0.9900
C(68)-H(68B)	0.9900
C(69)-H(69A)	0.9900
C(69)-H(69B)	0.9900
C(70)-C(71)	1.377(10)
C(70)-C(75)	1.408(9)
C(71)-C(72)	1.363(10)
C(72)-C(73)	1.384(12)
C(72)-H(72)	0.9500
C(73)-C(74)	1.392(11)
C(73)-H(73)	0.9500

C(74)-C(75)	1.401(10)
C(74)-H(74)	0.9500
C(75)-C(76)	1.478(10)
C(76)-H(76A)	0.9800
C(76)-H(76B)	0.9800
C(76)-H(76C)	0.9800
C(77)-C(78)	1.382(10)
C(77)-C(82)	1.385(10)
C(78)-C(79)	1.405(11)
C(78)-C(83)	1.507(12)
C(79)-C(80)	1.371(13)
C(79)-H(79)	0.9500
C(80)-C(81)	1.370(12)
C(80)-H(80)	0.9500
C(81)-C(82)	1.362(10)
C(81)-H(81)	0.9500
C(83)-H(83A)	0.9800
C(83)-H(83B)	0.9800
C(83)-H(83C)	0.9800
C(84)-C(85)	1.455(10)
C(84)-H(84)	0.9500
C(85)-C(90)	1.391(10)
C(85)-C(86)	1.402(9)
C(86)-C(87)	1.384(10)
C(86)-H(86)	0.9500
C(87)-C(88)	1.368(11)
C(87)-H(87)	0.9500
C(88)-C(89)	1.403(11)
C(88)-H(88)	0.9500
C(89)-C(90)	1.383(10)
C(89)-H(89)	0.9500
C(91)-C(93)	1.478(11)
C(91)-C(92)	1.514(11)
C(91)-H(91)	1.0000
C(92)-H(92A)	0.9800
C(92)-H(92B)	0.9800
C(92)-H(92C)	0.9800
C(93)-H(93A)	0.9800
C(93)-H(93B)	0.9800
C(93)-H(93C)	0.9800
C(94)-C(95)	1.393(11)
C(94)-C(99)	1.403(11)
C(95)-C(96)	1.394(10)
C(96)-C(97)	1.377(13)
C(96)-H(96)	0.9500
C(97)-C(98)	1.368(13)
C(97)-H(97)	0.9500
C(98)-C(99)	1.415(10)
C(1S)-Cl(2S)	1.745(12)

C(1S)-Cl(1S)	1.756(12)
C(1S)-H(1S1)	0.9900
C(1S)-H(1S2)	0.9900
C(18)-Ru(1)-C(1)	101.5(3)
C(18)-Ru(1)-S(1)	95.9(2)
C(1)-Ru(1)-S(1)	87.76(18)
C(18)-Ru(1)-S(2)	109.5(2)
C(1)-Ru(1)-S(2)	148.99(19)
S(1)-Ru(1)-S(2)	88.52(7)
C(18)-Ru(1)-O(1)	77.0(2)
C(1)-Ru(1)-O(1)	97.2(2)
S(1)-Ru(1)-O(1)	171.99(13)
S(2)-Ru(1)-O(1)	90.41(13)
C(28)-S(1)-Ru(1)	105.8(3)
C(33)-S(2)-Ru(1)	104.7(3)
C(20)-O(1)-C(25)	118.2(6)
C(20)-O(1)-Ru(1)	109.8(4)
C(25)-O(1)-Ru(1)	130.1(5)
C(1)-N(1)-C(4)	127.9(5)
C(1)-N(1)-C(2)	113.7(5)
C(4)-N(1)-C(2)	116.5(5)
C(1)-N(2)-C(11)	128.8(5)
C(1)-N(2)-C(3)	111.9(5)
C(11)-N(2)-C(3)	117.4(5)
N(1)-C(1)-N(2)	106.5(5)
N(1)-C(1)-Ru(1)	127.7(5)
N(2)-C(1)-Ru(1)	125.8(5)
N(1)-C(2)-C(3)	101.9(5)
N(1)-C(2)-H(2A)	111.4
C(3)-C(2)-H(2A)	111.4
N(1)-C(2)-H(2B)	111.4
C(3)-C(2)-H(2B)	111.4
H(2A)-C(2)-H(2B)	109.2
N(2)-C(3)-C(2)	102.1(5)
N(2)-C(3)-H(3A)	111.4
C(2)-C(3)-H(3A)	111.4
N(2)-C(3)-H(3B)	111.4
C(2)-C(3)-H(3B)	111.4
H(3A)-C(3)-H(3B)	109.2
C(5)-C(4)-C(9)	120.5(7)
C(5)-C(4)-N(1)	118.3(6)
C(9)-C(4)-N(1)	120.7(7)
C(6)-C(5)-F(1)	117.3(7)
C(6)-C(5)-C(4)	123.7(8)
F(1)-C(5)-C(4)	119.0(6)
C(5)-C(6)-C(7)	116.0(9)
C(5)-C(6)-H(6)	122.0
C(7)-C(6)-H(6)	122.0

C(8)-C(7)-C(6)	123.4(9)
C(8)-C(7)-H(7)	118.3
C(6)-C(7)-H(7)	118.3
C(7)-C(8)-C(9)	121.0(8)
C(7)-C(8)-H(8)	119.5
C(9)-C(8)-H(8)	119.5
C(4)-C(9)-C(8)	115.3(8)
C(4)-C(9)-C(10)	120.1(7)
C(8)-C(9)-C(10)	124.6(7)
C(9)-C(10)-H(10A)	109.5
C(9)-C(10)-H(10B)	109.5
H(10A)-C(10)-H(10B)	109.5
C(9)-C(10)-H(10C)	109.5
H(10A)-C(10)-H(10C)	109.5
H(10B)-C(10)-H(10C)	109.5
C(16)-C(11)-C(12)	118.9(7)
C(16)-C(11)-N(2)	119.3(6)
C(12)-C(11)-N(2)	121.3(6)
C(11)-C(12)-C(13)	118.0(7)
C(11)-C(12)-C(17)	120.6(7)
C(13)-C(12)-C(17)	121.3(7)
C(14)-C(13)-C(12)	121.8(8)
C(14)-C(13)-H(13)	119.1
C(12)-C(13)-H(13)	119.1
C(13)-C(14)-C(15)	120.6(8)
C(13)-C(14)-H(14)	119.7
C(15)-C(14)-H(14)	119.7
C(16)-C(15)-C(14)	118.0(8)
C(16)-C(15)-H(15)	121.0
C(14)-C(15)-H(15)	121.0
F(2)-C(16)-C(15)	119.0(7)
F(2)-C(16)-C(11)	118.4(6)
C(15)-C(16)-C(11)	122.5(7)
C(12)-C(17)-H(17A)	109.5
C(12)-C(17)-H(17B)	109.5
H(17A)-C(17)-H(17B)	109.5
C(12)-C(17)-H(17C)	109.5
H(17A)-C(17)-H(17C)	109.5
H(17B)-C(17)-H(17C)	109.5
C(19)-C(18)-Ru(1)	121.7(5)
C(19)-C(18)-H(18)	119.2
Ru(1)-C(18)-H(18)	119.2
C(20)-C(19)-C(24)	118.3(6)
C(20)-C(19)-C(18)	118.1(6)
C(24)-C(19)-C(18)	123.6(6)
O(1)-C(20)-C(21)	125.5(7)
O(1)-C(20)-C(19)	112.9(6)
C(21)-C(20)-C(19)	121.6(7)
C(20)-C(21)-C(22)	118.2(7)

C(20)-C(21)-H(21)	120.9
C(22)-C(21)-H(21)	120.9
C(23)-C(22)-C(21)	121.5(8)
C(23)-C(22)-H(22)	119.2
C(21)-C(22)-H(22)	119.2
C(22)-C(23)-C(24)	119.8(8)
C(22)-C(23)-H(23)	120.1
C(24)-C(23)-H(23)	120.1
C(23)-C(24)-C(19)	120.6(7)
C(23)-C(24)-H(24)	119.7
C(19)-C(24)-H(24)	119.7
O(1)-C(25)-C(27)	106.5(6)
O(1)-C(25)-C(26)	109.1(6)
C(27)-C(25)-C(26)	112.8(8)
O(1)-C(25)-H(25)	109.5
C(27)-C(25)-H(25)	109.5
C(26)-C(25)-H(25)	109.5
C(25)-C(26)-H(26A)	109.5
C(25)-C(26)-H(26B)	109.5
H(26A)-C(26)-H(26B)	109.5
C(25)-C(26)-H(26C)	109.5
H(26A)-C(26)-H(26C)	109.5
H(26B)-C(26)-H(26C)	109.5
C(25)-C(27)-H(27A)	109.5
C(25)-C(27)-H(27B)	109.5
H(27A)-C(27)-H(27B)	109.5
C(25)-C(27)-H(27C)	109.5
H(27A)-C(27)-H(27C)	109.5
H(27B)-C(27)-H(27C)	109.5
C(29)-C(28)-C(33)	118.6(7)
C(29)-C(28)-S(1)	121.1(6)
C(33)-C(28)-S(1)	120.2(6)
C(28)-C(29)-C(30)	121.4(8)
C(28)-C(29)-Cl(1)	119.7(6)
C(30)-C(29)-Cl(1)	118.9(7)
C(31)-C(30)-C(29)	119.0(8)
C(31)-C(30)-H(30)	120.5
C(29)-C(30)-H(30)	120.5
C(30)-C(31)-C(32)	120.6(8)
C(30)-C(31)-H(31)	119.7
C(32)-C(31)-H(31)	119.7
C(31)-C(32)-C(33)	122.3(9)
C(31)-C(32)-Cl(2)	118.8(6)
C(33)-C(32)-Cl(2)	118.9(7)
C(28)-C(33)-C(32)	118.0(8)
C(28)-C(33)-S(2)	120.3(6)
C(32)-C(33)-S(2)	121.6(7)
C(51)-Ru(2)-C(34)	101.8(3)
C(51)-Ru(2)-S(3)	94.3(2)

C(34)-Ru(2)-S(3)	94.43(19)
C(51)-Ru(2)-S(4)	105.8(2)
C(34)-Ru(2)-S(4)	152.07(19)
S(3)-Ru(2)-S(4)	87.95(6)
C(51)-Ru(2)-O(2)	78.2(3)
C(34)-Ru(2)-O(2)	92.2(2)
S(3)-Ru(2)-O(2)	170.93(15)
S(4)-Ru(2)-O(2)	89.05(14)
C(61)-S(3)-Ru(2)	105.1(2)
C(66)-S(4)-Ru(2)	105.2(2)
C(57)-O(2)-C(58)	118.4(7)
C(57)-O(2)-Ru(2)	109.6(4)
C(58)-O(2)-Ru(2)	131.2(6)
C(34)-N(3)-C(37)	127.1(6)
C(34)-N(3)-C(35)	112.6(6)
C(37)-N(3)-C(35)	119.6(6)
C(34)-N(4)-C(44)	127.9(6)
C(34)-N(4)-C(36)	113.5(6)
C(44)-N(4)-C(36)	118.6(6)
N(4)-C(34)-N(3)	108.0(6)
N(4)-C(34)-Ru(2)	124.5(5)
N(3)-C(34)-Ru(2)	127.0(5)
N(3)-C(35)-C(36)	102.7(6)
N(3)-C(35)-H(35A)	111.2
C(36)-C(35)-H(35A)	111.2
N(3)-C(35)-H(35B)	111.2
C(36)-C(35)-H(35B)	111.2
H(35A)-C(35)-H(35B)	109.1
N(4)-C(36)-C(35)	101.6(6)
N(4)-C(36)-H(36A)	111.4
C(35)-C(36)-H(36A)	111.4
N(4)-C(36)-H(36B)	111.4
C(35)-C(36)-H(36B)	111.4
H(36A)-C(36)-H(36B)	109.3
C(42)-C(37)-N(3)	125.1(9)
C(42)-C(37)-C(38)	123.0(8)
N(3)-C(37)-C(38)	111.8(8)
C(39)-C(38)-F(3)	120.4(10)
C(39)-C(38)-C(37)	121.0(10)
F(3)-C(38)-C(37)	118.6(8)
C(38)-C(39)-C(40)	116.5(10)
C(38)-C(39)-H(39)	121.7
C(40)-C(39)-H(39)	121.7
C(41)-C(40)-C(39)	125.9(10)
C(41)-C(40)-H(40)	117.1
C(39)-C(40)-H(40)	117.1
C(40)-C(41)-C(42)	117.6(11)
C(40)-C(41)-H(41)	121.2
C(42)-C(41)-H(41)	121.2

C(37)-C(42)-C(41)	116.0(10)
C(37)-C(42)-C(43)	117.9(9)
C(41)-C(42)-C(43)	126.1(10)
C(42)-C(43)-H(43A)	109.5
C(42)-C(43)-H(43B)	109.5
H(43A)-C(43)-H(43B)	109.5
C(42)-C(43)-H(43C)	109.5
H(43A)-C(43)-H(43C)	109.5
H(43B)-C(43)-H(43C)	109.5
C(45)-C(44)-N(4)	130.0(10)
C(45)-C(44)-C(49)	120.5(12)
N(4)-C(44)-C(49)	109.3(11)
C(46)-C(45)-C(44)	117.4(16)
C(46)-C(45)-C(50)	125.3(16)
C(44)-C(45)-C(50)	117.2(14)
C(45)-C(46)-C(47)	123(2)
C(45)-C(46)-H(46)	118.7
C(47)-C(46)-H(46)	118.7
C(48)-C(47)-C(46)	123.1(18)
C(48)-C(47)-H(47)	118.4
C(46)-C(47)-H(47)	118.4
C(47)-C(48)-C(49)	116(2)
C(47)-C(48)-H(48)	122.1
C(49)-C(48)-H(48)	122.1
F(4)-C(49)-C(44)	122.7(14)
F(4)-C(49)-C(48)	116.8(15)
C(44)-C(49)-C(48)	120.5(18)
C(45)-C(50)-H(50A)	109.5
C(45)-C(50)-H(50B)	109.5
H(50A)-C(50)-H(50B)	109.5
C(45)-C(50)-H(50C)	109.5
H(50A)-C(50)-H(50C)	109.5
H(50B)-C(50)-H(50C)	109.5
C(52)-C(51)-Ru(2)	121.1(5)
C(52)-C(51)-H(51)	119.4
Ru(2)-C(51)-H(51)	119.4
C(53)-C(52)-C(57)	119.0(8)
C(53)-C(52)-C(51)	123.2(8)
C(57)-C(52)-C(51)	117.8(6)
C(54)-C(53)-C(52)	121.7(10)
C(54)-C(53)-H(53)	119.1
C(52)-C(53)-H(53)	119.1
C(53)-C(54)-C(55)	118.9(9)
C(53)-C(54)-H(54)	120.5
C(55)-C(54)-H(54)	120.5
C(54)-C(55)-C(56)	122.9(8)
C(54)-C(55)-H(55)	118.6
C(56)-C(55)-H(55)	118.6
C(57)-C(56)-C(55)	116.7(9)

