Comment on "aftershock statistics for earthquakes in the St. Lawrence Valley" by Azadeh Fereidoni and Gail M. Atkinson

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Comment on "Aftershock Statistics for Earthquakes in the St. Lawrence Valley" by Azadeh Fereidoni and Gail M. Atkinson

by John E. Ebel

Fereidoni and Atkinson (2014) analyzed the aftershock sequences of four **M** ≥ 4.5 earthquakes that occurred in eastern Canada from 1982 to 2010 to estimate the Omori-law parameters for those aftershock sequences. They then used this information to assess the modern rate of aftershocks of the 1663 earthquake in the area of Charlevoix, Quebec. When they compared the estimated aftershock rate with the observed rate of modern seismicity at Charlevoix, they reported that the observed modern earthquake rate is higher than that predicted even using the Omori-law parameters from the most active aftershock sequence in eastern Canada that they analyzed. From this, they concluded that the current seismic activity in the Charlevoix area is not likely due to ongoing aftershocks of the 1663 earthquake.

The major conclusion of Fereidoni and Atkinson (2014) described in the previous paragraph is illustrated in figure 5 of their article. This figure, reproduced here in Figure 1, shows four charts, each for a different minimum aftershock magnitude threshold, that plot seismicity rate versus elapsed time. In addition to curves of predicted aftershock activity rates as a function of time, each chart also has several data points. In this comment, I express differences with both the data points and the predicted aftershock activity rates in Figure 1 (fig. 5 of Fereidoni and Atkinson, 2014).

Regarding the data in Figure 1, I do not understand the black datapoints (labeled "Complete observation"). For reference, in Table 1 I list the earthquakes from the Charlevoix seismic zone that have moment magnitudes **M** ≥ 4.3 for the time period from 1900 to February 2015, a time period of about 11.4 decades. This list comes from the catalog of Fereidoni *et al.* (2012) and uses their best-estimated moment magnitude as the magnitude reported in Table 1. Because the Fereidoni *et al.* (2012) earthquake catalog ends in 2008, a search for Charleviox earthquakes with **M** ≥ 4.3 (M_{Lg} ≥ 4.8) using the Natural Resources of Canada earthquake search website (http://www.earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php, last accessed August 2015) revealed no additional Charlevoix earthquakes with **M** ≥ 4.3 after 2008. As can be seen in Table 1, there is only 1 event with **M** ≥ 5.8, 2 events with **M** ≥ 5.3, 5 events with **M** ≥ 4.8, and 14 events with **M** ≥ 4.3. Table 2 shows the seismicity rate in number of events per decade, the parameter unit used in Figure 1, for each of these magnitude thresholds based on the data in Table 1. At an elapsed time of 30 decades (300 years), the observed seismicity rates in Figure 1 are plotted at ~1 **M** ≥ 5.8 earthquake per decade to almost 10 **M** ≥ 4.3 earthquakes per decade. However, the observed seismicity rates in Table 2 are about 5–10 times smaller than the corresponding Figure 1 data points. There appears to be a problem with the "Complete observation" data points that are plotted in Figure 1. For example, even with uncertainties in magnitude, there has not been anywhere near one **M** ≥ 5.8 earthquake per decade in the Charlevoix seismic zone since 1900. The same overestimation is true for the other magnitude thresholds shown in Figure 1.

There are also problems with the "Incomplete observation" data points in Figure 1. Fereidoni and Atkinson (2014) cite Ebel (1996) to argue that there were reports "of just six strong events (m_N > 5, or **M** > 4.5) in the focal region of the mainshock in the years following" the 1663 mainshock. This misrepresents the data given in Ebel (1996) in two ways. First, Ebel (1996) reported that three earthquakes were felt at Roxbury, Massachusetts, during the first 24 hours following the shaking associated with the 1663 mainshock, and I believe it is likely that these three events were strong aftershocks of the 1663 mainshock. On the other hand, there is no evidence to attribute the epicenters of the other three **M** > 5 earthquakes subsequent to 1663 in the earthquake catalog reported in Ebel (1996) to the Charlevoix seismic zone. In fact, Ebel (1996) reported no epicenters at all for any of the **M** > 5 earthquakes after 1663. Thus, all that is known with reasonable certainty is that at least three strong aftershocks took place in the 1663 epicentral zone during the first day after the mainshock. There is no information in Ebel (1996) about subsequent strong aftershocks of the 1663 event.

The second misrepresentation of Ebel (1996) concerns how many aftershocks with **M** ≥ 4.5 took place during the first several years after the 1663 earthquake. Ebel (1996) did not claim that his list of **M** > 5 earthquakes is complete for the second half of the seventeenth century, and this is certainly true for the Charlevoix region of Quebec. The sources used by Ebel (1996) were generally from southern New England and Trois Rivieres in Quebec, which are at large distances from the Charlevoix seismic zone. It is quite possible that aftershocks of the 1663 Charlevoix earthquake as large as m_N 5.4 (**M** 5.3) may not have been felt in Boston or were felt weakly by so few people that history did not record their occurrences. As an example, the 19 October 1939 earthquake at the Charlevoix seismic zone (m_N = 5.4, according

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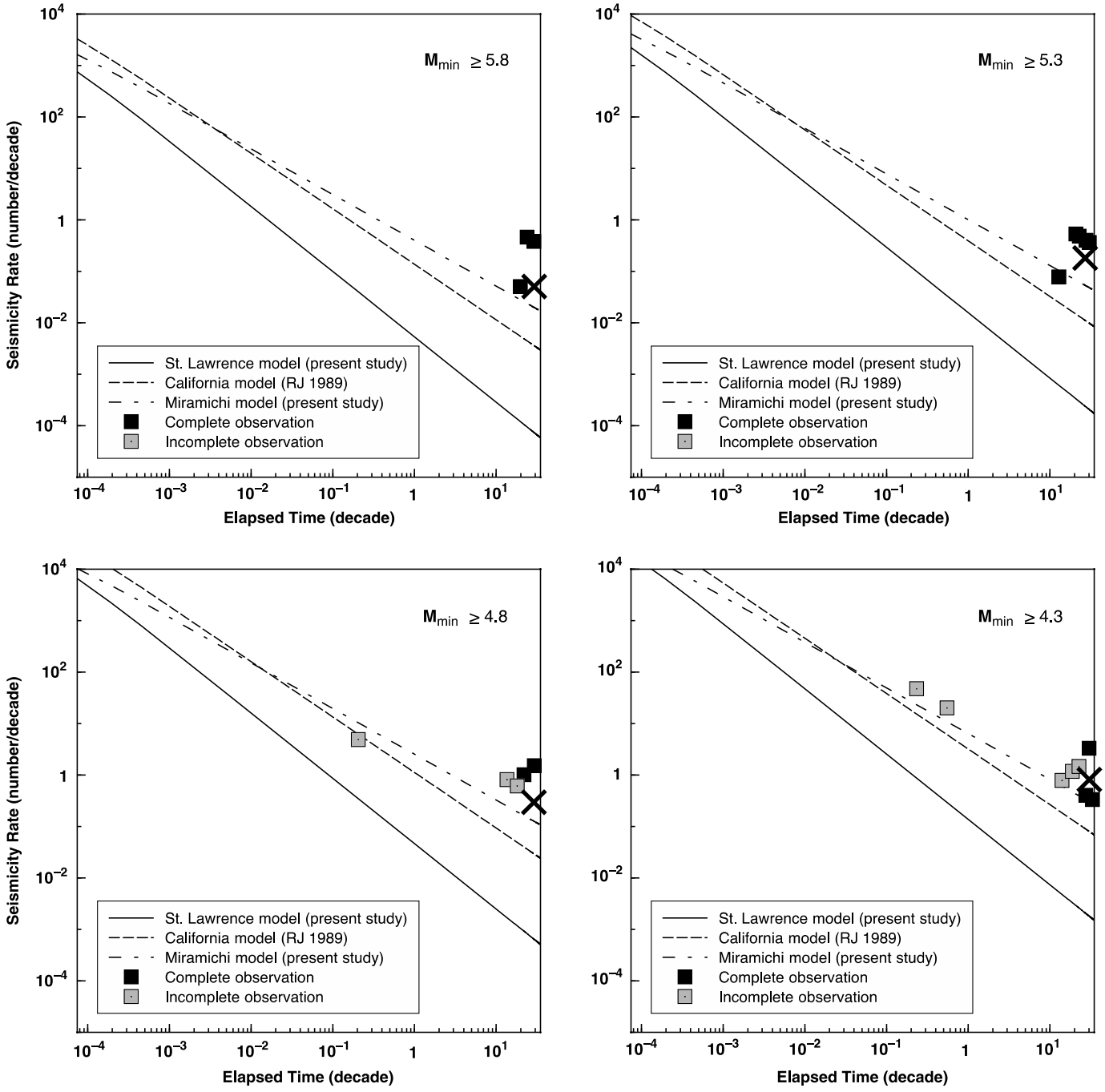

▲ **Figure 1.** Modified reproduction of figure 5 of Fereidoni and Atkinson (2014), which shows a comparison of the predicted and observed event rates for the 1663 **M** 7.0 earthquakes for different magnitude completenesses. The × symbols on each figure have been added to show the 300-yr earthquake rates found from the data in Table 1.

to Ebel *et al.*, 1986; **M** 5.3, in Fereidoni *et al.*, 2012) gave ground shaking in the modified Mercalli intensity (MMI) II or I range in southern New England (Smith, 1966). If modern earthquakes of this size may not have been noticed in southern New England, then it is not clear how many aftershocks with **M** ≥ 4.3 and **M** ≥ 4.8 might have taken place during the first year or first few years after the 1663 mainshock because they would not have been observed at all in southern New England, the area where the bulk of the historic reports evaluated by Ebel (1996) were made.