C(57)-C(56)-H(56)	121.7
C(55)-C(56)-H(56)	121.7
C(56)-C(57)-O(2)	126.2(8)
C(56)-C(57)-C(52)	120.9(8)
O(2)-C(57)-C(52)	112.9(6)
C(59)-C(58)-C(60)	116.5(12)
C(59)-C(58)-O(2)	112.3(9)
C(60)-C(58)-O(2)	111.5(9)
C(59)-C(58)-H(58)	105.2
C(60)-C(58)-H(58)	105.2
O(2)-C(58)-H(58)	105.2
C(58)-C(59)-H(59A)	109.5
C(58)-C(59)-H(59B)	109.5
H(59A)-C(59)-H(59B)	109.5
C(58)-C(59)-H(59C)	109.5
H(59A)-C(59)-H(59C)	109.5
H(59B)-C(59)-H(59C)	109.5
C(58)-C(60)-H(60A)	109.5
C(58)-C(60)-H(60B)	109.5
H(60A)-C(60)-H(60B)	109.5
C(58)-C(60)-H(60C)	109.5
H(60A)-C(60)-H(60C)	109.5
H(60B)-C(60)-H(60C)	109.5
C(66)-C(61)-C(62)	117.5(6)
C(66)-C(61)-S(3)	120.7(5)
C(62)-C(61)-S(3)	121.7(5)
C(63)-C(62)-C(61)	122.4(6)
C(63)-C(62)-Cl(3)	118.9(5)
C(61)-C(62)-Cl(3)	118.7(5)
C(62)-C(63)-C(64)	119.9(6)
C(62)-C(63)-H(63)	120.0
C(64)-C(63)-H(63)	120.0
C(65)-C(64)-C(63)	118.6(6)
C(65)-C(64)-H(64)	120.7
C(63)-C(64)-H(64)	120.7
C(64)-C(65)-C(66)	122.5(6)
C(64)-C(65)-Cl(4)	118.2(5)
C(66)-C(65)-Cl(4)	119.2(5)
C(61)-C(66)-C(65)	119.0(6)
C(61)-C(66)-S(4)	119.5(5)
C(65)-C(66)-S(4)	121.5(5)
C(84)-Ru(3)-C(67)	98.0(2)
C(84)-Ru(3)-S(5)	95.4(2)
C(67)-Ru(3)-S(5)	91.39(18)
C(84)-Ru(3)-S(6)	109.64(18)
C(67)-Ru(3)-S(6)	152.31(18)
S(5)-Ru(3)-S(6)	87.60(7)
C(84)-Ru(3)-O(3)	77.8(2)
C(67)-Ru(3)-O(3)	95.0(2)

S(5)-Ru(3)-O(3)	171.30(13)
S(6)-Ru(3)-O(3)	89.50(12)
C(94)-S(5)-Ru(3)	106.0(3)
C(99)-S(6)-Ru(3)	105.3(3)
C(90)-O(3)-C(91)	115.8(6)
C(90)-O(3)-Ru(3)	110.0(4)
C(91)-O(3)-Ru(3)	133.3(4)
C(67)-N(5)-C(70)	129.0(5)
C(67)-N(5)-C(68)	112.7(5)
C(70)-N(5)-C(68)	116.8(5)
C(67)-N(6)-C(77)	124.4(5)
C(67)-N(6)-C(69)	112.9(5)
C(77)-N(6)-C(69)	120.4(5)
N(5)-C(67)-N(6)	107.5(5)
N(5)-C(67)-Ru(3)	130.2(5)
N(6)-C(67)-Ru(3)	122.3(4)
N(5)-C(68)-C(69)	102.2(5)
N(5)-C(68)-H(68A)	111.3
C(69)-C(68)-H(68A)	111.3
N(5)-C(68)-H(68B)	111.3
C(69)-C(68)-H(68B)	111.3
H(68A)-C(68)-H(68B)	109.2
N(6)-C(69)-C(68)	101.2(5)
N(6)-C(69)-H(69A)	111.5
C(68)-C(69)-H(69A)	111.5
N(6)-C(69)-H(69B)	111.5
C(68)-C(69)-H(69B)	111.5
H(69A)-C(69)-H(69B)	109.3
C(71)-C(70)-C(75)	119.0(6)
C(71)-C(70)-N(5)	119.5(6)
C(75)-C(70)-N(5)	121.2(6)
C(72)-C(71)-C(70)	124.3(7)
C(72)-C(71)-F(5)	118.2(6)
C(70)-C(71)-F(5)	117.5(6)
C(71)-C(72)-C(73)	117.0(7)
C(71)-C(72)-H(72)	121.5
C(73)-C(72)-H(72)	121.5
C(72)-C(73)-C(74)	121.2(7)
C(72)-C(73)-H(73)	119.4
C(74)-C(73)-H(73)	119.4
C(73)-C(74)-C(75)	120.9(7)
C(73)-C(74)-H(74)	119.5
C(75)-C(74)-H(74)	119.5
C(74)-C(75)-C(70)	117.5(7)
C(74)-C(75)-C(76)	122.2(6)
C(70)-C(75)-C(76)	120.3(6)
C(75)-C(76)-H(76A)	109.5
C(75)-C(76)-H(76B)	109.5
H(76A)-C(76)-H(76B)	109.5

C(75)-C(76)-H(76C)	109.5
H(76A)-C(76)-H(76C)	109.5
H(76B)-C(76)-H(76C)	109.5
C(78)-C(77)-C(82)	118.8(7)
C(78)-C(77)-N(6)	121.6(7)
C(82)-C(77)-N(6)	119.5(6)
C(77)-C(78)-C(79)	117.8(8)
C(77)-C(78)-C(83)	120.9(7)
C(79)-C(78)-C(83)	121.3(7)
C(80)-C(79)-C(78)	120.6(7)
C(80)-C(79)-H(79)	119.7
C(78)-C(79)-H(79)	119.7
C(81)-C(80)-C(79)	121.9(7)
C(81)-C(80)-H(80)	119.0
C(79)-C(80)-H(80)	119.0
C(82)-C(81)-C(80)	116.8(8)
C(82)-C(81)-H(81)	121.6
C(80)-C(81)-H(81)	121.6
C(81)-C(82)-F(6)	118.9(7)
C(81)-C(82)-C(77)	123.7(7)
F(6)-C(82)-C(77)	117.5(6)
C(78)-C(83)-H(83A)	109.5
C(78)-C(83)-H(83B)	109.5
H(83A)-C(83)-H(83B)	109.5
C(78)-C(83)-H(83C)	109.5
H(83A)-C(83)-H(83C)	109.5
H(83B)-C(83)-H(83C)	109.5
C(85)-C(84)-Ru(3)	120.3(5)
C(85)-C(84)-H(84)	119.8
Ru(3)-C(84)-H(84)	119.8
C(90)-C(85)-C(86)	118.7(6)
C(90)-C(85)-C(84)	118.8(6)
C(86)-C(85)-C(84)	122.5(6)
C(87)-C(86)-C(85)	120.3(7)
C(87)-C(86)-H(86)	119.9
C(85)-C(86)-H(86)	119.9
C(88)-C(87)-C(86)	119.9(7)
C(88)-C(87)-H(87)	120.0
C(86)-C(87)-H(87)	120.0
C(87)-C(88)-C(89)	121.2(7)
C(87)-C(88)-H(88)	119.4
C(89)-C(88)-H(88)	119.4
C(90)-C(89)-C(88)	118.3(7)
C(90)-C(89)-H(89)	120.9
C(88)-C(89)-H(89)	120.9
O(3)-C(90)-C(89)	125.7(7)
O(3)-C(90)-C(85)	113.0(6)
C(89)-C(90)-C(85)	121.3(7)
C(93)-C(91)-O(3)	110.4(7)

C(93)-C(91)-C(92)	115.2(7)
O(3)-C(91)-C(92)	108.1(6)
C(93)-C(91)-H(91)	107.7
O(3)-C(91)-H(91)	107.7
C(92)-C(91)-H(91)	107.7
C(91)-C(92)-H(92A)	109.5
C(91)-C(92)-H(92B)	109.5
H(92A)-C(92)-H(92B)	109.5
C(91)-C(92)-H(92C)	109.5
H(92A)-C(92)-H(92C)	109.5
H(92B)-C(92)-H(92C)	109.5
C(91)-C(93)-H(93A)	109.5
C(91)-C(93)-H(93B)	109.5
H(93A)-C(93)-H(93B)	109.5
C(91)-C(93)-H(93C)	109.5
H(93A)-C(93)-H(93C)	109.5
H(93B)-C(93)-H(93C)	109.5
C(95)-C(94)-C(99)	117.8(7)
C(95)-C(94)-S(5)	122.9(6)
C(99)-C(94)-S(5)	119.3(6)
C(94)-C(95)-C(96)	123.4(8)
C(94)-C(95)-Cl(5)	119.8(6)
C(96)-C(95)-Cl(5)	116.8(7)
C(97)-C(96)-C(95)	118.7(8)
C(97)-C(96)-H(96)	120.7
C(95)-C(96)-H(96)	120.7
C(98)-C(97)-C(96)	119.1(7)
C(98)-C(97)-H(97)	120.5
C(96)-C(97)-H(97)	120.5
C(97)-C(98)-C(99)	123.4(8)
C(97)-C(98)-Cl(6)	117.1(6)
C(99)-C(98)-Cl(6)	119.4(7)
C(94)-C(99)-C(98)	117.7(7)
C(94)-C(99)-S(6)	121.1(5)
C(98)-C(99)-S(6)	121.3(7)
Cl(2S)-C(1S)-Cl(1S)	110.8(6)
Cl(2S)-C(1S)-H(1S1)	109.5
Cl(1S)-C(1S)-H(1S1)	109.5
Cl(2S)-C(1S)-H(1S2)	109.5
Cl(1S)-C(1S)-H(1S2)	109.5
H(1S1)-C(1S)-H(1S2)	108.1

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2x10^3$) for $3(C_{33}H_{30}Cl_2F_2N_2ORuS_2)CH_2Cl_2$ (**Ru-10**). The anisotropic displacement factor exponent takes the form: $–2p^2[h^2\ a^{*2}U^{11} + ... +2\ h\ k\ a^*\ b^*U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}

Ru(1)	37(1)	22(1)	23(1)	2(1)	2(1)	-7(1)
Cl(1)	42(1)	64(1)	47(1)	4(1)	4(1)	16(1)
Cl(2)	106(2)	34(1)	44(1)	7(1)	17(1)	-4(1)
S(1)	37(1)	28(1)	28(1)	4(1)	2(1)	1(1)
S(2)	56(1)	23(1)	32(1)	3(1)	9(1)	-7(1)
F(1)	48(3)	70(3)	40(2)	-12(2)	-5(2)	-2(2)
F(2)	43(2)	42(3)	49(2)	-13(2)	-1(2)	-10(2)
O(1)	35(2)	40(3)	32(2)	0(2)	-4(2)	-17(2)
N(1)	33(3)	23(3)	24(2)	0(2)	2(2)	-1(2)
N(2)	32(3)	21(3)	28(3)	0(2)	5(2)	-1(2)
C(1)	35(3)	25(3)	20(3)	-1(2)	-4(2)	-6(2)
C(2)	46(4)	21(3)	35(3)	5(3)	16(3)	1(3)
C(3)	33(3)	27(3)	29(3)	4(2)	11(3)	0(3)
C(4)	45(3)	26(3)	27(3)	2(2)	11(2)	-6(3)
C(5)	44(3)	44(4)	30(3)	7(3)	9(3)	2(3)
C(6)	52(5)	60(5)	52(4)	5(4)	15(4)	12(4)
C(7)	69(5)	50(5)	59(5)	0(4)	17(4)	14(4)
C(8)	82(5)	42(5)	36(4)	-6(3)	18(4)	-3(4)
C(9)	66(4)	28(4)	31(3)	-1(3)	13(3)	-4(3)
C(10)	74(5)	42(5)	30(4)	-1(3)	-2(3)	-28(4)
C(11)	35(3)	28(3)	27(3)	2(2)	1(2)	1(2)
C(12)	37(3)	31(3)	39(4)	9(3)	2(3)	-4(3)
C(13)	38(4)	46(4)	57(5)	17(3)	7(3)	7(3)
C(14)	48(4)	39(4)	63(5)	7(3)	16(4)	11(3)
C(15)	60(4)	28(4)	52(5)	-3(3)	8(4)	2(3)
C(16)	43(3)	27(3)	36(4)	0(3)	9(3)	-4(3)
C(17)	41(4)	47(4)	46(4)	8(3)	-7(3)	-16(3)
C(18)	32(3)	32(3)	23(3)	3(3)	-2(2)	-9(3)
C(19)	32(3)	28(3)	31(3)	6(2)	-1(2)	-5(2)
C(20)	34(3)	42(4)	29(3)	7(3)	2(2)	-13(3)
C(21)	35(3)	66(5)	41(4)	0(4)	-3(3)	-11(3)
C(22)	30(4)	72(6)	54(4)	1(4)	5(3)	1(4)
C(23)	41(4)	48(5)	49(4)	-1(3)	11(3)	-4(3)
C(24)	39(3)	36(4)	39(4)	-1(3)	-1(3)	-1(3)
C(25)	52(4)	59(5)	28(3)	-5(3)	3(3)	-29(4)
C(26)	69(6)	51(5)	43(4)	-9(4)	6(4)	-39(4)
C(27)	51(5)	70(6)	39(4)	-9(4)	7(3)	-32(4)
C(28)	49(3)	35(3)	21(3)	1(3)	11(3)	15(3)
C(29)	57(4)	40(4)	29(3)	0(3)	12(3)	20(3)
C(30)	64(5)	52(4)	36(4)	1(3)	8(4)	26(3)
C(31)	75(5)	40(4)	39(4)	6(3)	19(3)	25(3)
C(32)	80(5)	29(4)	31(4)	1(3)	12(3)	11(3)
C(33)	66(4)	32(3)	22(3)	-2(3)	10(3)	8(3)
Ru(2)	22(1)	24(1)	24(1)	-2(1)	3(1)	-1(1)
Cl(3)	50(1)	27(1)	42(1)	-7(1)	-7(1)	6(1)
Cl(4)	46(1)	35(1)	30(1)	7(1)	-4(1)	-1(1)
S(3)	34(1)	22(1)	26(1)	0(1)	0(1)	2(1)
S(4)	28(1)	24(1)	25(1)	1(1)	2(1)	1(1)
F(3)	78(3)	64(3)	54(3)	-14(3)	4(3)	7(3)

O(2)	46(3)	32(3)	48(3)	-17(2)	4(2)	7(2)
N(3)	40(3)	42(3)	25(3)	4(2)	-1(2)	-2(2)
N(4)	37(3)	57(4)	27(3)	-2(3)	8(2)	-5(3)
C(34)	31(3)	29(3)	27(3)	-2(2)	5(2)	1(3)
C(35)	54(4)	63(6)	26(3)	1(3)	-2(3)	-11(4)
C(36)	57(5)	110(9)	28(4)	2(4)	7(3)	-16(5)
C(37)	43(3)	59(4)	33(4)	11(3)	-12(3)	-10(3)
C(38)	54(4)	73(5)	36(4)	12(4)	-9(3)	-4(3)
C(39)	66(5)	64(6)	52(5)	3(4)	-8(4)	-11(4)
C(40)	50(4)	76(5)	41(4)	8(4)	-10(4)	-1(4)
C(41)	65(5)	81(6)	68(6)	6(5)	-8(5)	-6(5)
C(42)	38(4)	78(5)	68(6)	24(5)	-11(4)	8(3)
C(43)	98(8)	57(5)	81(7)	17(5)	10(6)	38(5)
C(44)	34(3)	83(4)	26(3)	2(3)	9(3)	-12(3)
C(45)	42(8)	87(5)	27(7)	-6(5)	10(8)	-27(4)
C(46)	41(8)	104(9)	33(6)	-2(7)	10(6)	-27(5)
C(47)	44(7)	119(9)	44(7)	8(8)	7(6)	-19(6)
C(48)	36(5)	117(9)	43(7)	18(8)	7(4)	-12(6)
C(49)	32(5)	103(8)	40(7)	10(8)	11(5)	-7(5)
C(50)	54(10)	65(7)	47(9)	-4(6)	17(9)	-25(7)
F(4)	52(8)	94(8)	69(8)	10(6)	16(6)	5(6)
C(45X)	42(8)	87(5)	27(7)	-6(5)	10(8)	-27(4)
C(46X)	41(8)	104(9)	33(6)	-2(7)	10(6)	-27(5)
C(47X)	44(7)	119(9)	44(7)	8(8)	7(6)	-19(6)
C(48X)	36(5)	117(9)	43(7)	18(8)	7(4)	-12(6)
C(49X)	32(5)	103(8)	40(7)	10(8)	11(5)	-7(5)
C(50X)	54(10)	65(7)	47(9)	-4(6)	17(9)	-25(7)
F(4X)	49(9)	98(9)	74(10)	15(8)	3(7)	23(7)
C(51)	31(3)	40(3)	23(3)	-5(3)	2(2)	-1(3)
C(52)	41(3)	44(4)	22(3)	-2(3)	2(3)	-12(3)
C(53)	49(4)	71(5)	31(4)	2(4)	6(3)	-27(4)
C(54)	74(6)	73(5)	41(4)	8(4)	-5(4)	-41(4)
C(55)	93(6)	48(5)	45(5)	9(4)	-22(4)	-38(4)
C(56)	87(5)	34(4)	38(4)	-2(3)	-16(4)	-7(4)
C(57)	52(4)	33(3)	28(3)	-1(3)	0(3)	-9(3)
C(58)	72(5)	69(6)	56(4)	-6(4)	17(4)	35(4)
C(59)	73(7)	44(6)	45(5)	-11(4)	8(5)	22(5)
C(60)	65(7)	54(8)	50(6)	-5(5)	14(5)	31(5)
C(58X)	72(5)	69(6)	56(4)	-6(4)	17(4)	35(4)
C(59X)	73(7)	44(6)	45(5)	-11(4)	8(5)	22(5)
C(60X)	65(7)	54(8)	50(6)	-5(5)	14(5)	31(5)
C(61)	23(3)	28(3)	26(3)	1(2)	4(2)	-7(2)
C(62)	29(3)	26(3)	32(3)	0(2)	4(2)	-7(2)
C(63)	34(3)	34(3)	31(3)	-7(3)	3(3)	-6(3)
C(64)	38(4)	35(3)	26(3)	0(2)	3(3)	-6(3)
C(65)	24(3)	31(3)	31(3)	6(2)	4(2)	-6(2)
C(66)	19(3)	26(3)	25(3)	-1(2)	8(2)	-5(2)
Ru(3)	28(1)	18(1)	38(1)	3(1)	14(1)	-2(1)
Cl(5)	49(1)	86(2)	56(1)	29(1)	6(1)	3(1)

Cl(6)	60(1)	37(1)	88(2)	1(1)	38(1)	-15(1)
S(5)	32(1)	30(1)	38(1)	8(1)	16(1)	2(1)
S(6)	35(1)	23(1)	53(1)	5(1)	18(1)	-6(1)
F(5)	53(3)	49(3)	37(2)	-3(2)	-3(2)	-4(2)
F(6)	45(2)	35(2)	46(2)	2(2)	0(2)	4(2)
O(3)	38(3)	23(2)	40(2)	-2(2)	9(2)	-5(2)
N(5)	28(3)	22(2)	34(3)	6(2)	12(2)	-2(2)
N(6)	28(3)	26(3)	31(3)	6(2)	12(2)	3(2)
C(67)	26(3)	20(3)	31(3)	2(2)	11(2)	-1(2)
C(68)	27(3)	32(3)	36(3)	7(3)	15(3)	1(3)
C(69)	29(3)	31(3)	35(3)	6(3)	17(3)	3(3)
C(70)	28(3)	22(3)	34(3)	4(2)	9(2)	-3(2)
C(71)	31(3)	32(3)	35(3)	5(2)	7(3)	-5(3)
C(72)	31(4)	36(3)	53(4)	14(3)	0(3)	-5(3)
C(73)	41(4)	26(3)	62(4)	12(3)	5(3)	-5(3)
C(74)	28(3)	25(3)	62(4)	0(3)	9(3)	-7(3)
C(75)	28(3)	25(3)	39(3)	1(2)	7(3)	-13(2)
C(76)	40(4)	32(4)	33(3)	-2(3)	5(3)	0(3)
C(77)	39(3)	27(3)	28(3)	3(2)	17(2)	6(2)
C(78)	49(4)	38(4)	33(3)	7(3)	13(3)	16(3)
C(79)	69(5)	38(4)	38(4)	10(3)	10(3)	26(3)
C(80)	71(5)	24(4)	49(4)	9(3)	23(3)	14(3)
C(81)	48(4)	31(3)	52(4)	1(3)	17(3)	3(3)
C(82)	36(4)	31(3)	39(3)	7(3)	13(3)	5(3)
C(83)	59(5)	52(5)	34(4)	-2(3)	-1(3)	21(4)
C(84)	21(3)	26(3)	39(3)	7(3)	17(2)	-5(2)
C(85)	28(3)	20(3)	42(3)	5(2)	12(2)	-4(2)
C(86)	29(3)	25(3)	42(4)	7(3)	14(3)	0(2)
C(87)	26(3)	41(4)	54(4)	9(3)	14(3)	8(3)
C(88)	24(3)	40(4)	52(4)	13(3)	7(3)	-2(3)
C(89)	20(3)	42(4)	47(4)	1(3)	6(3)	-6(3)
C(90)	24(3)	26(3)	45(3)	3(2)	12(2)	-3(2)
C(91)	37(4)	33(4)	61(5)	-10(3)	5(3)	-8(3)
C(92)	39(4)	41(4)	50(4)	-3(3)	3(3)	5(3)
C(93)	41(4)	34(4)	68(5)	-11(4)	17(4)	-9(3)
C(94)	37(3)	22(3)	50(3)	14(3)	19(3)	11(3)
C(95)	40(4)	36(4)	55(4)	16(3)	21(3)	11(3)
C(96)	53(4)	47(5)	53(4)	24(4)	30(3)	18(3)
C(97)	57(4)	31(4)	68(4)	16(4)	37(3)	8(3)
C(98)	43(4)	22(4)	68(4)	6(3)	28(3)	9(3)
C(99)	38(3)	19(3)	59(4)	8(3)	25(3)	11(3)
C(1S)	114(9)	116(11)	51(6)	18(6)	12(5)	-46(8)
Cl(1S)	96(2)	103(2)	73(2)	22(2)	-1(2)	-32(2)
Cl(2S)	77(2)	198(5)	89(2)	5(3)	16(2)	-22(2)

Table 5. Hydrogen coordinates ($x10^4$) and isotropic displacement parameters ($Å^2x10^3$) for $3(C_{33}H_{30}Cl_2F_2N_2ORuS_2)CH_2Cl_2$ (**Ru-10**).

	x	y	z	U(eq)
H(2A)	6792	2001	9186	40
H(2B)	5939	1817	8872	40
H(3A)	4829	2473	9151	35
H(3B)	5790	2832	9372	35
H(6)	10281	2031	8711	65
H(7)	9925	1340	8232	70
H(8)	8285	1235	7973	64
H(10A)	6013	1497	8243	74
H(10B)	6424	1766	7883	74
H(10C)	6041	2277	8169	74
H(13)	2371	4195	8856	56
H(14)	3036	5130	9130	59
H(15)	4839	5203	9303	56
H(17A)	3191	3220	8385	67
H(17B)	2675	2964	8732	67
H(17C)	3853	2745	8650	67
H(18)	6946	3119	7822	35
H(21)	10715	3759	8403	57
H(22)	11472	3122	7972	63
H(23)	10423	2610	7537	55
H(24)	8588	2690	7536	46
H(25)	9844	4084	8829	56
H(26A)	9937	5241	8723	81
H(26B)	10002	4844	8364	81
H(26C)	8918	5194	8457	81
H(27A)	8836	4737	9195	80
H(27B)	7839	4681	8920	80
H(27C)	8278	4035	9122	80
H(30)	3081	5395	7398	61
H(31)	4396	6190	7415	61
H(35A)	4117	2678	7549	58
H(35B)	4442	1923	7466	58
H(36A)	2706	1701	7403	78
H(36B)	2407	2478	7401	78
H(39)	6652	4140	7160	74
H(40)	8030	3486	6970	67
H(41)	7855	2387	6822	86
H(43A)	6576	1356	6821	118
H(43B)	5635	1613	6560	118
H(43C)	5415	1458	6958	118
H(46)	477	663	6432	71
H(47)	-799	1465	6368	83
H(48)	-500	2542	6543	78

H(50A)	2911	715	6500	82
H(50B)	2160	295	6739	82
H(50C)	2924	853	6910	82
H(46X)	1156	329	6514	71
H(47X)	-427	859	6354	83
H(48X)	-628	1976	6437	78
H(50D)	2986	691	7029	82
H(50E)	3551	1017	6708	82
H(50F)	2893	345	6653	82
H(51)	5544	2540	6175	38
H(53)	6934	3430	6130	60
H(54)	7477	4508	6218	76
H(55)	6285	5287	6386	76
H(56)	4496	5011	6479	64
H(58)	3045	4673	6367	78
H(59A)	3315	4417	6936	81
H(59B)	2143	4685	6842	81
H(59C)	2341	3910	6905	81
H(60A)	2063	4034	5984	84
H(60B)	1545	3668	6303	84
H(60C)	1347	4442	6240	84
H(58X)	3124	4584	6603	78
H(59D)	2547	3678	6864	81
H(59E)	1591	4171	6758	81
H(59F)	1761	3516	6534	81
H(60D)	3043	4776	6041	84
H(60E)	2099	4253	5982	84
H(60F)	1928	4908	6207	84
H(63)	3622	781	4888	40
H(64)	2771	1717	4644	39
H(68A)	5410	2434	5526	37
H(68B)	4971	2332	5126	37
H(69A)	4615	3429	5131	38
H(69B)	5389	3549	5475	38
H(72)	8218	871	5769	48
H(73)	7973	117	5307	52
H(74)	7199	453	4772	46
H(76A)	6318	1260	4412	53
H(76B)	6605	2015	4502	53
H(76C)	5533	1698	4630	53
H(79)	5624	5292	4345	58
H(80)	6854	5907	4670	57
H(81)	7732	5473	5168	52
H(83A)	5239	3575	4403	73
H(83B)	4870	4221	4187	73
H(83C)	4300	4026	4534	73
H(84)	8469	2067	4537	33
H(86)	9662	1116	4746	38
H(87)	10814	654	5176	48

H(88)	11259	1240	5679	47
H(89)	10578	2311	5764	43
H(91)	10581	3268	5640	52
H(92A)	9096	2975	5943	65
H(92B)	9489	3701	6057	65
H(92C)	8472	3613	5794	65
H(93A)	10363	4408	5599	71
H(93B)	10544	4087	5226	71
H(93C)	9380	4305	5323	71
H(96)	8721	4153	3168	60
H(97)	10266	4622	3428	61
H(1S1)	8661	5030	7728	112
H(1S2)	9173	4385	7562	112

Table 6. Torsion angles (°) for 3($C_{33}H_{30}Cl_2F_2N_2ORuS_2$)$CH_2Cl_2$ (**Ru-10**).