The consequences of the misrepresentations of the data from Ebel (1996) are important. In Figure 1, the incomplete-observation data point for $\mathbf{M}_{min} \geq 4.8$ is plotted at an elapsed time of about 0.2 decade, or about 2 yr. However, because all of the probable Charlevoix aftershocks in Ebel (1996) were observed for an elapsed time of no more than 1 day (about 2.7×10^{-4} decade), the incomplete-observation $\mathbf{M}_{min} \geq 4.8$ data point in Figure 1 should be plotted on the left side of the plot and not at an elapsed time of about 0.2 decade. I also question the data points

Table 1
List of M ≥4.3 Earthquakes in the Charlevoix Seismic Zone, 1900–2015

Date (yyyy/mm/dd)	Origin Time (hh:mm:ss.ss)	Latitude (°)	Longitude (°)	M
1910/02/N/A	N/A	48.0000	−70.0000	4.7
1924/09/30	08:52:00.00	47.8000	−69.8000	5.1
1925/03/01	02:19:00.00	47.8000	−69.8000	6.4
1925/03/01	04:30:00.00	47.8000	−69.8000	4.7
1925/03/21	15:22:00.00	47.8000	−69.8000	4.7
1930/12/25	22:07:00.00	47.3000	−70.4000	4.3
1931/01/08	00:13:00.00	47.3000	−70.4000	5.1
1939/06/24	17:20:00.00	47.3000	−70.4000	4.4
1939/10/19	11:53:00.00	47.8000	−70.0000	5.3
1939/10/27	01:36:00.00	47.8000	−70.0010	4.6
1945/10/09	13:18:00.00	47.7470	−70.1360	4.5
1952/10/14	22:03:00.00	47.8000	−69.8000	4.4
1979/08/19	22:49:00.00	47.6700	−69.9000	4.8
2005/03/06	06:17:00.00	47.7530	−69.7320	4.7

N/A, not available.

Table 2
Observed Seismicity Rates and Estimated Aftershock Activity Rates for the Charlevoix Seismic Zone, 1900–2015

M	Observed Number of Events	Observed Rate Per Decade	Predicted (M 7.0) Rate Per Decade	Predicted (M 7.5) Rate Per Decade
5.8	**M** ≥1	0.088	0.019 (0)	0.049 (1)
5.3	**M** ≥2	0.175	0.049 (1)	0.122 (1)
4.8	**M** ≥5	0.439	0.122 (1)	0.307 (4)
4.3	**M** ≥14	1.218	0.307 (4)	0.771 (9)

The numbers in parentheses in the last two columns are the expected number of earthquakes computed for the time period from 1900–2015.

at about 0.2 decade (rate of almost 100 earthquakes per decade) and at about 0.7 decade (rate of more than 10 earthquakes per decade) for the $\mathbf{M}_{min} \geq 4.3$ plot in Figure 1. These data points cannot be based on Ebel (1996), and I am not aware of any other historic source that supports these numbers of earthquakes for $\mathbf{M}_{min} \geq 4.3$ during the first decade after the 1663 Charlevoix event. It is not clear from Fereidoni and Atkinson (2014) what their basis is for these data points.

From all historic reports, it appears evident that the aftershock sequence following the 1663 Charlevoix mainshock was quite active (Ebel, 1996). For this reason, the comparison of the modern Charlevoix seismicity with an aftershock rate based on the Omori-law parameters from the 1982 Miramichi aftershock sequence by Fereidoni and Atkinson (2014) is quite appropriate. However, Fereidoni and Atkinson (2014) compute their aftershock rates based on a 1663 mainshock magnitude of **M** 7.0 (such as in Fig. 1), whereas Ebel (2011) presented analyses that show the 1663 earthquake could have been **M** 7.5 or perhaps even larger. In Table 2, I compute the rates of modern earthquakes for 1663 mainshock magnitudes of **M** 7.0 and **M** 7.5 at an elapsed time of 300 years after the mainshock. The aftershock rates for an **M** 7.5 mainshock are appropriate for the 1663 mainshock magnitude advocated by Ebel (2011). It can be inferred from Table 2 that the observed **M** ≥ 4.3 seismicity in the Charlevoix seismic zone since 1900 is approximately comparable to the predicted aftershock activity of the 1663 earthquake if that earthquake had **M** ∼ 7.5 and an aftershock sequence with similar Omori-law aftershock parameters as those from the 1982 Miramichi earthquake.

Fereidoni and Atkinson (2014) argued that "it is very unlikely that contemporary seismicity in Charlevoix represents aftershocks from the 1663 earthquake." However, I believe that their conclusion is drawn from misplotted observed data and from an underestimation of the 1663 mainshock magnitude. Correcting these two aspects of the Fereidoni and Atkinson (2014) analysis leads to the conclusion that the contemporary seismicity in Charlevoix could indeed primarily represent aftershocks from the 1663 earthquake.

DATA AND RESOURCES

The data used for Tables 1 and 2 and Figure 1 were acquired from the website http:// www.seismotoolbox.ca/Catalogs.html (17 August 2015) in the space-delimited ascii file ccsc09east.txt, as described in Fereidoni *et al.* (2012).

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