C(4)-N(1)-C(1)-N(2)	169.0(6)
C(2)-N(1)-C(1)-N(2)	5.7(7)
C(4)-N(1)-C(1)-Ru(1)	-9.8(9)
C(2)-N(1)-C(1)-Ru(1)	-173.1(5)
C(11)-N(2)-C(1)-N(1)	171.3(6)
C(3)-N(2)-C(1)-N(1)	8.0(7)
C(11)-N(2)-C(1)-Ru(1)	-9.8(9)
C(3)-N(2)-C(1)-Ru(1)	-173.1(4)
C(1)-N(1)-C(2)-C(3)	-16.3(7)
C(4)-N(1)-C(2)-C(3)	178.4(6)
C(1)-N(2)-C(3)-C(2)	-17.5(7)
C(11)-N(2)-C(3)-C(2)	177.1(6)
N(1)-C(2)-C(3)-N(2)	18.7(7)
C(1)-N(1)-C(4)-C(5)	104.5(8)
C(2)-N(1)-C(4)-C(5)	-92.6(8)
C(1)-N(1)-C(4)-C(9)	-83.4(9)
C(2)-N(1)-C(4)-C(9)	79.5(8)
C(9)-C(4)-C(5)-C(6)	2.0(12)
N(1)-C(4)-C(5)-C(6)	174.1(7)
C(9)-C(4)-C(5)-F(1)	-179.8(6)
N(1)-C(4)-C(5)-F(1)	-7.7(10)
F(1)-C(5)-C(6)-C(7)	178.9(7)
C(4)-C(5)-C(6)-C(7)	-2.9(13)
C(5)-C(6)-C(7)-C(8)	1.5(14)
C(6)-C(7)-C(8)-C(9)	0.6(15)
C(5)-C(4)-C(9)-C(8)	0.2(10)
N(1)-C(4)-C(9)-C(8)	-171.6(6)
C(5)-C(4)-C(9)-C(10)	179.6(7)
N(1)-C(4)-C(9)-C(10)	7.7(10)
C(7)-C(8)-C(9)-C(4)	-1.5(12)
C(7)-C(8)-C(9)-C(10)	179.2(8)
C(1)-N(2)-C(11)-C(16)	-68.9(9)
C(3)-N(2)-C(11)-C(16)	93.6(8)

C(1)-N(2)-C(11)-C(12)	119.1(8)
C(3)-N(2)-C(11)-C(12)	-78.3(8)
C(16)-C(11)-C(12)-C(13)	0.7(10)
N(2)-C(11)-C(12)-C(13)	172.6(6)
C(16)-C(11)-C(12)-C(17)	179.7(7)
N(2)-C(11)-C(12)-C(17)	-8.3(10)
C(11)-C(12)-C(13)-C(14)	1.1(12)
C(17)-C(12)-C(13)-C(14)	-178.0(7)
C(12)-C(13)-C(14)-C(15)	-2.3(13)
C(13)-C(14)-C(15)-C(16)	1.7(13)
C(14)-C(15)-C(16)-F(2)	-177.3(7)
C(14)-C(15)-C(16)-C(11)	0.1(12)
C(12)-C(11)-C(16)-F(2)	176.2(6)
N(2)-C(11)-C(16)-F(2)	4.1(10)
C(12)-C(11)-C(16)-C(15)	-1.3(11)
N(2)-C(11)-C(16)-C(15)	-173.4(7)
C(1)-Ru(1)-C(18)-C(19)	-100.1(5)
S(1)-Ru(1)-C(18)-C(19)	171.1(5)
S(2)-Ru(1)-C(18)-C(19)	80.5(5)
O(1)-Ru(1)-C(18)-C(19)	-5.2(5)
Ru(1)-C(18)-C(19)-C(20)	4.2(9)
Ru(1)-C(18)-C(19)-C(24)	-176.4(5)
C(25)-O(1)-C(20)-C(21)	9.5(11)
Ru(1)-O(1)-C(20)-C(21)	175.7(7)
C(25)-O(1)-C(20)-C(19)	-171.3(6)
Ru(1)-O(1)-C(20)-C(19)	-5.1(7)
C(24)-C(19)-C(20)-O(1)	-177.8(6)
C(18)-C(19)-C(20)-O(1)	1.6(9)
C(24)-C(19)-C(20)-C(21)	1.5(11)
C(18)-C(19)-C(20)-C(21)	-179.1(7)
O(1)-C(20)-C(21)-C(22)	177.2(7)
C(19)-C(20)-C(21)-C(22)	-2.0(12)
C(20)-C(21)-C(22)-C(23)	1.7(14)
C(21)-C(22)-C(23)-C(24)	-1.0(14)
C(22)-C(23)-C(24)-C(19)	0.5(12)
C(20)-C(19)-C(24)-C(23)	-0.7(11)
C(18)-C(19)-C(24)-C(23)	179.9(7)
C(20)-O(1)-C(25)-C(27)	-164.4(7)
Ru(1)-O(1)-C(25)-C(27)	32.7(9)
C(20)-O(1)-C(25)-C(26)	73.6(9)
Ru(1)-O(1)-C(25)-C(26)	-89.3(7)
Ru(1)-S(1)-C(28)-C(29)	178.8(5)
Ru(1)-S(1)-C(28)-C(33)	-1.5(6)
C(33)-C(28)-C(29)-C(30)	3.4(10)
S(1)-C(28)-C(29)-C(30)	-176.9(5)
C(33)-C(28)-C(29)-Cl(1)	-175.0(5)
S(1)-C(28)-C(29)-Cl(1)	4.7(8)
C(28)-C(29)-C(30)-C(31)	-1.9(11)
Cl(1)-C(29)-C(30)-C(31)	176.5(6)

C(29)-C(30)-C(31)-C(32)	-0.8(12)
C(30)-C(31)-C(32)-C(33)	1.8(12)
C(30)-C(31)-C(32)-Cl(2)	-177.4(6)
C(29)-C(28)-C(33)-C(32)	-2.3(10)
S(1)-C(28)-C(33)-C(32)	178.0(5)
C(29)-C(28)-C(33)-S(2)	175.6(5)
S(1)-C(28)-C(33)-S(2)	-4.1(8)
C(31)-C(32)-C(33)-C(28)	-0.3(11)
Cl(2)-C(32)-C(33)-C(28)	179.0(5)
C(31)-C(32)-C(33)-S(2)	-178.1(6)
Cl(2)-C(32)-C(33)-S(2)	1.2(9)
Ru(1)-S(2)-C(33)-C(28)	7.3(6)
Ru(1)-S(2)-C(33)-C(32)	-174.9(5)
C(44)-N(4)-C(34)-N(3)	-173.7(8)
C(36)-N(4)-C(34)-N(3)	6.9(10)
C(44)-N(4)-C(34)-Ru(2)	14.1(12)
C(36)-N(4)-C(34)-Ru(2)	-165.3(7)
C(37)-N(3)-C(34)-N(4)	171.6(7)
C(35)-N(3)-C(34)-N(4)	1.9(9)
C(37)-N(3)-C(34)-Ru(2)	-16.4(11)
C(35)-N(3)-C(34)-Ru(2)	173.9(6)
C(34)-N(3)-C(35)-C(36)	-9.3(10)
C(37)-N(3)-C(35)-C(36)	-179.9(8)
C(34)-N(4)-C(36)-C(35)	-12.3(11)
C(44)-N(4)-C(36)-C(35)	168.3(8)
N(3)-C(35)-C(36)-N(4)	11.9(10)
C(34)-N(3)-C(37)-C(42)	-75.2(11)
C(35)-N(3)-C(37)-C(42)	93.9(10)
C(34)-N(3)-C(37)-C(38)	108.2(8)
C(35)-N(3)-C(37)-C(38)	-82.7(9)
C(42)-C(37)-C(38)-C(39)	-0.1(13)
N(3)-C(37)-C(38)-C(39)	176.5(8)
C(42)-C(37)-C(38)-F(3)	178.9(8)
N(3)-C(37)-C(38)-F(3)	-4.5(10)
F(3)-C(38)-C(39)-C(40)	-177.2(7)
C(37)-C(38)-C(39)-C(40)	1.8(13)
C(38)-C(39)-C(40)-C(41)	-2.6(14)
C(39)-C(40)-C(41)-C(42)	1.5(15)
N(3)-C(37)-C(42)-C(41)	-177.2(8)
C(38)-C(37)-C(42)-C(41)	-1.0(13)
N(3)-C(37)-C(42)-C(43)	4.0(13)
C(38)-C(37)-C(42)-C(43)	-179.8(8)
C(40)-C(41)-C(42)-C(37)	0.3(14)
C(40)-C(41)-C(42)-C(43)	179.0(9)
C(34)-N(4)-C(44)-C(45)	91(2)
C(36)-N(4)-C(44)-C(45)	-90(2)
C(34)-N(4)-C(44)-C(49)	-93.9(14)
C(36)-N(4)-C(44)-C(49)	85.4(14)
N(4)-C(44)-C(45)-C(46)	175.8(16)

C(49)-C(44)-C(45)-C(46)	1(4)
N(4)-C(44)-C(45)-C(50)	-2(4)
C(49)-C(44)-C(45)-C(50)	-177(2)
C(44)-C(45)-C(46)-C(47)	0(4)
C(50)-C(45)-C(46)-C(47)	178(3)
C(45)-C(46)-C(47)-C(48)	-1(4)
C(46)-C(47)-C(48)-C(49)	0(3)
C(45)-C(44)-C(49)-F(4)	176(2)
N(4)-C(44)-C(49)-F(4)	0(2)
C(45)-C(44)-C(49)-C(48)	-1(3)
N(4)-C(44)-C(49)-C(48)	-176.9(17)
C(47)-C(48)-C(49)-F(4)	-177(2)
C(47)-C(48)-C(49)-C(44)	0(3)
C(34)-Ru(2)-C(51)-C(52)	-95.5(5)
S(3)-Ru(2)-C(51)-C(52)	169.0(5)
S(4)-Ru(2)-C(51)-C(52)	79.9(5)
O(2)-Ru(2)-C(51)-C(52)	-5.7(5)
Ru(2)-C(51)-C(52)-C(53)	-174.9(6)
Ru(2)-C(51)-C(52)-C(57)	6.6(9)
C(57)-C(52)-C(53)-C(54)	1.6(11)
C(51)-C(52)-C(53)-C(54)	-176.9(7)
C(52)-C(53)-C(54)-C(55)	-0.5(13)
C(53)-C(54)-C(55)-C(56)	0.1(13)
C(54)-C(55)-C(56)-C(57)	-0.7(12)
C(55)-C(56)-C(57)-O(2)	179.9(7)
C(55)-C(56)-C(57)-C(52)	1.8(11)
C(58)-O(2)-C(57)-C(56)	8.9(11)
Ru(2)-O(2)-C(57)-C(56)	179.6(6)
C(58)-O(2)-C(57)-C(52)	-172.9(6)
Ru(2)-O(2)-C(57)-C(52)	-2.2(7)
C(53)-C(52)-C(57)-C(56)	-2.2(11)
C(51)-C(52)-C(57)-C(56)	176.4(7)
C(53)-C(52)-C(57)-O(2)	179.5(6)
C(51)-C(52)-C(57)-O(2)	-2.0(9)
C(57)-O(2)-C(58)-C(59)	-94.1(12)
Ru(2)-O(2)-C(58)-C(59)	97.6(12)
C(57)-O(2)-C(58)-C(60)	133.2(10)
Ru(2)-O(2)-C(58)-C(60)	-35.1(13)
Ru(2)-S(3)-C(61)-C(66)	-10.7(5)
Ru(2)-S(3)-C(61)-C(62)	168.3(5)
C(66)-C(61)-C(62)-C(63)	-1.3(9)
S(3)-C(61)-C(62)-C(63)	179.7(5)
C(66)-C(61)-C(62)-Cl(3)	177.3(4)
S(3)-C(61)-C(62)-Cl(3)	-1.8(7)
C(61)-C(62)-C(63)-C(64)	-0.8(10)
Cl(3)-C(62)-C(63)-C(64)	-179.3(5)
C(62)-C(63)-C(64)-C(65)	1.6(10)
C(63)-C(64)-C(65)-C(66)	-0.4(10)
C(63)-C(64)-C(65)-Cl(4)	-179.9(5)

C(62)-C(61)-C(66)-C(65)	2.5(8)
S(3)-C(61)-C(66)-C(65)	-178.5(5)
C(62)-C(61)-C(66)-S(4)	-176.5(4)
S(3)-C(61)-C(66)-S(4)	2.5(7)
C(64)-C(65)-C(66)-C(61)	-1.7(9)
Cl(4)-C(65)-C(66)-C(61)	177.8(5)
C(64)-C(65)-C(66)-S(4)	177.3(5)
Cl(4)-C(65)-C(66)-S(4)	-3.2(7)
Ru(2)-S(4)-C(66)-C(61)	7.0(5)
Ru(2)-S(4)-C(66)-C(65)	-172.0(4)
C(70)-N(5)-C(67)-N(6)	170.8(6)
C(68)-N(5)-C(67)-N(6)	5.0(8)
C(70)-N(5)-C(67)-Ru(3)	-10.3(11)
C(68)-N(5)-C(67)-Ru(3)	-176.0(5)
C(77)-N(6)-C(67)-N(5)	170.9(6)
C(69)-N(6)-C(67)-N(5)	7.9(8)
C(77)-N(6)-C(67)-Ru(3)	-8.2(9)
C(69)-N(6)-C(67)-Ru(3)	-171.2(5)
C(67)-N(5)-C(68)-C(69)	-14.9(7)
C(70)-N(5)-C(68)-C(69)	177.5(6)
C(67)-N(6)-C(69)-C(68)	-16.5(7)
C(77)-N(6)-C(69)-C(68)	179.7(6)
N(5)-C(68)-C(69)-N(6)	17.3(7)
C(67)-N(5)-C(70)-C(71)	107.8(8)
C(68)-N(5)-C(70)-C(71)	-86.9(8)
C(67)-N(5)-C(70)-C(75)	-78.8(9)
C(68)-N(5)-C(70)-C(75)	86.5(7)
C(75)-C(70)-C(71)-C(72)	2.5(10)
N(5)-C(70)-C(71)-C(72)	176.0(6)
C(75)-C(70)-C(71)-F(5)	-177.6(6)
N(5)-C(70)-C(71)-F(5)	-4.1(9)
C(70)-C(71)-C(72)-C(73)	-1.3(11)
F(5)-C(71)-C(72)-C(73)	178.8(6)
C(71)-C(72)-C(73)-C(74)	1.7(11)
C(72)-C(73)-C(74)-C(75)	-3.2(11)
C(73)-C(74)-C(75)-C(70)	4.2(10)
C(73)-C(74)-C(75)-C(76)	-176.7(6)
C(71)-C(70)-C(75)-C(74)	-3.8(9)
N(5)-C(70)-C(75)-C(74)	-177.2(6)
C(71)-C(70)-C(75)-C(76)	177.1(6)
N(5)-C(70)-C(75)-C(76)	3.7(9)
C(67)-N(6)-C(77)-C(78)	114.1(8)
C(69)-N(6)-C(77)-C(78)	-84.1(8)
C(67)-N(6)-C(77)-C(82)	-69.6(9)
C(69)-N(6)-C(77)-C(82)	92.2(8)
C(82)-C(77)-C(78)-C(79)	5.6(10)
N(6)-C(77)-C(78)-C(79)	-178.1(6)
C(82)-C(77)-C(78)-C(83)	-176.0(6)
N(6)-C(77)-C(78)-C(83)	0.3(10)

C(77)-C(78)-C(79)-C(80)	-1.6(11)
C(83)-C(78)-C(79)-C(80)	-180.0(7)
C(78)-C(79)-C(80)-C(81)	-1.5(12)
C(79)-C(80)-C(81)-C(82)	0.4(12)
C(80)-C(81)-C(82)-F(6)	-176.4(6)
C(80)-C(81)-C(82)-C(77)	3.9(11)
C(78)-C(77)-C(82)-C(81)	-7.1(10)
N(6)-C(77)-C(82)-C(81)	176.6(6)
C(78)-C(77)-C(82)-F(6)	173.2(6)
N(6)-C(77)-C(82)-F(6)	-3.1(9)
C(67)-Ru(3)-C(84)-C(85)	-96.4(5)
S(5)-Ru(3)-C(84)-C(85)	171.4(4)
S(6)-Ru(3)-C(84)-C(85)	82.0(5)
O(3)-Ru(3)-C(84)-C(85)	-3.0(4)
Ru(3)-C(84)-C(85)-C(90)	4.4(8)
Ru(3)-C(84)-C(85)-C(86)	-173.7(5)
C(90)-C(85)-C(86)-C(87)	2.4(9)
C(84)-C(85)-C(86)-C(87)	-179.5(6)
C(85)-C(86)-C(87)-C(88)	1.3(10)
C(86)-C(87)-C(88)-C(89)	-1.0(10)
C(87)-C(88)-C(89)-C(90)	-2.9(10)
C(91)-O(3)-C(90)-C(89)	12.2(9)
Ru(3)-O(3)-C(90)-C(89)	-177.6(5)
C(91)-O(3)-C(90)-C(85)	-169.9(5)
Ru(3)-O(3)-C(90)-C(85)	0.3(6)
C(88)-C(89)-C(90)-O(3)	-175.6(6)
C(88)-C(89)-C(90)-C(85)	6.7(10)
C(86)-C(85)-C(90)-O(3)	175.5(5)
C(84)-C(85)-C(90)-O(3)	-2.7(8)
C(86)-C(85)-C(90)-C(89)	-6.5(9)
C(84)-C(85)-C(90)-C(89)	175.3(6)
C(90)-O(3)-C(91)-C(93)	139.5(6)
Ru(3)-O(3)-C(91)-C(93)	-27.8(9)
C(90)-O(3)-C(91)-C(92)	-93.8(7)
Ru(3)-O(3)-C(91)-C(92)	98.9(7)
Ru(3)-S(5)-C(94)-C(95)	172.3(5)
Ru(3)-S(5)-C(94)-C(99)	-6.8(6)
C(99)-C(94)-C(95)-C(96)	-1.5(11)
S(5)-C(94)-C(95)-C(96)	179.4(6)
C(99)-C(94)-C(95)-Cl(5)	179.0(5)
S(5)-C(94)-C(95)-Cl(5)	-0.2(9)
C(94)-C(95)-C(96)-C(97)	0.1(12)
Cl(5)-C(95)-C(96)-C(97)	179.7(6)
C(95)-C(96)-C(97)-C(98)	0.9(12)
C(96)-C(97)-C(98)-C(99)	-0.4(12)
C(96)-C(97)-C(98)-Cl(6)	175.7(6)
C(95)-C(94)-C(99)-C(98)	1.8(10)
S(5)-C(94)-C(99)-C(98)	-179.0(5)
C(95)-C(94)-C(99)-S(6)	-177.7(5)

S(5)-C(94)-C(99)-S(6)	1.5(8)
C(97)-C(98)-C(99)-C(94)	-0.9(10)
Cl(6)-C(98)-C(99)-C(94)	-177.0(5)
C(97)-C(98)-C(99)-S(6)	178.6(6)
Cl(6)-C(98)-C(99)-S(6)	2.5(8)
Ru(3)-S(6)-C(99)-C(94)	4.6(6)
Ru(3)-S(6)-C(99)-C(98)	-174.9(5)

Symmetry transformations used to generate equivalent atoms:

3.6.8 X-ray Structure of Ru-14

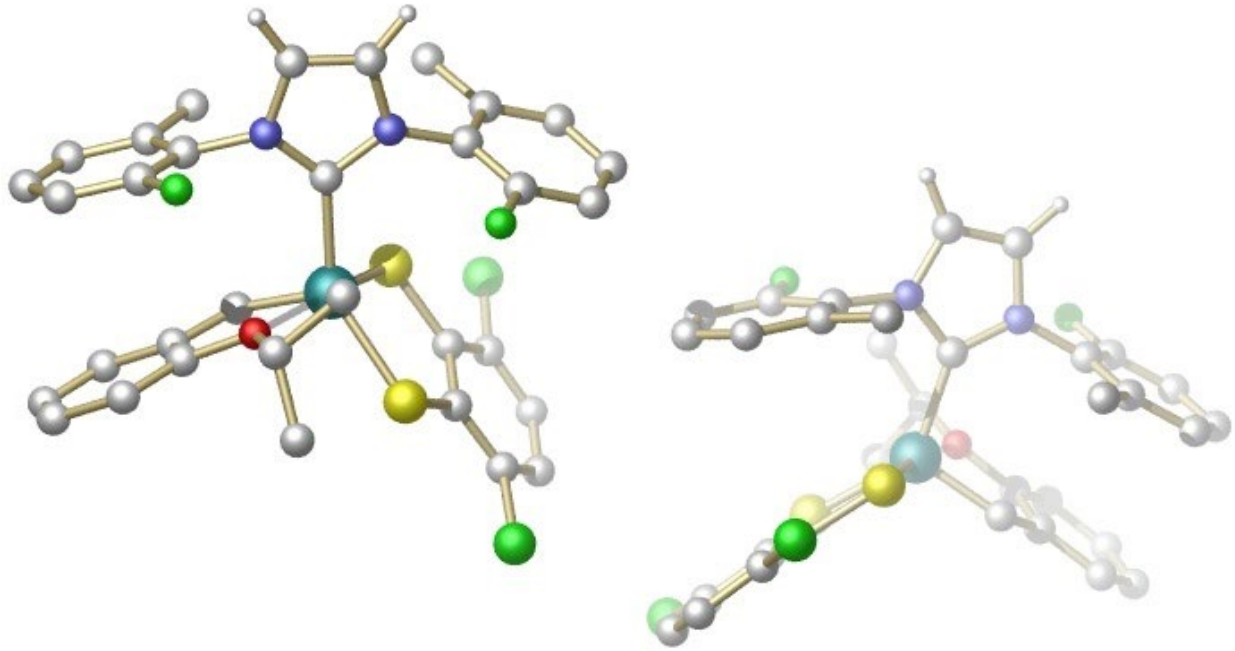


Table 7. Crystal data and structure refinement for $C_{33}H_{28}Cl_2F_2N_2ORuS_2$ (**Ru-14**).

Identification code	C33.50 H28 Cl2 F2 N2 O1.50 Ru S2	
Empirical formula	C33.50 H28 Cl2 F2 N2 O1.50 Ru S2	
Formula weight	758.68	
Temperature	100(2) K	
Wavelength	1.54178 Å	
Crystal system	Monoclinic	
Space group	$P2_1/c$	
Unit cell dimensions	a = 15.3836(8) Å	a= 90°.
	b = 17.6296(9) Å	b= 107.754(2)°.
	c = 24.9348(13) Å	g = 90°.
Volume	6440.4(6) $Å^3$	
Z	8	
Density (calculated)	1.565 Mg/m^3	
Absorption coefficient	7.049 mm^{-1}	
F(000)	3080	
Crystal size	0.600 x 0.160 x 0.120 mm^3	
Theta range for data collection	3.122 to 68.350°.	

Index ranges	-18<=h<=18, -21<=k<=20, -30<=l<=28
Reflections collected	74670
Independent reflections	11767 [R(int) = 0.0508]
Completeness to theta = 67.679°	99.8 %
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	11767 / 1 / 797
Goodness-of-fit on F^2	1.058
Final R indices [I>2sigma(I)]	R1 = 0.0504, wR2 = 0.1308
R indices (all data)	R1 = 0.0518, wR2 = 0.1322
Extinction coefficient	n/a
Largest diff. peak and hole	2.951 and -1.180 e.Å^{-3}

Table 8. Atomic coordinates (x10^4) and equivalent isotropic displacement parameters (Å^{2}x10^3) for $C_{33}H_{28}Cl_2F_2N_2ORuS_2$ (**Ru-14**). U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
Ru(1)	5157(1)	2453(1)	7108(1)	20(1)
S(1)	5564(1)	2589(1)	6318(1)	28(1)
S(2)	4159(1)	1542(1)	6661(1)	33(1)
Cl(1)	5690(1)	2493(1)	5074(1)	61(1)
Cl(2)	3151(2)	260(1)	5788(1)	89(1)
F(1)	5441(3)	3622(2)	8726(1)	56(1)
F(2)	2848(2)	3662(2)	6655(1)	46(1)
O(1)	4918(2)	2209(2)	7953(1)	25(1)
N(1)	5655(3)	4011(2)	7700(2)	31(1)
N(2)	4640(2)	4128(2)	6895(2)	27(1)
C(1)	5196(3)	3605(2)	7239(2)	24(1)
C(2)	5384(4)	4767(3)	7651(2)	42(1)
C(3)	4747(4)	4836(3)	7147(2)	39(1)
C(4)	6410(4)	3737(3)	8155(2)	34(1)
C(5)	7270(4)	3681(3)	8084(2)	39(1)
C(6)	7987(4)	3418(3)	8542(3)	55(2)
C(7)	7839(5)	3237(4)	9048(2)	60(2)
C(8)	6998(5)	3297(3)	9117(2)	56(2)
C(9)	6296(4)	3551(3)	8668(2)	43(1)
C(10)	7403(3)	3890(3)	7532(2)	41(1)
C(11)	4084(3)	3989(3)	6326(2)	31(1)
C(12)	3192(3)	3715(3)	6221(2)	37(1)
C(13)	2668(4)	3502(3)	5695(2)	45(1)
C(14)	3035(4)	3582(3)	5256(2)	47(1)
C(15)	3887(4)	3893(3)	5342(2)	42(1)
C(16)	4428(3)	4113(3)	5877(2)	35(1)
C(17)	5352(4)	4460(3)	5967(2)	44(1)
C(18)	4944(3)	1909(3)	5847(2)	35(1)
C(19)	5027(4)	1838(4)	5305(2)	49(1)
C(20)	4602(4)	1279(4)	4935(2)	59(2)
C(21)	4062(5)	788(4)	5096(2)	67(2)
C(22)	3909(4)	857(3)	5625(2)	57(2)

C(23)	4346(4)	1421(3)	6003(2)	40(1)
C(24)	6287(3)	2113(2)	7541(2)	25(1)
C(25)	6412(3)	1815(2)	8101(2)	25(1)
C(26)	7229(3)	1501(3)	8442(2)	30(1)
C(27)	7292(3)	1224(3)	8976(2)	35(1)
C(28)	6543(3)	1263(3)	9170(2)	36(1)
C(29)	5727(3)	1578(3)	8846(2)	32(1)
C(30)	5672(3)	1858(2)	8319(2)	24(1)
C(31)	4070(3)	2252(3)	8113(2)	32(1)
C(32)	3605(3)	1485(3)	8021(2)	38(1)
C(33)	3505(3)	2869(3)	7756(2)	38(1)
Ru(2)	-65(1)	6342(1)	7230(1)	19(1)
S(3)	164(1)	6403(1)	6378(1)	25(1)
S(4)	-1262(1)	7149(1)	6897(1)	23(1)
Cl(3)	135(1)	6891(1)	5150(1)	44(1)
Cl(4)	-2652(1)	8379(1)	6163(1)	46(1)
F(3)	604(2)	5044(2)	8848(1)	46(1)
F(4)	-2020(2)	5013(2)	6736(1)	38(1)
N(3)	807(2)	4829(2)	7797(2)	28(1)
N(4)	-195(2)	4636(2)	7000(2)	27(1)
O(2)	-163(2)	6461(2)	8131(1)	22(1)
C(34)	259(3)	5206(2)	7343(2)	24(1)
C(35)	682(4)	4050(3)	7739(2)	41(1)
C(36)	49(4)	3927(3)	7242(2)	40(1)
C(37)	1523(3)	5165(2)	8246(2)	28(1)
C(38)	1413(3)	5259(3)	8768(2)	34(1)
C(39)	2077(4)	5567(3)	9215(2)	45(1)
C(40)	2882(4)	5778(3)	9127(2)	49(1)
C(41)	3026(3)	5669(3)	8612(2)	44(1)
C(42)	2349(3)	5351(3)	8161(2)	36(1)
C(43)	2500(3)	5199(3)	7605(2)	44(1)
C(44)	-763(3)	4714(2)	6424(2)	29(1)
C(45)	-384(3)	4595(3)	5991(2)	34(1)
C(46)	-960(3)	4677(3)	5439(2)	37(1)
C(47)	-1866(3)	4877(3)	5328(2)	35(1)
C(48)	-2234(3)	4992(3)	5764(2)	33(1)
C(49)	-1672(3)	4903(2)	6307(2)	29(1)
C(50)	613(3)	4411(3)	6110(2)	46(1)
C(51)	-607(3)	7086(2)	5997(2)	26(1)
C(52)	-621(3)	7318(3)	5457(2)	33(1)
C(53)	-1208(4)	7865(3)	5156(2)	44(1)
C(54)	-1826(4)	8198(3)	5383(2)	46(1)
C(55)	-1854(3)	7970(3)	5906(2)	36(1)
C(56)	-1243(3)	7423(2)	6222(2)	26(1)
C(57)	1015(3)	6820(2)	7597(2)	23(1)
C(58)	1181(3)	7093(2)	8169(2)	22(1)
C(59)	1939(3)	7537(2)	8449(2)	28(1)
C(60)	2051(3)	7802(3)	8987(2)	32(1)
C(61)	1416(3)	7622(3)	9251(2)	34(1)

C(62)	654(3)	7177(3)	8988(2)	30(1)
C(63)	547(3)	6917(2)	8449(2)	22(1)
C(64)	-911(3)	6288(3)	8364(2)	30(1)
C(65)	-1512(3)	6975(3)	8321(2)	40(1)
C(66)	-1411(3)	5612(3)	8042(2)	37(1)
O(1T)	8944(4)	5116(4)	9609(2)	16(2)
C(1T)	9407(6)	4447(6)	9705(4)	28(2)
O(1S)	9182(7)	4850(7)	9633(3)	32(2)
C(1S)	9659(7)	4227(6)	9902(5)	18(3)

Table 9. Bond lengths (Å) and angles (°) for $C_{33}H_{28}Cl_2F_2N_2ORuS_2$ (**Ru-14**).

Ru(1)-C(24)	1.846(4)
Ru(1)-C(1)	2.055(4)
Ru(1)-S(1)	2.2543(10)
Ru(1)-S(2)	2.2656(11)
Ru(1)-O(1)	2.288(3)
S(1)-C(18)	1.745(5)
S(2)-C(23)	1.763(6)
Cl(1)-C(19)	1.750(7)
Cl(2)-C(22)	1.709(7)
F(1)-C(9)	1.372(7)
F(2)-C(12)	1.344(6)
O(1)-C(30)	1.385(5)
O(1)-C(31)	1.478(5)
N(1)-C(1)	1.356(6)
N(1)-C(2)	1.390(6)
N(1)-C(4)	1.438(6)
N(2)-C(1)	1.367(6)
N(2)-C(3)	1.384(6)
N(2)-C(11)	1.438(6)
C(2)-C(3)	1.343(8)
C(2)-H(2A)	0.9500
C(3)-H(3A)	0.9500
C(4)-C(9)	1.382(7)
C(4)-C(5)	1.391(8)
C(5)-C(6)	1.403(8)
C(5)-C(10)	1.498(7)
C(6)-C(7)	1.386(9)
C(6)-H(6A)	0.9500
C(7)-C(8)	1.360(10)
C(7)-H(7A)	0.9500
C(8)-C(9)	1.373(8)
C(8)-H(8A)	0.9500
C(10)-H(10A)	0.9800
C(10)-H(10B)	0.9800
C(10)-H(10C)	0.9800
C(11)-C(16)	1.394(7)
C(11)-C(12)	1.403(7)

C(12)-C(13)	1.366(8)
C(13)-C(14)	1.383(8)
C(13)-H(13A)	0.9500
C(14)-C(15)	1.376(8)
C(14)-H(14A)	0.9500
C(15)-C(16)	1.394(7)
C(15)-H(15A)	0.9500
C(16)-C(17)	1.500(7)
C(17)-H(17A)	0.9800
C(17)-H(17B)	0.9800
C(17)-H(17C)	0.9800
C(18)-C(19)	1.400(7)
C(18)-C(23)	1.399(8)
C(19)-C(20)	1.373(9)
C(20)-C(21)	1.343(11)
C(20)-H(20)	0.9500
C(21)-C(22)	1.415(10)
C(21)-H(21)	0.9500
C(22)-C(23)	1.393(7)
C(24)-C(25)	1.447(6)
C(24)-H(24A)	0.9500
C(25)-C(26)	1.400(6)
C(25)-C(30)	1.407(6)
C(26)-C(27)	1.392(6)
C(26)-H(26A)	0.9500
C(27)-C(28)	1.382(7)
C(27)-H(27A)	0.9500
C(28)-C(29)	1.386(7)
C(28)-H(28A)	0.9500
C(29)-C(30)	1.380(6)
C(29)-H(29A)	0.9500
C(31)-C(33)	1.502(6)
C(31)-C(32)	1.514(7)
C(31)-H(31A)	1.0000
C(32)-H(32A)	0.9800
C(32)-H(32B)	0.9800
C(32)-H(32C)	0.9800
C(33)-H(33A)	0.9800
C(33)-H(33B)	0.9800
C(33)-H(33C)	0.9800
Ru(2)-C(57)	1.838(4)
Ru(2)-C(34)	2.063(4)
Ru(2)-S(3)	2.2610(10)
Ru(2)-S(4)	2.2738(10)
Ru(2)-O(2)	2.305(3)
S(3)-C(51)	1.753(4)
S(4)-C(56)	1.759(4)
Cl(3)-C(52)	1.747(5)
Cl(4)-C(55)	1.710(5)

F(3)-C(38)	1.373(6)
F(4)-C(49)	1.348(5)
N(3)-C(34)	1.360(5)
N(3)-C(35)	1.389(6)
N(3)-C(37)	1.439(5)
N(4)-C(34)	1.366(5)
N(4)-C(36)	1.389(6)
N(4)-C(44)	1.441(5)
O(2)-C(63)	1.393(5)
O(2)-C(64)	1.470(5)
C(35)-C(36)	1.340(7)
C(35)-H(35A)	0.9500
C(36)-H(36A)	0.9500
C(37)-C(38)	1.373(7)
C(37)-C(42)	1.389(7)
C(38)-C(39)	1.373(7)
C(39)-C(40)	1.372(9)
C(39)-H(39A)	0.9500
C(40)-C(41)	1.381(9)
C(40)-H(40A)	0.9500
C(41)-C(42)	1.396(7)
C(41)-H(41A)	0.9500
C(42)-C(43)	1.499(7)
C(43)-H(43A)	0.9800
C(43)-H(43B)	0.9800
C(43)-H(43C)	0.9800
C(44)-C(49)	1.379(6)
C(44)-C(45)	1.392(7)
C(45)-C(46)	1.398(7)
C(45)-C(50)	1.506(7)
C(46)-C(47)	1.381(7)
C(46)-H(46A)	0.9500
C(47)-C(48)	1.385(7)
C(47)-H(47A)	0.9500
C(48)-C(49)	1.376(6)
C(48)-H(48A)	0.9500
C(50)-H(50A)	0.9800
C(50)-H(50B)	0.9800
C(50)-H(50C)	0.9800
C(51)-C(52)	1.400(6)
C(51)-C(56)	1.401(6)
C(52)-C(53)	1.376(7)
C(53)-C(54)	1.378(8)
C(53)-H(53A)	0.9500
C(54)-C(55)	1.377(7)
C(54)-H(54A)	0.9500
C(55)-C(56)	1.408(6)
C(57)-C(58)	1.452(5)
C(57)-H(57A)	0.9500

C(58)-C(63)	1.398(6)
C(58)-C(59)	1.400(6)
C(59)-C(60)	1.382(6)
C(59)-H(59A)	0.9500
C(60)-C(61)	1.371(7)
C(60)-H(60A)	0.9500
C(61)-C(62)	1.397(7)
C(61)-H(61A)	0.9500
C(62)-C(63)	1.381(6)
C(62)-H(62A)	0.9500
C(64)-C(65)	1.507(7)
C(64)-C(66)	1.510(6)
C(64)-H(64A)	1.0000
C(65)-H(65A)	0.9800
C(65)-H(65B)	0.9800
C(65)-H(65C)	0.9800
C(66)-H(66A)	0.9800
C(66)-H(66B)	0.9800
C(66)-H(66C)	0.9800
O(1T)-C(1T)	1.361(10)
O(1T)-H(1T)	0.8481
C(1T)-H(1T1)	0.9800
C(1T)-H(1T2)	0.9800
C(1T)-H(1T3)	0.9800
O(1S)-C(1S)	1.376(12)
O(1S)-H(1S)	0.9138
C(1S)-H(1S1)	0.9800
C(1S)-H(1S2)	0.9800
C(1S)-H(1S3)	0.9800

C(24)-Ru(1)-C(1)	104.58(18)
C(24)-Ru(1)-S(1)	94.74(13)
C(1)-Ru(1)-S(1)	91.79(12)
C(24)-Ru(1)-S(2)	115.69(13)
C(1)-Ru(1)-S(2)	139.58(12)
S(1)-Ru(1)-S(2)	88.43(4)
C(24)-Ru(1)-O(1)	77.68(15)
C(1)-Ru(1)-O(1)	92.55(14)
S(1)-Ru(1)-O(1)	172.02(8)
S(2)-Ru(1)-O(1)	92.59(8)
C(18)-S(1)-Ru(1)	105.94(18)
C(23)-S(2)-Ru(1)	105.41(19)
C(30)-O(1)-C(31)	118.5(3)
C(30)-O(1)-Ru(1)	110.7(2)
C(31)-O(1)-Ru(1)	129.9(2)
C(1)-N(1)-C(2)	111.6(4)
C(1)-N(1)-C(4)	125.4(4)
C(2)-N(1)-C(4)	122.6(4)
C(1)-N(2)-C(3)	111.0(4)

C(1)-N(2)-C(11)	125.0(4)
C(3)-N(2)-C(11)	123.7(4)
N(1)-C(1)-N(2)	103.9(4)
N(1)-C(1)-Ru(1)	129.7(3)
N(2)-C(1)-Ru(1)	125.8(3)
C(3)-C(2)-N(1)	106.4(4)
C(3)-C(2)-H(2A)	126.8
N(1)-C(2)-H(2A)	126.8
C(2)-C(3)-N(2)	107.2(4)
C(2)-C(3)-H(3A)	126.4
N(2)-C(3)-H(3A)	126.4
C(9)-C(4)-C(5)	119.7(5)
C(9)-C(4)-N(1)	120.7(5)
C(5)-C(4)-N(1)	119.6(4)
C(4)-C(5)-C(6)	117.5(5)
C(4)-C(5)-C(10)	120.1(5)
C(6)-C(5)-C(10)	122.4(5)
C(7)-C(6)-C(5)	120.8(6)
C(7)-C(6)-H(6A)	119.6
C(5)-C(6)-H(6A)	119.6
C(8)-C(7)-C(6)	121.5(6)
C(8)-C(7)-H(7A)	119.2
C(6)-C(7)-H(7A)	119.2
C(7)-C(8)-C(9)	117.7(6)
C(7)-C(8)-H(8A)	121.1
C(9)-C(8)-H(8A)	121.1
C(8)-C(9)-F(1)	119.0(5)
C(8)-C(9)-C(4)	122.8(6)
F(1)-C(9)-C(4)	118.2(5)
C(5)-C(10)-H(10A)	109.5
C(5)-C(10)-H(10B)	109.5
H(10A)-C(10)-H(10B)	109.5
C(5)-C(10)-H(10C)	109.5
H(10A)-C(10)-H(10C)	109.5
H(10B)-C(10)-H(10C)	109.5
C(16)-C(11)-C(12)	119.7(4)
C(16)-C(11)-N(2)	120.6(4)
C(12)-C(11)-N(2)	119.8(4)
F(2)-C(12)-C(13)	119.5(5)
F(2)-C(12)-C(11)	118.5(4)
C(13)-C(12)-C(11)	122.0(5)
C(12)-C(13)-C(14)	117.9(5)
C(12)-C(13)-H(13A)	121.0
C(14)-C(13)-H(13A)	121.0
C(15)-C(14)-C(13)	121.1(5)
C(15)-C(14)-H(14A)	119.4
C(13)-C(14)-H(14A)	119.4
C(14)-C(15)-C(16)	121.5(5)
C(14)-C(15)-H(15A)	119.3

C(16)-C(15)-H(15A)	119.3
C(15)-C(16)-C(11)	117.5(5)
C(15)-C(16)-C(17)	121.2(5)
C(11)-C(16)-C(17)	121.2(4)
C(16)-C(17)-H(17A)	109.5
C(16)-C(17)-H(17B)	109.5
H(17A)-C(17)-H(17B)	109.5
C(16)-C(17)-H(17C)	109.5
H(17A)-C(17)-H(17C)	109.5
H(17B)-C(17)-H(17C)	109.5
C(19)-C(18)-C(23)	118.3(5)
C(19)-C(18)-S(1)	121.3(5)
C(23)-C(18)-S(1)	120.4(4)
C(20)-C(19)-C(18)	123.3(6)
C(20)-C(19)-Cl(1)	117.2(5)
C(18)-C(19)-Cl(1)	119.5(4)
C(21)-C(20)-C(19)	118.2(6)
C(21)-C(20)-H(20)	120.9
C(19)-C(20)-H(20)	120.9
C(20)-C(21)-C(22)	121.1(6)
C(20)-C(21)-H(21)	119.4
C(22)-C(21)-H(21)	119.4
C(23)-C(22)-C(21)	120.6(7)
C(23)-C(22)-Cl(2)	120.1(5)
C(21)-C(22)-Cl(2)	119.3(5)
C(22)-C(23)-C(18)	118.3(5)
C(22)-C(23)-S(2)	122.3(5)
C(18)-C(23)-S(2)	119.5(4)
C(25)-C(24)-Ru(1)	120.5(3)
C(25)-C(24)-H(24A)	119.8
Ru(1)-C(24)-H(24A)	119.8
C(26)-C(25)-C(30)	117.9(4)
C(26)-C(25)-C(24)	124.1(4)
C(30)-C(25)-C(24)	118.0(4)
C(27)-C(26)-C(25)	120.5(4)
C(27)-C(26)-H(26A)	119.7
C(25)-C(26)-H(26A)	119.7
C(28)-C(27)-C(26)	119.7(4)
C(28)-C(27)-H(27A)	120.1
C(26)-C(27)-H(27A)	120.1
C(27)-C(28)-C(29)	121.2(4)
C(27)-C(28)-H(28A)	119.4
C(29)-C(28)-H(28A)	119.4
C(30)-C(29)-C(28)	118.8(4)
C(30)-C(29)-H(29A)	120.6
C(28)-C(29)-H(29A)	120.6
C(29)-C(30)-O(1)	125.7(4)
C(29)-C(30)-C(25)	121.8(4)
O(1)-C(30)-C(25)	112.5(3)

O(1)-C(31)-C(33)	106.1(3)
O(1)-C(31)-C(32)	109.1(4)
C(33)-C(31)-C(32)	113.3(4)
O(1)-C(31)-H(31A)	109.4
C(33)-C(31)-H(31A)	109.4
C(32)-C(31)-H(31A)	109.4
C(31)-C(32)-H(32A)	109.5
C(31)-C(32)-H(32B)	109.5
H(32A)-C(32)-H(32B)	109.5
C(31)-C(32)-H(32C)	109.5
H(32A)-C(32)-H(32C)	109.5
H(32B)-C(32)-H(32C)	109.5
C(31)-C(33)-H(33A)	109.5
C(31)-C(33)-H(33B)	109.5
H(33A)-C(33)-H(33B)	109.5
C(31)-C(33)-H(33C)	109.5
H(33A)-C(33)-H(33C)	109.5
H(33B)-C(33)-H(33C)	109.5
C(57)-Ru(2)-C(34)	103.51(17)
C(57)-Ru(2)-S(3)	94.00(12)
C(34)-Ru(2)-S(3)	94.19(12)
C(57)-Ru(2)-S(4)	113.79(13)
C(34)-Ru(2)-S(4)	142.38(12)
S(3)-Ru(2)-S(4)	88.15(4)
C(57)-Ru(2)-O(2)	77.98(14)
C(34)-Ru(2)-O(2)	92.37(13)
S(3)-Ru(2)-O(2)	170.66(8)
S(4)-Ru(2)-O(2)	90.73(7)
C(51)-S(3)-Ru(2)	105.58(15)
C(56)-S(4)-Ru(2)	105.88(15)
C(34)-N(3)-C(35)	111.5(4)
C(34)-N(3)-C(37)	125.5(3)
C(35)-N(3)-C(37)	122.4(4)
C(34)-N(4)-C(36)	111.8(3)
C(34)-N(4)-C(44)	126.3(3)
C(36)-N(4)-C(44)	121.4(4)
C(63)-O(2)-C(64)	117.8(3)
C(63)-O(2)-Ru(2)	109.6(2)
C(64)-O(2)-Ru(2)	131.1(2)
N(3)-C(34)-N(4)	103.3(3)
N(3)-C(34)-Ru(2)	130.5(3)
N(4)-C(34)-Ru(2)	125.0(3)
C(36)-C(35)-N(3)	107.1(4)
C(36)-C(35)-H(35A)	126.4
N(3)-C(35)-H(35A)	126.5
C(35)-C(36)-N(4)	106.3(4)
C(35)-C(36)-H(36A)	126.9
N(4)-C(36)-H(36A)	126.9
C(38)-C(37)-C(42)	120.0(4)

C(38)-C(37)-N(3)	120.1(4)
C(42)-C(37)-N(3)	119.8(4)
C(39)-C(38)-F(3)	118.4(5)
C(39)-C(38)-C(37)	122.7(5)
F(3)-C(38)-C(37)	118.9(4)
C(38)-C(39)-C(40)	117.5(5)
C(38)-C(39)-H(39A)	121.2
C(40)-C(39)-H(39A)	121.2
C(39)-C(40)-C(41)	121.3(5)
C(39)-C(40)-H(40A)	119.4
C(41)-C(40)-H(40A)	119.3
C(40)-C(41)-C(42)	120.8(5)
C(40)-C(41)-H(41A)	119.6
C(42)-C(41)-H(41A)	119.6
C(37)-C(42)-C(41)	117.7(5)
C(37)-C(42)-C(43)	120.4(4)
C(41)-C(42)-C(43)	121.9(5)
C(42)-C(43)-H(43A)	109.5
C(42)-C(43)-H(43B)	109.5
H(43A)-C(43)-H(43B)	109.5
C(42)-C(43)-H(43C)	109.5
H(43A)-C(43)-H(43C)	109.5
H(43B)-C(43)-H(43C)	109.5
C(49)-C(44)-C(45)	120.6(4)
C(49)-C(44)-N(4)	120.2(4)
C(45)-C(44)-N(4)	119.2(4)
C(44)-C(45)-C(46)	117.3(4)
C(44)-C(45)-C(50)	121.5(4)
C(46)-C(45)-C(50)	121.2(4)
C(47)-C(46)-C(45)	121.5(5)
C(47)-C(46)-H(46A)	119.3
C(45)-C(46)-H(46A)	119.3
C(46)-C(47)-C(48)	120.5(4)
C(46)-C(47)-H(47A)	119.7
C(48)-C(47)-H(47A)	119.7
C(49)-C(48)-C(47)	118.1(4)
C(49)-C(48)-H(48A)	120.9
C(47)-C(48)-H(48A)	120.9
F(4)-C(49)-C(48)	118.8(4)
F(4)-C(49)-C(44)	119.2(4)
C(48)-C(49)-C(44)	121.9(4)
C(45)-C(50)-H(50A)	109.5
C(45)-C(50)-H(50B)	109.5
H(50A)-C(50)-H(50B)	109.5
C(45)-C(50)-H(50C)	109.5
H(50A)-C(50)-H(50C)	109.5
H(50B)-C(50)-H(50C)	109.5
C(52)-C(51)-C(56)	117.0(4)
C(52)-C(51)-S(3)	122.1(4)

C(56)-C(51)-S(3)	120.9(3)
C(53)-C(52)-C(51)	123.0(5)
C(53)-C(52)-Cl(3)	118.4(4)
C(51)-C(52)-Cl(3)	118.5(4)
C(52)-C(53)-C(54)	119.6(5)
C(52)-C(53)-H(53A)	120.2
C(54)-C(53)-H(53A)	120.2
C(55)-C(54)-C(53)	119.2(5)
C(55)-C(54)-H(54A)	120.4
C(53)-C(54)-H(54A)	120.4
C(54)-C(55)-C(56)	121.6(5)
C(54)-C(55)-Cl(4)	117.7(4)
C(56)-C(55)-Cl(4)	120.7(4)
C(51)-C(56)-C(55)	119.6(4)
C(51)-C(56)-S(4)	119.0(3)
C(55)-C(56)-S(4)	121.4(4)
C(58)-C(57)-Ru(2)	120.2(3)
C(58)-C(57)-H(57A)	119.9
Ru(2)-C(57)-H(57A)	119.9
C(63)-C(58)-C(59)	118.5(4)
C(63)-C(58)-C(57)	118.5(4)
C(59)-C(58)-C(57)	123.0(4)
C(60)-C(59)-C(58)	120.8(4)
C(60)-C(59)-H(59A)	119.6
C(58)-C(59)-H(59A)	119.6
C(61)-C(60)-C(59)	119.4(4)
C(61)-C(60)-H(60A)	120.3
C(59)-C(60)-H(60A)	120.3
C(60)-C(61)-C(62)	121.6(4)
C(60)-C(61)-H(61A)	119.2
C(62)-C(61)-H(61A)	119.2
C(63)-C(62)-C(61)	118.4(4)
C(63)-C(62)-H(62A)	120.8
C(61)-C(62)-H(62A)	120.8
C(62)-C(63)-O(2)	125.8(4)
C(62)-C(63)-C(58)	121.3(4)
O(2)-C(63)-C(58)	112.9(3)
O(2)-C(64)-C(65)	110.0(4)
O(2)-C(64)-C(66)	106.6(3)
C(65)-C(64)-C(66)	113.2(4)
O(2)-C(64)-H(64A)	109.0
C(65)-C(64)-H(64A)	109.0
C(66)-C(64)-H(64A)	108.9
C(64)-C(65)-H(65A)	109.5
C(64)-C(65)-H(65B)	109.5
H(65A)-C(65)-H(65B)	109.5
C(64)-C(65)-H(65C)	109.5
H(65A)-C(65)-H(65C)	109.5
H(65B)-C(65)-H(65C)	109.5

C(64)-C(66)-H(66A)	109.5
C(64)-C(66)-H(66B)	109.5
H(66A)-C(66)-H(66B)	109.5
C(64)-C(66)-H(66C)	109.5
H(66A)-C(66)-H(66C)	109.5
H(66B)-C(66)-H(66C)	109.5
C(1T)-O(1T)-H(1T)	110.4
O(1T)-C(1T)-H(1T1)	109.4
O(1T)-C(1T)-H(1T2)	109.5
H(1T1)-C(1T)-H(1T2)	109.5
O(1T)-C(1T)-H(1T3)	109.5
H(1T1)-C(1T)-H(1T3)	109.5
H(1T2)-C(1T)-H(1T3)	109.5
C(1S)-O(1S)-H(1S)	117.5
O(1S)-C(1S)-H(1S1)	109.7
O(1S)-C(1S)-H(1S2)	109.2
H(1S1)-C(1S)-H(1S2)	109.5
O(1S)-C(1S)-H(1S3)	109.5
H(1S1)-C(1S)-H(1S3)	109.5
H(1S2)-C(1S)-H(1S3)	109.5

Symmetry transformations used to generate equivalent atoms:

Table 10. Anisotropic displacement parameters ($Å^2x10^3$) for $C_{33}H_{28}Cl_2F_2N_2ORuS_2$ (**Ru-14**). The anisotropic displacement factor exponent takes the form: $–2p^2[h^2 a^{*2}U^{11} + ... + 2 h k a^* b^* U^{12}]$.

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
Ru(1)	21(1)	19(1)	17(1)	0(1)	3(1)	0(1)
S(1)	31(1)	33(1)	18(1)	2(1)	7(1)	7(1)
S(2)	38(1)	24(1)	26(1)	4(1)	-8(1)	-7(1)
Cl(1)	49(1)	112(1)	22(1)	3(1)	11(1)	22(1)
Cl(2)	135(2)	54(1)	41(1)	10(1)	-29(1)	-48(1)
F(1)	78(2)	61(2)	38(2)	-4(1)	32(2)	-10(2)
F(2)	36(2)	59(2)	44(2)	14(1)	15(1)	4(1)
O(1)	22(1)	31(2)	22(1)	4(1)	7(1)	1(1)
N(1)	41(2)	26(2)	26(2)	-4(2)	12(2)	-7(2)
N(2)	33(2)	22(2)	28(2)	0(1)	11(2)	1(1)
C(1)	28(2)	24(2)	24(2)	0(2)	12(2)	-3(2)
C(2)	64(3)	26(2)	38(3)	-9(2)	18(2)	-3(2)
C(3)	55(3)	23(2)	43(3)	-1(2)	20(2)	6(2)
C(4)	49(3)	27(2)	23(2)	-5(2)	5(2)	-10(2)
C(5)	46(3)	33(3)	34(3)	-2(2)	5(2)	-16(2)
C(6)	47(3)	48(3)	58(4)	-3(3)	-4(3)	-15(3)
C(7)	74(4)	55(4)	35(3)	2(3)	-7(3)	-23(3)
C(8)	86(5)	47(3)	26(3)	0(2)	5(3)	-14(3)
C(9)	62(3)	40(3)	26(2)	-11(2)	15(2)	-14(2)
C(10)	36(3)	47(3)	41(3)	3(2)	16(2)	-12(2)
C(11)	38(2)	26(2)	28(2)	3(2)	8(2)	8(2)

C(12)	37(3)	35(3)	37(3)	11(2)	9(2)	11(2)
C(13)	36(3)	48(3)	44(3)	15(2)	1(2)	3(2)
C(14)	49(3)	48(3)	34(3)	9(2)	0(2)	8(2)
C(15)	47(3)	42(3)	33(3)	11(2)	7(2)	10(2)
C(16)	42(3)	29(2)	34(2)	6(2)	10(2)	9(2)
C(17)	53(3)	39(3)	43(3)	8(2)	21(2)	1(2)
C(18)	41(3)	34(2)	19(2)	-2(2)	-6(2)	19(2)
C(19)	43(3)	70(4)	24(2)	-7(2)	-4(2)	28(3)
C(20)	53(4)	79(5)	31(3)	-14(3)	-7(3)	23(3)
C(21)	85(5)	56(4)	30(3)	-20(3)	-26(3)	28(4)
C(22)	68(4)	36(3)	40(3)	-2(2)	-25(3)	7(3)
C(23)	45(3)	30(2)	28(2)	-1(2)	-14(2)	15(2)
C(24)	22(2)	29(2)	22(2)	-2(2)	6(2)	-1(2)
C(25)	27(2)	23(2)	22(2)	-1(2)	5(2)	0(2)
C(26)	28(2)	37(2)	25(2)	4(2)	9(2)	4(2)
C(27)	32(2)	48(3)	22(2)	10(2)	2(2)	6(2)
C(28)	39(3)	46(3)	21(2)	11(2)	8(2)	0(2)
C(29)	34(2)	38(2)	26(2)	5(2)	12(2)	-1(2)
C(30)	26(2)	23(2)	23(2)	1(2)	5(2)	-1(2)
C(31)	25(2)	39(3)	36(2)	10(2)	16(2)	3(2)
C(32)	23(2)	40(3)	52(3)	14(2)	13(2)	1(2)
C(33)	30(2)	40(3)	48(3)	12(2)	18(2)	6(2)
Ru(2)	21(1)	19(1)	16(1)	1(1)	5(1)	0(1)
S(3)	30(1)	27(1)	18(1)	0(1)	9(1)	0(1)
S(4)	23(1)	24(1)	21(1)	0(1)	3(1)	1(1)
Cl(3)	49(1)	64(1)	22(1)	3(1)	15(1)	2(1)
Cl(4)	40(1)	54(1)	40(1)	7(1)	4(1)	14(1)
F(3)	44(2)	60(2)	31(1)	10(1)	7(1)	-5(1)
F(4)	34(1)	53(2)	27(1)	5(1)	10(1)	-2(1)
N(3)	31(2)	21(2)	26(2)	3(1)	-1(2)	-2(1)
N(4)	29(2)	23(2)	22(2)	0(1)	-2(1)	-1(1)
O(2)	23(1)	27(1)	16(1)	-1(1)	7(1)	-4(1)
C(34)	23(2)	25(2)	22(2)	1(2)	4(2)	0(2)
C(35)	49(3)	21(2)	39(3)	4(2)	-8(2)	-3(2)
C(36)	48(3)	21(2)	39(3)	4(2)	-7(2)	-2(2)
C(37)	28(2)	20(2)	27(2)	2(2)	-6(2)	1(2)
C(38)	34(2)	33(2)	29(2)	7(2)	-1(2)	2(2)
C(39)	51(3)	40(3)	30(2)	2(2)	-9(2)	7(2)
C(40)	45(3)	35(3)	46(3)	-3(2)	-18(2)	1(2)
C(41)	31(2)	32(3)	59(3)	2(2)	-3(2)	-1(2)
C(42)	30(2)	25(2)	43(3)	4(2)	-2(2)	5(2)
C(43)	35(3)	48(3)	51(3)	-1(2)	18(2)	2(2)
C(44)	36(2)	22(2)	22(2)	-1(2)	-2(2)	-2(2)
C(45)	35(2)	31(2)	32(2)	-8(2)	4(2)	3(2)
C(46)	45(3)	38(3)	27(2)	-10(2)	8(2)	1(2)
C(47)	40(3)	33(2)	23(2)	-3(2)	-3(2)	1(2)
C(48)	28(2)	35(2)	29(2)	2(2)	1(2)	-1(2)
C(49)	34(2)	29(2)	22(2)	1(2)	6(2)	-5(2)
C(50)	38(3)	61(3)	37(3)	-15(2)	7(2)	10(2)

C(51)	31(2)	26(2)	17(2)	1(2)	1(2)	-9(2)
C(52)	36(2)	41(3)	22(2)	-1(2)	7(2)	-3(2)
C(53)	48(3)	56(3)	23(2)	6(2)	3(2)	2(3)
C(54)	46(3)	47(3)	34(3)	12(2)	-6(2)	7(2)
C(55)	34(2)	41(3)	27(2)	1(2)	-1(2)	-3(2)
C(56)	29(2)	26(2)	18(2)	1(2)	0(2)	-4(2)
C(57)	21(2)	28(2)	21(2)	1(2)	9(2)	1(2)
C(58)	24(2)	21(2)	21(2)	1(2)	7(2)	2(2)
C(59)	29(2)	30(2)	28(2)	-1(2)	10(2)	-2(2)
C(60)	32(2)	34(2)	29(2)	-6(2)	6(2)	-4(2)
C(61)	37(2)	39(3)	23(2)	-9(2)	6(2)	0(2)
C(62)	33(2)	37(2)	22(2)	-2(2)	11(2)	-1(2)
C(63)	25(2)	21(2)	19(2)	-1(2)	3(2)	1(2)
C(64)	25(2)	43(3)	24(2)	1(2)	11(2)	-6(2)
C(65)	30(2)	58(3)	37(3)	-10(2)	17(2)	-3(2)
C(66)	33(2)	50(3)	32(2)	-1(2)	15(2)	-13(2)

Table 11. Hydrogen coordinates ($x10^4$) and isotropic displacement parameters ($Å^2x10^3$) for $C_{33}H_{28}Cl_2F_2N_2ORuS_2$ (**Ru-14**).

	x	y	z	U(eq)
H(2A)	5605	5157	7921	50
H(3A)	4430	5286	6992	47
H(6A)	8581	3364	8505	67
H(7A)	8337	3067	9354	72
H(8A)	6900	3167	9464	67
H(10A)	8044	3818	7554	61
H(10B)	7017	3567	7233	61
H(10C)	7233	4423	7446	61
H(13A)	2070	3305	5632	54
H(14A)	2693	3419	4889	56
H(15A)	4112	3960	5030	50
H(17A)	5628	4576	6367	65
H(17B)	5743	4102	5845	65
H(17C)	5290	4928	5746	65
H(20)	4688	1241	4574	71
H(21)	3778	388	4850	80
H(24A)	6791	2133	7396	29
H(26A)	7745	1476	8309	36
H(27A)	7847	1008	9205	42
H(28A)	6588	1071	9534	43
H(29A)	5215	1602	8983	38
H(31A)	4222	2396	8519	38
H(32A)	3042	1511	8127	57
H(32B)	3459	1343	7624	57
H(32C)	4015	1105	8255	57

H(33A)	2930	2922	7845	57
H(33B)	3841	3349	7832	57
H(33C)	3374	2738	7357	57
H(35A)	989	3674	8002	50
H(36A)	-187	3450	7086	48
H(39A)	1984	5632	9571	54
H(40A)	3349	6003	9426	59
H(41A)	3593	5813	8564	53
H(43A)	3115	5364	7619	65
H(43B)	2435	4655	7523	65
H(43C)	2047	5480	7309	65
H(46A)	-723	4594	5134	45
H(47A)	-2240	4937	4949	42
H(48A)	-2857	5128	5690	39
H(50A)	750	4347	5753	69
H(50B)	983	4826	6325	69
H(50C)	755	3940	6328	69
H(53A)	-1188	8011	4793	53
H(54A)	-2229	8581	5181	56
H(57A)	1465	6889	7412	27
H(59A)	2381	7657	8266	34
H(60A)	2564	8106	9173	39
H(61A)	1496	7804	9621	40
H(62A)	219	7056	9176	36
H(64A)	-646	6147	8769	36
H(65A)	-2009	6855	8477	60
H(65B)	-1150	7396	8533	60
H(65C)	-1770	7121	7924	60
H(66A)	-1918	5476	8184	56
H(66B)	-1649	5739	7641	56
H(66C)	-989	5182	8092	56
H(1T)	9062	5363	9911	23
H(1T1)	10052	4543	9906	42
H(1T2)	9355	4199	9345	42
H(1T3)	9148	4117	9934	42
H(1S)	9545	5157	9557	48
H(1S1)	10219	4169	9797	28
H(1S2)	9281	3772	9791	28
H(1S3)	9815	4296	10311	28

Table 12. Torsion angles (°) for $C_{33}H_{28}Cl_2F_2N_2ORuS_2$ (**Ru-14**).

C(2)-N(1)-C(1)-N(2)	1.1(5)
C(4)-N(1)-C(1)-N(2)	-171.5(4)
C(2)-N(1)-C(1)-Ru(1)	-170.2(3)
C(4)-N(1)-C(1)-Ru(1)	17.2(6)
C(3)-N(2)-C(1)-N(1)	-1.2(5)
C(11)-N(2)-C(1)-N(1)	173.0(4)
C(3)-N(2)-C(1)-Ru(1)	170.6(3)

C(11)-N(2)-C(1)-Ru(1)	-15.2(6)
C(1)-N(1)-C(2)-C(3)	-0.6(6)
C(4)-N(1)-C(2)-C(3)	172.2(4)
N(1)-C(2)-C(3)-N(2)	-0.2(6)
C(1)-N(2)-C(3)-C(2)	0.9(6)
C(11)-N(2)-C(3)-C(2)	-173.4(4)
C(1)-N(1)-C(4)-C(9)	-105.1(5)
C(2)-N(1)-C(4)-C(9)	83.1(6)
C(1)-N(1)-C(4)-C(5)	76.8(6)
C(2)-N(1)-C(4)-C(5)	-95.0(6)
C(9)-C(4)-C(5)-C(6)	1.2(7)
N(1)-C(4)-C(5)-C(6)	179.3(4)
C(9)-C(4)-C(5)-C(10)	-179.3(5)
N(1)-C(4)-C(5)-C(10)	-1.2(7)
C(4)-C(5)-C(6)-C(7)	-1.1(8)
C(10)-C(5)-C(6)-C(7)	179.4(5)
C(5)-C(6)-C(7)-C(8)	0.8(9)
C(6)-C(7)-C(8)-C(9)	-0.6(9)
C(7)-C(8)-C(9)-F(1)	-179.6(5)
C(7)-C(8)-C(9)-C(4)	0.7(8)
C(5)-C(4)-C(9)-C(8)	-1.1(8)
N(1)-C(4)-C(9)-C(8)	-179.1(5)
C(5)-C(4)-C(9)-F(1)	179.2(4)
N(1)-C(4)-C(9)-F(1)	1.1(7)
C(1)-N(2)-C(11)-C(16)	-89.9(5)
C(3)-N(2)-C(11)-C(16)	83.6(6)
C(1)-N(2)-C(11)-C(12)	89.0(5)
C(3)-N(2)-C(11)-C(12)	-97.5(5)
C(16)-C(11)-C(12)-F(2)	-174.4(4)
N(2)-C(11)-C(12)-F(2)	6.7(6)
C(16)-C(11)-C(12)-C(13)	5.6(7)
N(2)-C(11)-C(12)-C(13)	-173.3(4)
F(2)-C(12)-C(13)-C(14)	178.4(4)
C(11)-C(12)-C(13)-C(14)	-1.6(8)
C(12)-C(13)-C(14)-C(15)	-2.5(8)
C(13)-C(14)-C(15)-C(16)	2.5(8)
C(14)-C(15)-C(16)-C(11)	1.5(7)
C(14)-C(15)-C(16)-C(17)	-179.3(5)
C(12)-C(11)-C(16)-C(15)	-5.4(7)
N(2)-C(11)-C(16)-C(15)	173.6(4)
C(12)-C(11)-C(16)-C(17)	175.4(4)
N(2)-C(11)-C(16)-C(17)	-5.6(7)
Ru(1)-S(1)-C(18)-C(19)	179.5(3)
Ru(1)-S(1)-C(18)-C(23)	-0.3(4)
C(23)-C(18)-C(19)-C(20)	-4.8(7)
S(1)-C(18)-C(19)-C(20)	175.3(4)
C(23)-C(18)-C(19)-Cl(1)	174.3(3)
S(1)-C(18)-C(19)-Cl(1)	-5.5(6)
C(18)-C(19)-C(20)-C(21)	1.7(8)

Cl(1)-C(19)-C(20)-C(21)	-177.5(5)
C(19)-C(20)-C(21)-C(22)	2.1(9)
C(20)-C(21)-C(22)-C(23)	-2.6(9)
C(20)-C(21)-C(22)-Cl(2)	175.3(5)
C(21)-C(22)-C(23)-C(18)	-0.6(7)
Cl(2)-C(22)-C(23)-C(18)	-178.5(4)
C(21)-C(22)-C(23)-S(2)	178.7(4)
Cl(2)-C(22)-C(23)-S(2)	0.8(6)
C(19)-C(18)-C(23)-C(22)	4.1(7)
S(1)-C(18)-C(23)-C(22)	-176.1(4)
C(19)-C(18)-C(23)-S(2)	-175.3(3)
S(1)-C(18)-C(23)-S(2)	4.6(5)
Ru(1)-S(2)-C(23)-C(22)	174.4(4)
Ru(1)-S(2)-C(23)-C(18)	-6.3(4)
C(1)-Ru(1)-C(24)-C(25)	96.1(3)
S(1)-Ru(1)-C(24)-C(25)	-170.8(3)
S(2)-Ru(1)-C(24)-C(25)	-80.3(3)
O(1)-Ru(1)-C(24)-C(25)	6.7(3)
Ru(1)-C(24)-C(25)-C(26)	175.7(3)
Ru(1)-C(24)-C(25)-C(30)	-5.6(5)
C(30)-C(25)-C(26)-C(27)	1.6(7)
C(24)-C(25)-C(26)-C(27)	-179.7(4)
C(25)-C(26)-C(27)-C(28)	-0.4(7)
C(26)-C(27)-C(28)-C(29)	-0.3(8)
C(27)-C(28)-C(29)-C(30)	-0.2(8)
C(28)-C(29)-C(30)-O(1)	-177.9(4)
C(28)-C(29)-C(30)-C(25)	1.5(7)
C(31)-O(1)-C(30)-C(29)	-4.3(6)
Ru(1)-O(1)-C(30)-C(29)	-174.4(4)
C(31)-O(1)-C(30)-C(25)	176.3(4)
Ru(1)-O(1)-C(30)-C(25)	6.2(4)
C(26)-C(25)-C(30)-C(29)	-2.1(6)
C(24)-C(25)-C(30)-C(29)	179.1(4)
C(26)-C(25)-C(30)-O(1)	177.3(4)
C(24)-C(25)-C(30)-O(1)	-1.5(5)
C(30)-O(1)-C(31)-C(33)	161.2(4)
Ru(1)-O(1)-C(31)-C(33)	-30.9(5)
C(30)-O(1)-C(31)-C(32)	-76.4(5)
Ru(1)-O(1)-C(31)-C(32)	91.6(4)
C(35)-N(3)-C(34)-N(4)	-1.0(5)
C(37)-N(3)-C(34)-N(4)	170.4(4)
C(35)-N(3)-C(34)-Ru(2)	167.0(4)
C(37)-N(3)-C(34)-Ru(2)	-21.6(7)
C(36)-N(4)-C(34)-N(3)	1.5(5)
C(44)-N(4)-C(34)-N(3)	-170.1(4)
C(36)-N(4)-C(34)-Ru(2)	-167.3(4)
C(44)-N(4)-C(34)-Ru(2)	21.0(6)
C(34)-N(3)-C(35)-C(36)	0.1(6)
C(37)-N(3)-C(35)-C(36)	-171.6(5)

N(3)-C(35)-C(36)-N(4)	0.8(6)
C(34)-N(4)-C(36)-C(35)	-1.5(6)
C(44)-N(4)-C(36)-C(35)	170.6(5)
C(34)-N(3)-C(37)-C(38)	107.7(5)
C(35)-N(3)-C(37)-C(38)	-81.7(6)
C(34)-N(3)-C(37)-C(42)	-76.3(6)
C(35)-N(3)-C(37)-C(42)	94.2(6)
C(42)-C(37)-C(38)-C(39)	3.2(7)
N(3)-C(37)-C(38)-C(39)	179.2(4)
C(42)-C(37)-C(38)-F(3)	-177.5(4)
N(3)-C(37)-C(38)-F(3)	-1.5(6)
F(3)-C(38)-C(39)-C(40)	180.0(4)
C(37)-C(38)-C(39)-C(40)	-0.8(7)
C(38)-C(39)-C(40)-C(41)	-1.3(8)
C(39)-C(40)-C(41)-C(42)	1.0(8)
C(38)-C(37)-C(42)-C(41)	-3.4(6)
N(3)-C(37)-C(42)-C(41)	-179.4(4)
C(38)-C(37)-C(42)-C(43)	175.6(4)
N(3)-C(37)-C(42)-C(43)	-0.4(6)
C(40)-C(41)-C(42)-C(37)	1.4(7)
C(40)-C(41)-C(42)-C(43)	-177.7(5)
C(34)-N(4)-C(44)-C(49)	-85.8(6)
C(36)-N(4)-C(44)-C(49)	103.3(5)
C(34)-N(4)-C(44)-C(45)	94.4(5)
C(36)-N(4)-C(44)-C(45)	-76.6(6)
C(49)-C(44)-C(45)-C(46)	0.2(7)
N(4)-C(44)-C(45)-C(46)	-179.9(4)
C(49)-C(44)-C(45)-C(50)	178.2(5)
N(4)-C(44)-C(45)-C(50)	-2.0(7)
C(44)-C(45)-C(46)-C(47)	0.7(7)
C(50)-C(45)-C(46)-C(47)	-177.2(5)
C(45)-C(46)-C(47)-C(48)	-0.9(8)
C(46)-C(47)-C(48)-C(49)	0.2(7)
C(47)-C(48)-C(49)-F(4)	179.9(4)
C(47)-C(48)-C(49)-C(44)	0.8(7)
C(45)-C(44)-C(49)-F(4)	179.9(4)
N(4)-C(44)-C(49)-F(4)	0.0(6)
C(45)-C(44)-C(49)-C(48)	-1.0(7)
N(4)-C(44)-C(49)-C(48)	179.2(4)
Ru(2)-S(3)-C(51)-C(52)	175.5(3)
Ru(2)-S(3)-C(51)-C(56)	-4.8(4)
C(56)-C(51)-C(52)-C(53)	1.6(7)
S(3)-C(51)-C(52)-C(53)	-178.7(4)
C(56)-C(51)-C(52)-Cl(3)	-177.9(3)
S(3)-C(51)-C(52)-Cl(3)	1.8(5)
C(51)-C(52)-C(53)-C(54)	-1.0(8)
Cl(3)-C(52)-C(53)-C(54)	178.5(4)
C(52)-C(53)-C(54)-C(55)	-1.0(8)
C(53)-C(54)-C(55)-C(56)	2.4(8)

C(53)-C(54)-C(55)-Cl(4)	-178.2(4)
C(52)-C(51)-C(56)-C(55)	-0.2(6)
S(3)-C(51)-C(56)-C(55)	-179.9(3)
C(52)-C(51)-C(56)-S(4)	179.5(3)
S(3)-C(51)-C(56)-S(4)	-0.2(5)
C(54)-C(55)-C(56)-C(51)	-1.8(7)
Cl(4)-C(55)-C(56)-C(51)	178.8(3)
C(54)-C(55)-C(56)-S(4)	178.5(4)
Cl(4)-C(55)-C(56)-S(4)	-0.9(6)
Ru(2)-S(4)-C(56)-C(51)	5.0(4)
Ru(2)-S(4)-C(56)-C(55)	-175.3(3)
C(34)-Ru(2)-C(57)-C(58)	-97.4(3)
S(3)-Ru(2)-C(57)-C(58)	167.3(3)
S(4)-Ru(2)-C(57)-C(58)	77.6(3)
O(2)-Ru(2)-C(57)-C(58)	-7.8(3)
Ru(2)-C(57)-C(58)-C(63)	6.3(5)
Ru(2)-C(57)-C(58)-C(59)	-172.4(3)
C(63)-C(58)-C(59)-C(60)	-0.7(6)
C(57)-C(58)-C(59)-C(60)	178.0(4)
C(58)-C(59)-C(60)-C(61)	0.5(7)
C(59)-C(60)-C(61)-C(62)	-0.2(7)
C(60)-C(61)-C(62)-C(63)	0.0(7)
C(61)-C(62)-C(63)-O(2)	179.1(4)
C(61)-C(62)-C(63)-C(58)	-0.1(6)
C(64)-O(2)-C(63)-C(62)	5.4(6)
Ru(2)-O(2)-C(63)-C(62)	172.9(4)
C(64)-O(2)-C(63)-C(58)	-175.3(3)
Ru(2)-O(2)-C(63)-C(58)	-7.8(4)
C(59)-C(58)-C(63)-C(62)	0.5(6)
C(57)-C(58)-C(63)-C(62)	-178.2(4)
C(59)-C(58)-C(63)-O(2)	-178.8(4)
C(57)-C(58)-C(63)-O(2)	2.4(5)
C(63)-O(2)-C(64)-C(65)	74.3(4)
Ru(2)-O(2)-C(64)-C(65)	-90.0(4)
C(63)-O(2)-C(64)-C(66)	-162.5(4)
Ru(2)-O(2)-C(64)-C(66)	33.2(5)

Symmetry transformations used to generate equivalent atoms: