Effects of magnitude, depth, and time on Cellular Seismology Forecasts

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EFFECTS OF MAGNITUDE, DEPTH, AND TIME ON CELLULAR SEISMOLOGY FORECASTS

a thesis

by

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EFFECTS OF MAGNITUDE, DEPTH, AND TIME ON CELLULAR SEISMOLOGY FORECASTS

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Dr. Alan Kafka, thesis advisor

This study finds that, in most cases analyzed to date, past seismicity tends to delineate zones where future earthquakes are likely to occur. Network seismicity catalogs for the New Madrid Seismic Zone (NMSZ), Australia (AUS), California (CA), and Alaska (AK) are analyzed using modified versions of the Cellular Seismology (CS) method of Kafka (2002, 2007). The percentage of later occurring earthquakes located near earlier occurring earthquakes typically exceeds the expected percentage for randomly distributed later occurring earthquakes, and the specific percentage is influenced by several variables, including magnitude, depth, time, and tectonic setting. At 33% map area coverage, hit percents are typically 85-95% in the NMSZ, 50-60% in AUS, 75-85% in CA, and 75-85% in AK. Statistical significance testing is performed on trials analyzing the same variables so that the overall regions can be compared, although some tests are inconclusive due to the small number of earthquake sample sizes. These results offer useful insights into understanding the capabilities and limits of CS studies, which can provide guidance for improving the seismicity-based components of seismic hazard assessments.

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1.0. INTRODUCTION

Cellular Seismology (CS) is a method developed by Kafka (2002, 2007) to investigate the extent to which the spatial distribution of past earthquakes delineates zones where future earthquakes are likely to occur. This method was originally developed to investigate one of the primary assumptions underlying many models of earthquake hazard mapping, i.e., that future earthquakes tend to occur near past earthquakes (e.g., Kafka, 2007). CS has also been applied in the realm of earthquake forecasting research as a simple null hypothesis for testing other, more complex, seismicity-based forecasting methods (e.g., Kafka and Ebel, 2011). The main objective of CS is to evaluate the extent to which past seismicity delineates zones where future earthquakes are likely to occur.

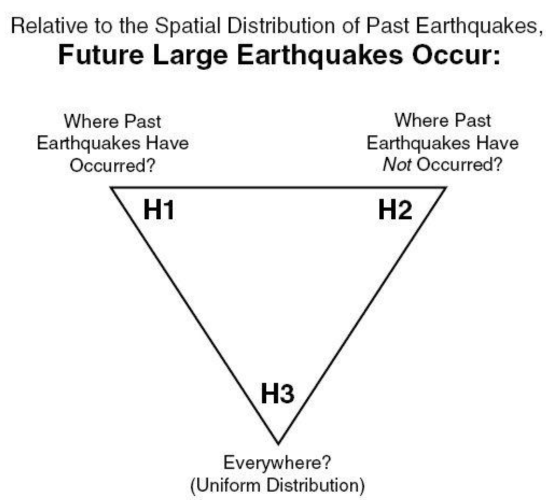


Figure 1. Earthquake forecasting ternary diagram depicting possible relationships between locations of past earthquakes and locations of future seismic activity (from Kafka, 2007).

The phenomenon of past seismicity delineating zones where future earthquakes are likely to occur can be illustrated by the ternary diagram shown in figure 1. H1 represents the hypothesis that future earthquakes will occur in zones where past earthquakes have occurred. H2 represents the hypothesis that future earthquakes will occur where past earthquakes have not occurred, and H3 represents the hypothesis that future earthquakes will be uniformly distributed.

The results of previous CS studies (e.g., Kafka, 2002, 2007; Kafka and Ebel, 2011) have revealed the following characteristics of the relationship between the spatial distribution of past versus future (i.e., earlier occurring versus later occurring) earthquakes: (1) In all the analyses conducted to date, hypothesis H1 has always been supported by the data, (2) In general, at least $^2/_3$ to $^3/_4$ of future earthquakes occur near past earthquakes, where "near" is defined by CS forecasts large enough to cover 33% of the map of the study area (as described below), (3) There is some evidence that percentages of successfully forecast earthquakes ("hits") for intraplate regions are, on average, lower than for plate boundary regions, but that difference is not strongly pronounced and is still not well-understood.

Although CS research to date has helped to elucidate the relationship between locations of past and future earthquake, there remain fundamental issues about CS that are still unresolved, such as:

- The differences in CS results for regions in different tectonic environments has been explored to some extent (e.g., Kafka, 2007), but there still remains much more to be understood about the effect of tectonic environment on CS results.
- The effect on CS results of the magnitude thresholds for earthquake catalogs used in the analysis has yet to be fully explored.
- The effect on CS results of the choice of the earthquake catalogs, and the choice of the cutoff time between earlier occurring and later occurring earthquakes has yet to be fully explored.
- There has been no testing of the effect of depth of seismicity on CS analyses.
- The effect of differences in spatial scale of the CS regions analyzed has not been fully explored.
- The shapes of most regions analyzed using CS have been latitude/longitude rectangles, but the pattern of seismicity is typically more irregular than what can be characterized by

rectangular regions, and there is a need for a systematic way of applying CS to polygon-shaped regions.

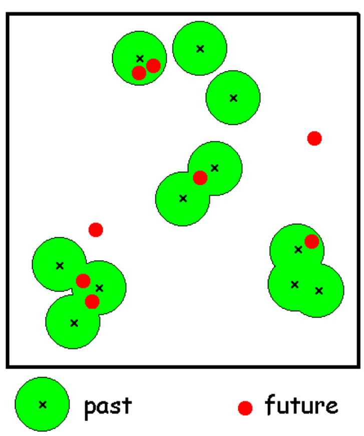
If these issues could be better resolved, then it would be possible to determine how CS hit percentages tend to vary for different situations, as well as to estimate future CS hit percentages for a given region. This would provide a stronger basis for using past seismicity in earthquake hazard mapping and in seismicity-based earthquake forecasting methods.

This work attempts to resolve these issues by quantifying the effects of several variables on CS results. A major question addressed in this study is whether there is an inherent difference in CS results between intraplate regions versus plate boundary regions. This is addressed by applying CS tests to regions in various tectonic settings, and manipulating the specific earthquake catalogs used in each trial to isolate the impacts of a particular variable on CS results. The New Madrid Seismic Zone (NMSZ) and Australia (AUS) were chosen to be representative of intraplate regions. California (CA) and Alaska (AK) were chosen to be representative of plate boundary regions, with CA being a transform fault type boundary and AK being a convergent type boundary. The testing of variables affecting CS forecasts in each region involved: (1) incrementally increasing the minimum magnitude cutoff of the later occurring earthquake catalog, (2) incrementally increasing the minimum magnitude cutoff of the earlier occurring earthquake catalog, (3) incrementally increasing the length of the time gap between the end of the earlier occurring earthquake catalog and the beginning of the later occurring earthquake catalog, (4) analyzing earthquakes whose epicenters fell only in a specific depth layer, and (5) analyzing smaller subzones of the larger regions.

2.0. PREVIOUS WORK

In his CS analyses of various regions, Kafka (2002, 2007) divided each region's earthquake catalog into a "before" (earlier occurring) and an "after" (later occurring) catalog, which we will refer to below as the CS "Pre-CAT" and "Post-CAT," respectively. Epicenters of the Pre-CAT earthquakes were plotted and circles of a given radius were constructed around each epicenter (figure 2). The radii were chosen so that a predetermined percentage of the total map area (P) was covered by Pre-CAT CS circles. Any Post-CAT earthquake whose epicenter fell into at least one of the Pre-CAT earthquake circles was referred to as a "hit," and the number of hits divided by the number of total Post-CAT earthquakes, multiplied by 100, was referred to as "hit percent" ($\hat{\rho}$). Analyses were performed at many scales, in various tectonic settings, and for a range of map area coverage percentages (figure 3a).

In previous CS studies, the hit percentages were consistently greater than the percentage of map area covered by the interiors of the CS circles (figure 3b). This observation supports hypothesis H1 of figure 1 more than the H2 or H3 hypotheses. If the observed hit

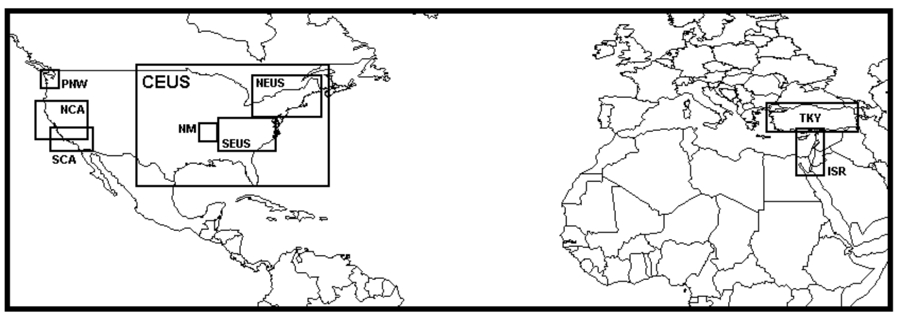


Choose a radius such that circles fill P percentage of map area
$\hat{\rho}$ = 6/8 = 75% = sample of binomial random variable, ρ
ρ = Probability("success")
Hit = red dots occurs within one of the green circles

Figure 2. Cartoon illustrating the CS method for investigating the tendency of past earthquakes to delineate zones of future seismic activity (from Kafka, 2007). Black x's are Pre-CAT earthquake epicenters, green circles are areas covered by Pre-CAT circles, red circles are Post-Cat earthquake epicenters.

percents were consistently less than the percentage of map area, then hypothesis H2 would be supported, and if the observed hit percents were consistently close to the percentage of map area, then hypothesis H3 would be supported.

The lowest hit percent for the regions analyzed by Kafka (2007) was 39% for a continental region north of the Himalayas, and the highest hit percent was 100% for a subduction zone. It is important to note that (previous to this thesis) no case had yet been found where the percentage of hits was less than the percentage of map area covered by the Pre-CAT circles (Kafka, 2007). This was strong evidence against hypotheses H2 and H3.



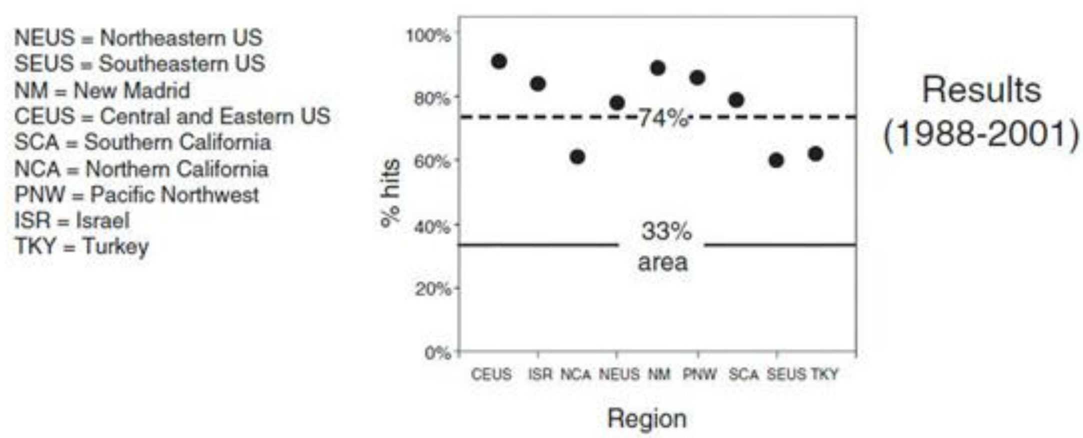


Figure 3a (top). Summary of region definitions and scales from Kafka (2002). Nine regions of various tectonic settings and sizes were analyzed. To achieve 33% map area coverage, CS radii were 15.5 km (NEUS), 31.0 km (SEUS), 13.5 km (NM), 36.0 km (CEUS), 13.2 km (SCA), 10.0 km (NCA), 9.2 km (PNW), 48.0 km (ISR), 26.0 km (TKY) (Kafka, 2002, 2007).

Figure 3b (bottom). Summary of hit percents of nine regions analyzed by Kafka (2002). All results for 33% map area coverage.

These previous CS works briefly investigated variables similar to those investigated extensively in this study. For example, results of including only the three largest magnitude earthquakes in a Post-CAT consisting of a combined catalog from all the regions analyzed yielded a hit percent of 64%, similar to the overall average of 74% (Kafka, 2002). Kafka (2007) incrementally increased the minimum magnitude cutoff of the Post-CAT to test if a certain magnitude range of later occurring earthquakes is better able to be forecasted by the entire magnitude range of earlier occurring earthquakes. Kafka (2007) also introduced the use of a simple count of the number of times hit percent increased, decreased, or stayed the same from one incremental step to the next as a way to test if any systematic change in percent hits was present. Kafka (2007) divided a Post-CAT catalog into several sequentially later sections as a test of how hit percent changed through time for a given region when using the same Pre-CAT. These ideas and procedures were consulted and adapted as this thesis developed into a more extensive investigation of the effects of these and other variables on CS results.

3.0. GEOLOGIC SETTING AND SEISMICITY

New Madrid Seismic Zone Geologic Setting

The NMSZ is located in southeastern Missouri, northeastern Arkansas, western Kentucky, and western Tennessee (figure 4). The NMSZ is in the northern part of the Mississippi embayment, an extension of the Coastal Plain (Stearns, 1957). The Reelfoot rift, a 300 km long by 70 km wide, northeast striking structure contains most of the seismic activity in the region. Most earthquake epicenters are found in one of three principal zones in the rift (figure 5): a 120 km linear segment, generally trending parallel to the rift axis, extending from Caruthersville, Missouri to Marked Tree, Arkansas; a 60 km region of northwest trending diffuse seismicity, between Dyersburg, Tennessee and just west of New Madrid, Missouri; and a 50 km linear zone, trending northeast in the northwest portion of the rift, from just west of New Madrid to Charleston, Missouri (Crone et al., 1985).

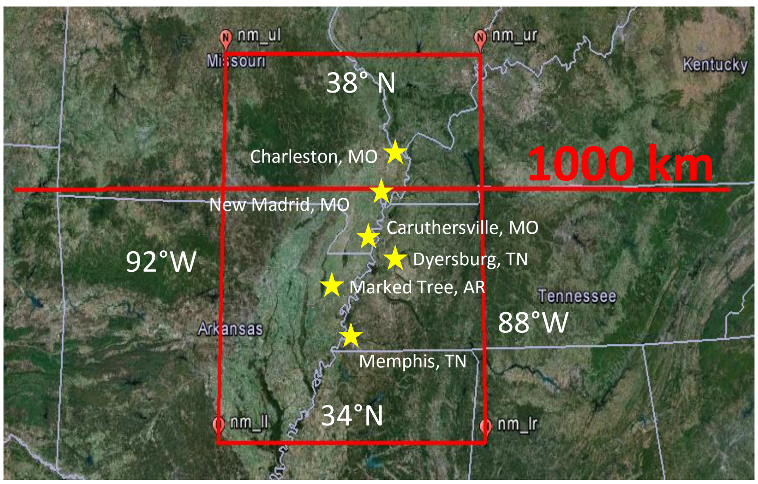


Figure 4. Size map of NMSZ, 1000 km bar for scale.

The largest recorded earthquakes in the NMSZ were the M7.7, M7.5, and M7.7 series of events from December, 1811 to February 1812 near New Madrid, Missouri. More recent major earthquakes in this region include 1895 (M6.6), 1968 (M5.4), 1976 (M5.0), and 1990 (M4.8) (United States Geological Survey, 2012).

Drill cores used to identify the stratigraphy of the region revealed unnamed Precambrian and Lower Cambrian red arkose and unnamed Upper Cambrian gray arkose overlain by unnamed marine carbonates and clastics. The sequence grades into continuous Upper Cambrian to Middle Ordovician marine carbonates from the Knox Group, with clastic content decreasing upward. Pennsylvanian clastic rocks were then deposited in the region (Crone et al., 1985). After uplift in the Late Paleozoic and Mesozoic brought increased rates of erosion, the Mississippi embayment was filled with unconsolidated clastic sediments as it subsided from the Late Cretaceous through the Cenozoic (Zoback et al., 1980). Geophysical methods were used to correlate reflections with the stratigraphy of the region. The magnetic basement and underlying reflectors, as revealed by seismic reflection profiles, are parallel to subparallel. Magnetic basement rocks in the region are found at a depth of about 4.3 km and are overlain by the unnamed arkoses (Crone et al., 1985). In contrast to the lack of structural relief shown by the magnetic basement, disrupted reflectors of the unnamed marine carbonates and Knox Group marine carbonates reveal an antiformal zone between the magnetic basement and the bottom of the Paleozoic rocks (figure 6). The

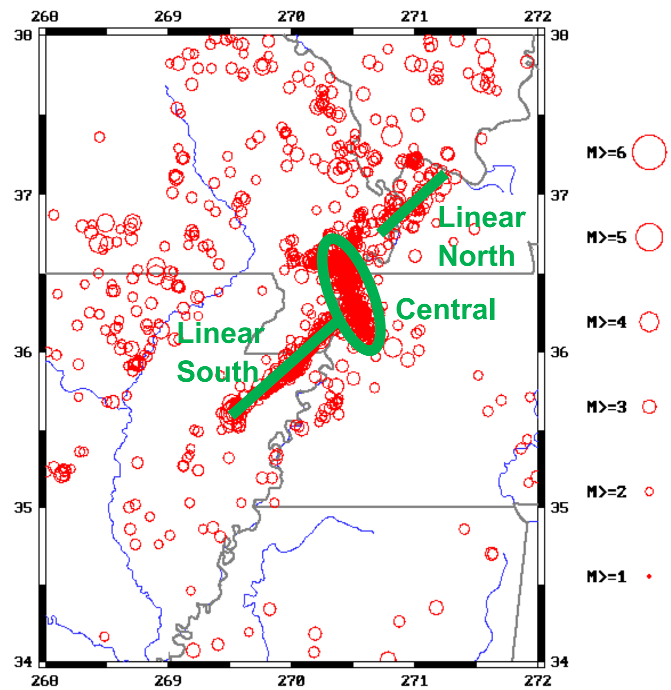


Figure 5. Site map of NMSZ with M≥2.0 earthquakes from 1974-2010 plotted (NMSZ, 1974). Green lines and green oval indicate three principal zones of Reelfoot rift.

contact between these upwarped reflectors and the bottom of the subparallel Paleozoic rocks is found at about 1.1 km. The contact between the Late Cretaceous and Cenozoic sediments is found at about 0.5 km (Crone et al., 1985).

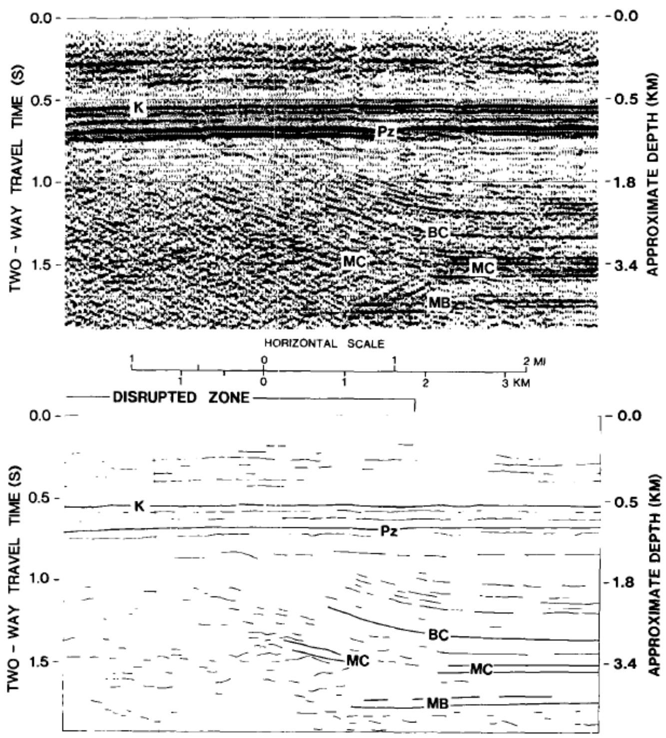


Figure 6. Seismic reflection (top) and approximate boundary lines (bottom) in NMSZ. Note warped layers between magnetic basement and Paleozoic rocks. Information from Dow Chemical No.1 Wilson and Houston Oil and Minerals No. 1 Singer wells. Exact location within NMSZ not provided because data is proprietary (Crone et al., 1985).

Although the origin of the warping is unknown, it is hypothesized to be the result of intrusion. Gravity and magnetic data do not highlight different layers in the rift, nor does seismic reflection data, so the proposed intrusive rocks must have density and magnetic properties similar to the surrounding sedimentary rocks. Felsic igneous rocks, commonly associated with rifts (Windley, 1984), meet these criteria (Crone et al., 1985). Igneous activity has been repeated episodically in the Reelfoot rift, so intrusion based warping is plausible (Zoback et al., 1980).

Australia Geologic Setting

Australia is located between the Indian and Pacific Oceans (figure 7). The geology in Australia is complex and varies across the continent, including Achaean cratonic material, Proterozoic belts to the west, and Phanerozoic material to the east (Johnson, 2004). The majority of present day Australia was attached to present day India and Antarctica during the suturing of Rodinia and remained together in northeastern Gondwana (Myers et al., 1996). When the supercontinent broke, Antarctica was still attached to Australia until it began rifting away in the Cretaceous (Johnson, 2004).

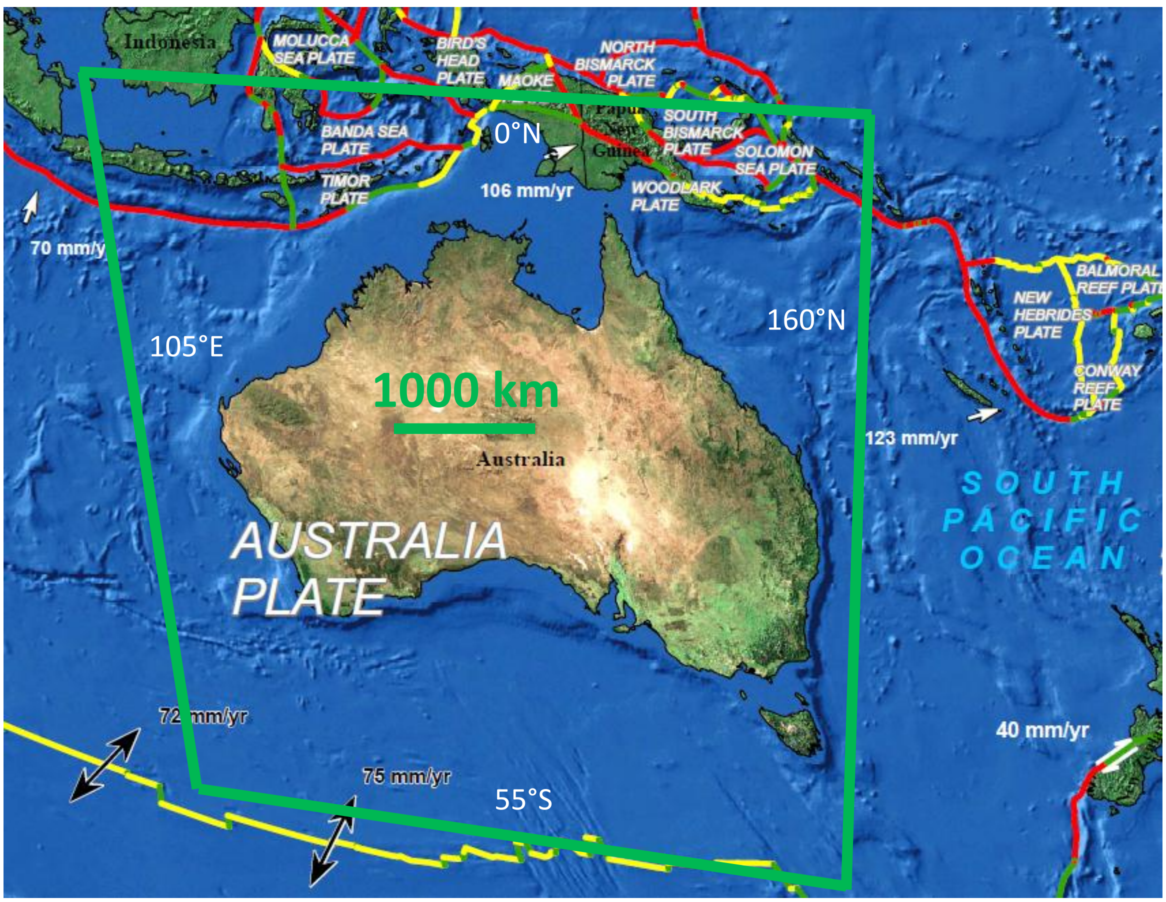


Figure 7. Site map of AUS, 1000 km bar for scale. Relative plate motion shown (Tectonic Plates, 2009).

Western, northern, and southern Australia are composed of Precambrian craton and shield material. Eastern Australia is composed of Jurassic to Cretaceous depositional material from transgressing seas along the eastern seaboard, forming marine, quartz rich, fossiliferous sandstones, shales, and interbedded coal seams (Brown et al., 1968). Surficial Quaternary marine shelf sediments and aeolian desert sand deposits are present in eastern Australia (Brown et al., 1968).

The largest recorded earthquake in this region was a 2004 offshore M8.1 event south of Tasmania. Other major earthquakes in Australia include 1906 (M7.6), 1968 (M6.9), and 1989 (M5.6) (The University of Western Australia, 2011). Australia experiences about two M≥5.0 and 0.25 M≥6.0 earthquakes per year (Leonard, 2008).

California Geologic Setting

California (figure 8) has a complex geologic history, and the provinces are derived from a series of island arc accretions, uplift, and erosion. Few rocks in this region are older than 600 million years, as much of the region has experienced metamorphism associated with the Nevadan orogeny. Remaining Proterozoic rocks are gneisses and schists and date to 1800 million years ago and are found in the Mojave and Basin and Ridge provinces. These crystalline rocks are overlain by relatively unaltered sedimentary rocks, also of Proterozoic age, in the Basin and Ridge province (figure 9). Deposition occurred in the Proterozoic sea, which extended further than the Basin and Ridge province, but other areas have been eroded or metamorphosed (Norris and Webb, 1990).

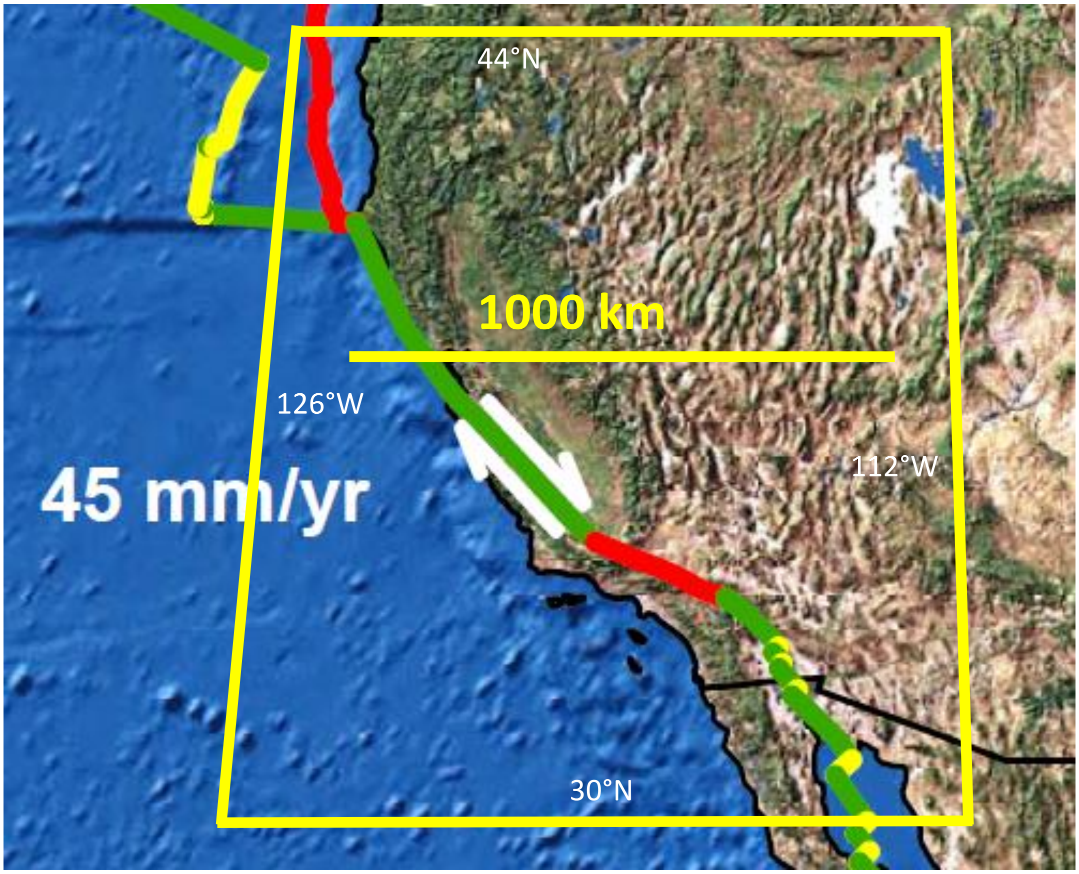


Figure 8. Site map of CA, 1000 km bar for scale. Relative plate motion shown (Tectonic Plates, 2009).

In the Paleozoic, a broad, shallow marine shelf extended from the Pacific Ocean to the eastern side of the current Sierra Nevada and Klamath Mountains, resulting in thick limestone deposits (Norris and Webb, 1990). Subduction along the continental margin in the Triassic led to a westward regression of the sea, and mountains were uplifted in eastern California (Norris and Webb 1990).

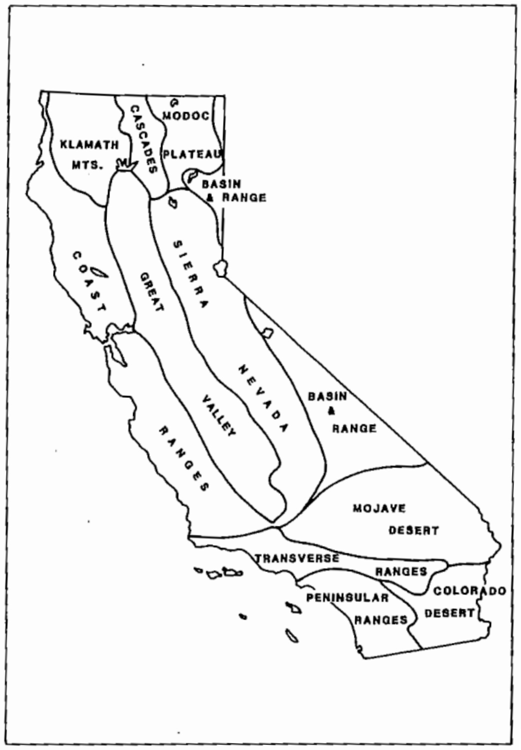


Figure 9. Major geologic provinces of CA (from Norris and Webb, 1990).

Further subduction in the Jurassic through Cretaceous accreted island arcs and pieces of land from as far as the western Pacific. The Nevadan orogeny began in the late Jurassic due in part to these crustal additions. As mountain building continued, late Jurassic sediments were eroded and deposited into the deep marine basin to the west, followed by the deposition of Cretaceous shallow shelf deposits. Few Cretaceous marine sediments are found in eastern California, so nonmarine sedimentary rocks, volcanic rocks, and intrusive rocks comprise the Mojave Desert and Basin and Ridge provinces. Deposition in the Cenozoic through present time consists of primarily marine sediments to the west of the Sierra Nevada Mountains (Norris and Webb, 1990).

The San Andreas fault system is a series of right-lateral strike-slip faults trending approximately northwest to southeast as a result of the Pacific and North American Plates sliding past each other at a rate of about 1.3 to 5.5 cm/yr (Atwater and Molnar, 1973). The system extends 1350 km from the Mexico-California border to the Mendocino Triple Junction in the Pacific Ocean south of the California-Oregon border (figure 10). Several other fault systems, including the Rodgers Creek, Hayward, Calaveras, Newport-Inglewood, Whittier, Palos Verdes, Elsinore, San Jacinto, and Imperial systems run parallel to the San Andreas system (Harden, 2004).

The characteristics of the San Andreas fault system varies significantly over the entire system, with movement across different zones confined to a single strand, spread across several fault strands, limited to a linear section, or distributed across a wide region. The zone encompassing active faults ranges from about 100 km wide at the northern end to about 300 km wide at the southern end (Harden, 2004). Portions of the fault parallel to the plate boundary deform by dominantly wrench (i.e., strike-slip) movement, but elsewhere show evidence of transpression on segments oriented obliquely to the convergence vector between both sides of the fault, thus resulting in compressional folding, faulting, and uplift (Harden, 2004).

Matching of geologic features on both sides of the fault (i.e., piercing points) has identified 315 km of total offset, with movement beginning about 23.5 million years ago. This yields a minimum average displacement rate of about 1.34 cm/yr (Harden, 2004). The largest recorded earthquake on the San Andreas system was the Fort Tejon M8.0 event in 1857. More recent major earthquakes along the San Andreas system include 1906 (M7.8), 1989 (M6.9), and 1994 (M6.7) (United States Geological Survey, 2012). Different sections of the fault system

Figure 10. Major sections of San Andreas fault shown as thick black line. Major roads through California shown as thin black lines.

have different histories in terms of major earthquake recurrence intervals and focal mechanisms, but in general, California experiences about 7.85 ± 0.92 M≥5 and 0.013 ± 0.012 M≥7.5 earthquakes per year (Felzer, 2009).

Alaska Geologic Setting

Alaska (figure 11) has three distinctly different tectonic environments within its boundaries, including the Aleutian-Alaska subduction zone, the northern end of the transform boundary between the Pacific and North American Plates, and the more stable, accretionary belt interior (Simkin, 2006). Due to the convergence vector between the Pacific plate and Alaska, the relative motion along the Aleutian arc goes from nearly pure convergence to nearly pure strike-slip. The subduction zone creating the Alaska Peninsula and Aleutian Islands extends from about 51.0° to 58.0°N and 156°W to 172°E. The transform boundary associated with the Alaska Panhandle and Alexander Archipelago extends from about 55.0° to 60.5°N and 130.0° to 141.0°W. The interior of the territory extends from about 62.0° to 68.0°N and 141.0° to 160.0°W (Simkin, 2006).

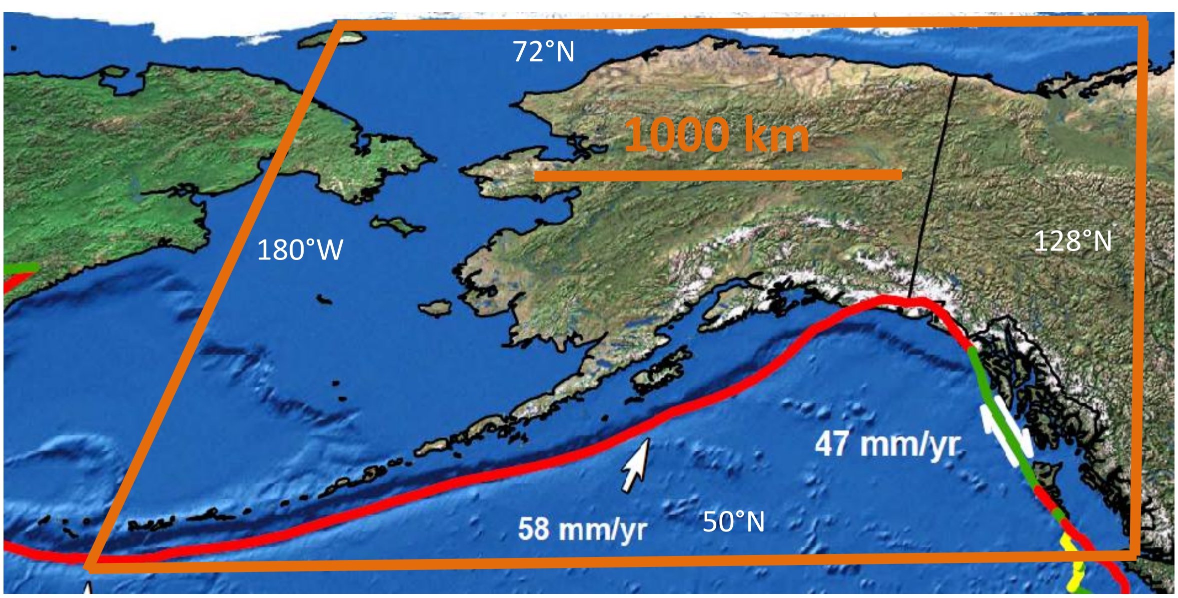


Figure 11. Site map of AK, 1000 km bar for scale. Relative plate motion shown (Tectonic Plates, 2009).

Northwestward subduction of a 3400 km stretch of the Pacific Plate beneath the North American Plate, resulting in the Aleutian Island arc (House et al., 1981), began in the Eocene and continues to the present day (Scholl et al., 1987). Rates of convergence between the plates vary from about 6.2 cm/yr in southern Alaska to about 7.2 cm/yr in the central Aleutian Islands (DeMets et al., 1994). An Eocene volcanic sequence is overlain by Oligocene to Miocene marine sedimentary rocks, which are overlain by a Pliocene and Quaternary sedimentary and an igneous sequence (Holbrook et al., 1999). Lavas in the Aleutian arc are predominantly basalts to dacites (Kay et al., 1982).

The largest recorded earthquake along the arc was a M9.2 event in 1964 (Butler, 2012). Other major earthquakes along the Aleutian-Alaska subduction zone include 1938 (M8.2), 1946 (M8.6), 1957 (M8.6), and 1965 (M8.7) (United States Geological Survey, 2012). Alaska experiences about 150 M≥4.5 earthquakes per year, including an average of 0.22 M≥7.5 earthquakes per year from 1960 to 2010 (West).

4.0. PROJECT DESIGN

4.1. Reasons for Chosen Variables

Each of the variables investigated in this study tests the extent to which future earthquakes tend to occur near past earthquakes in a different way. The results from these investigations will be used to compare intraplate regions and plate boundary regions, in terms of their CS characteristics. If hit percents are not significantly affected by a given variable in each region, then the hit percents can be compared more directly between regions because the individual hit percents have been shown to not be a product of the sampling of the characteristics of the regions' seismicities, such as variations in magnitude, depth, and size of the region.

An important question is whether CS analyses of small magnitude earthquakes can be used to draw conclusions about large magnitude earthquakes. The Gutenberg-Richter recurrence relationship for earthquakes shows that there are approximately ten times as many earthquakes for a 1.0 magnitude unit step down as for the previous magnitude (Gutenberg and Richter, 1956). For example, there are generally about 10 times as many magnitude 5.0 earthquakes as there are magnitude 6.0 earthquakes. Even though there are many more small magnitude earthquakes than large magnitude earthquakes, large magnitude earthquakes, of course, tend to be the most damaging. It is therefore valuable to be able to use small magnitude events, for which there is more available data, to gain an understanding about large magnitude events, which are associated with greater hazards.

Variable tests in which the Post-CAT cutoff magnitude is increased test whether the entire magnitude range of Pre-CAT earthquakes is better able to forecast a certain magnitude range of Post-CAT earthquakes. In these tests, the Pre-CAT includes small, moderate, and large magnitude events, but the Post-CAT is reduced from including small, moderate, and large magnitude events, to just moderate and large magnitude events, and finally to only large magnitude events. If there is no statistically significant change in hit percent with this Post-CAT change, that might mean the entire magnitude range of earlier occurring earthquakes can be used to determine the extent to which any magnitude range of later occurring earthquakes will occur near those Pre-CAT events. If hit percent decreases with this Post-CAT change, that might mean the entire magnitude range of Pre-CAT earthquakes are not as well able to forecast large magnitude earthquakes as small-to-moderate magnitude earthquakes. If hit percent increases with this Post-CAT change, that might mean the entire magnitude range of Pre-CAT earthquakes is better able to forecast large magnitude earthquakes than small-to-moderate magnitude earthquakes.

Variable tests in which the Pre-CAT cutoff magnitude is increased test whether the largest magnitude Post-CAT earthquakes are better able to be forecast by a certain magnitude range of Pre-CAT earthquakes. In these tests, the Post-CAT includes only the largest magnitude earthquakes (1% of the available data), but the Pre-CAT is reduced from including small, moderate, and large magnitude events, to just moderate and large magnitude events, and finally to only large magnitude events. If there is no change in hit percent with this Pre-CAT change, that might mean the extent to which the largest magnitude later occurring earthquakes tend to be located near earlier occurring earthquakes can be determined by any magnitude range of those Pre-CAT events. If hit percent decreases with this Pre-CAT change, that might mean the largest magnitude earthquakes are better able to be forecasted by small-to-moderate magnitude earthquakes than large magnitude earthquakes. If hit percent increases with this

Pre-CAT change, that might mean the largest magnitude earthquakes are better able to be forecasted by the largest magnitude earlier earthquakes than by small-to-moderate magnitude earthquakes.

Previously, CS has only been analyzed as a two dimensional problem (i.e., from the perspective of a map view of the study reagion), using circles surrounding the epicenters of earthquakes that are considered to be near enough to the surface that their epicenters are all that is necessary to represent their location. However, deeper earthquakes may have different CS characteristics than shallow earthquakes, and understanding the CS characteristics of deeper earthquakes requires analyzing this third (i.e., depth) dimension. Each region and subzone is divided into a shallow, intermediate, and deep layer. If there is no change in hit percent with this change in depth, that might mean the tendency for future earthquakes to occur near past earthquakes is not affected by the depth of the events. If hit percent decreases with this change in depth, that might mean deeper earthquakes do not happen near previous earthquakes as often as shallow earthquakes. If hit percent increases with this change in depth, that might mean deeper earthquakes occur near previous earthquakes more frequently than shallow earthquakes. This seems particularly relevant at subduction zones, where the trace of the plate boundary extends well below the lithosphere.

Another important question is whether CS results remain constant through time. It would be valuable if a hit percent found from a past, extensive earthquake catalog could be used as a guide for the tendency for future earthquakes to occur near previous earthquakes in that region. The time progression variable analyzed in this study considers the hit percent from a certain Pre-CAT and adjacent (in time) Post-CAT and investigates if the hit percent changes as the time gap between the end of the Pre-CAT and the beginning of the Post-CAT is increased.

The catalogs were divided into five and ten year segments, which were considered long enough to maintain a large sample size of earthquakes in each segment, but small enough to have several time segments in each set of trials. If there is no change in hit percent with this increase in the gap, that might mean the hit percent is a fundamental characteristic of the region (independent of time). If there is an increase or decrease in hit percent with this increase in the gap, that might mean the hit percent is merely an artifact of the particular chosen catalogs.

In each of the variable analyses discussed above, the variable of spatial scaling is tested by the analysis of subzones. By dividing a larger region into smaller, localized subzones, the CS results can be tested to determine if they are just an artifact of the particular boundaries chosen for a given region, or are instead a more inherent and fundamental measure of the tendency for past earthquakes to delineate zones where future earthquakes are likely to occur in a given tectonic environment. If there is no difference in hit percent between the overall region and the subzones, that might mean that hit percent is a characteristic of that particular tectonic region. If there is a difference in hit percent between the overall region and the subzones, however, that might mean the results are a product of the particular catalog pair, boundaries, or sample size rather than an inherent characteristic of the region itself.

4.2. Reasons for Choosing the Four Regions in This Study

To apply the CS method, the earthquake catalog for a chosen region must be complete for events above some magnitude threshold. This is the threshold above which the earthquakes are thought to be reliably recorded. The four chosen regions were selected with the intent of including different tectonic environments and a variety of region sizes, while also having a complete catalog for a significant duration of time. This choice of study regions makes it possible to investigate the effects of tectonic environment and geographic size of a chosen region on CS results. To that end, two intraplate regions and two plate boundary regions were chosen, and each category included one smaller and one larger area. By testing regions of different tectonic settings, the question of whether intraplate regions behave similarly to plate boundary regions (in terms of CS results) can be addressed.

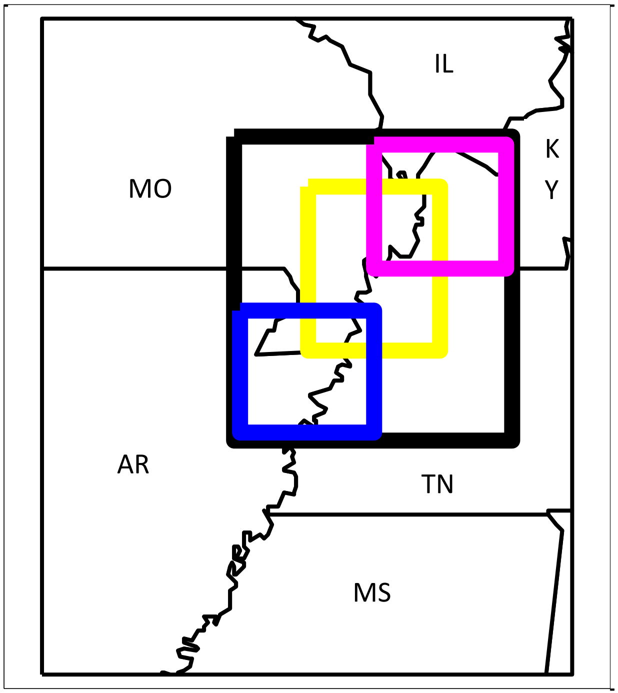


Figure 12. Boundaries of NMSZ and subzones. Complete region shown as thin black line, 34.0 to 38.0°N, 88.0 to 92.0°W. Black subzone shown as thick black line, 35.5 to 37.25°N, 88.5 to 90.5°W. Yellow subzone shown as yellow line, is 36.0 to 37.0°N, 89.0 to 90.0°W. Blue box shown as 35.5 to 36.25°N, 89.5 to 90.5°W. Purple subzone shown as purple line, 36.5 to 37.25°N, 88.5 to 89.5°W.

The bicentennial anniversary of the NMSZ 1811-1812 earthquake sequence renewed interest in the potential hazards of the NMSZ, so it was chosen as a prime example of a highly active zone of intraplate seismicity. The University of Memphis maintains earthquake records for the NMSZ from 1974 through the present (The University of Memphis, 2012), so the earthquakes in that region are well documented.

The presence of the Reelfoot rift provided a feature on which to focus the investigation. Along with the Complete NMSZ region, subzones within the NMSZ were defined such that the three principal sections of the Reelfoot rift described above were assigned their own subzone (figure 12). In figure 12, the Black subzone contained all three principal sections of the rift, the

Yellow subzone contained the Central section, the Blue subzone contained the Linear South section, and the Purple subzone contained the Linear North section.

Given that the NMSZ is a relatively small in area, AUS was selected as a spatially larger intraplate region. The Advanced National Seismic System (ANSS) maintains a composite earthquake catalog of worldwide events (ANSS, 2012), with available date ranges varying for different regions. The ANSS catalog maintains earthquake data for AUS from 1963 through the present (ANSS, 2012).

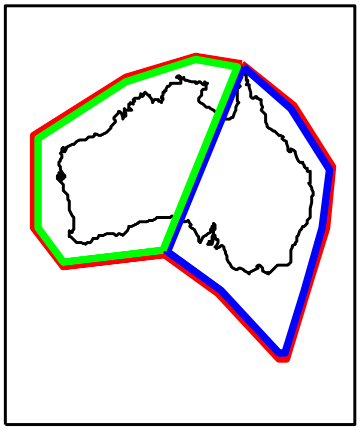


Figure 13. Boundaries of AUS and subzones. Complete region shown as red line. West subzone shown as green line. East subzone shown as blue line.

In AUS, there is no rift (or other prominent geologic feature) similar to the Reelfoot rift of the NMSZ along which most of the earthquakes occur. Earthquakes tend to be more dispersed in AUS than in the NMSZ, so subzones within AUS were simply defined geographically as West and East. This division was made such that the subzones were approximately equal in size (figure 13).

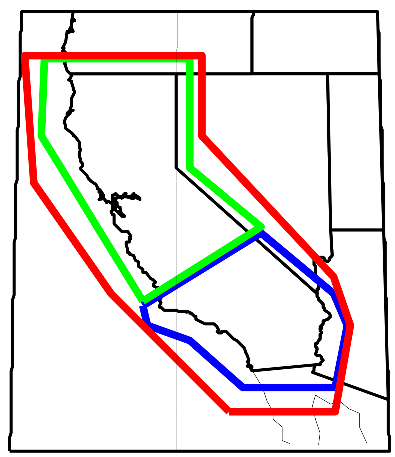


Figure 14. Boundaries of CA and subzones. Complete region shown as red line. North subzone shown as green line. South subzone shown as blue line.

Plate boundary regions, being much more active than intraplate regions, tend to have more complete earthquake records, so selecting plate boundary type regions was not restricted by the availability of seismicity data. CA is one of the most active seismic zones in the United States, and due to the large population in the region, it is a particularly important region to study with relevance for seismic hazards. The ANSS catalog maintains earthquake data for this region from 1911 through the present (ANSS, 2012).

Most of the CA earthquake epicenters are located along (or very near) the San Andreas Fault, and many major cities are located near the fault. Subzones within CA were defined such that San Francisco, a city with a history of large and damaging earthquakes, was the approximate center of the North subzone, and the remainder of the region falling in the South subzone (figure 14).

To provide a contrast with the transform plate boundary type of CA, AK, which includes a subduction zone, was also chosen. There are several other tectonic boundaries, dominated by strike-slip fault systems that are accommodating the convergence of various terranes, but the subduction zone described below was the primary boundary of interest for the AK region. The University of Alaska, Fairbanks maintains earthquake records for this region from 1898 through the present (ANSS, 2012).

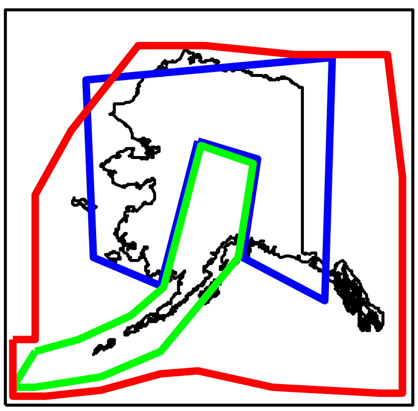


Figure 15. Boundaries of AK and subzones. Complete region shown as red line. Active subzone shown as green line. Nonactive subzone shown as blue line.

The portion of AK producing the most earthquakes in the region is where the Pacific Plate is subducting beneath the North American Plate. The portion of AK to the north and northeast of the plate boundary has a lower seismicity rate. Subzones within AK were defined such that the Aleutian Island chain was in the “Active” subzone, and the remainder of the region was in the “Nonactive” subzone (figure 15). It is possible that the AK Nonactive subzone behaves more similarly to intraplate regions, in terms of CS results, than it does to the area directly surrounding the plate boundary.

4.3. Reasons for Chosen Years

The regions chosen all had an earthquake catalog which had been maintained for at least several decades. This ensured that, even when the complete catalog is divided into shorter catalogs for investigation, there would still be a sufficient number of earthquakes to test for statistical significance. For each region, for the increasing Post-CAT, increasing Pre-CAT, and depth variables, five Pre-CAT/Post-CAT pairs were defined from the entire catalog for that particular region. The same Pre-CAT/Post-CAT pairs were used for both the complete regions and their respective subzones.

The choice of Pre-CAT/Post-CAT pairs was intended to include a variety of Pre-CAT starting points, Pre-CAT ending points, Post-CAT starting points, Post-CAT ending points, lengths of Pre-CATs, lengths of Post-CATs, and gap lengths between the end of the Pre-CAT and start of the Post-CAT. However, the possible choices were limited by the length of the entire catalog for a particular region. For example, the entire catalog for the NMSZ begins in 1974, so no Pre-CAT/Post-CAT pair could include years prior to 1974 for the NMSZ or its subzones. Similarly, earthquake detection methods in the past (before recently upgraded monitoring networks) were only able to record larger magnitude earthquakes, so catalogs were not as complete for smaller magnitudes events in the past than they are in recent years. Pre-CAT/Post-CAT pairs were defined so that they accounted for distant past years in the catalog possibly being incomplete, even at moderate magnitudes. This was accomplished by using long year durations for distant past catalogs and by not using distant past years in the time progression variable catalogs.

With a catalog starting in 1974, the NMSZ had the fewest available years of all investigated regions. The chosen Pre-CAT/Post-CAT year pairs were 1974-1999/2000-2010, 2009/2010, 1990-1994/2000-2004, 1980-1981/2005-2006, and 1988/2000-2009. These selections made use of the entirety of the data set by having a Pre-CAT start in 1974 and a Post-CAT end in 2010. There was also variation in the lengths of Pre-CATs and Post-CATs, ranging from one to 26 years and one to 11 years, respectively. There were gaps between the Pre-CAT and Post-CAT ranging from zero to 11 years. An issue with these year pair choices is the small sample size for earthquakes in the shorter catalogs. This is somewhat a product of the lack of length for the entire catalog and the desire to create variety in the catalog pairs discussed above. The effects of the small sample sizes in various catalogs are discussed below in the *Results* and *Assumptions and Known Problems* sections. For the NMSZ, the minimum magnitude cutoffs were M1.4 for the Complete region and ranged from M1.4 to M2.0 for the subzones.

The Complete AUS catalog began in 1965, allowing for slightly more variation in the Pre-CAT/Post-CAT pairs than for the NMSZ. The chosen pairs were 1965-1999/2000-2010, 1990-1994/2000-2004, 2000-2004/2005-2009, 1980-1982/1995-1997, and 1988/2000-2009. The selections again made use of the entire data set, while attempting to vary the characteristics of the pairs. The Pre-CATs and Post-CATs ranged in length from one to 35 years and three to 11 years, respectively, and there were gaps between the Pre-CAT and Post-CAT ranging from zero to 14 years. Prior to the mid-1970's few earthquakes of magnitude smaller than about M4.5 were recorded in the area (Australian Government: Geoscience Australia, 2012). Earthquakes as low as about M2.0 have only been consistently recorded in the most recent decades. Therefore, the minimum magnitude cutoffs were set at M4.5 for the Complete region and for both subzones.

The California Integrated Seismic Network (CISN) is the Californian partner of the ANSS, and the available catalog began in 1911. The chosen Pre-CAT/Post-CAT pairs were 1970-1989/1990-1999, 1990-1994/2000-2004, 1911-1960/1961-2010, 1980-1984/1995-2004, and 1918-2003/2004-2006. The earlier beginning of the catalog allowed for more variation in the selections than was available in the intraplate regions, and the Pre-CATs and Post-CATs ranged in length from five to 86 years and three to 50 years, respectively, and there were gaps between the Pre-CAT and Post-CAT ranging from zero to 12 years. One concern with these choices is that the northern portion of CA was not as well monitored as the southern portion until about 1967. This means that data from the North subzone could not be used for the 1911-1960/1961-2010 Pre-CAT/Post-CAT pair. Due to the high rate of seismicity in CA, the minimum magnitude cutoffs were set at 4.0 for the Complete region and for both subzones.

The Alaska Earthquake Information Center (AEIC) is one of the Alaskan partners of the ANSS, and the available catalog began in 1898. The chosen Pre-CAT/Post-CAT pairs were 1990-1994/2000-2004, 1970-1989/1990-1999, 1898-1972/1973-2010, 1980-1984/1995-2004, and 1988-1989/1990-1991. Again, the larger extent of the entire catalog allowed for more variation in the pair selections than was available in the intraplate regions. The Pre-CATs and Post-CATs ranged in length from two to 75 years and two to 38 years, respectively, and there were gaps between the Pre-CAT and Post-CAT ranging from zero to 12 years. Due to the high rate of seismicity in AK, the minimum magnitude cutoffs were set to 4.0 for the Complete region and for both subzones.

For the time progression variable, a complete and relatively lengthy earthquake catalog is also necessary, but the tested years were more systematically chosen than for the increasing Post-CAT, increasing Pre-CAT, and depth variables described above. Tests were done at five and

10 year segments, and the starting point was based on the completeness of a particular catalog. For example, the first five year segment in the time progression variable for the NMSZ, for which the entire catalog began in 1974, was 1975-1979. With the first year segment as the Pre-CAT, the remaining available catalog was divided into five year segments for the Post-CAT (i.e., 1980-1984, 1985-1989, 1990-1994, 1995-1999, 2000-2004, and 2005-2009). The entire catalog was divided again so that the year segments were ten years long (i.e., 1980-1989, 1990-1999, and 2000-2009). Since the AUS, CA, and AK regions' entire catalogs started earlier than the NMSZ's, the beginning of the time progression variable could be started earlier for these regions. The five year segment tests began with the first year segment as 1970-1974, and the 10 year segment test began with the first year segment as 1970-1979. Although the CA and AK region catalogs extend even further into the past, the distant past years were not included in the time progression variable due to the likely inaccuracies in earthquake locations. For more explanation on the details of the time progression variable steps, see the *Variables to Analyze and Methods* section below.

5.0. VARIABLES TO ANALYZE AND METHODS

5.1. Spatial Scale

The first set of tests involved investigating the effects of spatial scale on hit percent. This investigation explored the unresolved issue of whether hit percent results for a broad region (e.g., the entire NMSZ) were similar to those of localized subzones within that broader region. It is important to resolve this issue to know if CS results are just an artifact of the particular boundaries chosen for a region or are instead a more inherent and fundamental measure of the tendency for past earthquakes to delineate zones where future earthquakes are likely to occur in a given tectonic environment.

Several boundary boxes of different sizes and locations were defined within each region of interest, and the same year definitions for the Pre-CAT/Post-CAT pairings were processed for each boundary box. This allowed for comparisons between the Complete region and the subzones, as well as between the subzones. Analyzing the different size boxes for the same percent map coverage areas allows the subzones to be compared.

Statistically similar values of hit percent for different boundary box sizes is evidence that, within the region of interest, there is no effect of scaling on hit percent. Statistically different values of hit percent for different boundary box sizes is evidence that there is an effect on hit percent due to spatial scaling in the region of interest.

Several Pre-CAT and Post-CAT combinations were tested for each subzone and for each Complete region of interest. After selecting a Pre-CAT and Post-CAT combination, the record of earthquakes for all years comprising those catalogs was tested for completeness by checking the Gutenberg-Richter recurrence relationship. Earthquake frequency is generally found to be logarithmically related to magnitude. Thus, for a catalog to be considered complete, the log of the cumulative number of earthquakes (N) with magnitude greater than or equal to a given magnitude (M) should follow a straight line when log(N) is plotted against M. The record of earthquakes might not be complete for smaller magnitudes, which would be seen in the form of N being lower for those smaller magnitudes than would be expected for a straight line fit to the higher-magnitude data. Thus, when analyzing plots of log(N) versus M, the smallest magnitude above which the logarithmic relationship is linear was identified and established as the minimum magnitude cutoff for completeness for that region (figures 16a-16b). All earthquakes with magnitudes lower than the minimum magnitude cutoff were then removed from the catalogs. After this minimum magnitude threshold was determined, the complete catalog was divided into the Pre-CAT and the Post-CAT sections.

The minimum magnitude threshold for the Pre-CAT should be low enough to provide a large enough sample that it could be considered to be representative of the seismicity of the region of interest, but also high enough that the catalog could be considered complete. The

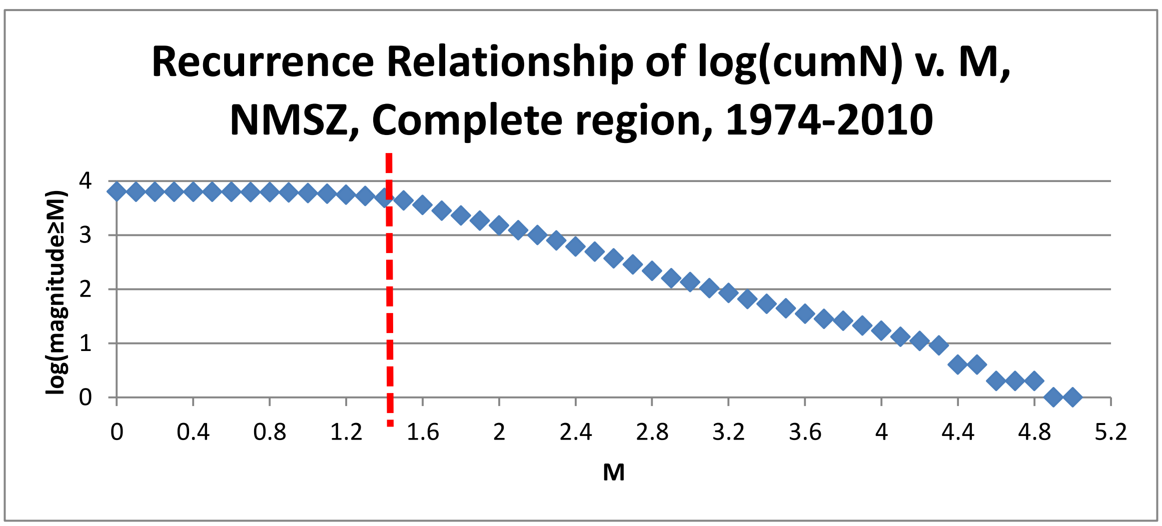


Figure 16a. Selection of catalog minimum magnitude cutoff based on Gutenberg-Richter recurrence relationship. Example from NMSZ Complete region, 1974-2010. Red dashed line indicates magnitude less than which expected linear trend for log of cumulative number of earthquakes of magnitude greater than or equal to a certain magnitude step plotted versus magnitude is broken. Minimum magnitude cutoff set at M1.4.

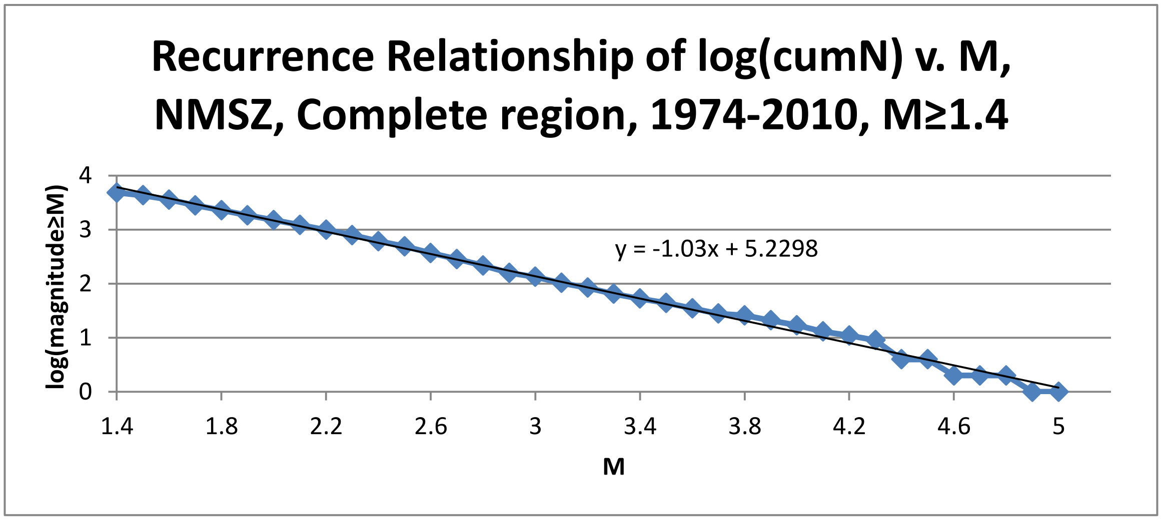


Figure 16b. Plot of recurrence relationship only for M≥1.4.

minimum magnitude threshold for the Post-CAT should be low enough to include enough events that tests of statistical significance could be conducted, but also high enough that it could be considered to be a good proxy for the large earthquakes that are of concern in earthquake hazard analysis. As is the case in all studies of seismicity, it was difficult to assure that these characteristics of the catalogs were met. Thus, below in the section on magnitude, the effects of magnitude cutoffs on CS results are explored.

Using a program written in C, the CS radii which produced the desired percentage of map coverage area were calculated. Map coverage percentages of 4, 10, 20, 33, and 50% were used as representative values for each region to investigate the relationship between P and the percentage of hits.

The specific percentages of map coverage chosen for this study were somewhat arbitrary, but they were based on the following logic: (1) Using radii large enough to create a forecast region that covers 100% of the map area would successfully forecast all future earthquakes, but that forecast method would not be useful; (2) Creating a forecast region that covers 0% of the map area would also not be useful because no future earthquakes would be forecasted. Useful forecasts, thus, come from intermediate percentages of map coverage. The percentage of map area should be high enough to actually forecast some future events, but small enough to make such a forecast useful. It has been found in previous studies that using 33% map area generally yields approximately ⅔ to ¾ hits, which is a reasonable compromise, given the above constraints. Thus, most of the following discussion will be based on trials using 33% map area coverage, but choosing 33% is just for useful, illustrative purposes and does not necessarily represent anything fundamental about the earthquake process.

For a given region and its associated Pre-CAT, the CS radius that yields a given percentage of map area was determined. These calculations are dependent on the size of the region, the number of Pre-CAT earthquakes, and the distribution of Pre-CAT epicenters. The hit counts for the specific catalogs were found for each map area percentage (i.e., 4, 10, 20, 33, and 50%), and hit percent was calculated by dividing the hit count by the total number of Post-CAT earthquakes. The results were plotted to produce a map showing epicenters of the Pre-CAT earthquakes, the zones covered by the Pre-CAT earthquake circles, and the epicenters of the Post-CAT earthquakes.

After hit counts for different subzones or entire regions and/or different Pre-CAT and Post-CAT parameters had been found, statistical significance testing was performed to determine whether the difference in observed percentages of hits was likely due to factors other than pure chance. The mathematical explanation of these tests is detailed below in the *Statistical Analysis* section.

5.2. Magnitude

Another unresolved CS issue is whether the magnitude of earthquakes analyzed has an effect on the extent to which CS successfully forecasts the locations of future earthquakes. The investigation of this variable has important implications on the ability to use CS to forecast the locations of the very large and destructive earthquakes that are of concern in earthquake hazard assessment and earthquake prediction.

Analysis of the effect of magnitude threshold involved initially processing a Pre-CAT and a Post-CAT combination as described above in the *Spatial Scale* section, using the minimum magnitude cutoff for both catalogs. Then, the minimum magnitude cutoff of the Post-CAT was increased by 0.2 magnitude units, and the catalogs were processed again. The minimum magnitude cutoff for the Post-CAT was repeatedly increased until it reached the maximum magnitude in the data. This served as a way to check if there was any difference in the ability of smaller magnitude past earthquakes to forecast smaller or larger magnitude future earthquakes.

Another CS magnitude test involved increasing the minimum magnitude cutoff of the Pre-CAT and using that modified Pre-CAT to forecast the largest magnitude Post-CAT earthquakes. The minimum magnitude cutoff for the Post-CAT was set so that only the approximately 1% largest magnitude number of Post-CAT earthquakes were included. The minimum magnitude cutoff for the Pre-CAT was set at the minimum possible value based on the completeness analysis, and the catalogs were processed. The minimum magnitude cutoff for the Pre-CAT was then increased by 0.2 magnitude units, the revised radii needed for 4, 10, 20, 33, and 50% map coverage were calculated, and the catalogs were processed again. The minimum magnitude cutoff for the Pre-CAT was repeatedly increased until it reached the maximum magnitude in the data. This served as a way to check if larger magnitude past earthquakes are any more successful than smaller magnitude past earthquakes at forecasting the largest magnitude future earthquakes.

5.3. Depth

Another unresolved CS issue is the effects of depth on the success rates of CS forecasts. CS had so far been analyzed as a 2-dimentional (i.e., map view) problem, using circles surrounding the epicenters of earthquakes that were considered to be near enough to the surface that their epicenters represented their location. However, deeper earthquakes may have different CS characteristics than shallow earthquakes, and understanding the CS characteristics of deeper earthquakes required analyzing this third (i.e., depth) dimension. Consider, for example, a subduction zone, in which some of the earthquakes are deep and follow a dipping plane beneath other shallow earthquakes. In this type of case, although a Post-CAT earthquake might be “near” a Pre-CAT earthquake in map view, it might be far from that same Pre-CAT earthquake in the depth direction. The problem then needed to be considered in three, rather than two, dimensions.

The third dimension of depth was included by conducting CS analyses for earthquake hypocenters in a series of layers corresponding to different depth layers and analyzing each layer separately. For each region studied, the earthquakes were sorted by depth and divided into three layers. The layer catalogs were resorted chronologically, Pre-CATs and Post-CATs were created for each layer, and the standard CS analyses were performed at each layer.

The layers were chosen by plotting all earthquakes from the region as a function of depth, and visually identifying natural breaks in the clustering of the earthquakes in these plots. To avoid bias, no a priori tectonic information was used in the layer definitions. For the NMSZ, the hypocenters of shallow earthquakes were less than 6 km, intermediate earthquakes were between 6 and 11.5 km, and deep earthquakes were from 11.5 to 32.9 km. For AUS, the hypocenters of shallow earthquakes were less than 10 km, intermediate earthquakes were between 10 and 30 km, and deep earthquakes were from 30 to 168 km. For CA, the hypocenters of shallow earthquakes were less than 15 km, intermediate earthquakes were between 15 and 30 km, and deep earthquakes were from 30 to 121.3 km. For AK, the hypocenters of shallow earthquakes were less than 25 km, intermediate earthquakes were between 25 and 140 km, and deep earthquakes were from 140 to 250 km.

5.4. Time Progression

Another unresolved CS issue is the extent to which the percentage of hits for a particular region remains constant through time, given the same Pre-CAT, but sequentially later Post-CATs. Investigating this question involved varying the length of the time gap between the end of the Pre-CAT and the beginning of the Post-CAT.

Consider, for example, a catalog consisting of earthquakes from 1990-2009. The Pre-CAT is set as 1990-1994 for all trials. For the first trial, the Post-CAT is 1995-1999, so the Pre-CAT and Post-CAT are temporally adjacent. For the second trial, the Post-CAT is 2000-2004, so the Pre-CAT and Post-CAT are temporally separated by a single time segment (of five years). For the final trial, the Post-CAT is 2005-2009, so the Pre-CAT and Post-CAT are temporally separated by two time segments. The change in hit percent as the Pre-CAT and Post-CAT are increasingly separated in time serves to test if hit percent remains constant in a region, given the same Pre-CAT.

To perform this type of test, an overall catalog was defined for completeness. The Pre-CAT was defined as the first available five year segment. For the first test, the Post-CAT was defined as the five year segment temporally adjacent to the Pre-CAT (i.e., no time gap between the end of the Pre-CAT and the beginning of the Post-CAT). The Pre-CAT circle radius, hit count, and hit percent were calculated for this catalog pair. For the next test, the Post-CAT was defined as the five year segment sequentially later than the previous trial (i.e., a five year time gap between the end of the Pre-CAT and beginning of the Post-CAT). The hit count and hit percent were calculated for this catalog pair. This process was repeated until the progression had stepped through every five year segment available to be used as a Post-CAT. The process was then repeated using the first available ten year segment as the Pre-CAT and subsequent ten year segments as the Post-CATs.

The first trial (i.e., zero time gap Post-CAT) is statistically compared against the subsequent trials (i.e., non-zero time gap Post-CATs) to determine if hit percent changed over time for the given region. Given the example above, the hit percent from the Post-CAT 1995-1999 trial is compared against the hit percent from the Post-CAT 2000-2004 trial and the Post-CAT 2005-2009 trial.

5.5. Statistical Analysis

Several methods were combined to determine if the difference between hit percents for a particular region or variable was statistically significant. Although CS is designed such that catalogs of various sizes and regions of various areas and tectonic settings can be compared, applying conventional tools for statistical analysis may not be as adaptive. For example, small sample sizes in many catalogs leads to the need to use a small sample binomial test as opposed to a large sample binomial test. In terms of the variables involving tests at certain increments of data (e.g., magnitude steps and time progression), a two-tailed binomial test was used to avoid any a priori assumptions regarding the directionality of the hypothesized change in hit percent. This means that differences in test results at certain increments may be statistically significant in a certain direction for one increment, but then statistically significant in the opposite direction for the next increment. To test whether these fluctuations were generally systematic in a certain direction, the number of times hit percent increased when the increment step was applied, the number of times it decreased, and the number of times it remained the same were counted. If, for example, there was a systematic decrease in hit percent with the incremental step in that variable, a significantly larger number of “decreases” than “increases” would be expected. This leads to the applications of another, simpler, binomial test where the expected proportion of successes (“increases”) is p = 0.5.

Of the regions analyzed, there were two intraplate regions (NMSZ, AUS) and two plate boundary regions (CA, AK). Each variable test (incremental change of the Post-CAT minimum magnitude, incremental change of the Pre-CAT minimum magnitude, depth, time progression) was applied to every region and its respective subzones, and statistical significance tests were performed.

Within a region, a two sample, two-tailed binomial test was used to determine whether the differences in observed hit percents are likely due to factors other than pure chance. A two-tailed, two sample binomial test was chosen for this analysis because the sets of data were discrete, had different numbers of total trials, and each trial had a possible outcome of either a hit or a miss, modeled here as a “success” or “failure,” respectively (Larsen and Marx, 2006). The formula used to test for statistical significance is:

$$z = \frac{\left(\frac{x}{n}\right) - \left(\frac{y}{m}\right)}{\sqrt{\frac{p_e(1-p_e)}{n} + \frac{p_e(1-p_e)}{m}}}, \qquad (1)$$

where z is the z-score used to find the probability (p-value) that a value that extreme would happen by chance, x is the number of hits in catalog one, n is the number of Post-CAT earthquakes in catalog one, y is the number of hits in catalog two, m is the number of Post-CAT earthquakes in catalog two, and:

$$p_e = \frac{x+y}{n+m}\ . \qquad (2)$$

Using a standard normal curve cumulative area table, the p-value associated with the calculated z-score is found. A two sided statistical test is considered to determine if the difference between two observed hit percent values is statistically significant. The null hypothesis, H_0, is $\hat{\rho}_1=\hat{\rho}_2$, and the alternative hypothesis, H_1, is $\hat{\rho}_1\neq\hat{\rho}_2$. A two sided test is used so that no a priori assumptions need to be made regarding which hit percent is higher. For a significance level α, if the p-value is less than or equal to α, then the two catalogs being compared are concluded to have statistically significant differences in hit percents, and H_0 is rejected in favor of H_1.

This binomial test was applied to adjacent incremental steps for the variables involving an incremental step change (Post-CAT magnitude change, Pre-CAT magnitude change, and time progression) and the depth layering variable.

Given the two-tailed testing method, a statistically significant result between adjacent step increments did not necessarily indicate a systematic trend in changing percentage of hits. Similarly, a lack of statistically significant results did not necessarily indicate a lack of a systematic trend in changing percentage of hits. A pair of adjacent steps could be significantly different in a certain direction (e.g., increasing hit percent), and the next pair of adjacent steps could be significantly different in the opposite direction (e.g., decreasing hit percent). While these data points show a difference between the adjacent points, the up and down fluctuation of hit percent indicates that there is no overall trend in terms of in what direction the percentage of hits is changing. Similarly, a series of several adjacent step increments could change hit percent in the same direction (e.g., decreasing hit percent), but no statistical differences be found between any adjacent increments. It is possible that no single incremental step would show an extreme enough change to be considered significant, but there is still an overall trend in terms of in what direction hit percent is changing.

To address these possibilities, a count was taken of the number of times the percentage of hits increased, decreased, and stayed the same between adjacent step increments for an entire variable change. For example, for the CA Complete region, Pre-CAT: 1970-1989, Post-CAT: 1990-1999, as the minimum magnitude cutoff of the Post-CAT was increased from M4.0 to M7.0 by 0.2 magnitude units, hit percent increased 8 times, decreased 3 times, and stayed the same 5 times. These count results can be interpreted by another binomial test where the null hypothesis is that the number of “increasing” hit percent counts is equal to the number of “decreasing” hit percent counts, so the probability of a success (increasing hit percent), given the null hypothesis, is p = 0.5.

In many cases, the number of trials (number of incremental steps) was too small to use a large sample binomial test. To use a large sample test, the following must be satisfied (Larsen and Marx, 2006):

$$0 < mp_o - 3\sqrt{mp_o(1-p_o)} < mp_o + 3\sqrt{mp_o(1-p_o)} < m \, , \qquad (3)$$

where m is the number of trials (m = number of data points in given variable – 1), and $p_o = 0.5$. Given this restriction, more than nine incremental steps (i.e., more than ten data points) in the given changing variable were needed to perform a large sample binomial test. If the number of incremental steps was too small, a probability density function (pdf) was created from a Bernoulli distribution. This is represented as (Larsen and Marx, 2006):

$$p_x(k) = \binom{m}{k} (p_o)^k (1 - p_o)^{m-k} , \tag{4}$$

where k is the number of successes in m number of trials, $p_o$is the probability of success on a given trial, and $p_x(k)$is the probability of a value of k that extreme being chosen by random chance. Given the assumption that the number of increasing and decreasing hit percent changes are equal, (4) can be reduced to:

$$p_x(k) = \binom{m}{k} (0.5)^m , \tag{5}$$

where $\binom{m}{k}$ is an m choose k combination, given by:

$$\frac{m!}{k!(m-k)!} . \tag{6}$$

For a given number of trials, the critical region is pieced together using the pdf created from (5). For example, the pdf with five trials (i.e., five incremental steps between six data points), is seen in table 1. By adding the probability that a k of zero or five will happen by chance, a combined critical region is found to be 0.0625. This value is similar to the desired critic al region of α = 0.05. Using a small sample binomial test does not yield a critical region exactly equal to the 1- α level, but combined regions can approximate the desired size of the critical region. If the number of successes (i.e., number of hit percent increases) falls in the created approximated region, then there is evidence that the percentage of hits is changing with a systematic trend, as opposed to unsystematic fluctuation. This trend may be seen even if no statistically significant differences were found between adjacent increment steps. Due to the constraints of the available combined critical regions for small sample sizes, trials with less than five earthquakes in the Pre-CAT and/or Post-CAT were not considered large enough to be analyzed for statistical significance in this study.

k successes	probability(K=k), with m=5 and p_o=0.5
0	0.0313
1	0.1562
2	0.3125
3	0.3125
4	0.1562
5	0.0313

Table 1. Probability density function for number of successes of five trials (i.e., five incremental steps between six data points), and probability of success on any single trial p_o=0.5.

This combination of tests (binomial test and increase/decrease count) was used to evaluate whether a given variable affected the percentage of hits. Hit percent may not have been affected by a variable because the differences between incremental steps were not statistically significant, and if they were significant, they may not have shown a systematic directional trend.

Hit percents across the regions could then be judiciously compared by taking into account which variables had statistically affected hit percent within a specific region.

6.0. RESULTS

Each tested variable illustrates a different aspect of the extent to which past seismicity delineates zones where future earthquakes are likely to occur. As such, the results for each variable (changing minimum magnitude cutoff of the Post-CAT, changing minimum magnitude cutoff of the Pre-CAT, depth layering, time progression) will be discuss separately, and their potential application to the question of differences between intraplate versus plate boundary region CS characteristics analyzed in the respective sections. As discussed in the *Variables to Analyze and Methods* section, a combination of mathematical tests was applied to determine statistical significance, and both components of this combination are reported here. All comments on statistical significance are in reference to the 95% confidence level, and all hit percents are in reference to 33% map area coverage. Interpretations of these results are reserved for the *Discussion* section.

6.1. Changing Post-CAT Minimum Magnitude Cutoff

The changing minimum magnitude cutoff of the Post-CAT variable maintains the minimum magnitude cutoff of the Pre-CAT at the lowest possible value based on the Gutenberg-Richter recurrence relationship, and increases the minimum magnitude cutoff of the Post-CAT at 0.2 magnitude unit increments. The trials that are considered to have too few earthquakes in the Pre-CAT or Post-CAT to be analyzed for statistical significance are designated by orange shading on the plot. More detailed procedures and reasons for testing this variable are discussed in the *Variables to Analyze and Methods* section.

<u>New Madrid Seismic Zone: Changing Post-CAT Results</u>

The plots of hit percent with changing minimum magnitude cutoff of the Post-CAT for the Complete NMSZ region and the Black, Yellow, Blue, and Purple subzones are shown in figures 17a-17e, respectively. For statistically significant results, hit percents ranged from the upper-90's to the upper-50's. These hit percents are typical of previous CS studies.

In the Complete region, there is one statistically significant decrease in hit percent from one magnitude to the next adjacent step. That is the decrease in hit percent from 96% to 94% between Post-CAT minimum magnitude cutoffs of M1.6 to M1.8 for the 1974-1999/2000-2010 catalog. The difference between these hit percents has a p-value of 0.013. When considering those data points having a minimum magnitude cutoff of less than or equal to M3.2 (i.e., the statistically significant portion of the data), there is a statistically significant downward trend in hit percent with increasing minimum magnitude cutoff of the Post-CAT for the 1974-1999/2000-2010, 1990-1994/2000-2004, and 1988/2000-2009 catalogs. The hit percents decrease between adjacent steps in eight out of nine increments, which is a p-value of 0.020. The hit percents then increase for the largest minimum magnitude cutoffs of the Post-CAT, but these data are using very small sample sizes (i.e., less than five Post-CAT earthquakes).

A similar, but less pronounced trend is seen in the Black and Yellow subzones. In the Black subzone, the steps from M1.6 to M1.8 and M1.8 to M2.0 are statistically significant decreases in hit percent for the 1988/2000-2009 catalog. The downward trend in hit percent is statistically significant for the 1974-1999/2000-2010 and 1988/2000-2009 catalogs, when considering magnitude cutoffs of ≤M3.2. The same magnitude increments are statistically significant in the Yellow subzone, and the same year pairs have statistically significant downward trending hit percents for magnitude cutoffs of ≤M3.0.

Hit percents in the Blue and Purple subzones do not follow as distinct a trend as the other subzones. Neither subzone has any statistically significant changes in hit percent between two adjacent increments. There is no statistically significant trend in hit percent in the Blue subzone, and only the 1980-1981/2005-2006 catalog has a statistically significant downward trend in hit percent in the Purple subzone.

With the exception of the 1980-1981/2005-2006 year pair for the Purple subzone, all catalogs end with 100% hits at the highest Post-CAT magnitude cutoff. Even for the catalogs which show a statistically significant downward trend discussed above, those hit percents increase sharply as the minimum magnitude cutoff of the Post-CAT is raised from moderate magnitude to large magnitude events. This portion of the data, however, is not statistically significant due to the small number of earthquakes in the catalogs.

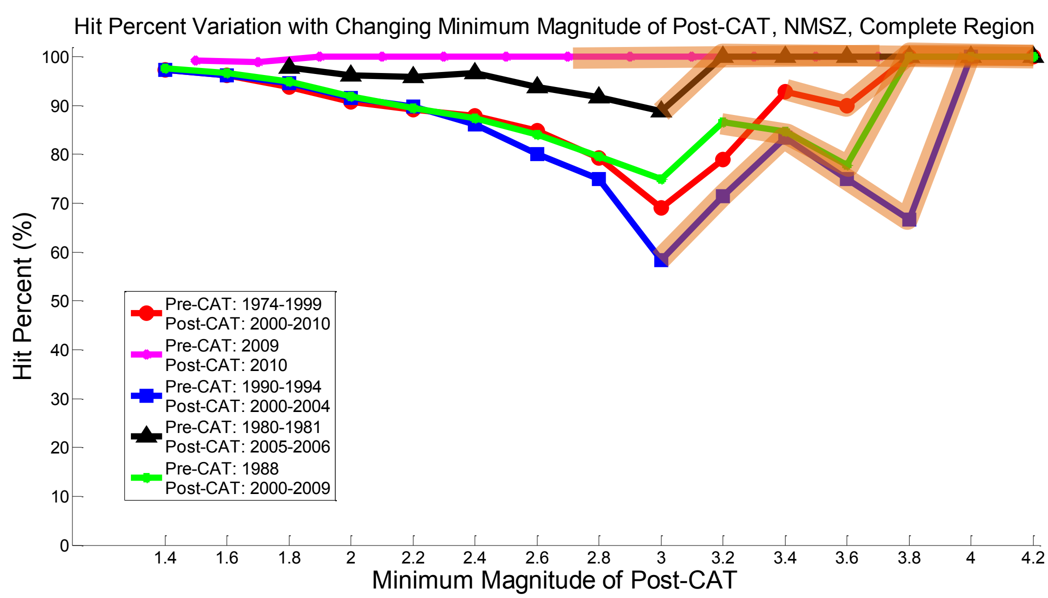


Figure 17a. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in NMSZ Complete region. Minimum magnitude cutoff of Pre-CAT: 1974-19992000-2010 (M1.4), 2009/2010 (M1.5), 1990-1994/2000-2004 (M1.4), 1980-1981/2005-2006 (M1.8), 1988/2000-2009 (M1.4). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

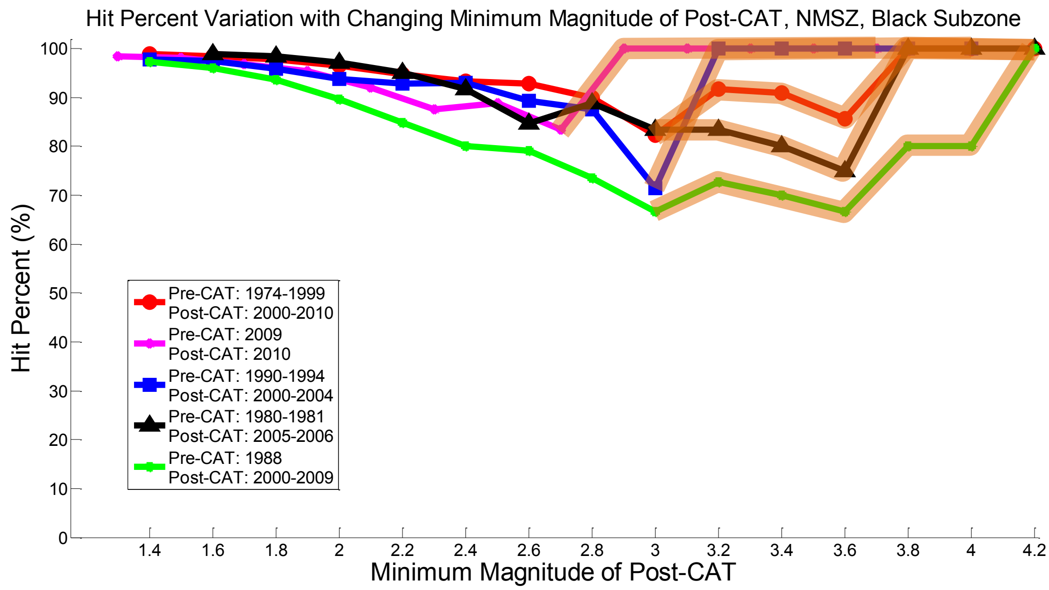


Figure 17b. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in NMSZ Black subzone. Minimum magnitude cutoff of Pre-CAT: 1974-19992000-2010 (M1.4), 2009/2010 (M1.3), 1990-1994/2000-2004 (M1.4), 1980-1981/2005-2006 (M1.6), 1988/2000-2009 (M1.4). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

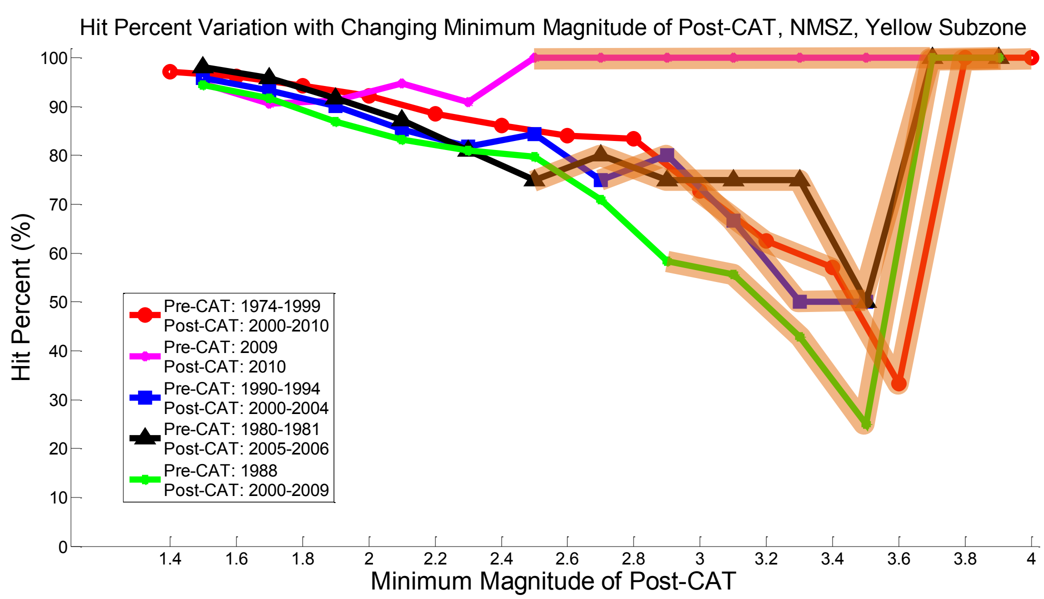


Figure 17c. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in NMSZ Yellow subzone. Minimum magnitude cutoff of Pre-CAT: 1974-19992000-2010 (M1.4), 2009/2010 (M1.5), 1990-1994/2000-2004 (M1.5), 1980-1981/2005-2006 (M1.5), 1988/2000-2009 (M1.5). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

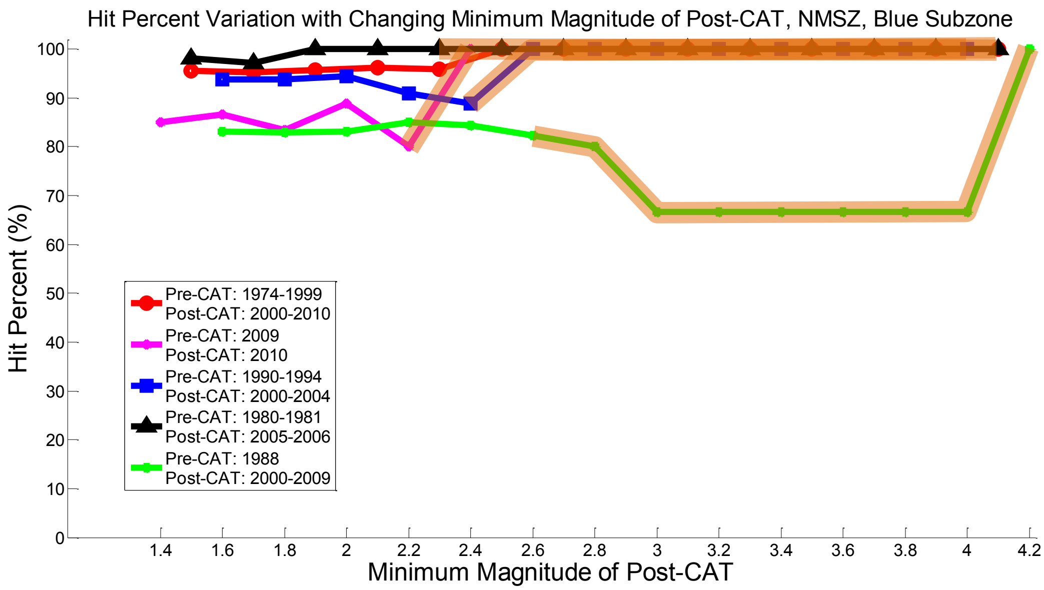


Figure 17d. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in NMSZ Blue subzone. Minimum magnitude cutoff of Pre-CAT: 1974-19992000-2010 (M1.5), 2009/2010 (M1.4), 1990-1994/2000-2004 (M1.6), 1980-1981/2005-2006 (M1.5), 1988/2000-2009 (M1.6). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

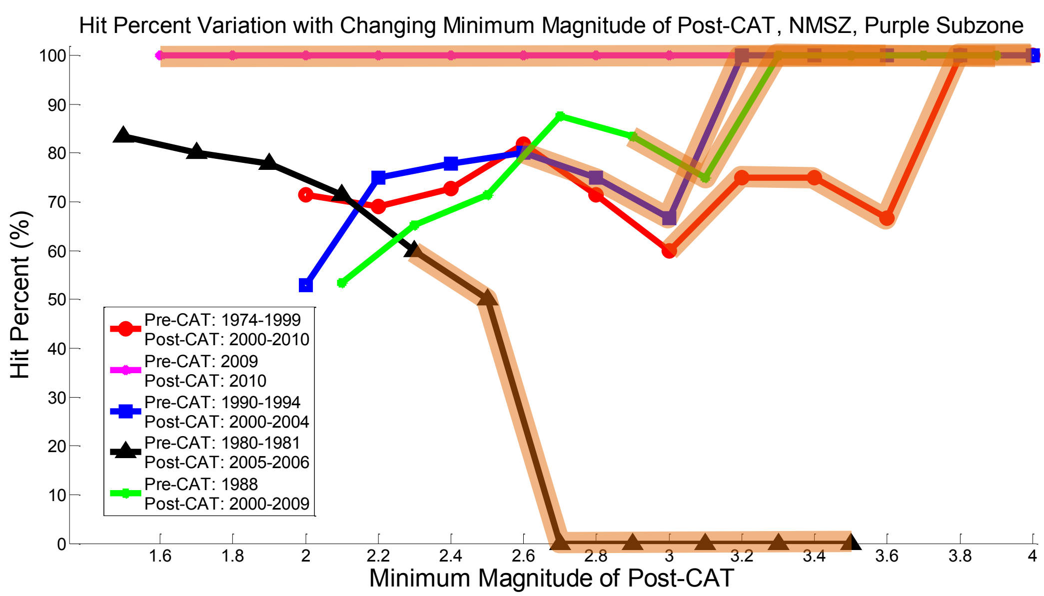


Figure 17e. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in NMSZ Purple subzone. Minimum magnitude cutoff of Pre-CAT: 1974-19992000-2010 (M2.0), 2009/2010 (M1.6), 1990-1994/2000-2004 (M2.0), 1980-1981/2005-2006 (M1.5), 1988/2000-2009 (M2.1). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

Australia: Changing Post-CAT Results

The plots of hit percent with changing minimum magnitude cutoff of the Post-CAT for the Complete AUS region and the West and East subzones are shown in figures 18a-18c, respectively. For statistically significant results, hit percents ranged from the upper-80's to low-20's. These are some of the lowest hit percents on record, based on previous CS results, and they are, in general, lower than the NMSZ results (and also lower than the 33% map area covered by these CS forecasts).

None of the AUS catalogs for any subzone have any statistically significant difference between hit percents for adjacent steps, and none of the AUS catalogs have a statistically significant trend in hit percent. The hit percent results vary highly and fluctuate rapidly. When considering statistically significant portions of the data set, the 1965-1999/2000-2010 catalog has a hit percent consistently higher than the other year pairs, and the 2000-2004/2005-2009 and 1988/2000-2009 catalogs have hit percents consistently lower than the other year pairs. There were no Pre-CAT earthquakes in the 1988/2000-2009 year pair for the East subzone (i.e., there were no earthquakes in the eastern part of the continent in 1988), so there are no hit percent results available for that subzone and year combination.

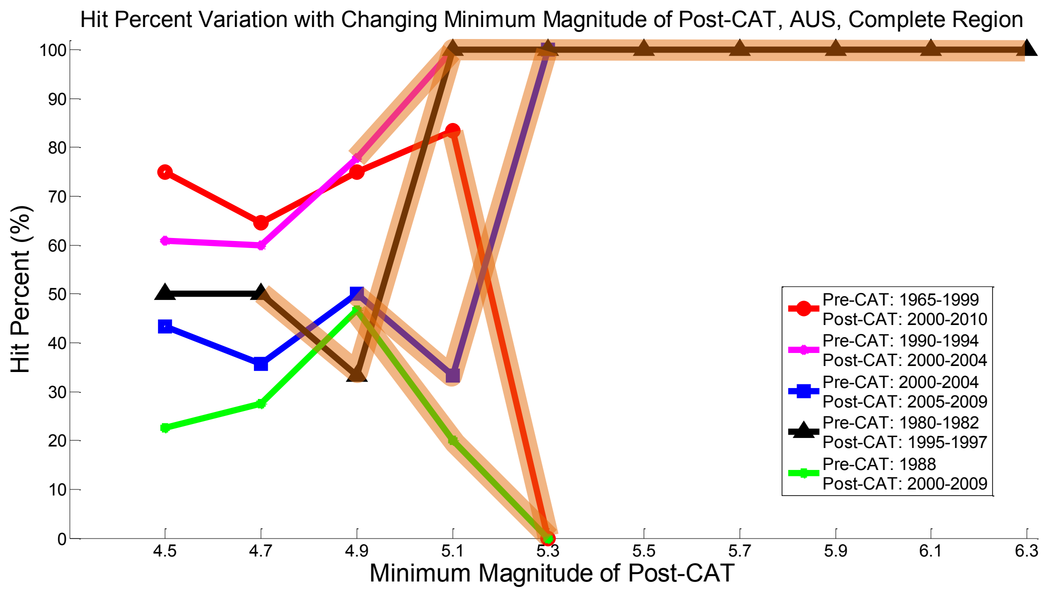


Figure 18a. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in AUS Complete region. M4.5 minimum magnitude cutoff of Pre-CAT for all catalogs. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

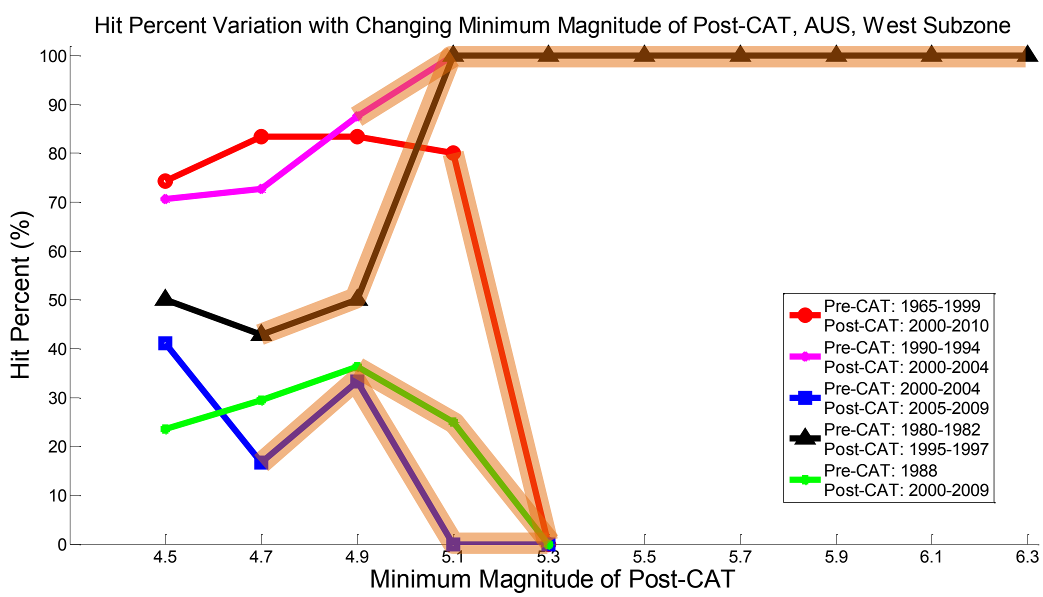


Figure 18b. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in AUS West subzone. M4.5 minimum magnitude cutoff of Pre-CAT for all catalogs. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

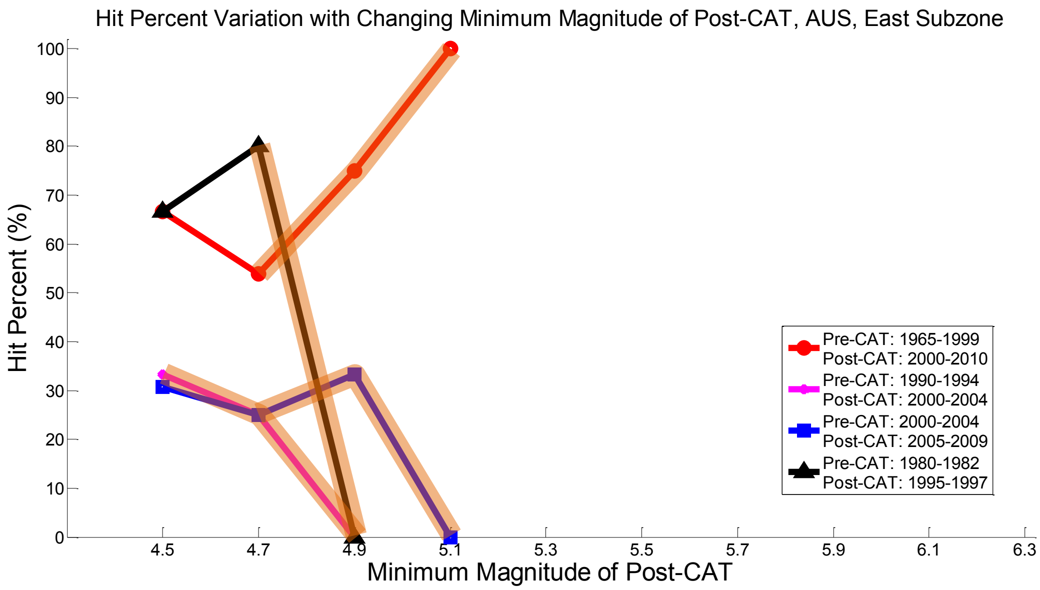


Figure 18c. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in AUS East subzone. M4.5 minimum magnitude cutoff of Pre-CAT for all catalogs. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

California: Changing Post-CAT Results

The plots of hit percent with changing minimum magnitude cutoff of the Post-CAT for the Complete CA region and North and South subzones are shown in figures 19a-19c, respectively. For statistically significant results, most hit percents ranged from the mid-70's to the upper-90's, although the 1980-1984/1995-2004 year pair for the South subzone recorded values in the low-50's. These results are typical of previous CS studies.

None of the CA catalogs for any area have any statistically significant differences between hit percents for adjacent steps, and none of the CA catalogs have a statistically significant trend in hit percent. The data are relatively flat compared to the NMSZ (which showed a general downward trend) and relatively steady compared to AUS (which showed high fluctuation between adjacent hit percent points). There are no year pairs that are consistently higher or lower than the other catalogs. In the large magnitude Post-CAT cutoff portion of the dataset (i.e., small sample size), there is no tendency for hit percents to increase, as there was in the NMSZ.

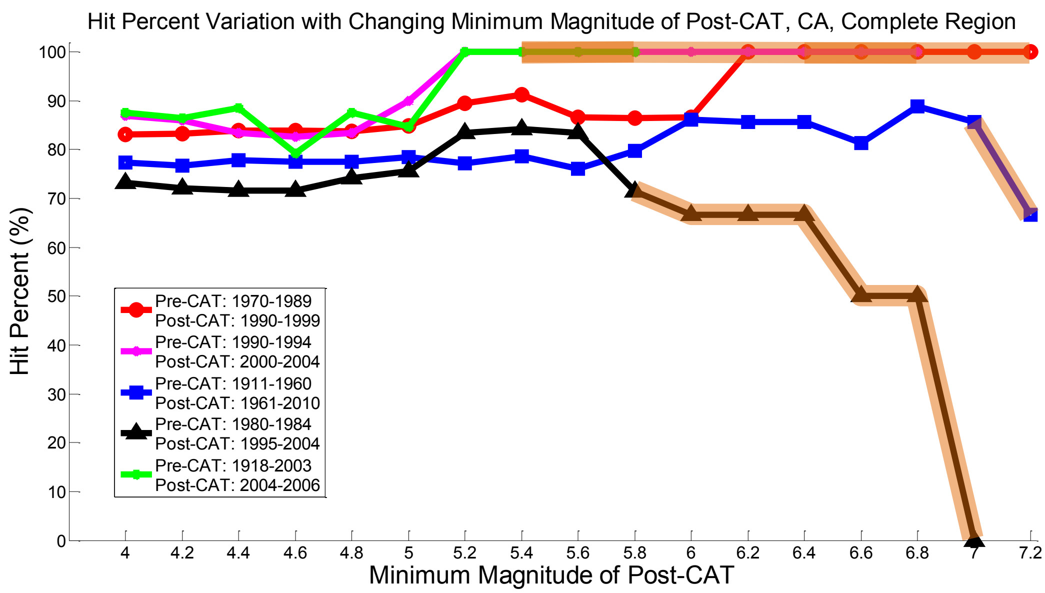


Figure 19a. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in CA Complete region. M4.0 minimum magnitude cutoff of Pre-CAT for all catalogs. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

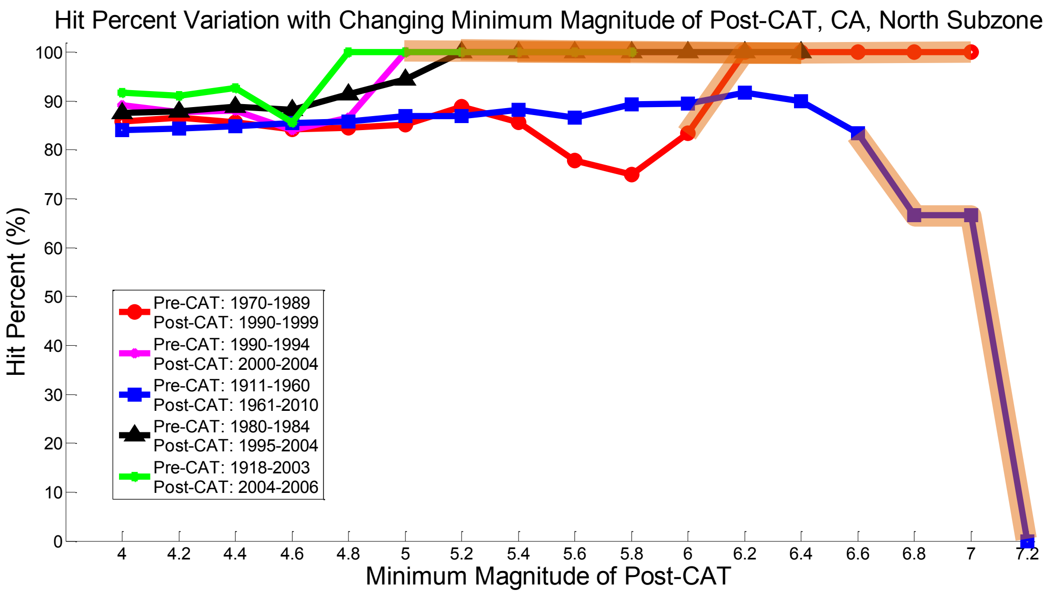


Figure 19b. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in CA North subzone. M4.0 minimum magnitude cutoff of Pre-CAT for all catalogs. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

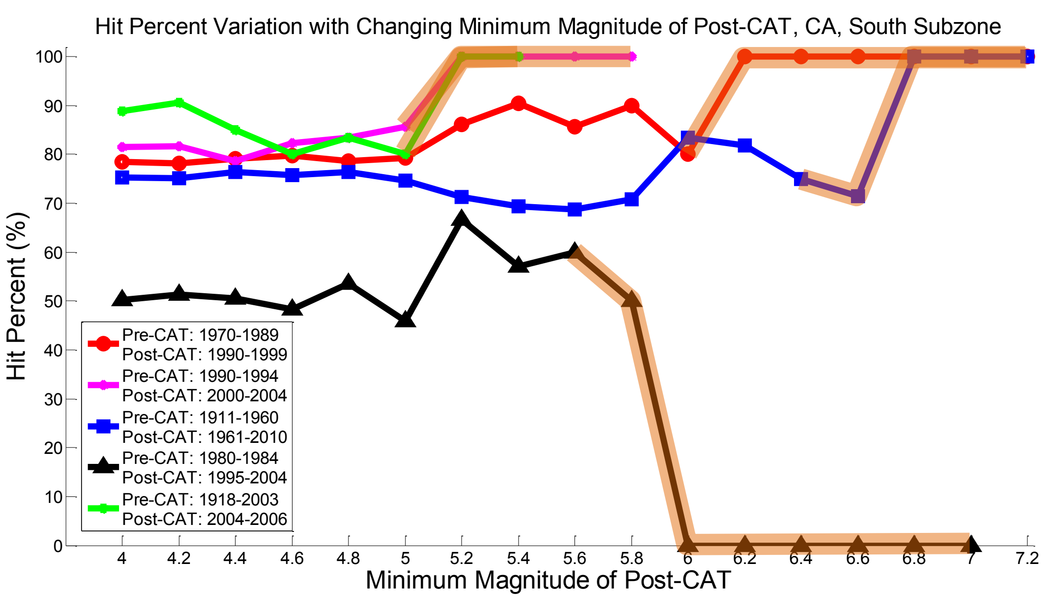


Figure 19c. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in CA South subzone. M4.0 minimum magnitude cutoff of Pre-CAT for all catalogs. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

Alaska: Changing Post-CAT Results

The plots of hit percent with changing minimum magnitude cutoff of the Post-CAT for the Complete AK region and Active and Nonactive subzones are shown in figures 20a-20c, respectively. For statistically significant results, hit percents in the Complete region and Active subzone ranged from the low-70's to mid-90's, while hit percents in the Nonactive subzone ranged from the low-30's to mid-80's.

In the Active subzone, there is one statistically significant increase in hit percent from one magnitude to the next adjacent step. That is between the Post-CAT minimum magnitude cutoffs M4.6 to M4.8 for the 1898-1972/1973-2010 catalog. When considering the statistically significant portions of these results, there are no statistically significant trends in hit percent. In the Complete region and Active subzone, the large magnitude Post-CAT cutoff hit percents behave similarly to those of the NMSZ. For all year pairs except the 1990-1994/2000-2004 Active subzone, there are 100% hits for the largest Post-CAT minimum magnitude cutoff step. These results are, in general, similar to the CA results.

In the Nonactive subzone, there are no statistically significant differences in hit percent from one magnitude to the next adjacent step, and there are no statistically significant trends in hit percent. The tendency for hit percents to increase at the largest magnitude Post-CAT cutoffs is not observed in the Nonactive subzone. Only two of the Nonactive subzone year pairs have 100% hits for the largest Post-CAT magnitude cutoff. The Nonactive subzone hit percents are, in general, lower than for the Complete region or Active subzone. The data are most similar to the AUS results in terms of high variability between catalogs and high fluctuation within a catalog, but have higher hit percents than most AUS results.

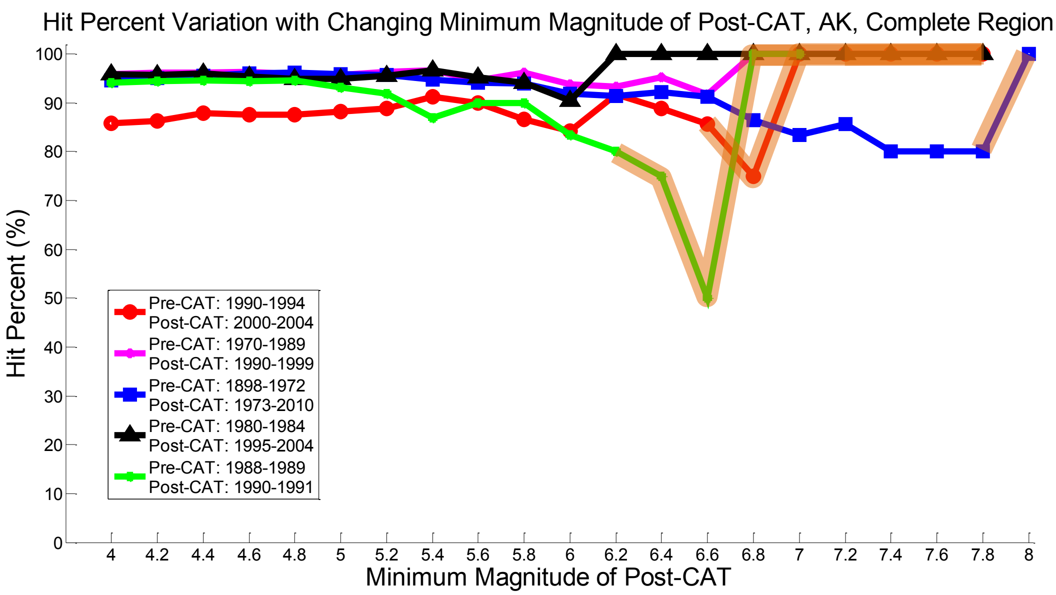


Figure 20a. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in AK Complete region. M4.0 minimum magnitude cutoff of Pre-CAT for all catalogs. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

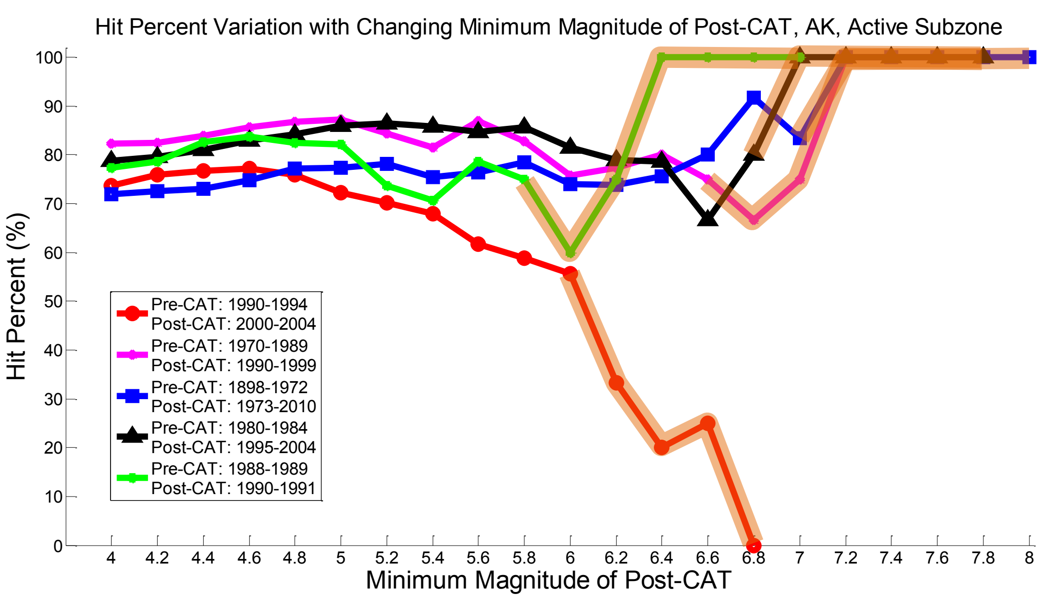


Figure 20b. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in AK Active subzone. M4.0 minimum magnitude cutoff of Pre-CAT for all catalogs. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

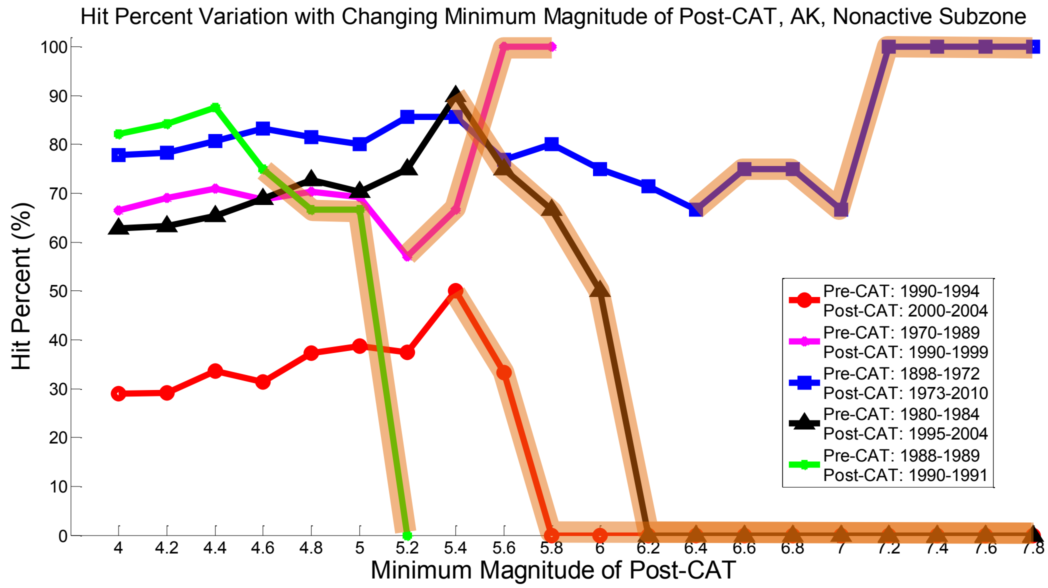


Figure 20c. Plot of hit percent with changing minimum magnitude cutoff of Post-CAT in AK Nonactive subzone. M4.0 minimum magnitude cutoff of Pre-CAT for all catalogs. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

6.2. Changing Pre-CAT Minimum Magnitude Cutoff

The changing minimum magnitude cutoff of the Pre-CAT variable maintains the minimum magnitude cutoff of the Post-CAT at a high enough magnitude such that 1% of the Post-CAT events with the largest magnitude are included, and increases the minimum magnitude cutoff of the Pre-CAT at 0.2 magnitude unit increments. This variable was only applied to the complete regions (i.e., not to any subzones). This is because the 1% largest magnitude number of earthquakes is usually a very small sample size, even for the complete regions, so limiting the Post-CAT to a specific subzone would too often create a sample size which is too small to yield statistically significant results. The data is also only statistically significant up to a certain Pre-CAT magnitude cutoff, because the number of Pre-CAT earthquakes defining the Pre-CAT circles becomes too small to be considered a complete sample. The trials that are considered to have too few earthquakes in the Pre-CAT or Post-CAT to be considered statistically significant are designated by orange shading on the plots. More detailed procedures and reasons for testing this variable are discussed in the *Variables to Analyze and Methods* section.

New Madrid Seismic Zone: Changing Pre-CAT Results

The plot of hit percent with changing minimum magnitude cutoff of the Pre-CAT for the Complete NMSZ region is shown in figure 21. The 1974-1999/2000-2010, 1990-1994/2000-2004, and 1988/2000-2009 Post-CATs have enough earthquakes so that their hit percents are statistically significant: 19, 12, and 24 earthquakes, respectively. Only three earthquakes make up the largest 1% of the 2009/2010 and 1980-1981/2005-2006 Post-CATs, so their results are not statistically significant.

The catalogs with statistical significance typically have hit percents ranging from the mid-70’s to mid-80’s, and these results are very consistent when considering those data points having a minimum magnitude cutoff of less than or equal to M3.2 (i.e., the statistically significant portion of the data). All three year pairs show a similar trend of a decrease in hit percent to the upper-40’s to low-60’s for the largest magnitude cutoffs of the Pre-CAT, although this trend is not statistically significant. There are no statistically significant changes in hit percent between any adjacent magnitude cutoff steps. The hit percents are approximately the same as those of CA and AK for the changing Post-CAT minimum magnitude cutoff variable.

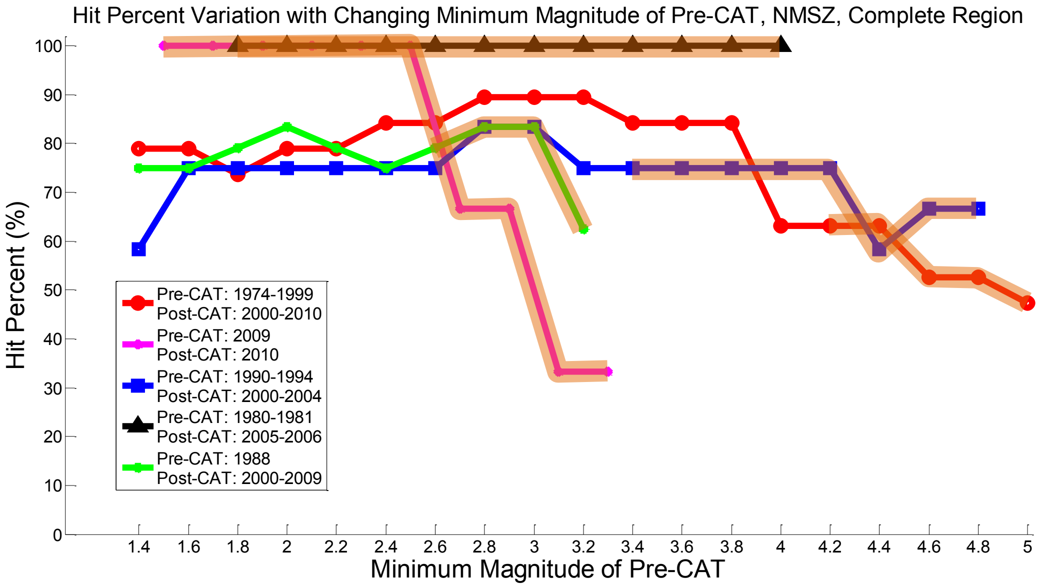


Figure 21. Plot of hit percent with changing minimum magnitude cutoff of Pre-CAT in NMSZ Complete region. Minimum magnitude cutoff of Post-CAT: 1974-19992000-2010 (M3.2), 2009/2010 (M3.3), 1990-1994/2000-2004 (M3.0), 1980-1981/2005-2006 (M4.0), 1988/2000-2009 (M3.0). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

Australia: Changing Pre-CAT Results

The plot of hit percent with changing minimum magnitude cutoff of the Pre-CAT for the Complete AUS region is shown in figure 22. To include only the 1% of the Post-CAT events with the largest magnitude resulted in only one or two earthquakes for all Post-CATs, so the sample sizes tested are extremely small. The sample sizes are too small to draw statistically significant conclusions from any of the data points, and the results shown in figure 22 cannot be considered as a basis for any conclusions about CS in this region.

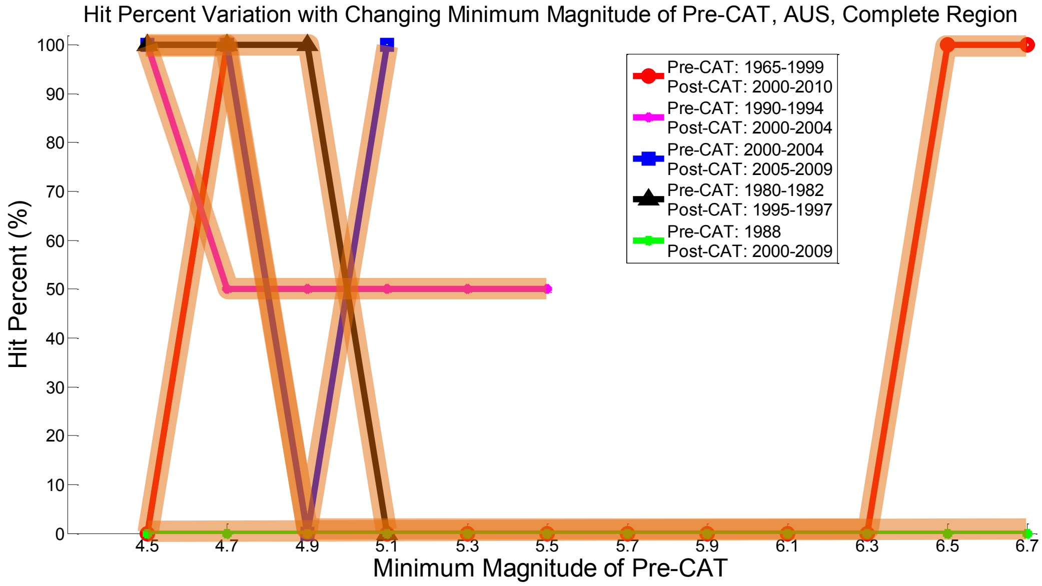


Figure 22. Plot of hit percent with changing minimum magnitude cutoff of Pre-CAT in AUS Complete region. Minimum magnitude cutoff of Post-CAT: 1965-1999/2000-2010 (M5.3), 1990-1994/2000-2004 (M5.1), 2000-2004/2005-2009 (M5.3), 1980-1982/1995-1997 (M6.3), 1988/2000-2009 (M5.3). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

<u>California: Changing Pre-CAT Results</u>

The plot of hit percent with changing minimum magnitude cutoff of the Pre-CAT for the Complete CA region is shown in figure 23. The 1970-1989/1990-1999, 1911-1960/1961-2010, and 1980-1984/1995-2004 Post-CATs have enough earthquakes that their hit percents can be analyzed for statistical significance. Only two earthquakes are in the largest 1% of the 1990-1994/2000-2004 and 1918-2003/2004-2006 Post-CATs, so their results are not considered significant.

For this region, the catalogs for which the results are statistically significant typically have hit percents ranging from the upper-50's to upper-90's. These results vary somewhat between the catalogs, but there are no statistically significant changes in hit percent between any adjacent magnitude cutoff steps.

Hit percents do not have to be compared only between adjacent magnitude steps. When comparing the smallest Pre-CAT cutoff (M4.0) with the magnitude cutoffs near the end of the statistically significant portion of the data, the 1911-1960/1961-2010 catalog pair shows statistically different hit percents. The M4.0 Pre-CAT cutoff yields 29 hits out of 33 Post-CAT earthquakes. The M6.8 Pre-CAT cutoff yields 19 hits, and this difference has a p-value of 0.011. The six Pre-CAT earthquakes used to find this result are above the five earthquake minimum needed for analysis of statistical significance in this study, but are close to this defined threshold. Using the 38 earthquakes at the M6.0 Pre-CAT cutoff step yields 29 hits, which is the same as that of the M4.0 Pre-CAT cutoff. The hit percents are consistent up to this magnitude cutoff, and the other catalog pairs are statistically consistent through their respective significant magnitude cutoffs.

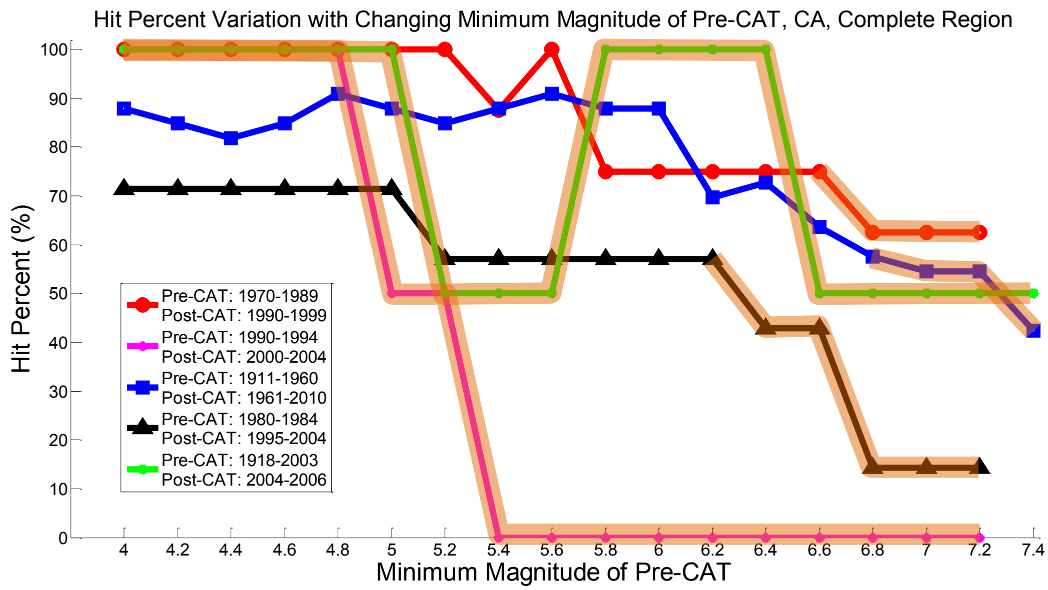


Figure 23. Plot of hit percent with changing minimum magnitude cutoff of Pre-CAT in CA Complete region. Minimum magnitude cutoff of Post-CAT: 1970-1989/1990-1999 (M6.5), 1990-1994/2000-2004 (M5.9), 1911-1960/1961-2010 (M6.1), 1980-1984/1995-2004 (M5.8), 1918-2003/2004-2006 (M5.6). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

Alaska: Changing Pre-CAT Results

The plot of hit percent with changing minimum magnitude cutoff of the Pre-CAT for the Complete AK region is shown in figure 24. All of the Post-CATs have enough earthquakes so that their hit percents are statistically significant.

For the statistically significant portion of the Pre-CAT magnitude cutoffs, hit percents range from the mid-50's to mid-90's, and these results are more tightly grouped than the CA results. None of the catalogs have a statistically significant trend in hit percent, but there are several significant decreases in hit percent from one magnitude cutoff to the next step.

Although these decreases in hit percent fall after the statistically significant portion of the Pre-CAT magnitude cutoffs, they include the Pre-CAT M6.6 to M6.8 step in the 1970-1989/1990-1999 catalog, the M7.8 to M8.0 and M8.6 to M8.8 steps in the 1898-1972/1973-2010 catalog, and the M6.2 to M6.4 step in the 1980-1984/1995-2004 catalog.

Similar to CA, three of the catalog pairs show a statistical decrease in hit percent between the smallest Pre-CAT magnitude cutoff and the end of the significant portion of the data. In the 1990-1994/2000-2004 catalog pair, the M4.0 Pre-CAT cutoff yields 14 hits out of 15 Post-CAT earthquakes. Using seven Pre-CAT earthquakes at the M6.6 cutoff yields eight hits. This difference has a p-value of 0.026. The M6.2 Pre-CAT cutoff uses 15 earthquakes and results in 12 hits, and this difference has a p-value of just 0.566. In the 1970-1989/1990-1999 catalog pair, the M4.0 Pre-CAT cutoff yields 28 hits out of 30 Post-CAT earthquakes. Using seven Pre-CAT earthquakes at the M7.0 cutoff yields 16 hits. This difference has a p-value of 0.001. The M6.6 Pre-CAT cutoff uses 18 earthquakes and results in 25 hits, and this difference has a p-value of 0.456. In the 1898-1972/1973-2010 catalog pair, the M4.0 Pre-CAT cutoff yields 96 hits out of 105 Post-CAT earthquakes. Using five Pre-CAT earthquakes at the M8.0 cutoff yields 82 hits. This difference has a p-value of 0.014. The M7.8 Pre-CAT cutoff uses eight earthquakes and results in 93 hits, and this difference has a p-value of 0.510.

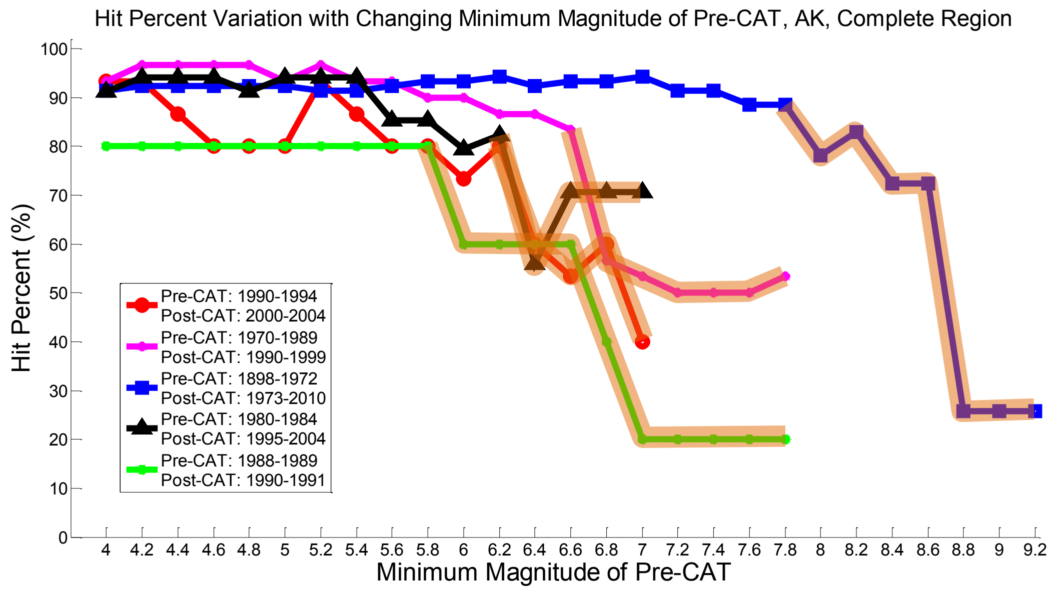


Figure 24. Plot of hit percent with changing minimum magnitude cutoff of Pre-CAT in AK Complete region. Minimum magnitude cutoff of Post-CAT: 1990-1994/2000-2004 (M6.1), 1970-1989/1990-1999 (M6.2), 1898-1972/1973-2010 (M6.2), 1980-1984/1995-2004 (M6.1), 1988-1989/1990-1991 (M6.3). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

6.3. Depth Layering

The depth variable divides each Pre-CAT/Post-CAT pair into a shallow, intermediate, and deep layer. CS is then performed on the earthquakes that occurred within each layer. All magnitude earthquakes are included, down to the smallest magnitude for which the catalog is considered complete (based on the Gutenberg-Richter recurrence relationship). The data were divided based on approximate visual grouping, not necessarily on any tectonic relationship, and the defined depth points of division were different for each region. The trials that are considered to have too few earthquakes in the Pre-CAT or Post-CAT to be considered statistically significant are designated by orange shading on the plot. More detailed procedures and reasons for testing this variable are discussed in the *Variables to Analyze and Methods* section.

<u>New Madrid Seismic Zone: Depth Results</u>

The plots of hit percent with depth layers for the Complete NMSZ region and the Black, Yellow, Blue, and Purple subzones are shown in figures 25a-25e, respectively. Hit percents for the Complete region and Black and Yellow subzones ranged from the mid-70's to upper-90's, and hit percents for the Blue and Purple subzones ranged from the mid-40's to upper-90's. The Purple subzone did not have any shallow earthquakes for the 1988/2000-2009 catalog pair or any deep earthquakes for the 2009/2010 or 1988/2000-2009 catalog pairs.

In most cases, there was a tendency for intermediate depth earthquakes to have a higher hit percent than shallow or deep earthquakes, and many of these differences were statistically significant. In 24 hit percent comparisons between shallow and intermediate depth earthquakes within a catalog, 14 had a statistically significant difference. In all 14 cases, the intermediate depth hit percent was higher. In 23 hit percent comparisons between intermediate and deep earthquakes within a catalog, 13 had a statistically significant difference. In all 13 cases, the intermediate depth hit percent was higher. When comparing hit percents between shallow and deep earthquakes within a catalog, three out of 23 differences were statistically significant. In all three cases, the shallow depth hit percent was higher.

In the Complete NMSZ region, the intermediate layer had a statistically higher hit percent than the corresponding shallow layer three times and the corresponding deep layer three times. In the Black subzone, the intermediate layer had a statistically higher hit percent than the corresponding shallow layer four times and the corresponding deep layer five times. In the Yellow subzone, the intermediate layer had a statistically higher hit percent than the corresponding shallow layer five times and the corresponding deep layer four times. In the Blue subzone, the intermediate layer had a statistically higher hit percent than the corresponding shallow layer two times and the corresponding deep layer five times. There were no statistically significant differences in hit percent between depth layers within a catalog pair for the Purple subzone.

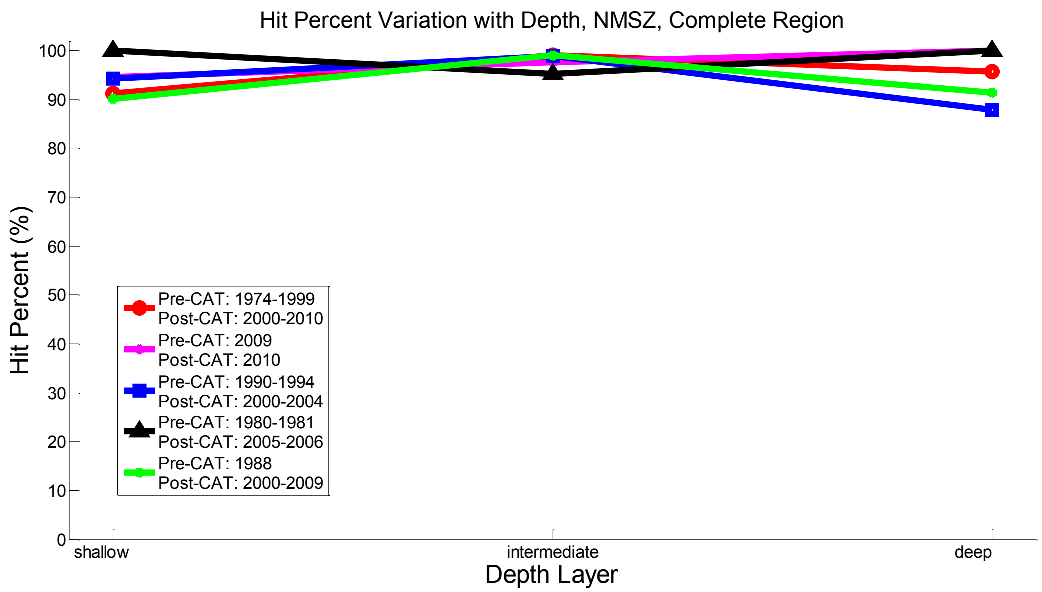


Figure 25a. Plot of hit percent with depth in NMSZ Complete region. Depth layers defined by: shallow (less than 6 km), intermediate (between 6 and 11.5 km), deep (greater than or equal to 11.5 km).

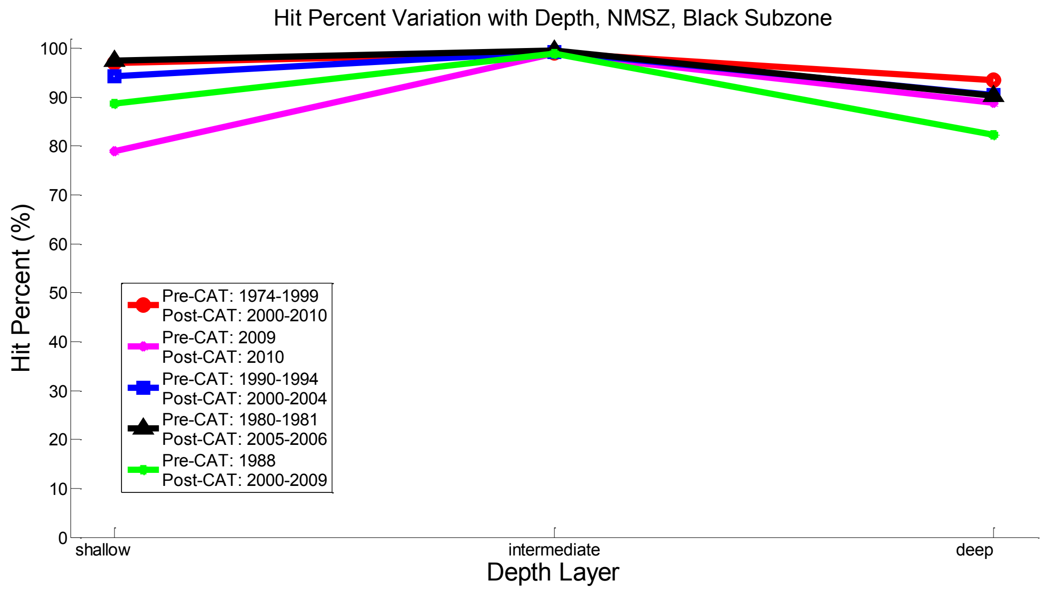


Figure 25b. Plot of hit percent with depth in NMSZ Black subzone. Depth layers defined by: shallow (less than 6 km), intermediate (between 6 and 11.5 km), deep (greater than or equal to 11.5 km).

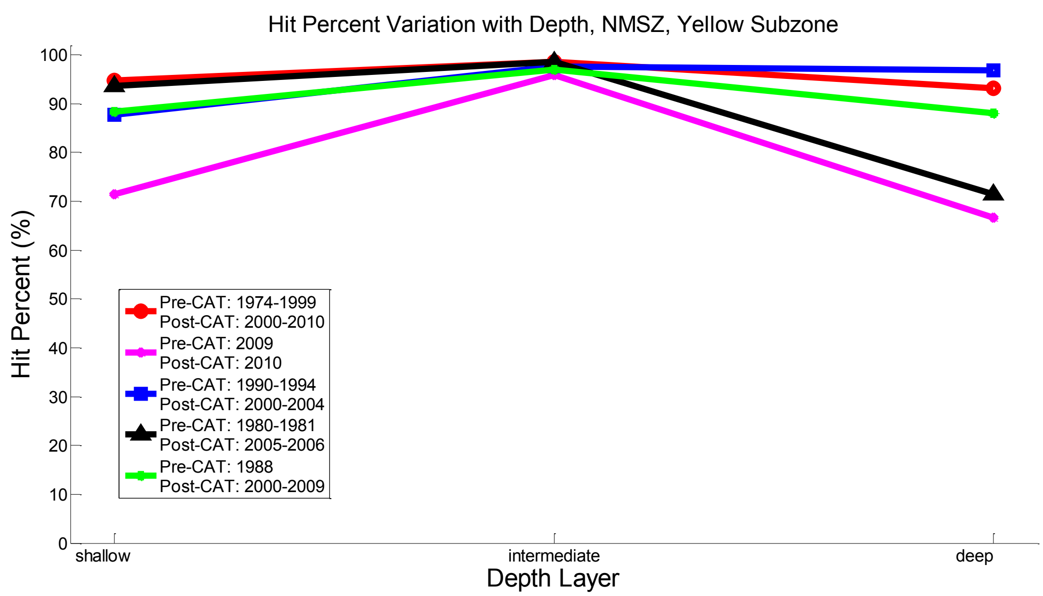


Figure 25c. Plot of hit percent with depth in NMSZ Yellow subzone. Depth layers defined by: shallow (less than 6 km), intermediate (between 6 and 11.5 km), deep (greater than or equal to 11.5 km).

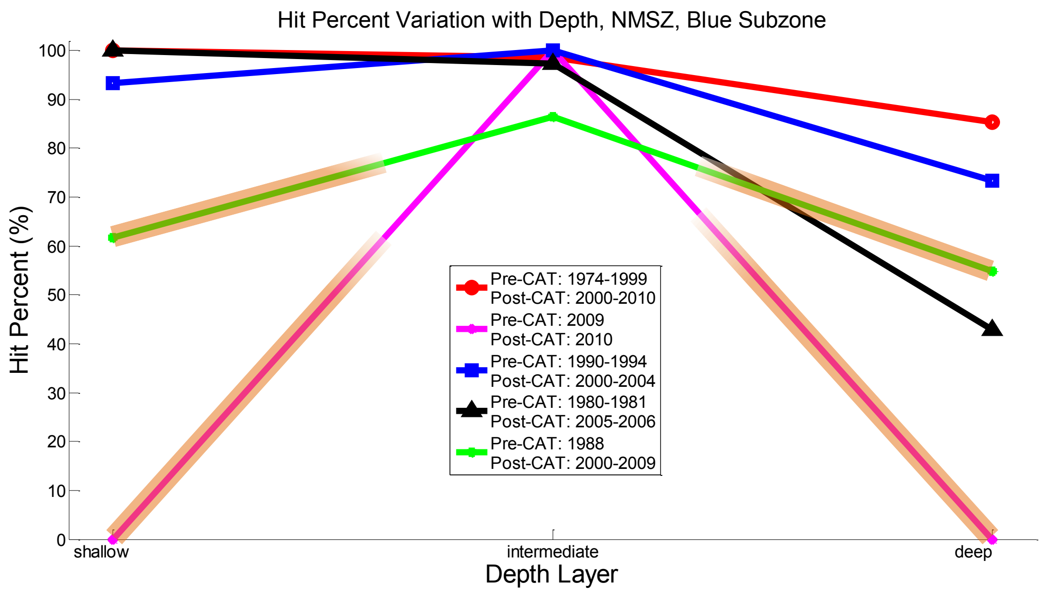


Figure 25d. Plot of hit percent with depth in NMSZ Blue subzone. Depth layers defined by: shallow (less than 6 km), intermediate (between 6 and 11.5 km), deep (greater than or equal to 11.5 km). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

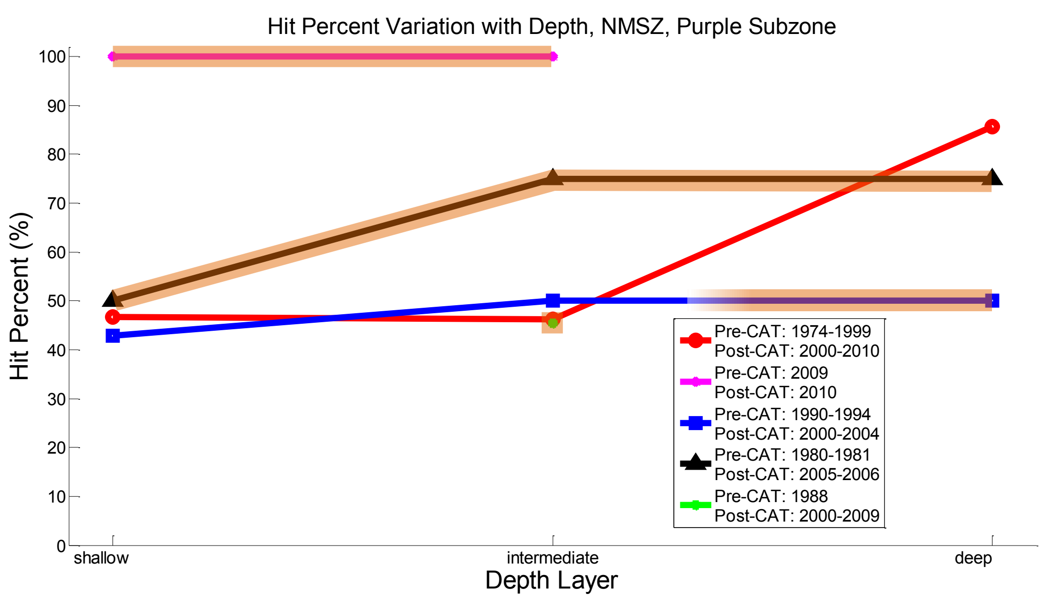


Figure 25e. Plot of hit percent with depth in NMSZ Purple subzone. Depth layers defined by: shallow (less than 6 km), intermediate (between 6 and 11.5 km), deep (greater than or equal to 11.5 km). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

Australia: Depth Results

The plots of hit percent with depth layers for the Complete AUS region and the West and East subzones are show in figures 26a-26c, respectively. Hit percents for the Complete region and West subzone ranged from the low-20's to mid-90's. There were no shallow earthquakes for the 1980-1982/1995-1997 catalog pair. The East subzone did not have any Pre-CAT earthquakes for the 1988/2000-2009 catalog pair, did not have any shallow Pre-CAT earthquakes for the 1965-1999/2000-2010 or 1990-1994/2000-2004 catalog pairs, did not have any intermediate Pre-CAT earthquakes for the 1980-1982/1995-1997 catalog pair, did not have any deep earthquakes for the 1990-1994/2000-2004 catalog pair, and did not have any deep Pre-CAT earthquakes for the 2000-2004/2005-2009 catalog pair. This resulted in the collection of only six out of a possible 15 data points for the East subzone (i.e., three depth layers for each of the five catalog pairs).

In the Complete region and West subzone, deep earthquakes had a statistically higher hit percent than did shallow or intermediate depth earthquakes for the 2000-2004/2005-2009 catalog pair. In the West subzone, deep earthquakes had a statistically higher hit percent than did intermediate depth earthquakes for the 1988/2000-2009 catalog pair. There were no statistically significant differences in hit percent between depth layers within a catalog pair for the East subzone.

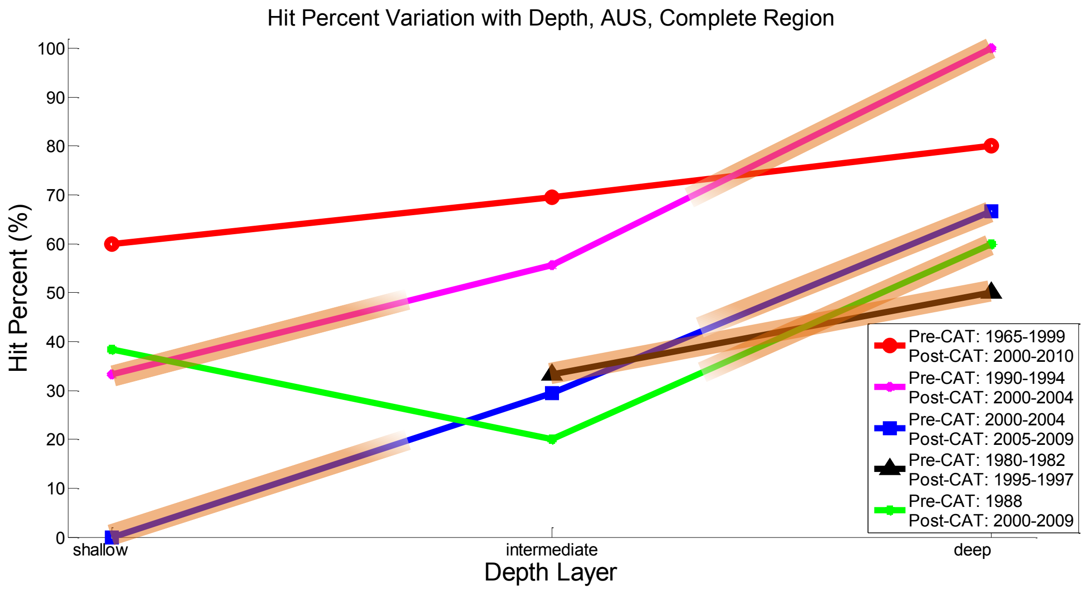


Figure 26a. Plot of hit percent with depth in AUS Complete region. Depth layers defined by: shallow (less than 10 km), intermediate (between 10 and 30 km), deep (greater than or equal to 30 km). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

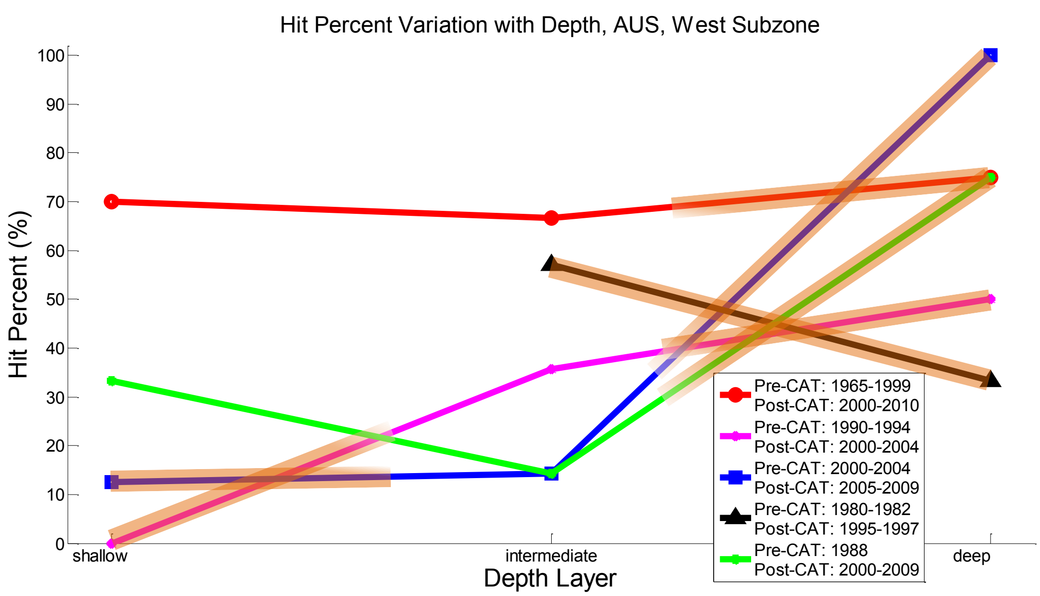


Figure 26b. Plot of hit percent with depth in AUS West subzone. Depth layers defined by: shallow (less than 10 km), intermediate (between 10 and 30 km), deep (greater than or equal to 30 km). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

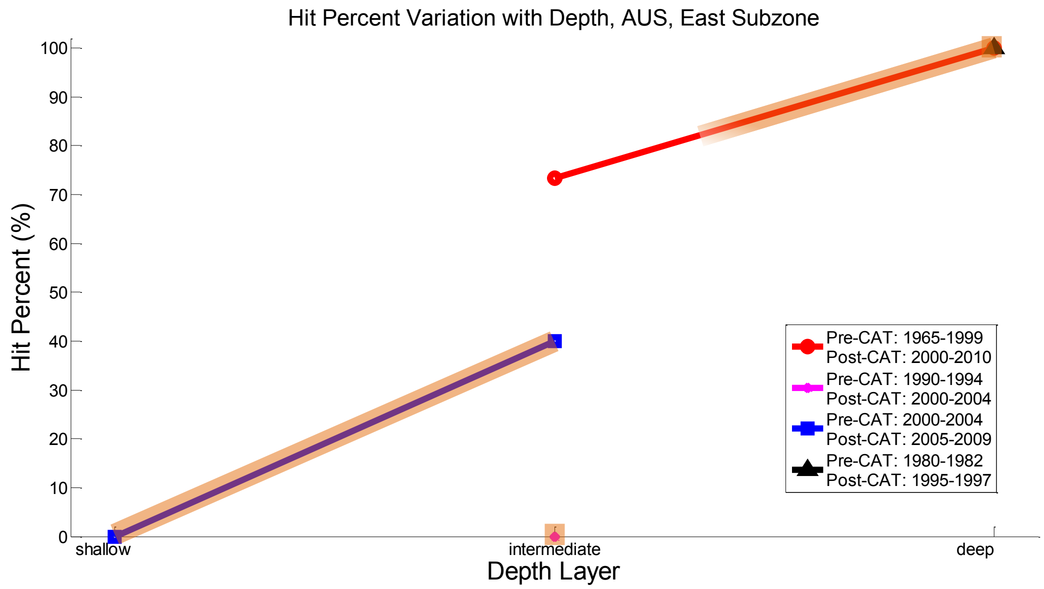


Figure 26c. Plot of hit percent with depth in AUS East subzone. Depth layers defined by: shallow (less than 10 km), intermediate (between 10 and 30 km), deep (greater than or equal to 30 km). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

California: Depth Results

The plots of hit percent with depth layers for the Complete CA region and the North and South subzones are show in figures 27a-27c, respectively. Hit percents typically ranged from the mid-40's to upper-90's, although these values vary highly. The North subzone did not have any Pre-CAT intermediate earthquakes for the 1911-1960/1961-2010 catalog pair, did not have any Pre-CAT deep earthquakes for the 1911-1960/1961-2010 catalog pair, and did not have any Post-CAT deep earthquakes for the 1918-2003/2004-2006 catalog pair. The South subzone did not have any deep earthquakes for the 1970-1989/1990-1999, 1990-1994/2000-2004, 1980-1984/1995-2004, or 1918-2003/2004-2006 catalog pairs.

Hit percents are relatively constant with depth, but there are statistically significant differences. These differences tend to show decreasing hit percent with depth. In the Complete region, the 1911-1960/1961-2010 catalog pair shallow layer hit percent was statistically higher than the intermediate and deep layer hit percents. The deep layer hit percent was statistically lower than the shallow and intermediate layer hit percents in the 1918-2003/2004-2006 catalog pair. The shallow layer hit percent was statistically higher than the intermediate layer hit percent for the North subzone 1980-1984/1995-2004 and South subzone 1911-1960/1961-2010 catalog pairs.

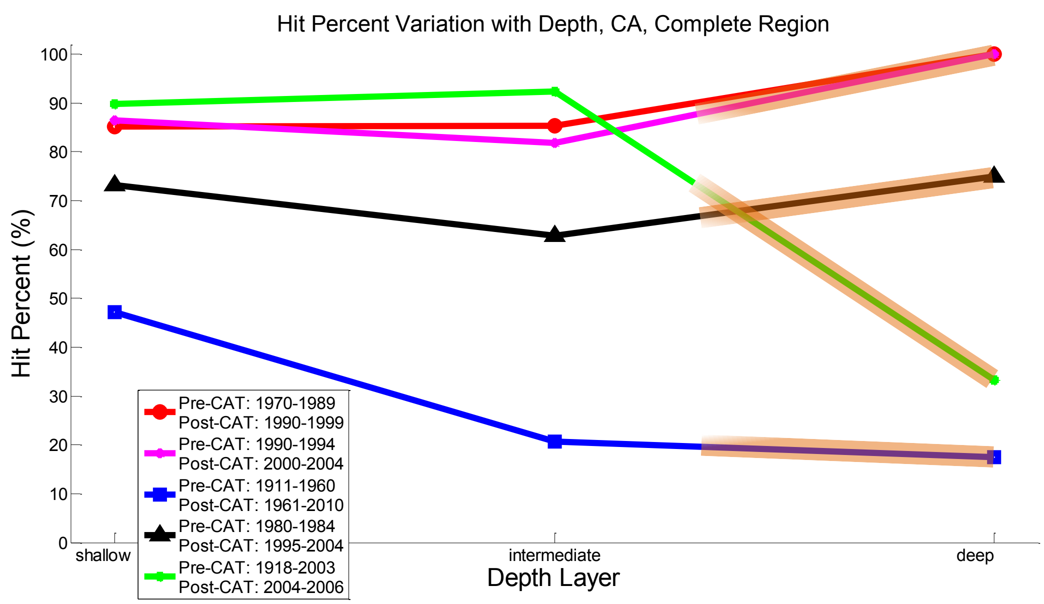


Figure 27a. Plot of hit percent with depth in CA Complete region. Depth layers defined by: shallow (less than 15 km), intermediate (between 15 and 30 km), deep (greater than or equal to 30 km). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

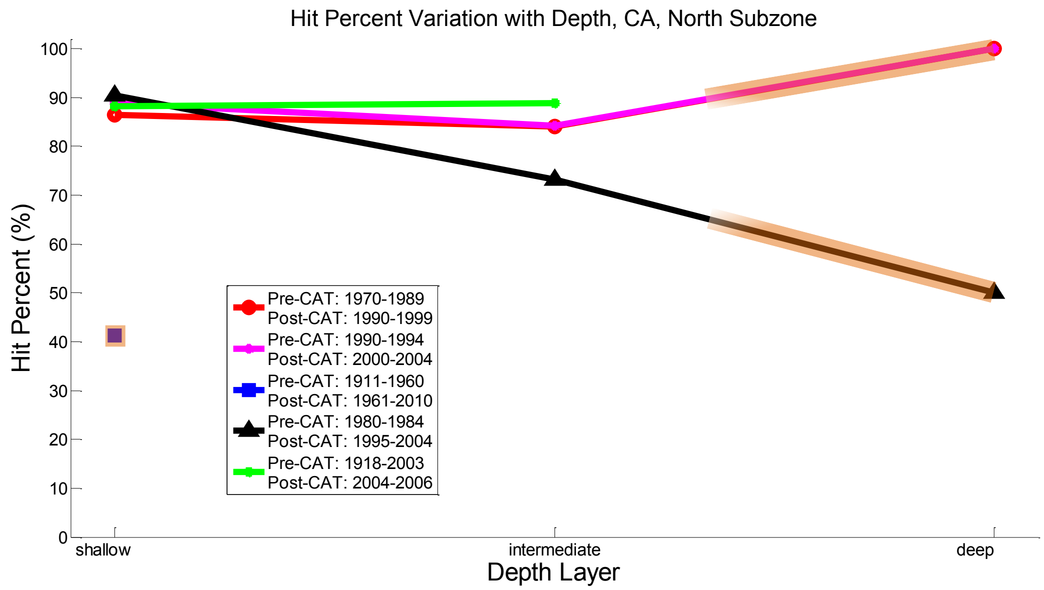


Figure 27b. Plot of hit percent with depth in CA North subzone. Depth layers defined by: shallow (less than 15 km), intermediate (between 15 and 30 km), deep (greater than or equal to 30 km). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

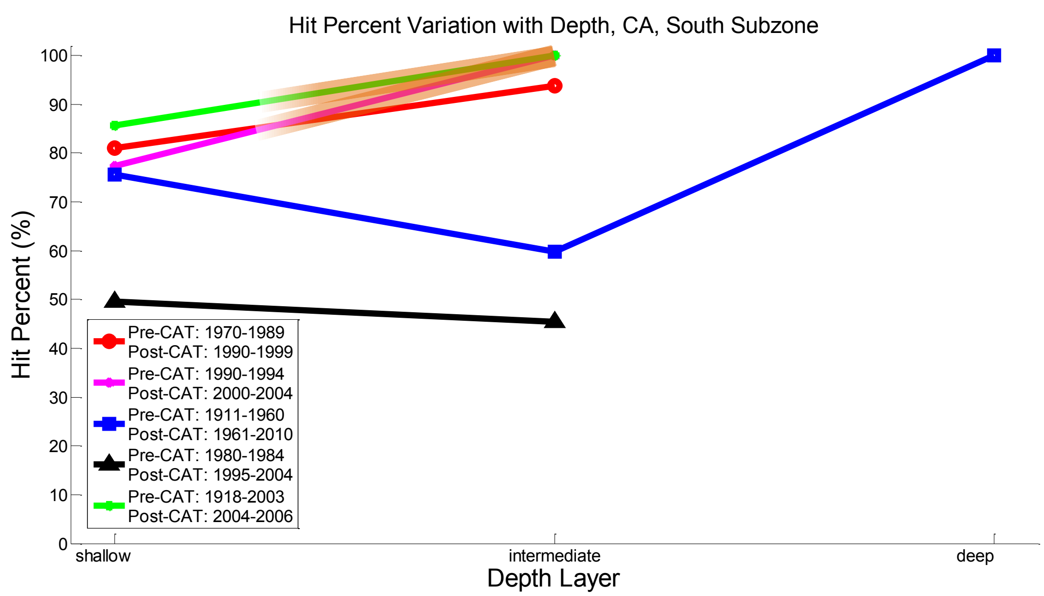


Figure 27c. Plot of hit percent with depth in CA South subzone. Depth layers defined by: shallow (less than 15 km), intermediate (between 15 and 30 km), deep (greater than or equal to 30 km). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

Alaska: Depth Results

The plots of hit percent with depth layers for the Complete AK region and the Active and Nonactive subzones are show in figures 28a-28c, respectively. Hit percents for the Complete region and Active subzone ranged from the low-60's to upper-90's. Hit percents for the Nonactive subzone ranged from the low-20's to low-70's. The Nonactive subzone did not have any deep earthquakes for the 1990-1994/2000-2004, 1980-1984/1995-2004, 1988-1989/1990-1991, or Post-CAT 1970-1989/1990-1999 catalog pairs. Unlike the case for the other regions analyzed, hit percents tended to increase with depth for AK, and many differences between layers were statistically significant. There were no statistically significant differences in which the shallower layer had a higher hit percent.

In the Complete region, all five hit percent differences between the shallow and intermediate depth layers showed the intermediate layer to be significantly higher. Four of the comparisons between the shallow and deep layers showed the deep layer to be significantly higher. One of the comparisons between the intermediate and deep layers showed a significant difference, with a higher hit percent in the deep layer.

In the Active subzone, all five hit percent differences between the shallow and intermediate depth layers showed the intermediate layer to be significantly higher. All five of the comparisons between the shallow and deep layers also showed the deep layer to be significantly higher. Two of the comparisons between the intermediate and deep layers showed a significant difference, both with a higher hit percent in the deep layer.

The increase in hit percents from the shallow to intermediate depth layer in the 1980-1984/1995-2004 was the only statistically significant difference in hit percent in the Nonactive subzone.

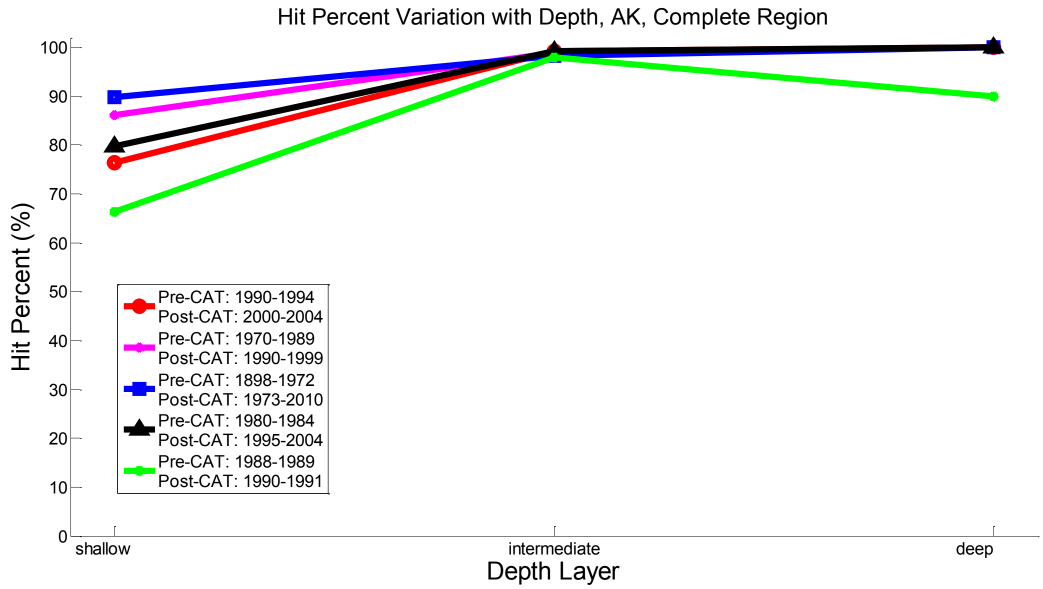


Figure 28a. Plot of hit percent with depth in AK Complete region. Depth layers defined by: shallow (less than 25 km), intermediate (between 25 and 140 km), deep (greater than or equal to 140 km).

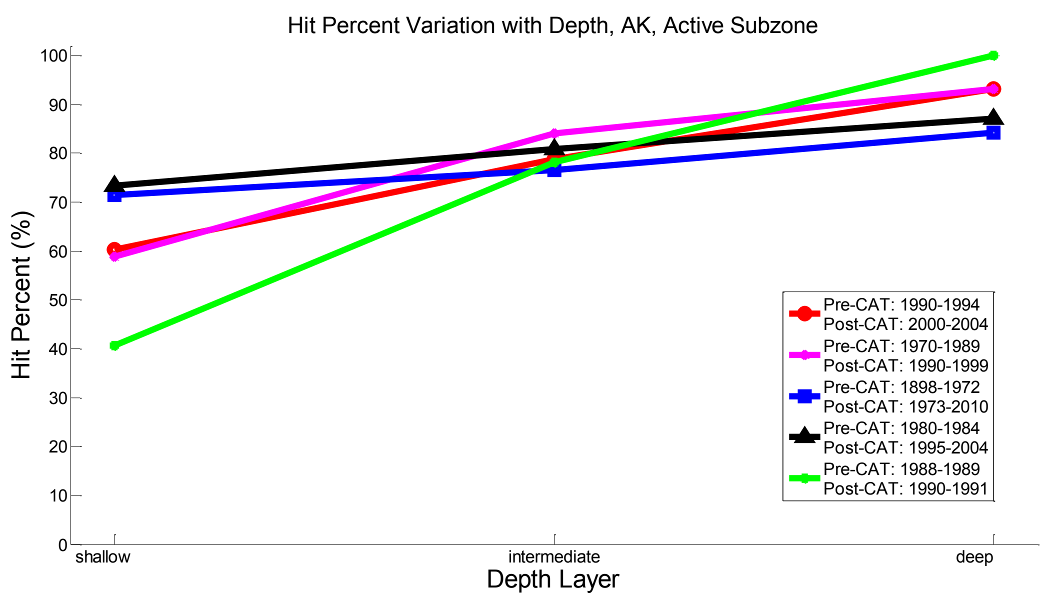


Figure 28b. Plot of hit percent with depth in AK Active subzone. Depth layers defined by: shallow (less than 25 km), intermediate (between 25 and 140 km), deep (greater than or equal to 140 km).

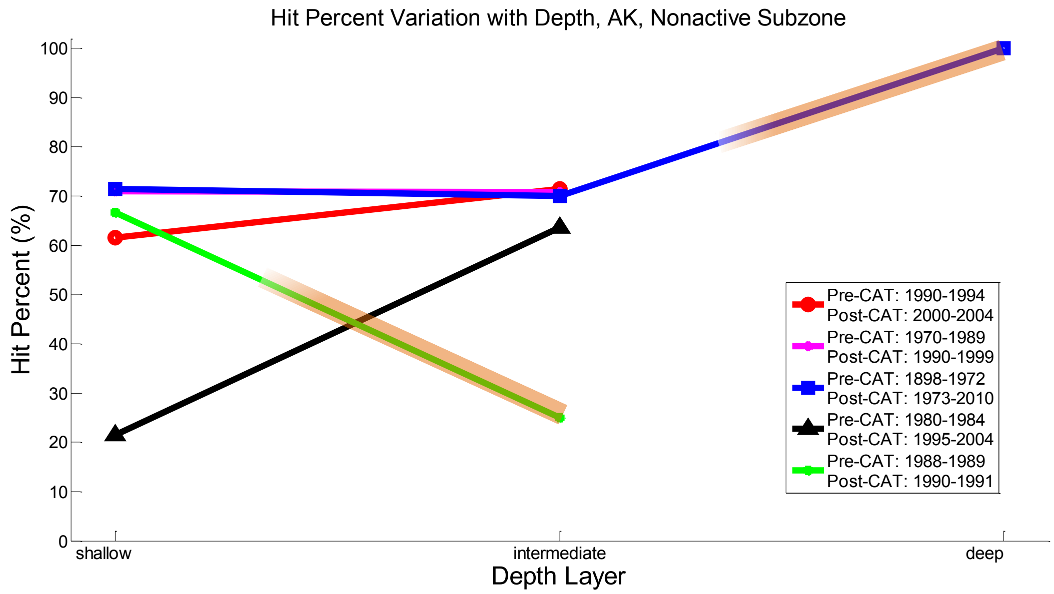


Figure 28c. Plot of hit percent with depth in AK Nonactive subzone. Depth layers defined by: shallow (less than 25 km), intermediate (between 25 and 140 km), deep (greater than or equal to 140 km). Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

6.4. Time Progression

The time progression variable maintains the same Pre-CAT for several trials. The Post-CAT in the first trial is temporally adjacent to the Pre-CAT, and then the time span of the Post-CAT is progressively moved further away from the Pre-CAT in subsequent trials. The hit percent from the zero time gap Post-CAT trial is compared against the ensuing non-zero time gap Post-CAT trials. All depths and magnitudes of the earthquakes are included, down to the smallest magnitude for which the catalog is considered complete, based on the Gutenberg-Richter recurrence relationship. The total catalog is divided into five and 10 year segments, which is the amount by which the Post-CAT is shifted in each trial. The trials that are considered to have too few earthquakes in the Pre-CAT or Post-CAT to be considered statistically significant are designated by orange shading on the plot. More detailed procedures and reasons for testing this variable are discussed in the *Variables to Analyze and Methods* section.

New Madrid Seismic Zone: Time Progression Results

Any statistically significant differences in hit percent between the zero time gap trial in each set and the non-zero time gap trials are shown in tables 2a-2e. The Complete region and Black and Yellow subzones typically have hit percents in the mid-90's. The Blue subzone has hit percents that range from the upper-70's to mid-90's. The Purple subzone has hit percents that range from the mid-40's to upper-80's.

The plots of hit percent with Post-CAT years for the Complete NMSZ region and Black, Yellow, Blue, and Purple subzones are shown in figures 29a-29f. Figures 29a-29e use five year segments, while figure 29f uses 10 year segments. For the five year segment trials, each successive plot uses a later five year segment as the Pre-CAT (i.e., figure 29a uses 1975-1979 as the Pre-CAT, figure 29b uses 1980-1984 as the Pre-CAT, etc.).

For the 1975-1979 Pre-CAT (figure 29a), the Complete region 2000-2004 and 2005-2009 Post-CAT hit percents are statistically higher than the 1980-1984 Post-CAT hit percent. The 2000-2004 and 2005-2009 Post-CAT hit percents for the Black subzone are also statistically higher than the 1980-1984 Post-CAT hit percent. In addition to the 2000-2004 and 2005-2009 Post-CATs, the 1995-1999 Post-CAT hit percent is also statistically higher than the 1980-1984 Post-CAT hit percent for the Yellow subzone. For the Blue subzone, the 2005-2009 Post-CAT hit percent is statistically higher than the 1980-1984 Post-CAT hit percent. For the Purple subzone, the 1985-1989, 1990-1994, and 2000-2004 Post-CAT hit percents are statistically lower than the 1980-1984 Post-CAT hit percent.

For the 1980-1984 Pre-CAT (figure 29b), the Complete region 2000-2004 and 2005-2009 Post-CAT hit percents are statistically higher than the 1985-1989 Post-CAT hit percent. The 2005-2009 Post-CAT hit percent for the Black subzone is statistically higher than the 1985-1989 Post-CAT hit percent. In the Yellow subzone, the 1995-1999, 2000-2004, and 2005-2009 Post-CAT hit percents are all statistically higher than the 1985-1989 Post-CAT hit percent. In the Blue subzone, the 1990-1994 Post-CAT hit percent is statistically lower than the 1985-1989 Post-CAT hit percent, and the 2005-2009 Post-CAT hit percent is statistically higher. For the Purple subzone, the 1995-1999 Post-CAT hit percent is statistically higher than the 1985-1989 Post-CAT hit percent.

For the 1985-1989 Pre-CAT (figure 29c), the 2000-2004 and 2005-2009 Post-CAT hit percents are statistically higher than the 1990-1994 Post-CAT hit percent for the Complete region and the Black and Yellow subzones. For the Blue subzone, the 2005-2009 Post-CAT hit percent is statistically higher than the 1990-1994 Post-CAT hit percent. There are no statistically significant differences in hit percent for different Post-CATs for the Purple subzone.

For the 1990-1994 Pre-CAT (figure 29d), both the 2000-2004 and 2005-2009 Post-CAT hit percents are statistically higher than the 1995-1999 Post-CAT hit percent for the Complete region. Although the hit percents for the Black, Yellow, and Blue subzones show similar trends to the Complete region, the differences are not statistically significant. There are no significant differences in hit percent for different Post-CATs for any of the subzones.

For the 1995-1999 Pre-CAT (figure 29e), there is a significant increase in hit percent between the 2000-2004 and 2005-2009 Post-CAT hit percents for the Blue subzone. There is not a significant difference in hit percent for the Complete region or the Black, Yellow, or Purple subzones.

For the 10 year segment trial with the Pre-CAT 1980-1989 (figure 29f), there is a significant increase in hit percent between the 1990-1999 and 2000-2009 Post-CAT hit percents for the Complete region and the Black, Yellow, and Blue subzones, but there is no significant difference for the Purple subzone.

NMSZ, Complete Region

Pre-CAT 1975-1979	Post-CAT 1980-1984	Post-CAT 1985-1989 —	Post-CAT 1990-1994 —	Post-CAT 1995-1999 —	Post-CAT 2000-2004 ↑	Post-CAT 2005-2009 ↑
	Pre-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994 —	Post-CAT 1995-1999 —	Post-CAT 2000-2004 ↑	Post-CAT 2005-2009 ↑
		Pre-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999 —	Post-CAT 2000-2004 ↑	Post-CAT 2005-2009 ↑
			Pre-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004 ↑	Post-CAT 2005-2009 ↑
				Pre-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009 —

Pre-CAT 1980-1989	Post-CAT 1990-1999	Post-CAT 2000-2009 ↑

Table 2a. Chart of statistically significant changes in hit percent for NMSZ Complete region progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

NMSZ, Black Subzone

Pre-CAT 1975-1979	Post-CAT 1980-1984	Post-CAT 1985-1989 −	Post-CAT 1990-1994 −	Post-CAT 1995-1999 −	Post-CAT 2000-2004 ↑	Post-CAT 2005-2009 ↑
	Pre-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994 −	Post-CAT 1995-1999 −	Post-CAT 2000-2004 −	Post-CAT 2005-2009 ↑
		Pre-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999 −	Post-CAT 2000-2004 ↑	Post-CAT 2005-2009 ↑
			Pre-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004 −	Post-CAT 2005-2009 −
				Pre-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009 −

Pre-CAT 1980-1989	Post-CAT 1990-1999	Post-CAT 2000-2009 ↑

Table 2b. Chart of statistically significant changes in hit percent for NMSZ Black subzone progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

NMSZ, Yellow Subzone

Pre-CAT 1975-1979	Post-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009
	Pre-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009
		Pre-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009
			Pre-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009
				Pre-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009

Pre-CAT 1980-1989	Post-CAT 1990-1999	Post-CAT 2000-2009

Table 2c. Chart of statistically significant changes in hit percent for NMSZ Yellow subzone progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

NMSZ, Blue Subzone

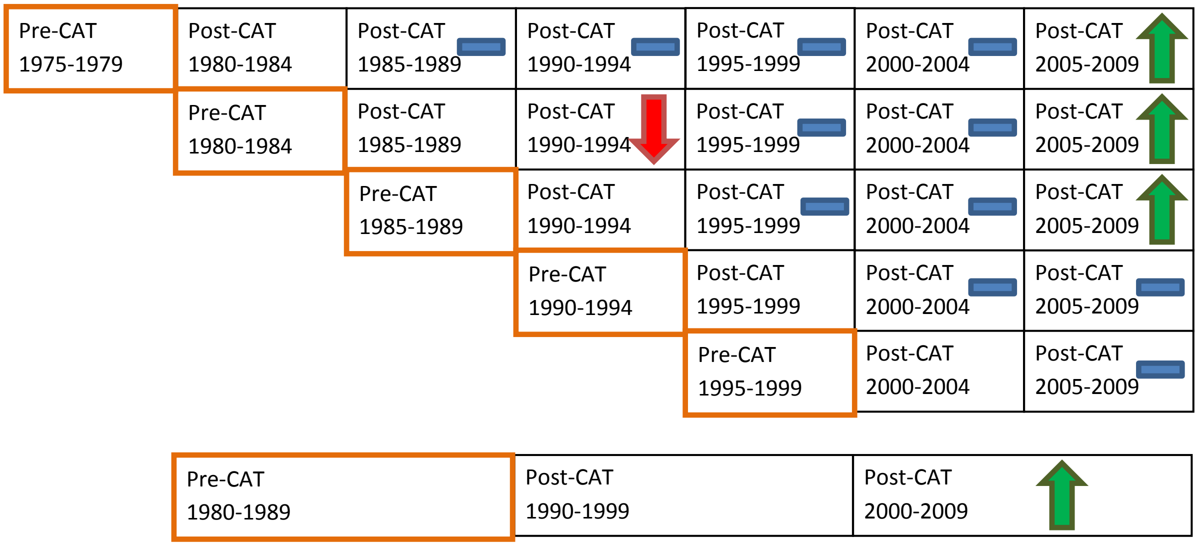


Table 2d. Chart of statistically significant changes in hit percent for NMSZ Blue subzone progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

NMSZ, Purple Subzone

Pre-CAT 1975-1979	Post-CAT 1980-1984	Post-CAT 1985-1989 ↓	Post-CAT 1990-1994 ↓	Post-CAT 1995-1999 –	Post-CAT 2000-2004 ↓	Post-CAT 2005-2009 –
	Pre-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994 –	Post-CAT 1995-1999 ↑	Post-CAT 2000-2004 –	Post-CAT 2005-2009 –
		Pre-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999 –	Post-CAT 2000-2004 –	Post-CAT 2005-2009 –
			Pre-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004 –	Post-CAT 2005-2009 –
				Pre-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009 –

Pre-CAT 1980-1989	Post-CAT 1990-1999	Post-CAT 2000-2009 –

Table 2e. Chart of statistically significant changes in hit percent for NMSZ Purple subzone progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

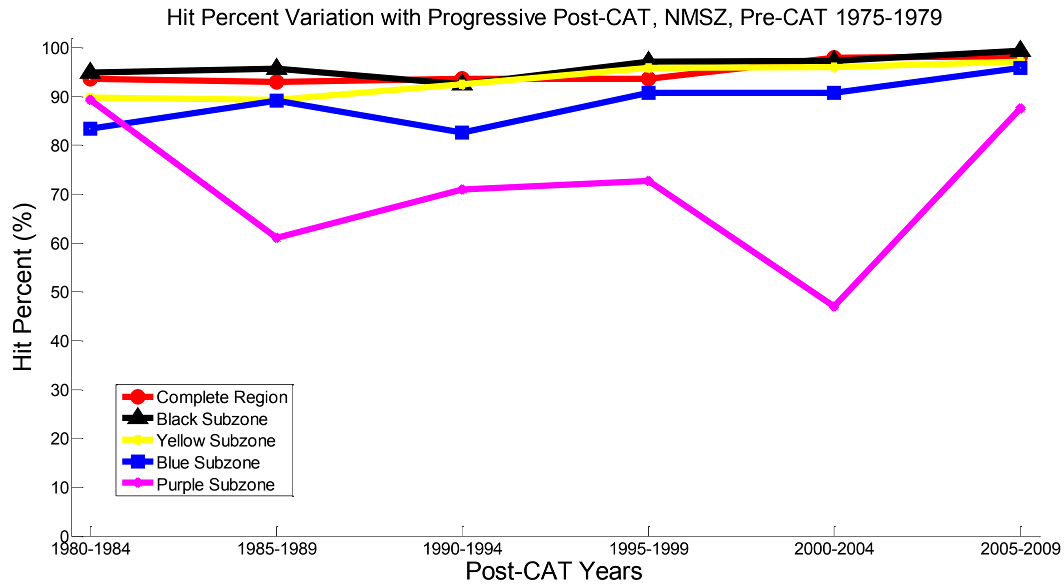


Figure 29a. Hit percent with progressive Post-CAT in NMSZ. Pre-CAT 1975-1979.

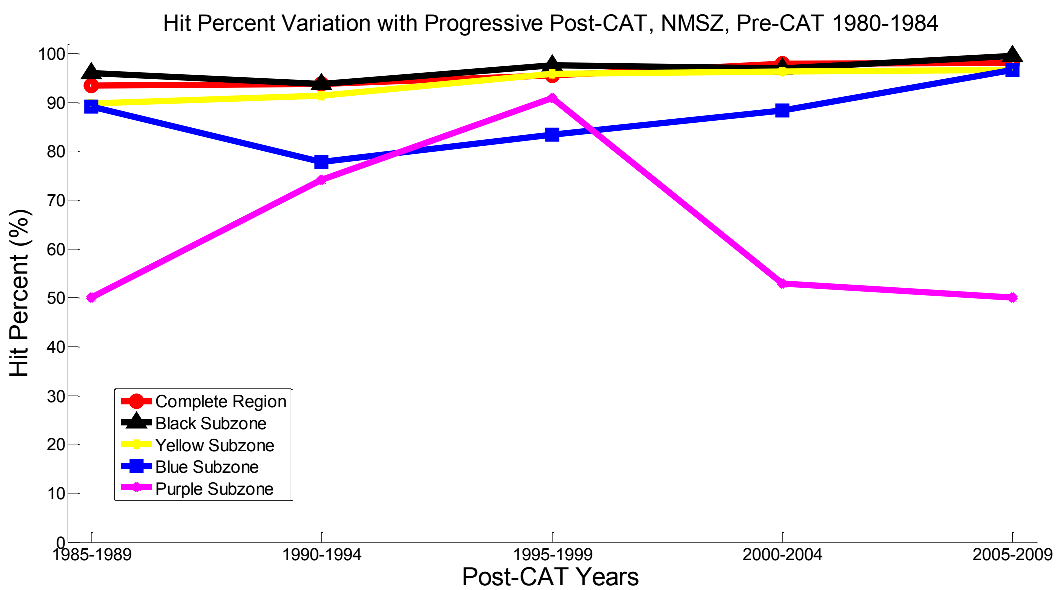


Figure 29b. Hit percent with progressive Post-CAT in NMSZ. Pre-CAT 1980-1984.

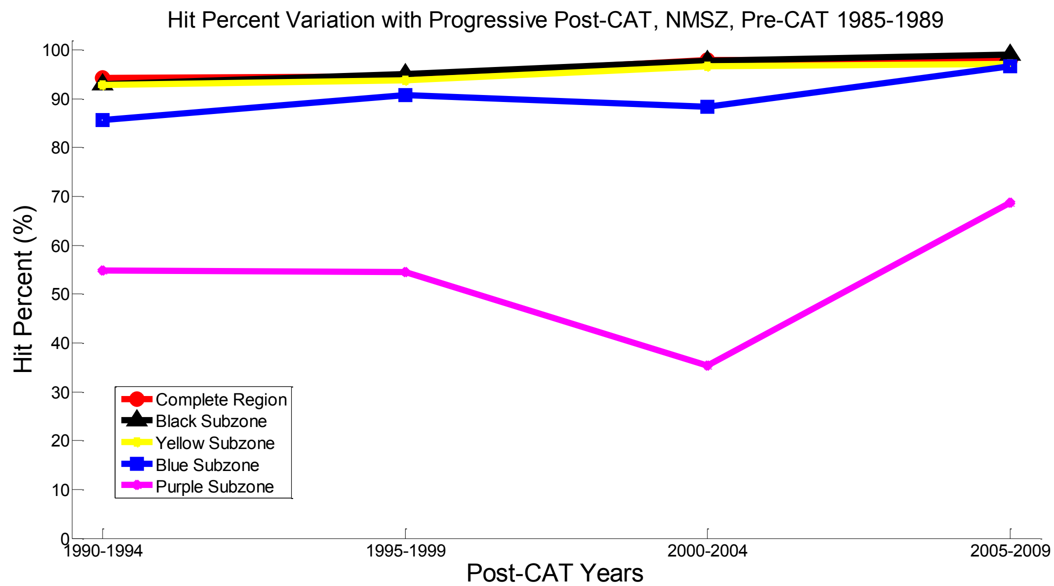


Figure 29c. Hit percent with progressive Post-CAT in NMSZ. Pre-CAT 1985-1989.

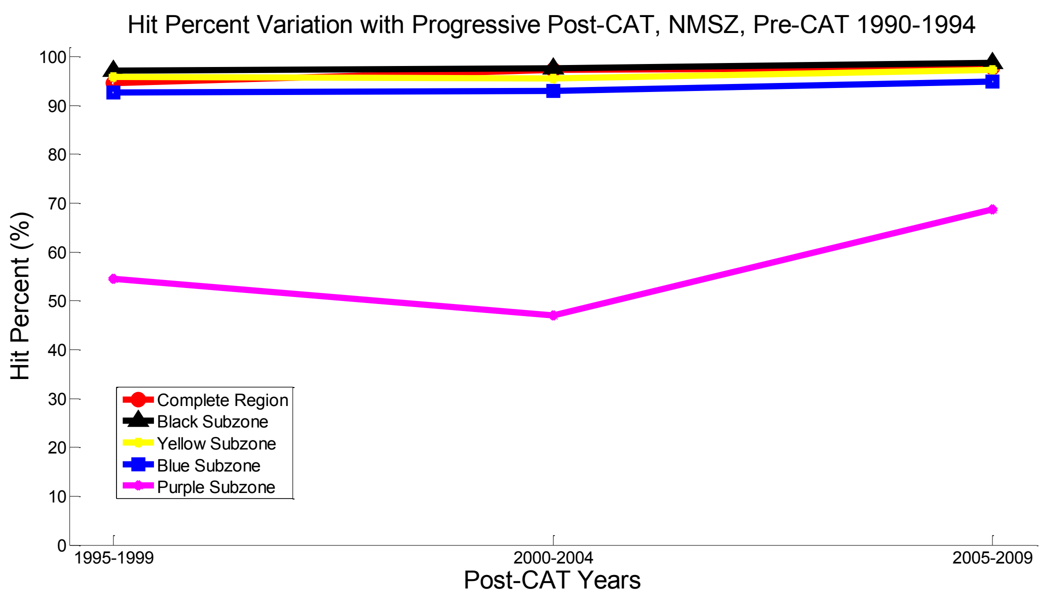


Figure 29d. Hit percent with progressive Post-CAT in NMSZ. Pre-CAT 1990-1994.

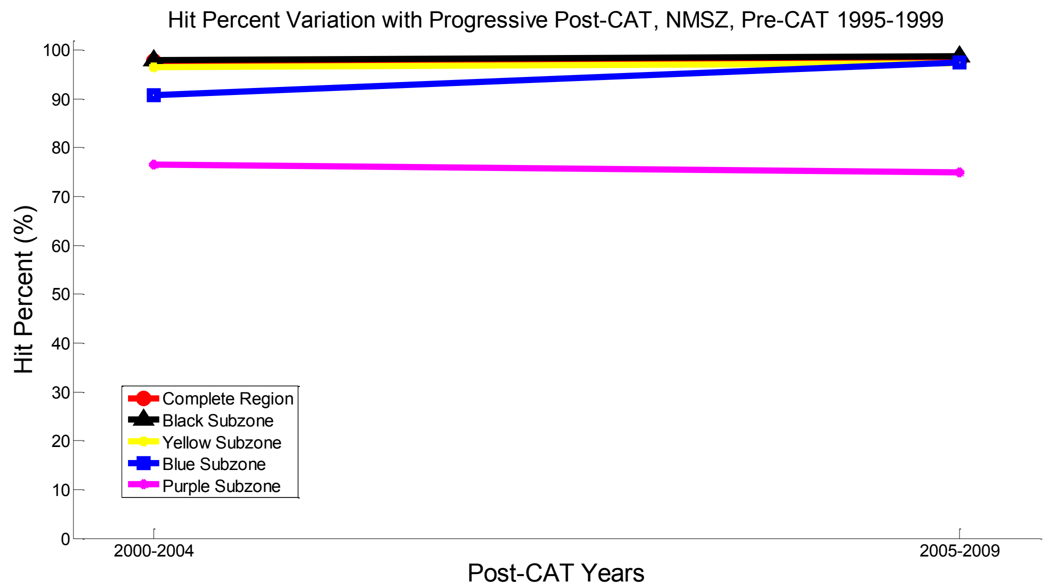


Figure 29e. Hit percent with progressive Post-CAT in NMSZ. Pre-CAT 1995-1999.

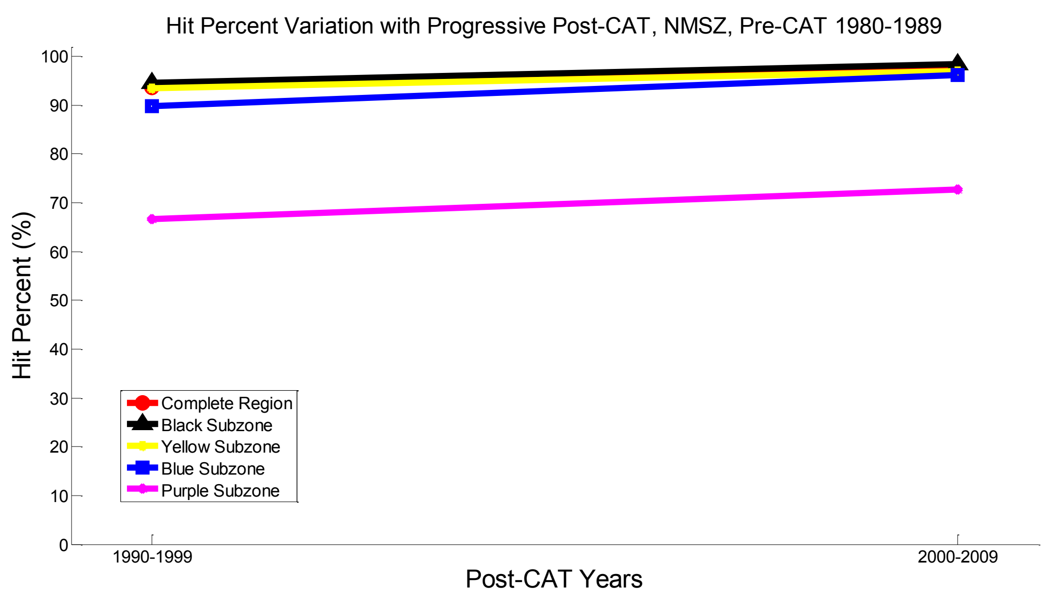


Figure 29f. Hit percent with progressive Post-CAT in NMSZ. Pre-CAT 1980-1989.

Australia: Time Progression Results

Any statistically significant differences in hit percent between the zero time gap trial in each set and the non-zero time gap trials are shown in tables 3a-3c. Hit percents are typically in the mid-20's to mid-60's.

The plots of hit percent with Post-CAT years for the Complete AUS region and West and East subzones are shown in figures 30a-30h. Figures 30a-30f use five year segments, while figures 30g-30h use 10 year segments. Each successive plot uses a Pre-CAT one segment later than the preceding plot (i.e., figure 30a uses 1970-1974 as the Pre-CAT, figure 30b uses 1975-1979 as the Pre-CAT, etc.).

For the 1970-1974 Pre-CAT (figure 30a), the Complete region 1985-1989 Post-CAT hit percent is statistically lower than the 1975-1979 Post-CAT hit percent. The 1985-1989 Post-CAT hit percent is also statistically lower than the 1975-1979 Post-CAT hit percent in the West subzone, along with the 1990-1994 Post-CAT hit percent. The Complete region and both subzones share a similar trend of decrease, then increase, then decrease in hit percent for the 1985-1989, 1990-1994, and 1995-1999 Post-CATs, respectively.

For the 1975-1979 Pre-CAT (figure 30b), both the Complete region and West subzone 1985-1989 and 1990-1994 Post-CAT hit percents are statistically lower than the 1980-1984 Post-CAT hit percent. The Complete region and both subzones share a similar trend of decrease, then increase, then decrease in hit percent for the 1990-1994, 2000-2004, and 2005-2009 Post-CATs, respectively.

For the 1980-1984 Pre-CAT (figure 30c), both the Complete region and West subzone 1995-1999 and 2005-2009 Post-CAT hit percents are statistically higher than the 1985-1989 Post-CAT hit percent. The Complete region and both subzones share a similar trend of increase, then decrease, then increase in hit percent for the 1995-1999, 2000-2004, and 2005-2009 Post-CATs, respectively.

There are no statistically significant differences in hit percent for the 1985-1989 Pre-CAT (figure 30d), and the hit percents remain relatively constant for the Complete region and both subzones.

For the 1990-1994 Pre-CAT (figure 30e), the Complete region 2005-2009 Post-CAT hit percent is statistically lower than the 1995-1999 Post-CAT hit percent, and the change in hit percent is very similar for the Complete region and West subzone.

There are no statistically significant differences in hit percent for the 1995-1999 Pre-CAT (figure 30f).

There are also no significant hit percent differences for the 10 year segment trials (figures 30g-30h). For the 1970-1979 Pre-CAT, the Complete region and West subzone show a similar change in hit percent, and the Complete region and both subzones show a similar change in hit percent for the 1980-1989 Pre-CAT.

AUS, Complete Region

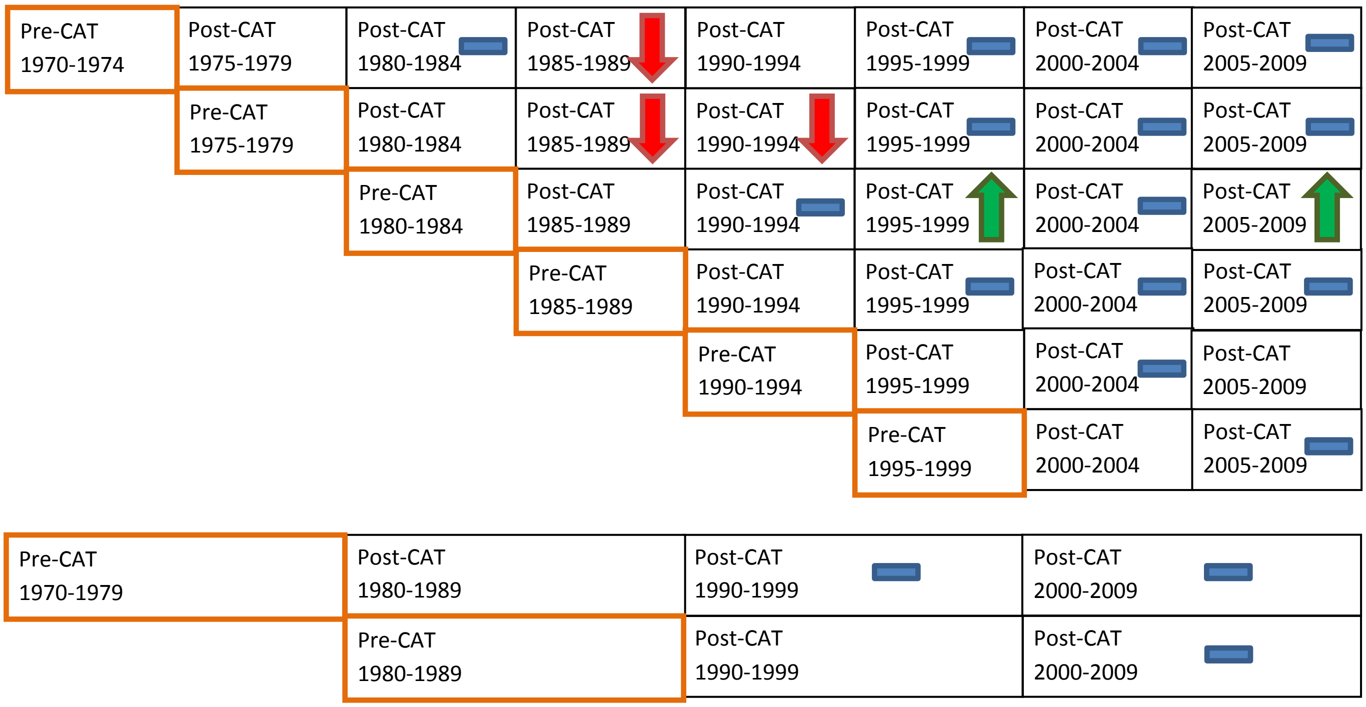


Table 3a. Chart of statistically significant changes in hit percent for AUS Complete region progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

AUS, West Subzone

Pre-CAT 1970-1974	Post-CAT 1975-1979	Post-CAT 1980-1984 –	Post-CAT 1985-1989 ↓	Post-CAT 1990-1994 ↓	Post-CAT 1995-1999 –	Post-CAT 2000-2004 –	Post-CAT 2005-2009 –
	Pre-CAT 1975-1979	Post-CAT 1980-1984	Post-CAT 1985-1989 ↓	Post-CAT 1990-1994 ↓	Post-CAT 1995-1999 –	Post-CAT 2000-2004 –	Post-CAT 2005-2009 –
		Pre-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994 –	Post-CAT 1995-1999 ↑	Post-CAT 2000-2004 –	Post-CAT 2005-2009 ↑
			Pre-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999 –	Post-CAT 2000-2004 –	Post-CAT 2005-2009 –
				Pre-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004 –	Post-CAT 2005-2009 –
					Pre-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009 –

Pre-CAT 1970-1979	Post-CAT 1980-1989	Post-CAT 1990-1999 –	Post-CAT 2000-2009 –
	Pre-CAT 1980-1989	Post-CAT 1990-1999	Post-CAT 2000-2009 –

Table 3b. Chart of statistically significant changes in hit percent for AUS West subzone progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

AUS, East Subzone

Pre-CAT 1970-1974	Post-CAT 1975-1979	Post-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009
	Pre-CAT 1975-1979	Post-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009
		Pre-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009
			Pre-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009
				Pre-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009
					Pre-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009

Pre-CAT 1970-1979	Post-CAT 1980-1989	Post-CAT 1990-1999	Post-CAT 2000-2009
	Pre-CAT 1980-1989	Post-CAT 1990-1999	Post-CAT 2000-2009

Table 3c. Chart of statistically significant changes in hit percent for AUS East subzone progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

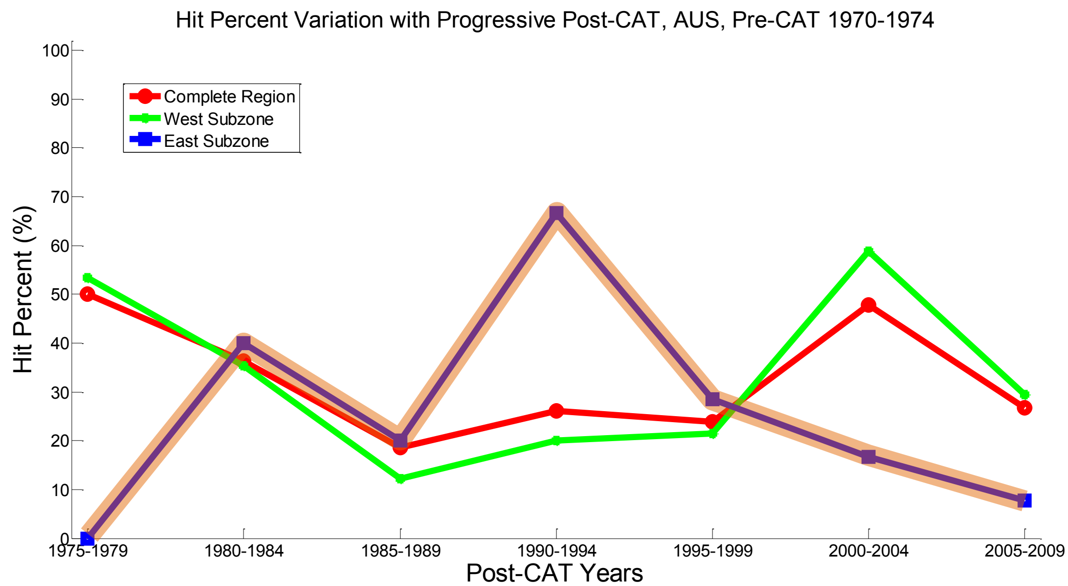


Figure 30a. Hit percent with progressive Post-CAT in AUS. Pre-CAT 1970-1974. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

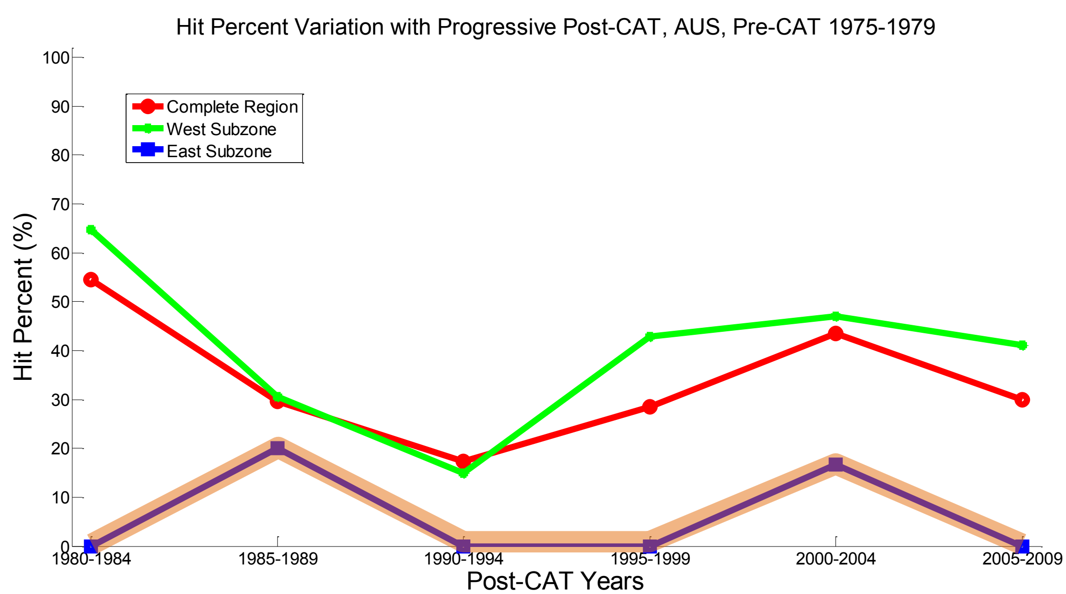


Figure 30b. Hit percent with progressive Post-CAT in AUS. Pre-CAT 1975-1979. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

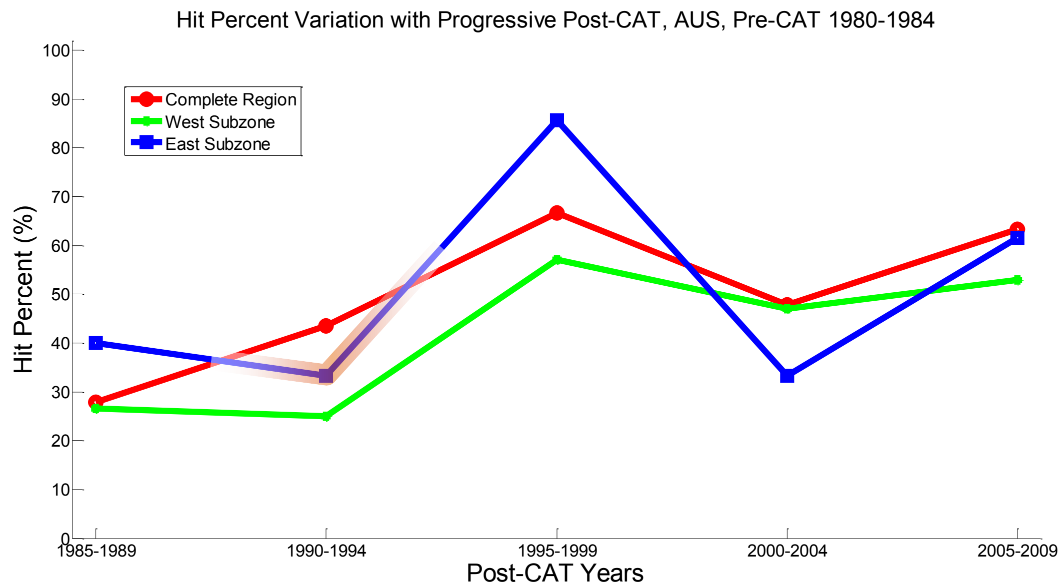


Figure 30c. Hit percent with progressive Post-CAT in AUS. Pre-CAT 1980-1984. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

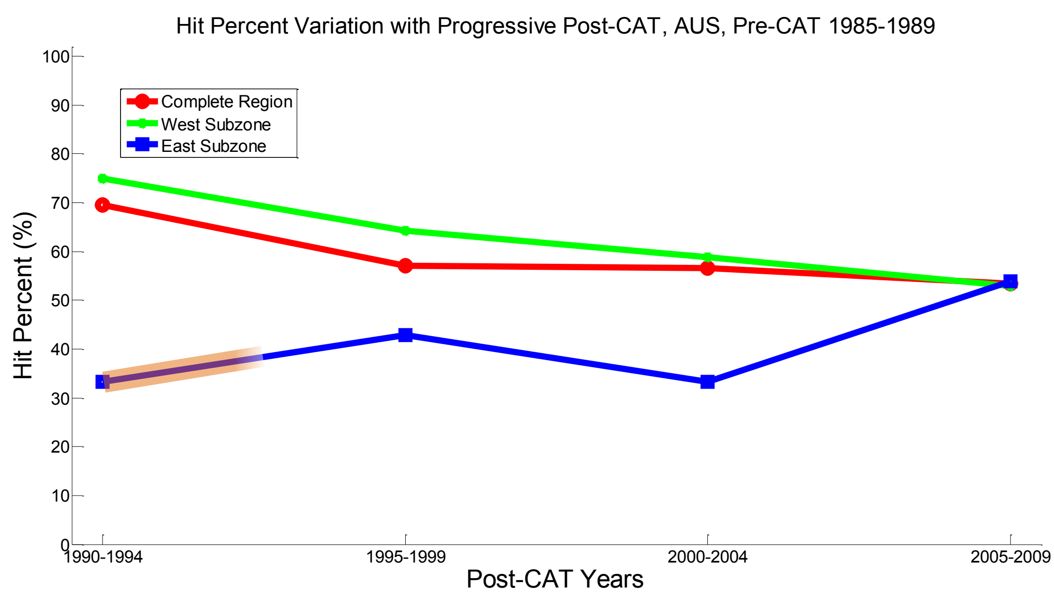


Figure 30d. Hit percent with progressive Post-CAT in AUS. Pre-CAT 1985-1989. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

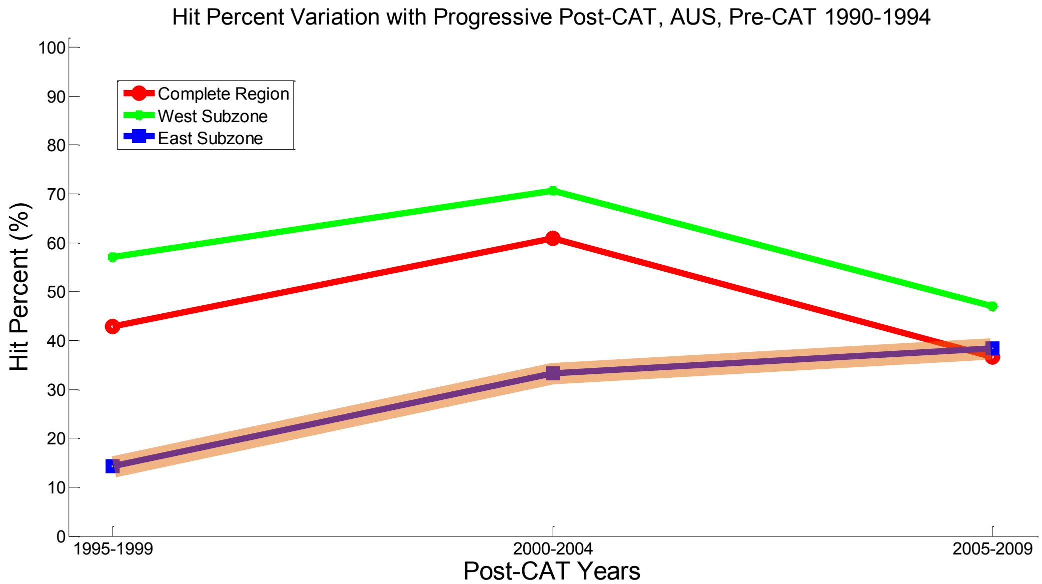


Figure 30e. Hit percent with progressive Post-CAT in AUS. Pre-CAT 1990-1994. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

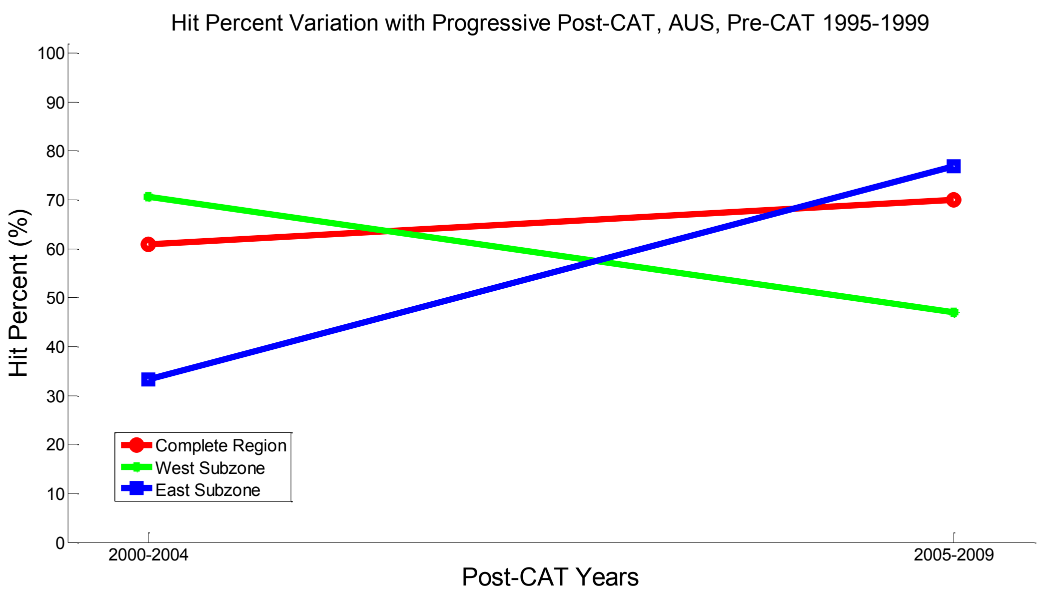


Figure 30f. Hit percent with progressive Post-CAT in AUS. Pre-CAT 1995-1999.

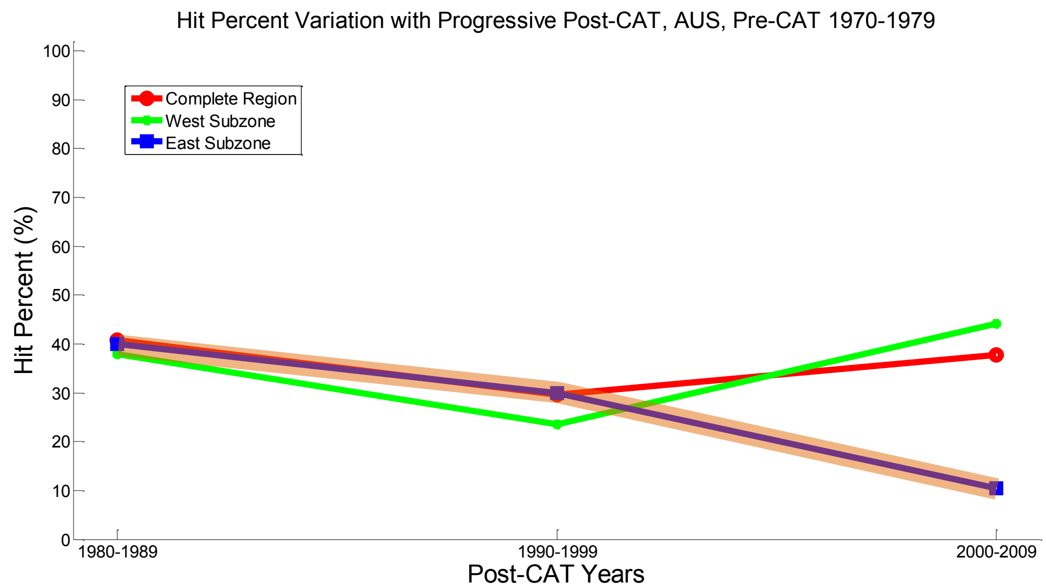


Figure 30g. Hit percent with progressive Post-CAT in AUS. Pre-CAT 1970-1979. Orange shading indicates trial for which the Pre-CAT or Post-CAT earthquake sample size was too small to consider results statistically significant.

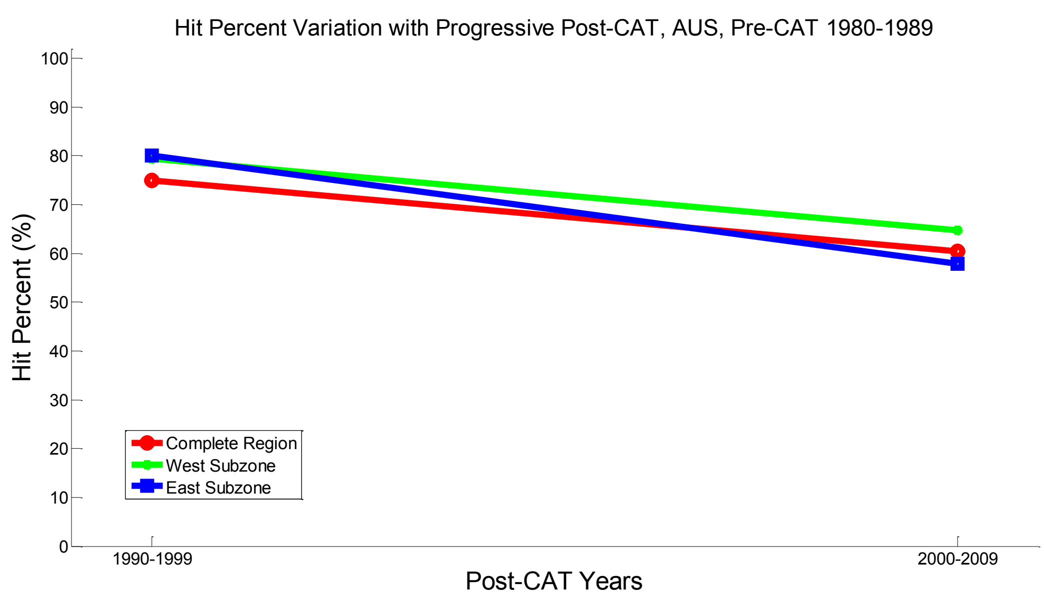


Figure 30h. Hit percent with progressive Post-CAT in AUS. Pre-CAT 1980-1989.

California: Time Progression Results

Any statistically significant differences in hit percent between the zero time gap trial in each set and the non-zero time gap trials are shown in tables 4a-4c. Hit percents are typically in the low-60's to low-90's.

The plots of hit percent with Post-CAT years for the Complete CA region and North and South subzones are shown in figures 31a-31h. Figures 31a-31f use five year segments, while figures 31g-31h use 10 year segments. Each successive plot uses a Pre-CAT one segment later than the preceding plot (i.e., figure 31a uses 1970-1974 as the Pre-CAT, figure 31b uses 1975-1979 as the Pre-CAT, etc.).

For the 1970-1974 Pre-CAT (figure 31a), the Complete region 1985-1989 Post-CAT hit percent is statistically higher than the 1975-1979 Post-CAT hit percent, and the 1990-1994 Post-CAT hit percent is statistically lower. In the North subzone, the 1980-1984, 1985-1989, and 2005-2009 Post-CAT hit percents are statistically higher than the 1975-1979 Post-CAT hit percent. In the South subzone, the 1980-1984, 1985-1989, 1990-1994, 2000-2004, and 2005-2009 Post-CAT hit percents are statistically lower than the 1975-1979 Post-CAT hit percent.

For the 1975-1979 Pre-CAT (figure 31b), the Complete region 1995-1999, 2000-2004, and 2005-2009 Post-CAT hit percents are statistically lower than the 1980-1984 Post-CAT hit percent. In the North subzone, all five subsequent Post-CAT segments are statistically lower than the 1980-1984 Post-CAT hit percent. In the South subzone, the 1990-1994 and 1995-1999 Post-CAT hit percents are statistically higher than the 1980-1984 Post-CAT hit percent.

For the 1980-1984 Pre-CAT (figure 31c), the Complete region and South subzone 1990-1994 and 1995-1999 Post-CAT hit percents are statistically lower than the 1985-1989 Post-CAT hit percent. There are no statistically significant differences in hit percent for the North subzone.

For the 1985-1989 Pre-CAT (figure 31d), the South subzone 1995-1999 Post-CAT hit percent is statistically lower than the 1990-1994 Post-CAT hit percent, and the 2005-2009 Post-CAT is statistically higher. There are no statistically significant differences in hit percent for the Complete region or the North subzone.

For the 1990-1994 Pre-CAT (figure 31e), both subsequent Post-CAT hit percents are statistically lower than the 1995-1999 Post-CAT hit percent for the South subzone. There are no statistically significant differences in hit percent for the Complete region or the North subzone.

There are no statistically significant differences in hit percent for the 1995-1999 Pre-CAT (figure 31f).

For the 1970-1979 Pre-CAT (figure 31g), the Complete region and North subzone 1990-1999 and 2000-2009 Post-CAT hit percents are statistically lower than the 1980-1989 Post-CAT hit percent. The 1990-1999 Post-CAT hit percent is statistically higher than the 1980-1989 Post-CAT hit percent for the South subzone.

For the 1980-1989 Pre-CAT (figure 31h), the Complete region and South subzone 2000-2009 Post-CAT hit percent is statistically higher than the 1990-1999 Post-CAT hit percent. There is no statistical difference between the hit percents for the North subzone.

CA, Complete Region

Pre-CAT 1970-1974	Post-CAT 1975-1979	Post-CAT 1980-1984 −	Post-CAT 1985-1989 ↑	Post-CAT 1990-1994 ↓	Post-CAT 1995-1999 −	Post-CAT 2000-2004 −	Post-CAT 2005-2009 −
	Pre-CAT 1975-1979	Post-CAT 1980-1984	Post-CAT 1985-1989 −	Post-CAT 1990-1994 −	Post-CAT 1995-1999 ↓	Post-CAT 2000-2004 ↓	Post-CAT 2005-2009 ↓
		Pre-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994 ↓	Post-CAT 1995-1999 ↓	Post-CAT 2000-2004 −	Post-CAT 2005-2009 −
			Pre-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999 −	Post-CAT 2000-2004 −	Post-CAT 2005-2009 −
				Pre-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004 −	Post-CAT 2005-2009 −
					Pre-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009 −

Pre-CAT 1970-1979	Post-CAT 1980-1989	Post-CAT 1990-1999 ↓	Post-CAT 2000-2009 ↓
	Pre-CAT 1980-1989	Post-CAT 1990-1999	Post-CAT 2000-2009 ↑

Table 4a. Chart of statistically significant changes in hit percent for CA Complete region progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

CA, North Subzone

Pre-CAT 1970-1974	Post-CAT 1975-1979	Post-CAT 1980-1984 ↑	Post-CAT 1985-1989 ↑	Post-CAT 1990-1994 –	Post-CAT 1995-1999 –	Post-CAT 2000-2004 –	Post-CAT 2005-2009 ↑
	Pre-CAT 1975-1979	Post-CAT 1980-1984	Post-CAT 1985-1989 ↓	Post-CAT 1990-1994 ↓	Post-CAT 1995-1999 ↓	Post-CAT 2000-2004 ↓	Post-CAT 2005-2009 ↓
		Pre-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994 –	Post-CAT 1995-1999 –	Post-CAT 2000-2004 –	Post-CAT 2005-2009 –
			Pre-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999 –	Post-CAT 2000-2004 –	Post-CAT 2005-2009 –
				Pre-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004 –	Post-CAT 2005-2009 –
					Pre-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009 –

Pre-CAT 1970-1979	Post-CAT 1980-1989	Post-CAT 1990-1999 ↓	Post-CAT 2000-2009 ↓
	Pre-CAT 1980-1989	Post-CAT 1990-1999	Post-CAT 2000-2009 –

Table 4b. Chart of statistically significant changes in hit percent for CA North subzone progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

CA, South Subzone

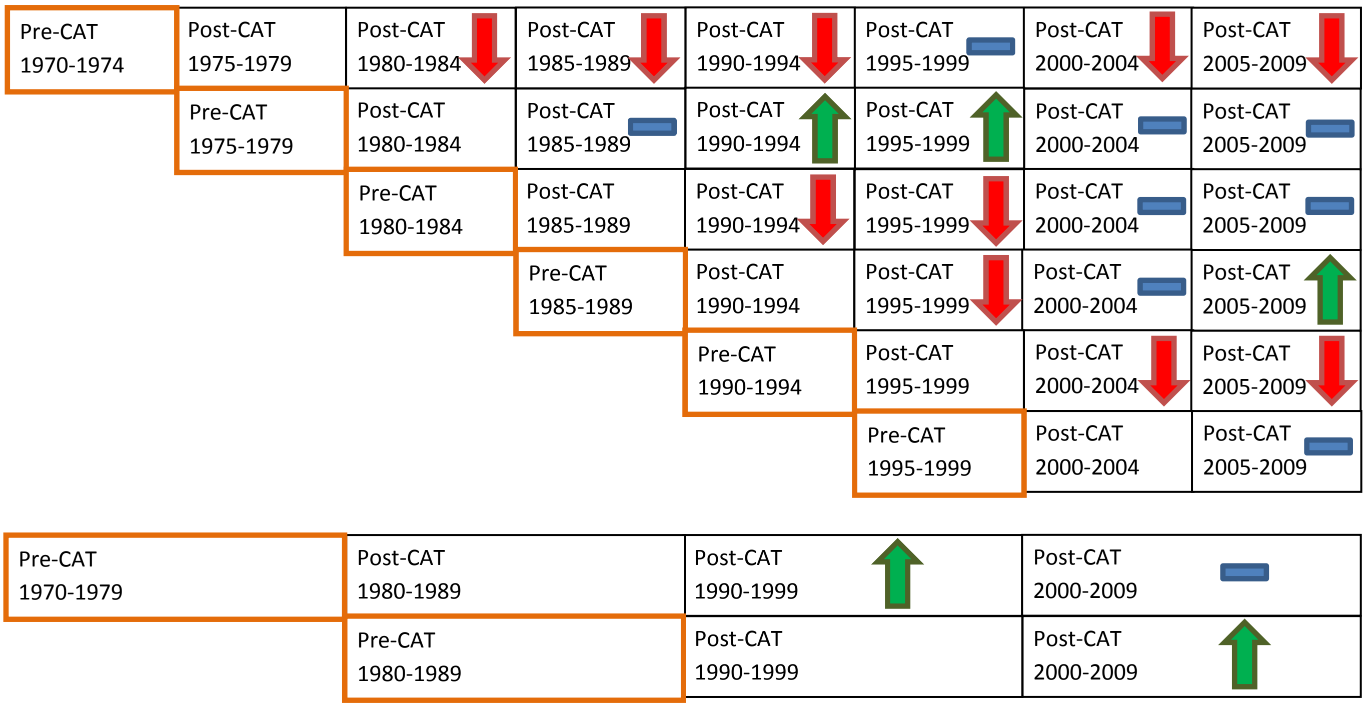


Table 4c. Chart of statistically significant changes in hit percent for CA South subzone progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

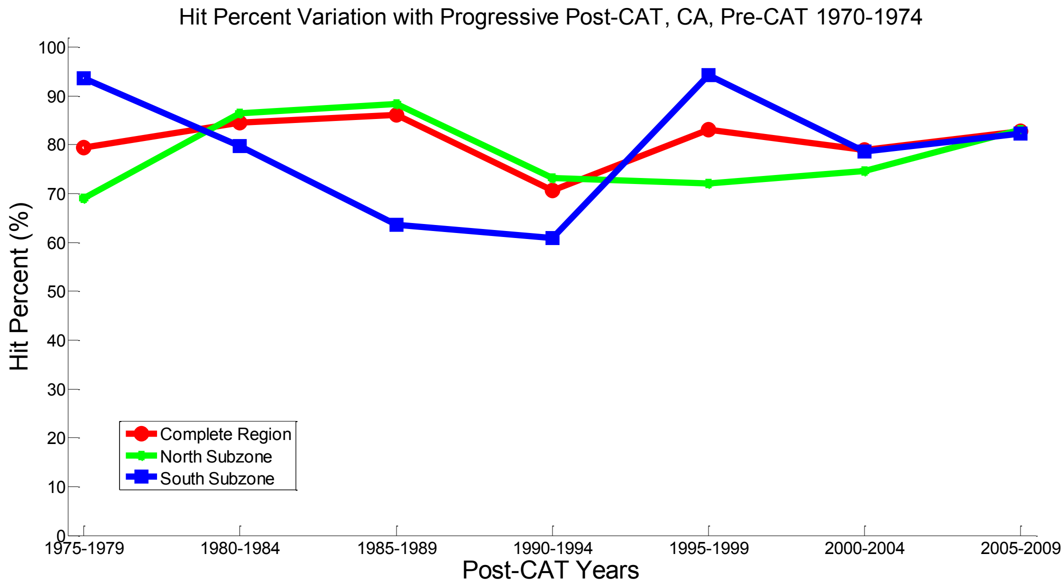


Figure 31a. Hit percent with progressive Post-CAT in CA. Pre-CAT 1970-1974.

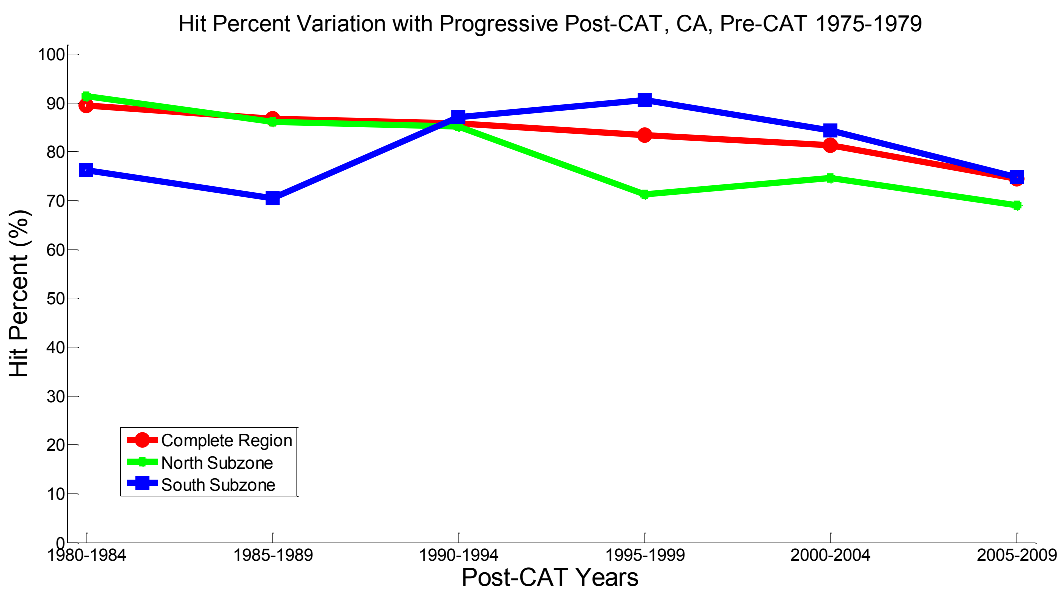


Figure 31b. Hit percent with progressive Post-CAT in CA. Pre-CAT 1975-1979.

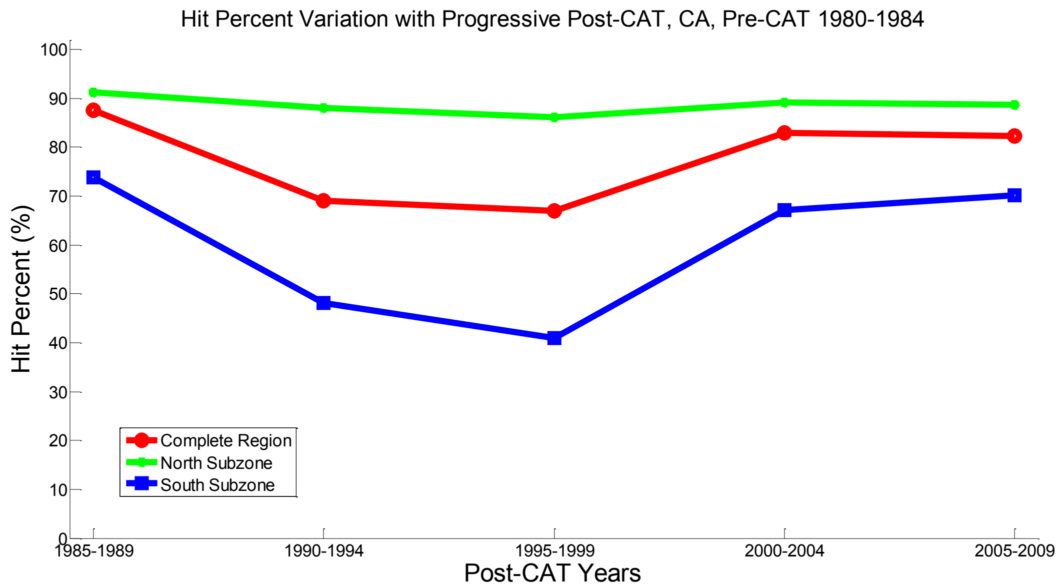


Figure 31c. Hit percent with progressive Post-CAT in CA. Pre-CAT 1980-1984.

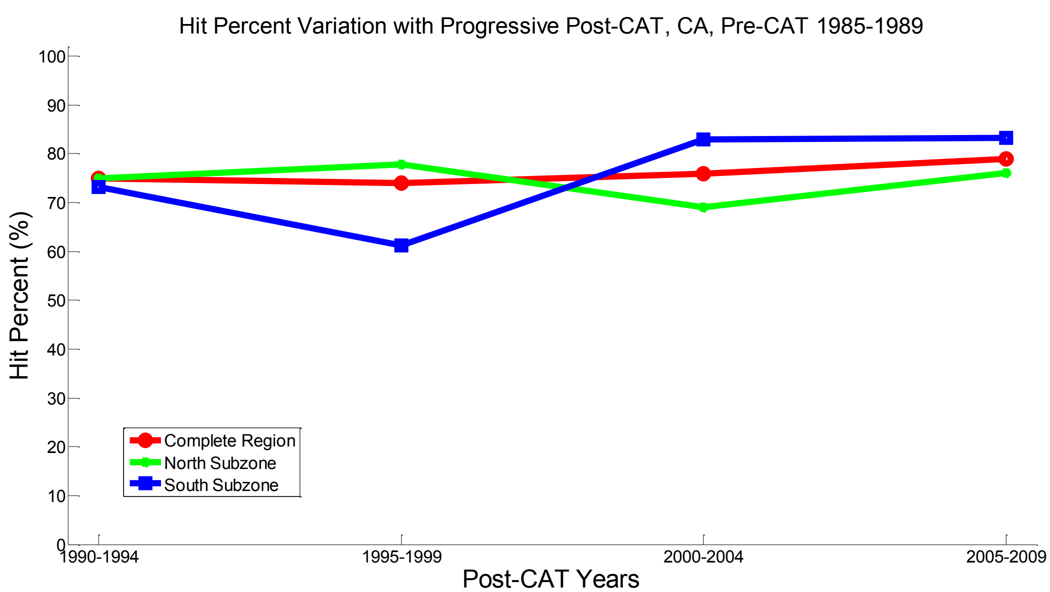


Figure 31d. Hit percent with progressive Post-CAT in CA. Pre-CAT 1985-1989.

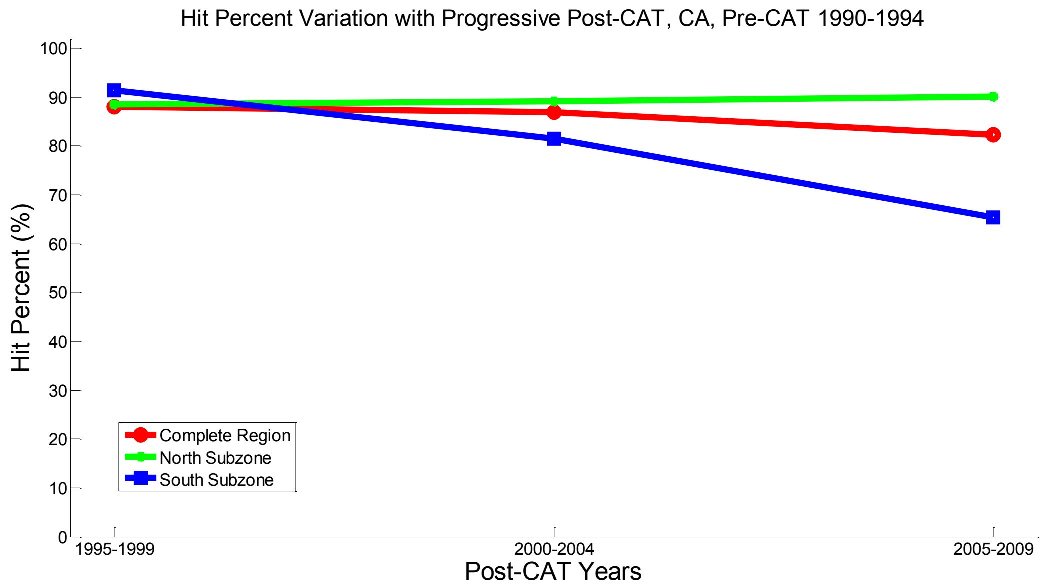


Figure 31e. Hit percent with progressive Post-CAT in CA. Pre-CAT 1990-1994.

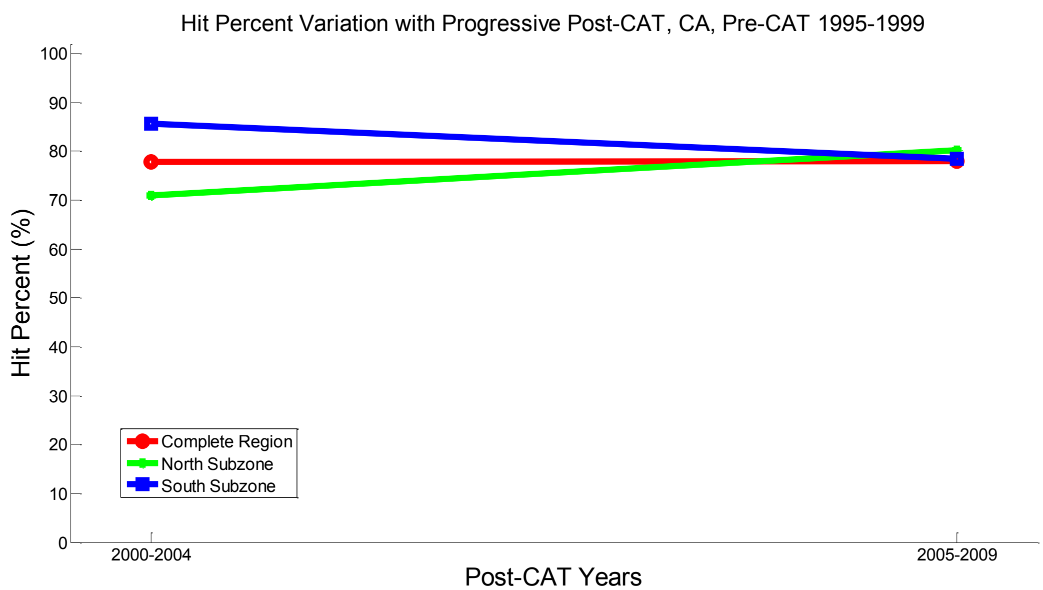


Figure 31f. Hit percent with progressive Post-CAT in CA. Pre-CAT 1995-1999.

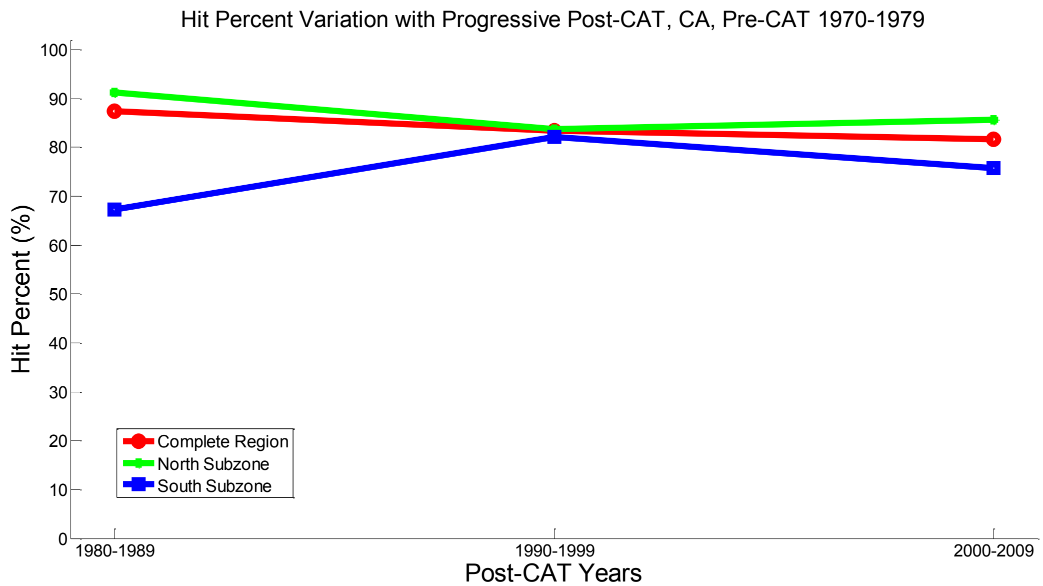


Figure 31g. Hit percent with progressive Post-CAT in CA. Pre-CAT 1970-1979.

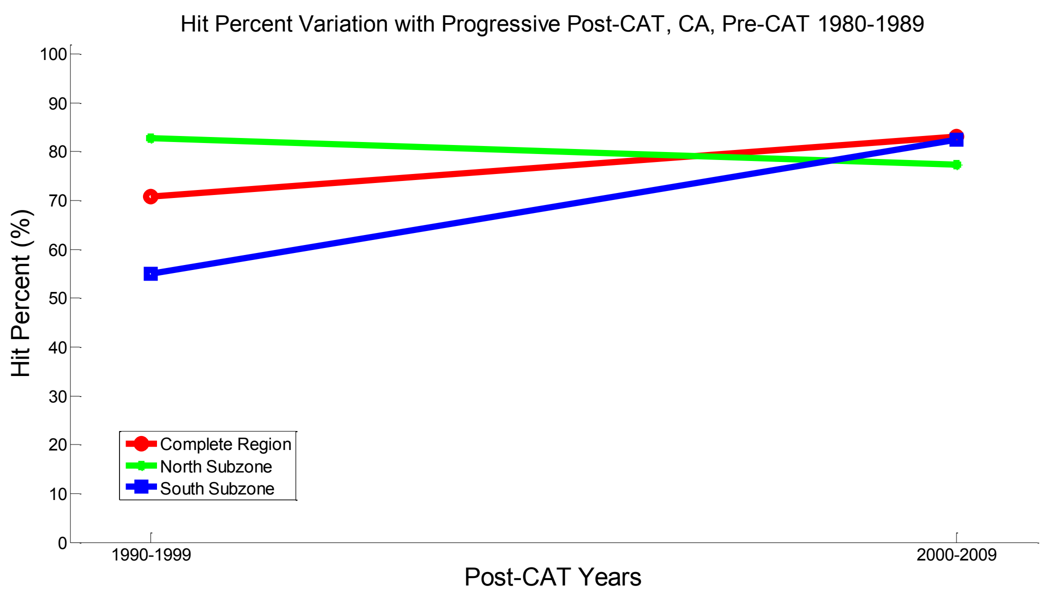


Figure 31h. Hit percent with progressive Post-CAT in CA. Pre-CAT 1980-1989.

Alaska: Time Progression Results

Any statistically significant differences in hit percent between the zero time gap trial in each set and the non-zero time gap trials are shown in tables 5a-5c. Hit percents are typically in the low-60's to mid-90's. The Nonactive subzone has hit percents that are consistently lower than the Complete region or the Active subzone.

The plots of hit percent with Post-CAT years for the Complete AK region and Active and Nonactive subzones are shown in figures 32a-32h. Figures 32a-32f use five year segments, while figures 32g-32h use 10 year segments. Each successive plot uses a Pre-CAT one segment later than the preceding plot (i.e., figure 32a uses 1970-1974 as the Pre-CAT, figure 32b uses 1975-1979 as the Pre-CAT, etc.).

For the 1970-1974 Pre-CAT (figure 32a), the Complete region 1985-1989, 1990-1994, and 2000-2004 Post-CAT hit percents are statistically lower than the 1975-1979 Post-CAT hit percent. In the Active subzone, the 1980-1984, 1985-1989, 2000-2004, and 2005-2009 Post-CAT hit percents are statistically lower than the 1975-1979 Post-CAT hit percent. In the Nonactive subzone, the 1985-1989, 1990-1994, 1995-1999, and 2005-2009 Post-CAT hit percents are statistically lower than the 1975-1979 Post-CAT hit percents.

For the 1975-1979 Pre-CAT (figure 32b), the Complete region 1985-1989, 1990-1994, and 2000-2004 Post-CAT hit percents are statistically lower than the 1980-1984 Post-CAT hit percent, and the 1995-1999 Post-CAT hit percent is statistically higher. The Active subzone 1995-1999 and 2005-2009 Post-CAT hit percents are statistically higher than the 1980-1984 Post-CAT hit percent. The Nonactive subzone 1985-1989 and 1990-1994 Post-CAT hit percents are statistically lower than the 1980-1984 Post-CAT hit percent.

For the 1980-1984 Pre-CAT (figure 32c), the Complete region 1995-1999 Post-CAT hit percent is statistically higher than the 1985-1989 Post-CAT hit percent, and the 2005-2009 Post-CAT hit percent is statistically lower. The Nonactive subzone 1990-1994, 2000-2004, and 2005-2009 Post-CAT hit percents are statistically lower than the 1985-1989 Post-CAT hit percent. There are no statistically significant differences in hit percent for the Active subzone.

For the 1985-1989 Pre-CAT (figure 32d), the Complete region and Nonactive subzone 2000-2004 Post-CAT hit percents are statistically lower than the 1990-1994 Post-CAT hit percent. There are no statistically significant differences in hit percent for the Active subzone.

For the 1990-1994 Pre-CAT (figure 32e), both subsequent Post-CAT hit percents are statistically lower than the 1995-1999 Post-CAT hit percent for the Complete region and Nonactive subzone. There are no statistically significant differences in hit percent for the Active subzone.

For the 1995-1999 Pre-CAT (figure 32f), the Nonactive subzone 2005-2009 Post-CAT hit percent is statistically lower than the 2000-2004 Post-CAT hit percent. There are no statistically significant differences in hit percent for the Complete region or the Active subzone.

For the 1970-1979 Pre-CAT (figure 32g), both subsequent Post-CAT hit percents for the Complete region are statistically higher than the 1980-1989 Post-CAT hit percent. The 1990-1999 Post-CAT for the Active subzone is also statistically higher than the 1980-1989 Post-CAT hit percent. There are no statistically significant differences in hit percent for the Nonactive subzone.

For the 1980-1989 Pre-CAT (figure 32h), the 2000-2009 Post-CAT hit percent is statistically lower than the 1990-1999 Post-CAT hit percent for the Complete region and the Active and Nonactive subzones.

AK, Complete Region

Pre-CAT 1970-1974	Post-CAT 1975-1979	Post-CAT 1980-1984 —	Post-CAT 1985-1989 ↓	Post-CAT 1990-1994 ↓	Post-CAT 1995-1999 —	Post-CAT 2000-2004 ↓	Post-CAT 2005-2009 —
	Pre-CAT 1975-1979	Post-CAT 1980-1984	Post-CAT 1985-1989 ↓	Post-CAT 1990-1994 ↓	Post-CAT 1995-1999 ↑	Post-CAT 2000-2004 ↓	Post-CAT 2005-2009 —
		Pre-CAT 1980-1984	Post-CAT 1985-1989	Post-CAT 1990-1994 —	Post-CAT 1995-1999 ↑	Post-CAT 2000-2004 —	Post-CAT 2005-2009 ↓
			Pre-CAT 1985-1989	Post-CAT 1990-1994	Post-CAT 1995-1999 —	Post-CAT 2000-2004 ↓	Post-CAT 2005-2009 —
				Pre-CAT 1990-1994	Post-CAT 1995-1999	Post-CAT 2000-2004 ↓	Post-CAT 2005-2009 ↓
					Pre-CAT 1995-1999	Post-CAT 2000-2004	Post-CAT 2005-2009 —

Pre-CAT 1970-1979	Post-CAT 1980-1989	Post-CAT 1990-1999 ↑	Post-CAT 2000-2009 ↑
	Pre-CAT 1980-1989	Post-CAT 1990-1999	Post-CAT 2000-2009 ↓

Table 5a. Chart of statistically significant changes in hit percent for AK Complete region progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

AK, Active Subzone

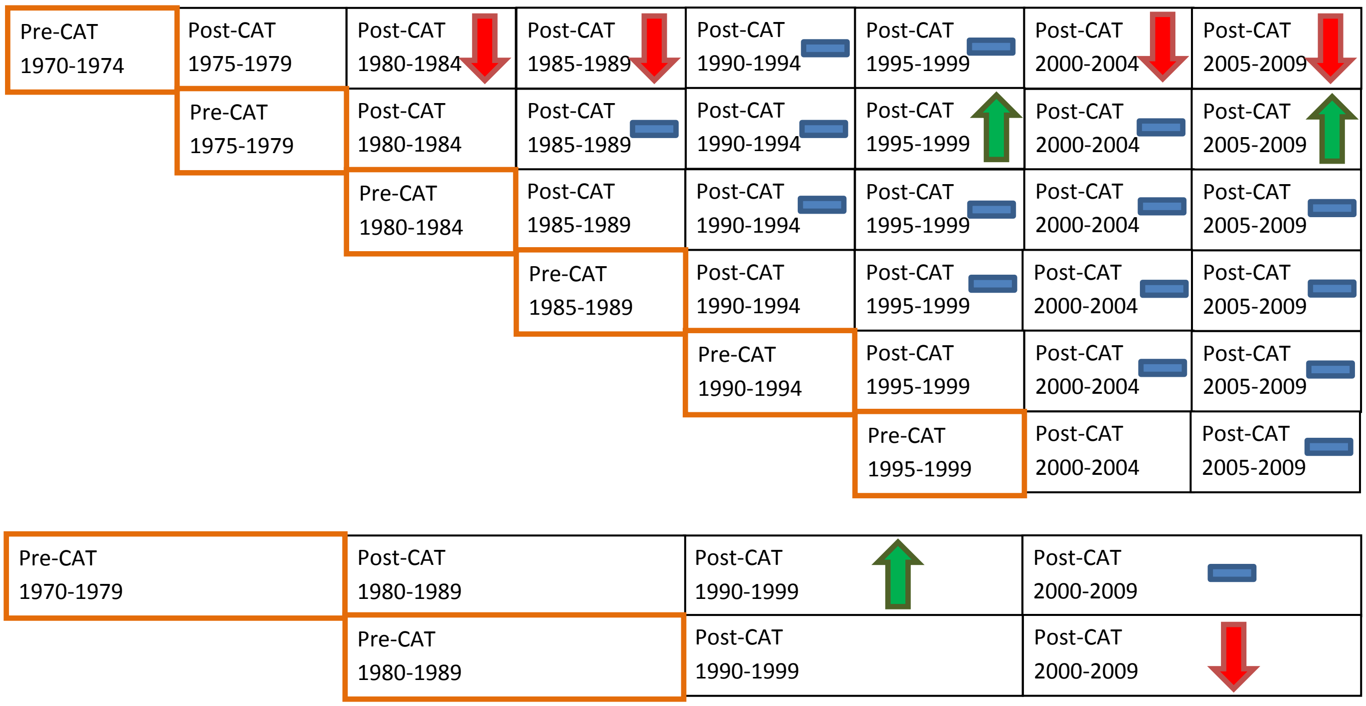


Table 5b. Chart of statistically significant changes in hit percent for AK Active subzone progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

AK, Nonactive Subzone

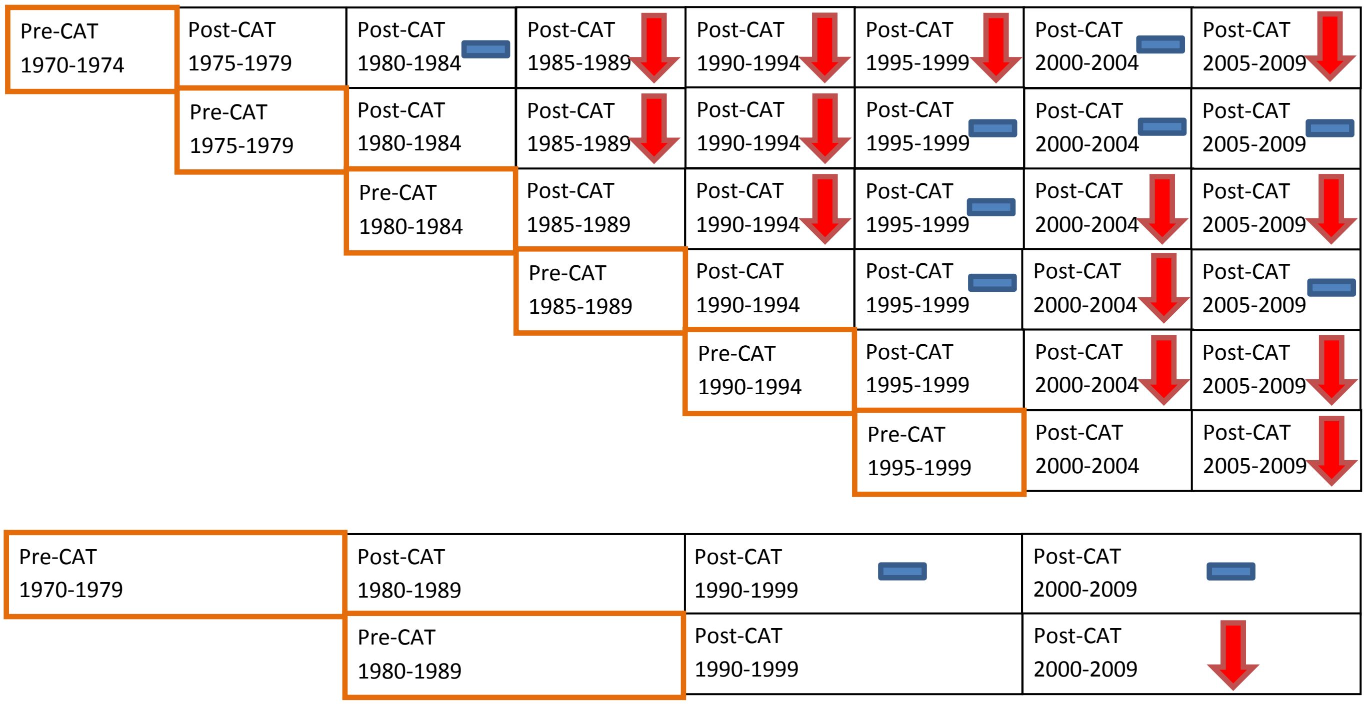


Table 5c. Chart of statistically significant changes in hit percent for AK nonactive subzone progression variable. Orange box is Pre-CAT for trial, first Post-CAT is temporally adjacent (i.e., zero time gap) to Pre-CAT, subsequent Post-CATs have non-zero time gap. Blue dash indicates no significant difference between zero time gap Post-CAT and non-zero time gap Post-CAT. Green up arrow indicates significantly higher hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT. Red down arrow indicates significantly lower hit percent for non-zero time gap Post-CAT than for zero time gap Post-CAT.

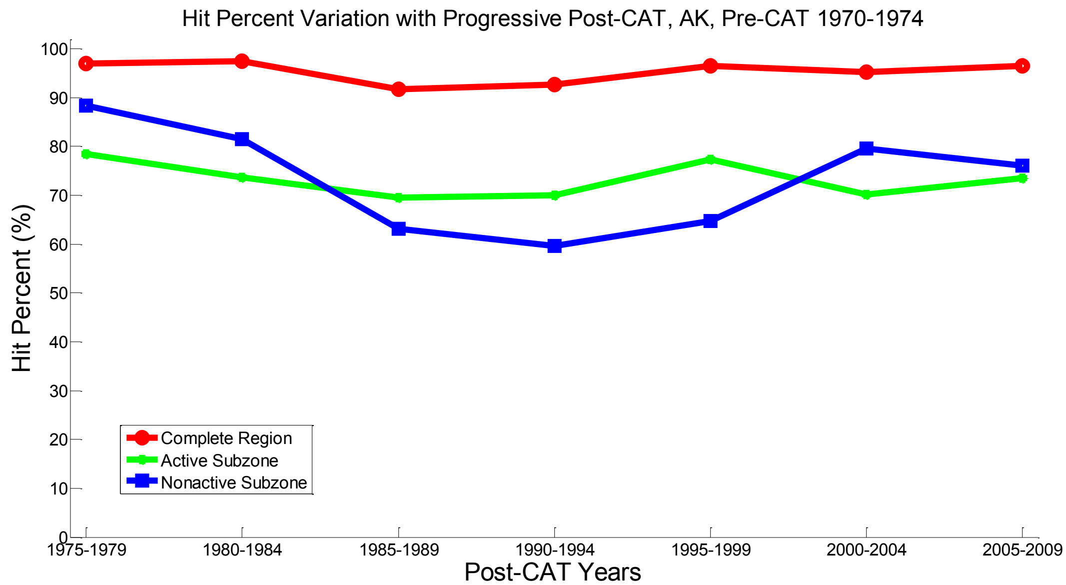


Figure 32a. Hit percent with progressive Post-CAT in AK. Pre-CAT 1970-1974.

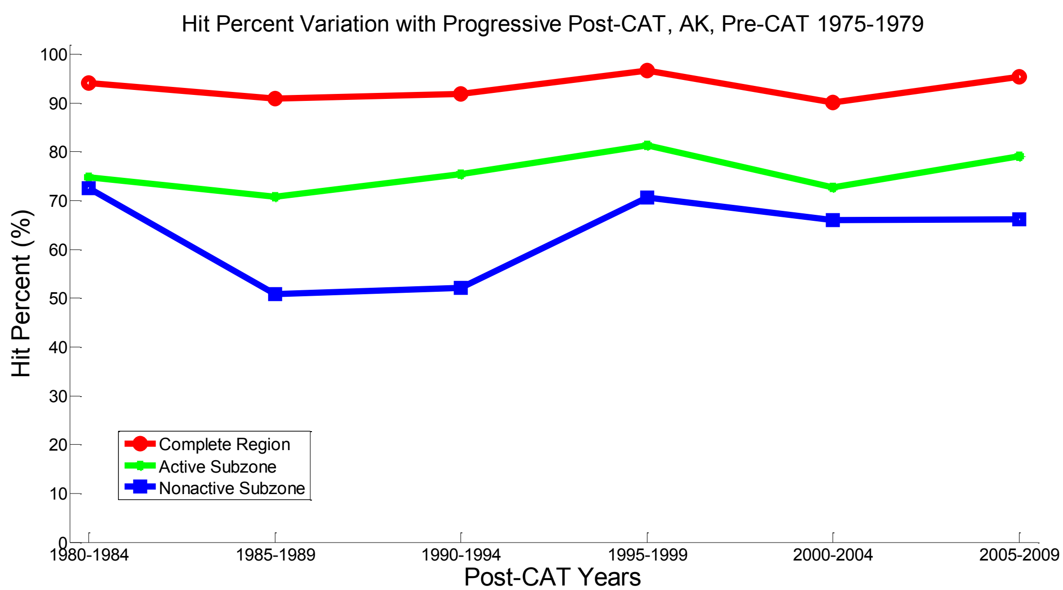


Figure 32b. Hit percent with progressive Post-CAT in AK. Pre-CAT 1975-1979.

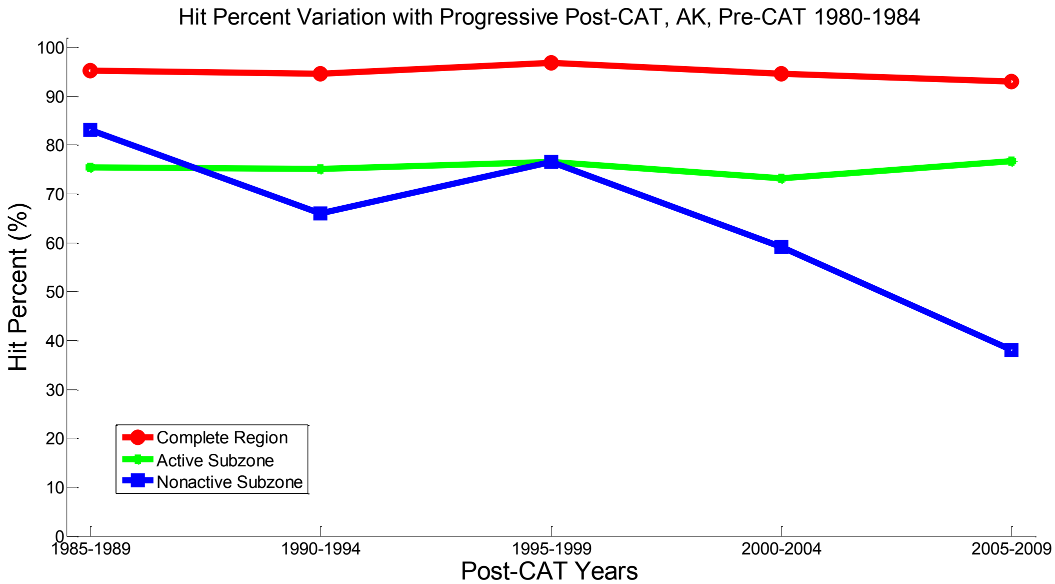


Figure 32c. Hit percent with progressive Post-CAT in AK. Pre-CAT 1980-1984.

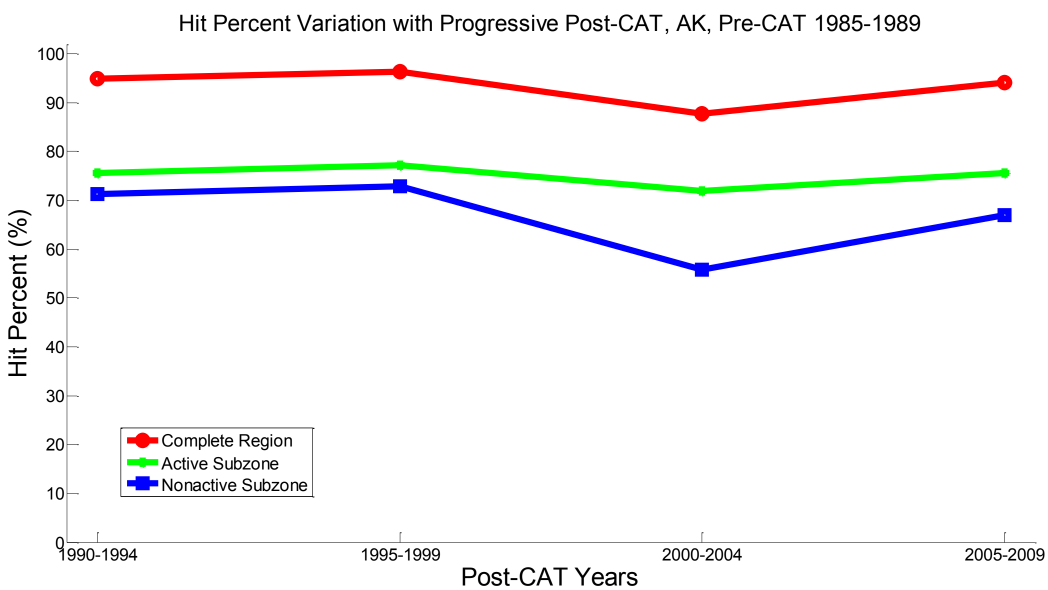


Figure 32d. Hit percent with progressive Post-CAT in AK. Pre-CAT 1985-1989.

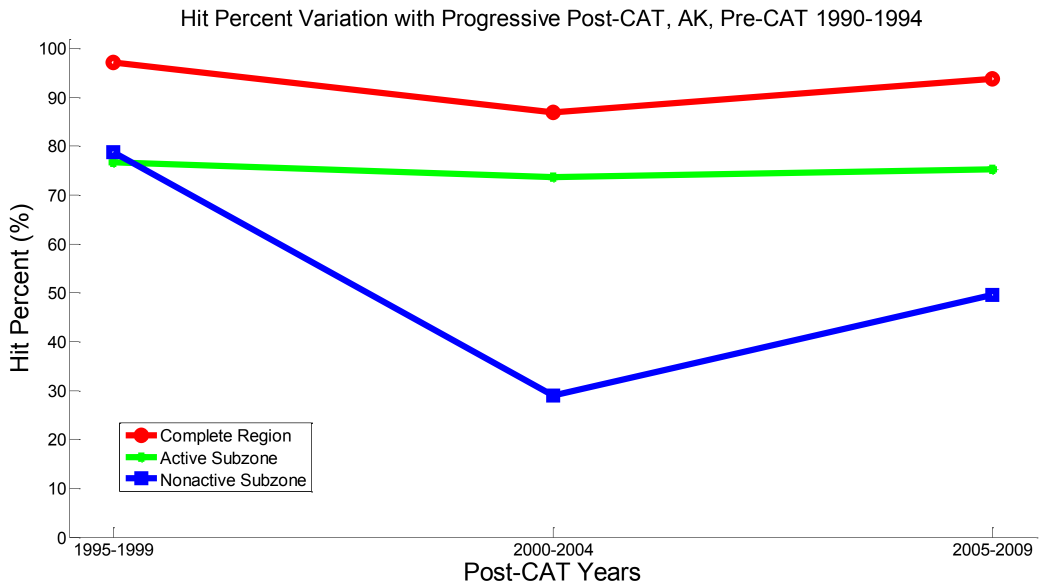


Figure 32e. Hit percent with progressive Post-CAT in AK. Pre-CAT 1990-1994.

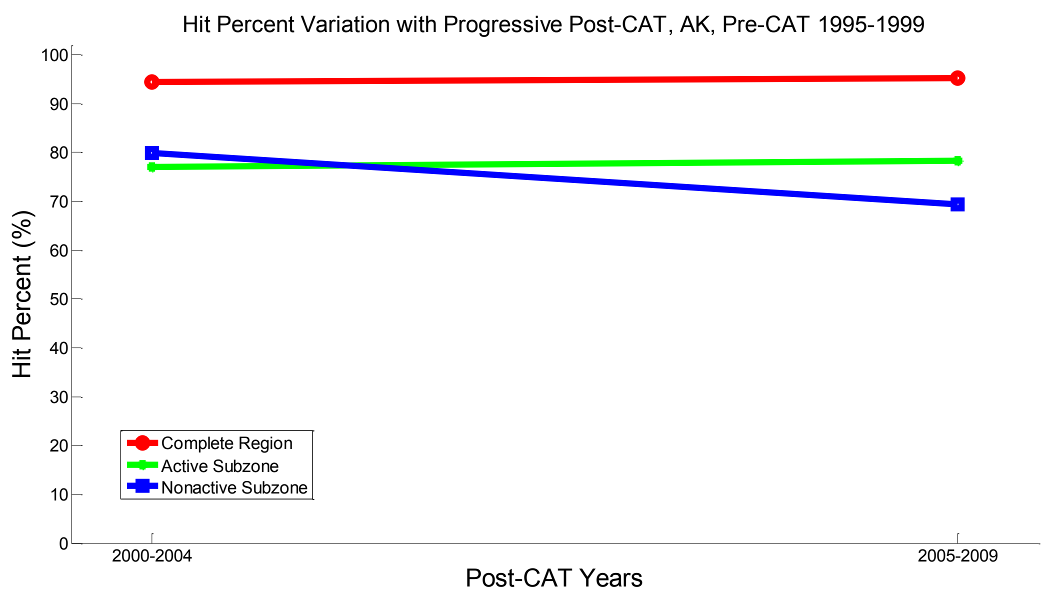


Figure 32f. Hit percent with progressive Post-CAT in AK. Pre-CAT 1995-1999.

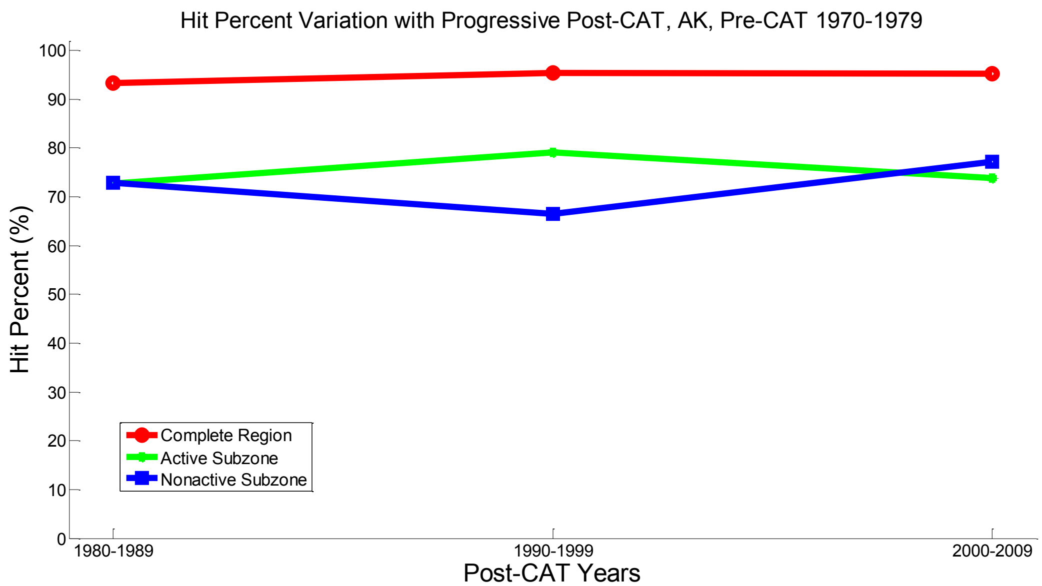


Figure 32g. Hit percent with progressive Post-CAT in AK. Pre-CAT 1970-1979.

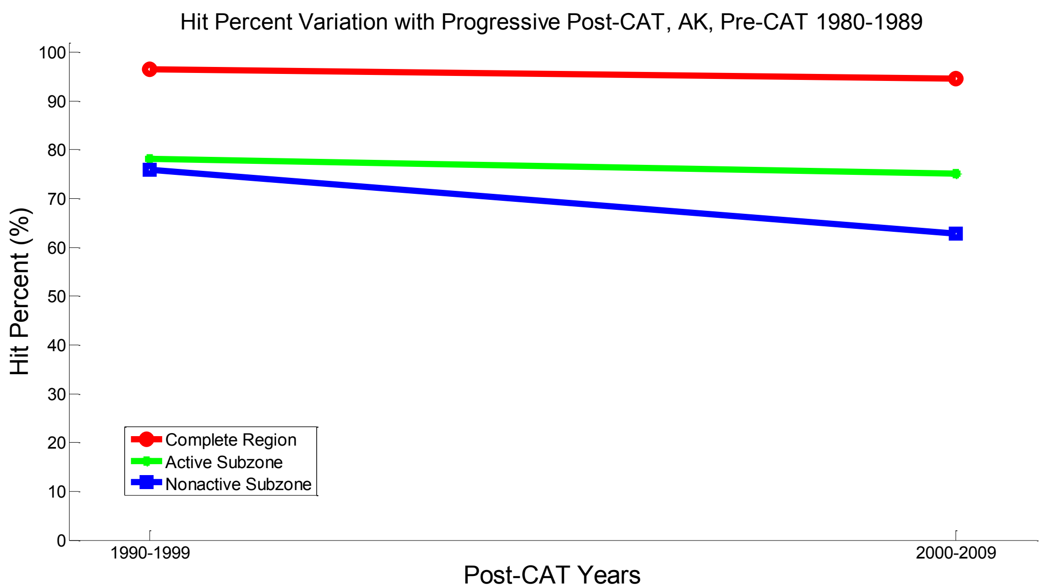


Figure 32h. Hit percent with progressive Post-CAT in AK. Pre-CAT 1980-1989.

7.0. ASSUMPTIONS AND KNOWN PROBLEMS

There are several basic assumptions underlying this work and CS testing in general. These assumptions, while reasonable, need to be considered as inherent, but known, issues with the procedures and CS results. CS is still a relatively new method, and to date has only been applied by Kafka and colleagues. This originality calls for an explicit declaration of these fundamental assumptions associated with the procedure and an evaluation of their potential influence on the interpretation of results. These issues generally revolve around the quality of the catalogs being analyzed. Every calculation and result discussed here is dependent on the quality of the earthquake catalogs from which the Pre-CAT and Post-CAT were derived. An additional issue is that this study (as well as all seismicity-based forecasting studies) is inherently based on sampling a very short time, and we are: (1) assuming that short sample is generally representative of the long-term past, and (2) attempting to use that short sample to draw conclusions about (far into) the future.

The ability to determine whether or not there is a statistically significant difference between two CS results is highly dependent on the number of earthquakes in the samples analyzed. It is difficult to mathematically demonstrate that the difference between two or more hit percents can be attributed to a factor other than random chance if the Pre-CAT or Post-CAT sample sizes are small. This problem was most notable for CS analyses of the largest magnitude earthquakes. Even in seismically active areas, the number of very large magnitude earthquakes is small, and thus, sample sizes for those trials were inherently small. This issue was considered when drawing conclusions to ensure that any seemingly notable differences in hit percents were statistically significant as opposed to being an artifact of small sample sizes. In general, if either or both Post-CAT sample sizes were less than five earthquakes, then it was not possible to statistically determine significantly different hit percents at the 95% confidence level. This issue does not have an immediate resolution. More time, and thus, more earthquakes, will yield larger sample sizes for the very large magnitude earthquakes. Determining statistical significance will then be more viable, even for analyses of large magnitude events. The statistics used to analyze the trials are detailed in the *Variables to Analyze and Methods* section. The specific trials which this issue most affected, and the impacts of small samples sizes on CS results, are more completely detailed in the *Results* and *Discussion* sections.

CS assumes that a catalog is complete down to the lowest magnitude for which the Gutenberg-Richter recurrence relationship is linear. This is important for both the Pre-CAT and Post-CAT. The radius surrounding the earthquakes in a given Pre-CAT that are used to define the percentage of map area covered is only accurate if all of the earthquakes from the given timeframe are represented. If earthquakes are absent from the catalog, then the Pre-CAT circles will have a radius larger than the true value. Furthermore, obtaining an accurate percentage of hits requires all potential earthquakes in the Post-CAT be included. If an earthquake which would have been a hit or a miss is missing from the catalog, the hit percent will be artificially low or high, respectively. To minimize these negative effects of catalog completeness, catalogs were chosen for regions and time spans that were well monitored.

One of the purposes for choosing a minimum magnitude cutoff and not including earthquakes below that cutoff is that not all earthquakes of a sufficiently small magnitude will be recorded by seismographs. This is especially true for older catalogs. As seismic networks became more dense and seismic monitoring became more widespread, it became more likely that a smaller magnitude earthquake would be recorded, but this level of completeness was only realized in the most recent few decades. The catalogs analyzed in this study were chosen with the knowledge of when the particular network was established and to what time point the catalog is considered complete.

CS assumes that all earthquakes in a catalog are accurately located. This is important for both the Pre-CAT and the Post-CAT. If a Pre-CAT earthquake is mislocated, the Pre-CAT circles will not be properly drawn, and thus might show too much or too little overlap. If a Post-CAT earthquake is mislocated, it may be incorrectly classified as a hit or a miss, particularly if its correct location is near the edge of a Pre-CAT circle. This assumption has again become less problematic with the advance of network monitoring technology through time. The earthquake epicenters in older catalogs are probably less accurate than epicenters from more recent years, but catalogs were chosen as to not place too much reliance on the locational accuracy in very old catalogs. It is reasonable to consider this assumption to be accurate based on the high quality of data monitoring, and, in general, mislocated earthquakes are less detrimental to the validity of CS results than missing earthquakes.

Similarly, CS assumes that the other parameters of all earthquakes analyzed here (e.g., magnitude, depth) are accurately reported. These parameters are most important when the specific variable is being tested. Accurate magnitudes are important when performing the tests of changing minimum magnitude of the Post-CAT and changing minimum magnitude of the Pre-CAT. Accurate depths are needed when performing the depth layers test. It is reasonable to consider these assumptions to be accurate based on the high quality of data monitoring, and small inaccuracies should have minimal impact on overall CS results.

The CS method assumes that errors in the percent area calculation and radius determination are small. There will be round-off errors associated with each calculation, but it is reasonable to assume any difference between the actual percent area and the calculated percent area covered by a particular radius is negligible. This is made more true by ensuring the size of the cells used to calculate percent area are small relative to the radius used in the calculation. The area calculation program used in this study has been tested many times by Kafka and colleagues using both visually hand-calculated examples, as well as analytically calculated examples as test cases, and the program has always produced results with the necessary accuracy for CS studies.

This work assumes the designed tests can isolate the particular variable of interest for a given trial in order to gauge the impact of that variable on CS results. This assumption is more difficult to assess than those discussed above because the effects of other variables undoubtedly interfere with the results of any particular trial. This complication is mitigated by the large number of trials performed and several layers of comparable data analyzed. This study assumes that the impacts of a particular variable will be apparent when considering all of the available data and that large scale trends due to the variable of interest will overcompensate for minor contamination from other variables.

The method of statistical analysis performed in this study (i.e., binomial tests) requires that all samples be independent. Aftershocks were not removed from the catalogs analyzed here because the complexities and uncertainties associated with removing aftershocks are not consistent with CS's underlying philosophy of a procedure that is designed to be as simple as possible. For example, it is impossible to determine at what point an aftershock sequence ends and a different, independent, mainshock occurs. Attempting to eliminate all dependent events potentially eliminates data which should not have been removed. Instead, a "minimally invasive" approach (i.e., retain all earthquakes in the catalog) is taken here. The issue of removing aftershocks should be examined in future research, but for this study, it is assumed that it is reasonable to apply the statistical tests as if each event in the Post-CATs is independent. Also, Kafka and colleagues have experimented with applying CS to the same Post-CAT with and without aftershocks removed, and no differences were found in the fundamental conclusions based on the CS results.

The regions chosen for this study have had well-monitored, dense seismic networks for an extensive period of time and include a variety of tectonic settings. The extent to which the results from this study can be applied in general is currently unknown. It is possible these results can be used to interpret the frequency with which future earthquakes will occur near past earthquakes in other regions, but the degree to which these results can be used will not be known until further testing is completed and suitable catalogs are developed in other areas.

8.0. DISCUSSION

8.1. Changing Post-CAT Minimum Magnitude Cutoff

Of the regions studied, the NMSZ exhibited the most notable effect on hit percent with the incrementally increasing minimum magnitude cutoff of the Post-CAT variable (figure 33). This effect was particularly evident in the Complete region and Black and Yellow subzones. For trials with a large enough sample size of earthquakes to be considered statistically significant, these areas showed a decreasing trend in hit percent with the increasing minimum magnitude cutoff of the Post-CAT. This general trend was not observed in the NMSZ Blue or Purple subzones, AUS, CA, or AK.

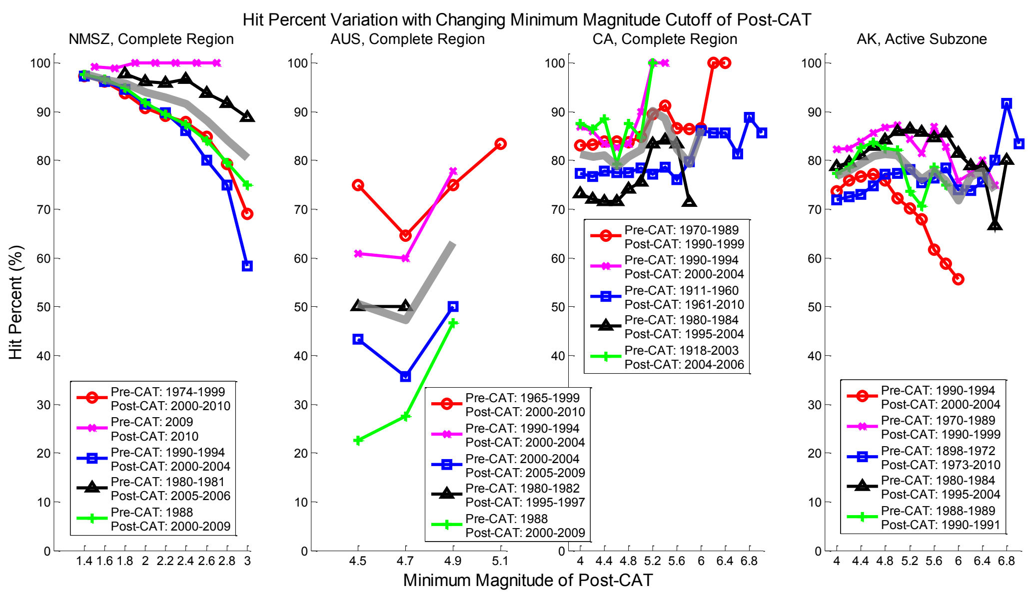


Figure 33. Hit percent with changing minimum magnitude cutoff of Post-CAT in NMSZ Complete region, AUS Complete region, CA Complete region, and AK Active subzone for catalogs with statistically significant number of Pre-CAT and Post-CAT earthquakes. Gray line is mean of all catalogs at each Post-CAT magnitude increment. In NMSZ, minimum magnitude cutoff of Pre-CAT: 1974-19992000-2010 (M1.4), 2009/2010 (M1.5), 1990-1994/2000-2004 (M1.4), 1980-1981/2005-2006 (M1.8), 1988/2000-2009 (M1.4). In AUS, M4.5 minimum magnitude cutoff of Pre-CAT for all catalogs. In CA, M4.0 minimum magnitude cutoff of Pre-CAT for all catalogs. In AK, M4.0 minimum magnitude cutoff of Pre-CAT for all catalogs.

New Madrid Seismic Zone: Discussion of Changing Post-CAT

In the NMSZ Complete region and Black and Yellow subzones, 14 of the 15 catalog pairs (five catalog pairs for each of the three areas) show a decrease in hit percent as the minimum magnitude cutoff of the Post-CAT is increased from a small magnitude (e.g., M1.4 to M2.0) to a moderate magnitude (e.g., M2.2 to M3.0). This downward trend continues through the trials for which there are at least five earthquakes in the Post-CAT (i.e., approximately M3.2 for the Complete region and Black subzone and approximately M3.0 for the Yellow subzone). However, 13 of those 14 catalogs then increase to 100% hits when the minimum magnitude cutoff of the Post-CAT is at its highest magnitude (e.g., M4.2) (figures 17a-17c). These increases in sample size are from small sample size Post-CATs. The high hit percents, even though based on just a few earthquakes, suggest that the distribution of large magnitude later occurring earthquakes is not completely random in these NMSZ areas.

One could speculate that hit percents would level to the mid-70's to mid-80's for large magnitude cutoffs, given an appropriately large sample size Post-CAT (figure 34, green dashed line). This speculation is based on the high hit percents observed for the large sample size, small magnitude cutoff trials, the high hit percents observed for the small sample size, large magnitude cutoff trials, and the similarity of NMSZ hit percents to plate boundary hit percents for other variable tests (discussed below). If CS results for the NMSZ are also consistent with plate boundary regions for the Post-CAT magnitude cutoff variable, then hit percents will level as indicated (i.e., low-70's to low-90's). The pink line in figure 34 represents a hypothetical trend of hit percents at large magnitude Post-CAT cutoffs if the small sample size results are, in fact, a true representation of the large sample size testing (i.e., mid-90's to upper-90's). This result is, however, considered unlikely because such high hit percents are not observed for large magnitude tests in other regions. It also does not fit with other observations that hit percent would decrease at significant samples sizes and then increase again. The blue line in figure 34 represents the speculated result that hit percents from large sample size trials would continue to decrease with the increasing Post-CAT magnitude cutoff until consistent with previous CS results for intraplate regions (i.e., low-50's to low-70's). This result is considered unlikely because NMSZ hit percents are more similar to plate boundary regions than intraplate regions for other variable tests. It is based on the assumption that NMSZ hit percents would only match intraplate region hit percents for this particular variable. It is possible, however, that there might be some hint here of what would explain the uniqueness of the NMSZ, a plate boundary-like zone in the deep interior of a plate. Further CS analyses of this region might clarify this issue.

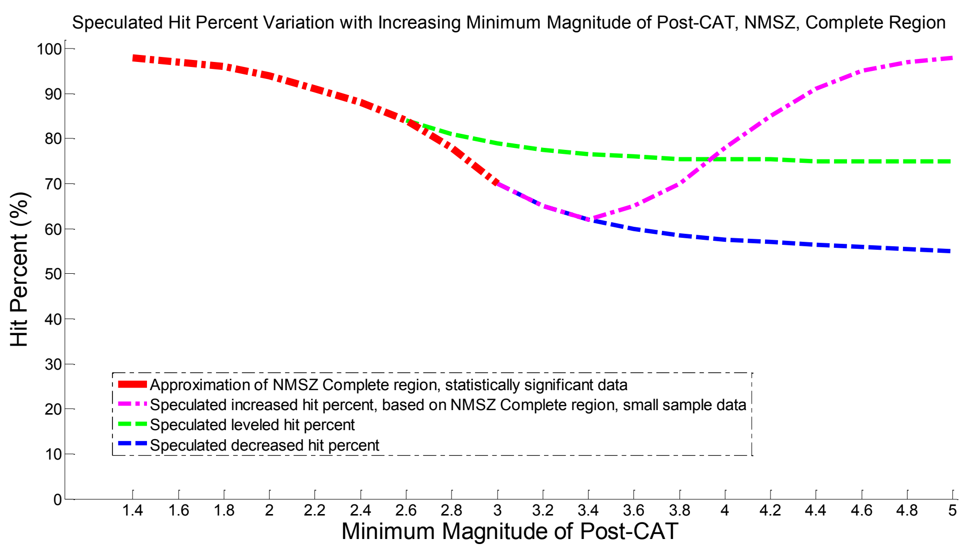


Figure 34. Hit percents with increasing minimum magnitude cutoff of Post-CAT in NMSZ Complete region for large number of earthquake sample size. Red line approximates actual small Post-CAT cutoff magnitude, large sample size data. Purple dashed-dotted line approximates actual large Post-CAT cutoff magnitude, small sample size data. Green dashed line speculates large Post-CAT cutoff magnitude hit percents if hit percents level to results similar to plate boundary regions. Blue dashed line speculates large Post-CAT cutoff magnitude hit percents if hit percents decrease to results similar to intraplate regions.

The NMSZ most closely fits into hypothesis H1 from figure 1, i.e., that future earthquakes tend to occur near where past earthquakes have occurred. The decrease in hit percent with an increase in minimum magnitude cutoff of the Post-CAT for the Complete region and Black and Yellow subzones indicates that these areas have a more substantial contribution from the H2 and H3 hypotheses for moderate Post-CAT magnitude cutoffs (e.g., M2.2 to M3.0) than they do for small Post-CAT magnitude cutoffs (e.g., M1.4 to M2.0). This means that, in these areas, the entire magnitude range of earlier occurring earthquakes is better able to forecast small magnitude later occurring earthquakes than it is able to forecast moderate magnitude later occurring earthquakes.

The application of these ideas for large magnitude Post-CAT earthquakes changes based on which of the speculated large sample size, large magnitude Post-CAT cutoffs (i.e., M4.0 and greater) in figure 34 is most accurate. If a large sample size of large magnitude Post-CAT earthquakes yields a hit percent consistent with a leveling of the downward trend seen in the statistically significant portion of the data (green line), as hypothesized above, or yields a hit percent which confirms the increase to a very high hit percent at the largest magnitude Post-CAT cutoffs (pink line), it would indicate that the majority of large magnitude later occurring earthquakes are located near earlier occurring earthquakes. For the green line, this tendency would be less prevalent for large magnitude later occurring earthquakes than for small magnitude later occurring earthquakes, while for the pink line, this tendency would be more prevalent for large magnitude later occurring earthquakes than for moderate magnitude later occurring earthquakes. If a large sample size of large magnitude Post-CAT earthquakes yields a hit percent which continues the downward trend (blue line) seen in the statistically significant portion of the data, it would indicate that large magnitude, later occurring earthquakes support the H2 or H3 hypotheses more than the small and moderate magnitude Post-CAT earthquakes do.

Seismic activity in intraplate regions is often attributed to reactivation of ancient zones of weakness (e.g., Sykes, 1978). Although these reactivated faults are often difficult to identify and correlate to present day earthquake locations, this hypothesis seems particularly relevant in a failed rift zone such as the NMSZ. It is possible that such a feature is the source of small magnitude earthquakes.

If a feature such as the buried Reelfoot rift zone is controlling the seismic activity, then its tectonic environment could reasonably be assumed to act more like a plate boundary region, with the earthquakes persistently occurring in the vicinity of the feature. Small releases of stress along the rift zone would explain the high hit percent for the small magnitude Post-CAT cutoff trials (e.g., M1.4 to M2.0). The rift zone might not be storing enough seismic energy to consistently produce moderate to large magnitude earthquakes (e.g., M2.2 and greater), so their locations are more scattered than those of small magnitude events. The locations of the large magnitude earthquakes could be explained by thoroughgoing faults which are splays off of the rift, but not restricted to its principal zones. Why such a distribution of stored and released seismic energy might be present in the NMSZ remains and unresolved question.

The Blue and Purple subzones do not show the same decreasing trend in hit percent with an increase in Post-CAT minimum magnitude cutoff as does the Complete NMSZ region (figures 17d-17e). Their hit percents are also slightly lower than the Complete region and Black and Yellow subzones. However, the Blue and Purple subzones still have hit percents which are greater than 33% (i.e., great than the percentage of map area coverage) and are similar to the hit percents hypothesized for the leveled trend of large sample size, large magnitude Post-CATs in the green line of figure 34. The combination of these results may indicate that the Blue and Purple subzones are not as seismically influenced by the Reelfoot rift as the Complete region and Black and Yellow subzones. It is possible that the Central principal zone of the rift is more active than the Linear South or Linear North zones.

Australia: Discussion of Changing Post-CAT

AUS consistently has the lowest hit percents of the regions studied here, but in most cases the hit percents are still above 33% for the changing Post-CAT magnitude cutoff variable (figures 18a-18c). Catalogs for this region were only considered complete down to M4.5, which restricted the analysis of small magnitude trials. The lack of small magnitude data makes a complete analysis difficult due to the inability to establish trends that can then be considered for the small sample size, large magnitude data, as was done for the NMSZ. Without the small magnitude data, only a few data points are statistically significant for each catalog pair. It is possible that smaller magnitude earthquakes would show CS results which are consistent with other intraplate regions, such as the NMSZ, but a more complete catalog would be required for testing that hypothesis.

The relatively low hit percents indicate that AUS is characteristically closer to the H3 (i.e., future earthquakes will be uniformly distributed) hypothesis than other regions, at least for the available magnitude range. Australia is centered on the Australian Plate. Western Australia has been stable since the breakup of Gondwana, and eastern Australia, while an assembly of many accreted terranes, was last altered tectonically in the Mesozoic.

The lack of any trends or observable consistency in hit percent within a portion of the region, or for a particular catalog pair, is evidence that past activity in AUS is not a good indicator of locations of future large earthquakes. If there were still lithostatic stress releases remnant from the eastern continent's early formation, it may be expected that the East subzone would show higher hit percents than the Complete region or the West subzone. AUS's hit percent results are similar to the CS result found by Kafka (2007) for global Stable Continental Regions (SCRs, 55% hits), which is consistent with the fact that, of the regions analyzed in this study, AUS is the most purely SCR.

California: Discussion of Changing Post-CAT

The consistency of hit percents in CA for the statistically significant Post-CAT magnitude steps indicate that earthquakes of different sizes in the region are relatively consistent in terms of their proximity to previously occurring earthquakes. This may mean that the factors controlling the release of that earthquake energy are the same for both small and large energy buildups. This is in contrast with the NMSZ (discussed above), in which movement along the buried Reelfoot rift is hypothesized to only be large enough to control the seismicity of small magnitude earthquakes.

This idea of a constant reservoir of earthquake energy makes sense for a plate boundary setting and a major throughgoing fault system such as the San Andreas. The Pacific and North American Plates are sliding past each other at an approximately constant rate, so the buildup of energy is approximately a constant across the fault (at least for regions that are similarly oriented relative to the vector of convergence). The San Andreas is part of a large fault system, so there are many splays of various sizes throughout the region. The stored energy is most likely to be released in the fault system, so epicenters are likely to be constrained near the fault system, but any given fault splay could produce a variety of magnitude earthquakes.

The hit percents found for CA are not only consistent across the range of Post-CAT magnitude cutoffs (figures 19a-19c), but are also consistent with previous CS results. Kafka

(2007) found about 87% hits for global plate boundary regions, which is very similar to the CA results for the changing Post-CAT cutoff variable (mid-70's to upper-90's).

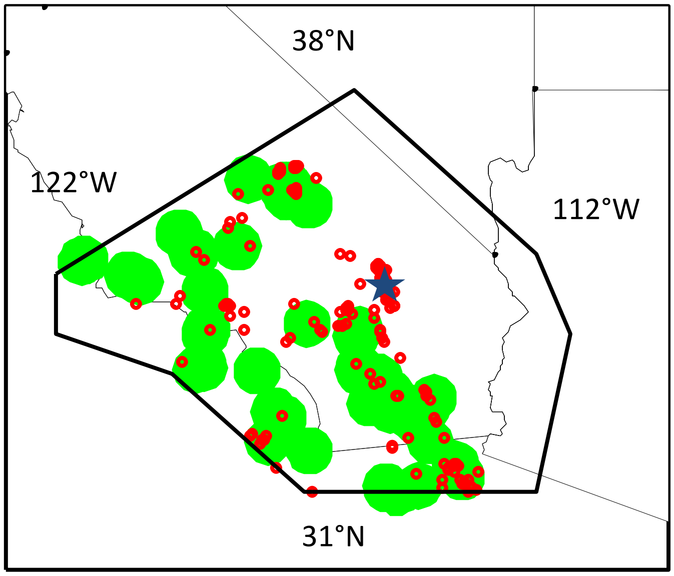


Figure 35. CS map for CA South subzone, 1980-1984 Pre-CAT/1995-2004 Post-CAT. For 33% map coverage, 33 km radius, 50% hits. Blue star indicates epicenter of Hector Mine, October 16th, 1999, M7.1 earthquake.

The relatively low hit percents seen in the Complete region and South subzone 1980-1984/1995-2004 catalog pair are likely the result of the M7.1 Hector Mine earthquake which occurred on October 16th, 1999 (United States Geological Survey, 2012). This large event produced many aftershocks (i.e., a large percentage of the earthquakes in the Post-CAT), but occurred in a remote area with little past seismic activity. The Pre-CAT, only five years long, was not long enough to include any earthquakes in the region of the Hector Mine earthquake (figure 35). Only many years of further monitoring of this region would make it possible to discern whether the seismicity in the Hector Mine region is a persistent feature, or just an anomalous event.

A possible concern when comparing CA and NMSZ results is that the CS analysis was not performed on CA earthquakes below M4.0 due to the extremely large number of small magnitude earthquakes in the region. The decreasing trend in hit percent with increasing Post-CAT magnitude cutoff seen in the NMSZ was observed at small magnitudes (i.e., M3.0 and smaller). It is unclear whether a similar effect would be seen in CA if the changing Post-CAT cutoff magnitude variable was applied to earthquakes smaller than M4.0. It is hypothesized that this effect would not be seen because the San Andreas and associated faults control not only large magnitude, but also small magnitude seismicity in the region.

Alaska: Discussion of Changing Post-CAT

As with CA, the AK changing Post-CAT cutoff variable Complete region and Active subzone results are comparable to those found in previous CS studies for global plate boundary regions. For statistically significant steps, the Complete regions and Active subzone hit percents are also very consistent as the Post-CAT magnitude cutoff increases (figures 20a-20b). The Nonactive subzone has generally lower hit percents than the Complete region and Active subzone, but the statistically significant steps are still relatively consistent as the Post-CAT magnitude cutoff increases (figure 20c).

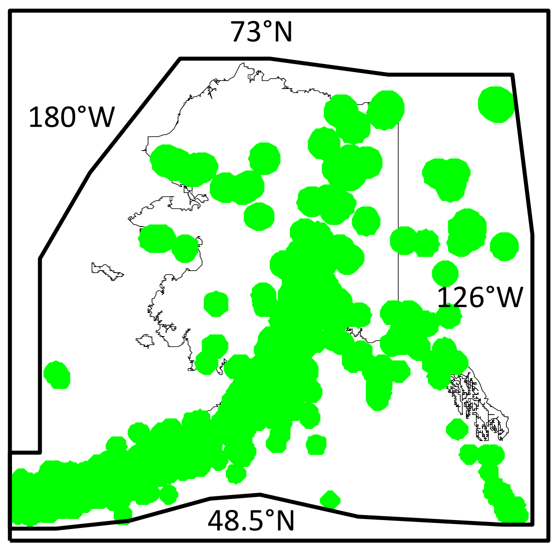


Figure 36a. 1980-1984 Pre-CAT circles in AK Complete region. For 33% map area coverage, 67 km.

The hypothesized impact of the Aleutian-Alaska subduction zone on CS results in AK is similar to the impact of the San Andreas fault on CS results in CA. The Pacific Plate is subducting under the North American Plate along a relatively localized zone, so energy releases of all sizes are primarily constrained to this planar region. The Active subzone most directly highlights the CS characteristics of the subduction zone, and is also the set of results most closely resembling those of CA and previous plate boundary region CS results (Kafka, 2007). If movement along the subduction zone is the primary factor controlling the seismicity of the region, then the area surrounding the subduction zone should have relatively high hit percents, no matter the Post-CAT cutoff magnitude, because the buildup and release of energy is repeatedly occurring along the same source zone.

Statistically significant hit percents in the AK Complete region range from the mid-80's to the mid-90's, while hit percents in the Active subzone range from the low-70's to mid-80's. The higher hit percents in the Complete region are again likely related to the Aleutian-Alaska subduction zone controlling the majority of earthquake energy release in the region. Based on a CS map of the Complete region (figure 36a), it is clear that the vast majority of earthquakes are located along the subduction zone, but the Pre-CAT circle radii were chosen to fill 33% of the entire map area. Since only a few earthquakes occur in the areas that are not along the subduction zone, all Pre-CAT circles in the region must have a larger radius to cover 33% of the map, including those along the subduction zone. This effect is seen when looking at a CS map of the Active subzone (figure 36b). The radius needed to cover 33% map area is reduced from 67 km in the Complete region to 18 km in the Active subzone, although the Post-CAT earthquakes being forecasted are mostly the same. Focusing on the Active subzone might yield CS results more characteristic of a subduction zone boundary than considering the AK Complete region.

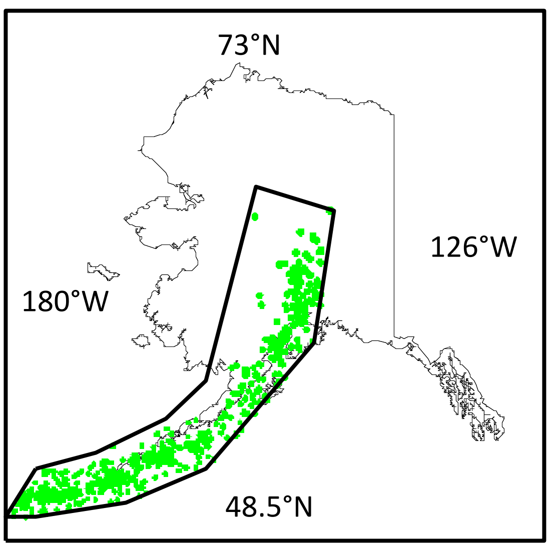


Figure 36b. 1980-1984 Pre-CAT circles in AK Active subzone. For 33% map area coverage, 18 km.

These types of issues associated with choosing CS circle radii are fundamental to the way that CS was designed and represent a trade-off between wanting to account for regions of high rates of past seismicity versus wanting to assure that no past earthquakes are left out of the analysis. This trade-off was investigated by Kafka and Ebel (2011) who found that, for a study of California, information about rates of seismicity did not improve the predictability of locations of future earthquakes.

The Nonactive subzone includes most of the accretionary belts of the region and the northern end of the Pacific and North American Plate transform boundary, making it somewhat of a combination of an intraplate and plate boundary region. The observed hit percents fit with this assessment, as they are lower than the Active subzone, but not as low as the changing Post-CAT magnitude variable results for AUS. The results also have the characteristic of a larger spread between the catalog pairs than the Active subzone, indicating that the hit percents may be more a product of the given catalog pair, rather than a characteristic of the region.

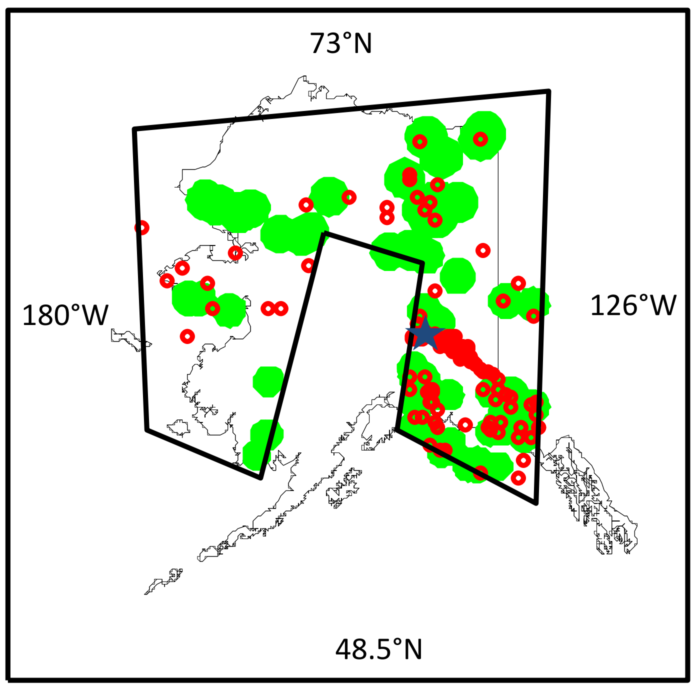


Figure 37. CS map for AK Nonactive subzone, 1990-1994 Pre-CAT/2000-2004 Post-CAT. For 33% map area coverage, 66 km radius, 29% hits. Blue star indicates epicenter of central Alaska, November 3rd, 2002, M7.9 earthquake.

The relatively low hit percents seen in the Nonactive subzone 1990-1994/2000-2004 catalog pair might be the result of the M7.9 central AK earthquake on November 3rd, 2002 (United States Geological Survey, 2012). Similar to the Hector Mine earthquake in CA, the Pre-CAT, only five years long, was not long enough to include any earlier occurring earthquake to cover the portion of the map containing this event and its aftershocks (figure 37).

The concerns of only performing CS analysis down to M4.0 discussed for CA also apply to AK. However, it is again hypothesized that a decreasing trend in hit percent for small magnitude earthquakes would not be seen in AK to the extent that it was in the NMSZ because the Aleutian-Alaska subduction zone controls not only large magnitude, but also small magnitude seismicity in the region.

Changing Post-CAT: Comparison of Intraplate Regions v. Plate Boundary Regions

The hit percents in the plate boundary regions, CA and AK, are more consistent as the minimum magnitude cutoff of the Post-CAT is increased than are the hit percents in the intraplate regions, the NMSZ and AUS. When considering the areas in the NMSZ whose seismicity is hypothesized to be predominately controlled by the Reelfoot rift, hit percents decreased with the increasing Post-CAT magnitude cutoff and ranged from the mid-70's to upper-90's. When considering the AUS region and areas in the NMSZ whose seismicity is hypothesized to be less controlled by the Reelfoot rift (which are considered move representative of intraplate regions), hit percents ranged from the mid-40's to low-80's and were highly variable. When considering the Complete CA region and the Active subzone of the AK region (which is considered more representative of a subduction zone boundary than the Complete AK region, as discussed previously), the hit percents for the plate boundary regions ranged from the mid-70's to the mid-80's.

It is hypothesized that the consistently high hit percents in the plate boundary regions are due to the constant nature of the mechanics of the San Andreas fault system and Aleutian-Alaska subduction zone. A similar constant source of energy buildup and release appears to be available in some portions of the NMSZ for small magnitude events in the form of the Reelfoot rift, but not in AUS or other portions of the NMSZ.

8.2. Changing Pre-CAT Minimum Magnitude Cutoff

The most notable result from the incrementally increasing minimum magnitude cutoff of the Pre-CAT variable was the lack of any pronounced change in hit percent, for statistically significant steps, as the Pre-CAT was increased (figure 38). This consistency indicates that, within a region, a certain magnitude range of earlier occurring earthquakes is not any better able to forecast the locations of large magnitude later occurring earthquakes than is another magnitude range of earlier occurring earthquakes. This might mean that small magnitude earthquakes, for which more data is available, can be used effectively to forecast the locations of large magnitude earthquakes, which tend to be more destructive.

New Madrid Seismic Zone: Discussion of Changing Pre-CAT

The CS results for the changing Pre-CAT magnitude cutoff in the NMSZ are consistent with the results for the changing Post-CAT magnitude cutoff. As discussed above, it was hypothesized that, if given a large sample size of large magnitude Post-CAT earthquakes, the NMSZ hit percent would level in the mid-70’s to mid-80’s. When isolating only the largest magnitude Post-CAT earthquakes, hit percents for the NMSZ were in the mid-70’s to mid-80’s (figure 38).

In the changing Post-CAT cutoff variable, a decrease in hit percent was observed as the Post-CAT cutoff was increased from small magnitude (e.g., M1.4 to M2.0) to moderate magnitude (e.g., M2.2 to M3.0) earthquakes. It was hypothesized that this was because the location of the Reelfoot rift was controlling the seismicity of the small magnitude earthquakes, but had less of an impact on the locations of the large magnitude earthquakes in the region. The decrease in hit percent effect is not seen in the changing Pre-CAT variable, which is further evidence that the location of the Reelfoot rift is only controlling the seismicity of the small magnitude events. By the design of the changing Pre-CAT variable, there are no small magnitude events included in the Post-CAT. Thus, the increase in hit percent due to small magnitude earthquakes along the Reelfoot rift forecasting other small magnitude earthquakes is not observed.

Australia: Discussion of Changing Pre-CAT

Using the 1% largest magnitude earthquake for the Post-CAT was intended to highlight which magnitude range of earlier occurring earthquakes is most effective at forecasting the locations of the largest later occurring earthquakes. While accomplishing that goal for the larger sample size catalogs, using only 1% of the earthquakes was ineffective for smaller sample size catalogs. Particularly for AUS, where the largest Post-CAT sample size was just 56 earthquakes total, using at least 10% of the largest earthquakes in the catalog may have been more effective.

Given the data, there was no discernible pattern to the hit percents for AUS. This is similar to the changing Post-CAT cutoff variable, which showed inconsistent and highly variable results within a catalog pair.

California: Discussion of Changing Pre-CAT

The ability to forecast the largest magnitude earthquakes is particularly important in CA due to the high population density, number of major cities, and frequency of large earthquakes. The seismic network in CA is more than sufficient to record not only the large magnitude, widely felt earthquakes, but also smaller magnitude events. If a particular magnitude range of earlier occurring earthquakes is better able to forecast large magnitude later occurring earthquakes (e.g., M6.0 and greater), CA should have the data to monitor that phenomenon.

The changing Pre-CAT cutoff variable results show similar hit percents for the largest magnitude Post-CAT earthquakes as were seen for the changing Post-CAT cutoff variable. Statistically significant hit percents range from the mid-50's to the upper-90's (figure 38). Although these data are not as consistent from one catalog pair to another as are the hit percents for the CA changing Post-CAT cutoff variable, this variability can be attributed to the smaller sample size.

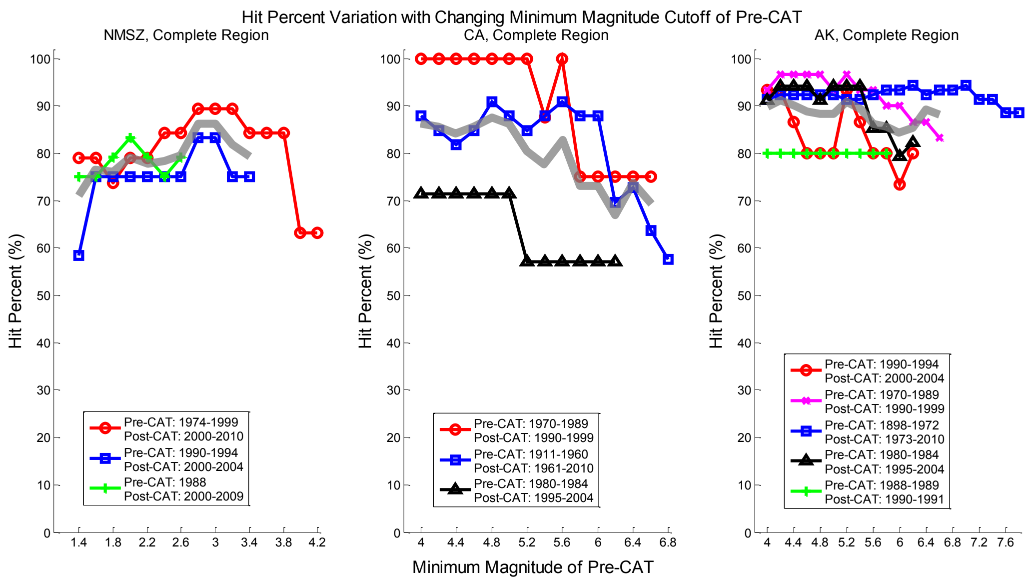


Figure 38. Hit percents with changing minimum magnitude cutoff of Pre-CAT in complete regions for catalogs with statistically significant number of Pre-CAT and Post-CAT earthquakes. Gray line is mean of all catalogs at each Pre-CAT magnitude increment. In NMSZ, minimum magnitude cutoff of Post-CAT: 1974-19992000-2010 (M3.2), 2009/2010 (M3.3), 1990-1994/2000-2004 (M3.0), 1980-1981/2005-2006 (M4.0), 1988/2000-2009 (M3.0). In AUS, minimum magnitude cutoff of Post-CAT: 1965-1999/2000-2010 (M5.3), 1990-1994/2000-2004 (M5.1), 2000-2004/2005-2009 (M5.3), 1980-1982/1995-1997 (M6.3), 1988/2000-2009 (M5.3). In CA, minimum magnitude cutoff of Post-CAT: 1970-1989/1990-1999 (M6.5), 1990-1994/2000-2004 (M5.9), 1911-1960/1961-2010 (M6.1), 1980-1984/1995-2004 (M5.8), 1918-2003/2004-2006 (M5.6). In AK, minimum magnitude cutoff of Post-CAT: 1990-1994/2000-2004 (M6.1), 1970-1989/1990-1999 (M6.2), 1898-1972/1973-2010 (M6.2), 1980-1984/1995-2004 (M6.1), 1988-1989/1990-1991 (M6.3).

These hit percents remained approximately constant through nearly the entire statistically significant portion of the Pre-CAT steps. Only at the largest magnitude Pre-CAT cutoffs (e.g., M6.5 and greater) is there a difference between the ability of moderate magnitude earlier occurring earthquakes (e.g., M4.0 to 6.0) versus large magnitude earlier occurring earthquakes (e.g., M6.0 and greater) to forecast the locations of the largest magnitude later occurring earthquakes (i.e., M6.0 and greater). This may mean that, in CA, there is no greater tendency for large magnitude earthquakes to occur near previous large magnitude earthquakes than to occur near moderate magnitude earthquakes.

If this is, in fact, the case in general, then this is important because the sample size of large magnitude (i.e., M6.0 and greater) earthquakes is small compared to that of moderate magnitude earthquakes. Being able to use the larger data sets associated with moderate magnitude earthquakes to forecast the locations of large magnitude earthquakes might make hazard maps more accurate.

Alaska: Discussion of Changing Pre-CAT

The results for AK are similar to those for CA, although the human impacts may not be as pronounced due to lower population density in the AK region. Changing Pre-CAT cutoff variable hit percents range from the low-80’s to upper-90’s (figure 38) and are again similar to those seen at the largest magnitude steps of the changing Post-CAT cutoff variable.

A statistical difference between the M4.0 Pre-CAT step and the largest Pre-CAT step for which the trial was considered significant (e.g., M7.5) is present in four of the five catalog pairs. These differences are not present, however, if the sample size needed for the test to be considered significant is increased from five to about 10. This may indicate that, in AK, any magnitude range of earlier occurring earthquakes can be used with equal success to forecast the locations of large magnitude later occurring earthquakes (e.g., M6.0 and greater), assuming the catalog sample size is moderately large. As with CA, this is important because large sample sizes of data regarding the locations of moderate magnitude earthquakes in the region are already available. Using them to forecast the locations of large magnitude events would be more readily applicable than waiting for a larger sample size of large magnitude earthquakes.

<u>Changing Pre-CAT: Comparison of Intraplate Regions v. Plate Boundary Regions</u>

Hit percents in both the intraplate and plate boundary regions are statistically constant with the increasing minimum magnitude cutoff of the Pre-CAT. Both of the plate boundary regions show a significantly lower hit percent at the highest Pre-CAT magnitude cutoffs when compared to the smallest magnitude cutoffs, but this decrease is not seen in the incremental testing. No such decrease was seen in the intraplate regions, although this may be due to the smaller sample sizes of those catalogs. Hit percents for the changing Pre-CAT minimum magnitude cutoff in the NMSZ were slightly lower than results for other variables, and hit percents for the changing Pre-CAT minimum magnitude cutoff in the plate boundary regions were approximately equal to results for other variables.

8.3. Depth Layering

The most notable effect on hit percent with depth was observed in the subduction zone boundary region, AK, particularly in the Complete region and Active subzone. These areas showed an increase in hit percent with increasing depth, for trials with enough Pre-CAT and Post-CAT earthquakes to be considered statistically significant (figure 39). Less robust effects included a higher hit percent at intermediate depths than at shallow or deep depths in the NMSZ and a decrease in hit percent with depth in CA.

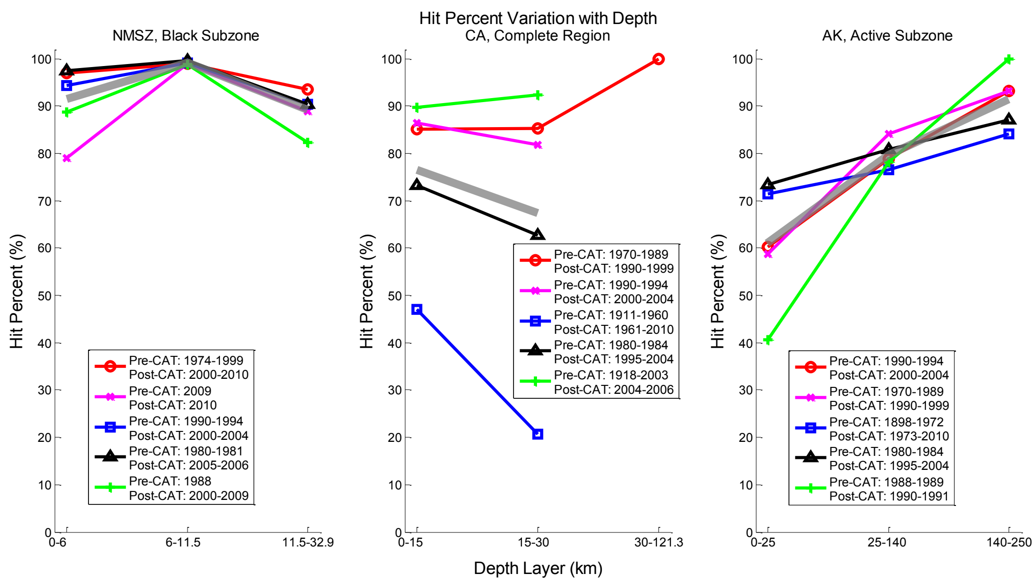


Figure 39. Hit percents with depth for catalogs with statistically significant number of Pre-CAT and Post-CAT earthquakes. Gray line is mean of all catalogs at each depth layer. In NMSZ Black subzone depth layers defined by: shallow (less than 6 km), intermediate (between 6 and 11.5 km), deep (greater than or equal to 11.5 km). In CA Complete region, depth layers defined by: shallow (less than 15 km), intermediate (between 15 and 30 km), deep (greater than or equal to 30 km). In AK Active subzone, depth layers defined by: shallow (less than 25 km), intermediate (between 25 and 140 km), deep (greater than or equal to 140 km).

New Madrid Seismic Zone: Depth Discussion

In the NMSZ Complete region and Black, Yellow, and Blue subzones combined, 13 of the 20 catalog pairs (five catalog pairs for each of the four areas) have a statistically higher hit percent for intermediate depth earthquakes than for shallow and deep earthquakes (figure 39). The mid-90’s to upper-90’s hit percents observed in the intermediate layer are most similar to those seen at the small magnitude steps of the changing Post-CAT magnitude cutoff variable. Hit percents for the shallow and deep layers are similar to those seen at the moderate to large magnitude steps of the Post-CAT cutoff variable, including low-80’s to mid-90’s for the Complete region and Black subzone, low-70's to mid-90's for the Yellow subzone, and mid-40's to upper-90's for the Blue subzone.

If the hypothesis introduced above is accurate (i.e., the buried Reelfoot rift is controlling the seismic activity, particularly small magnitude events, of the NMSZ), then an increase in hit percent at a certain depth layer may indicate the depth of the Reelfoot rift. In the NMSZ, the intermediate depth layer was set as earthquakes with epicenters between 6 and 11.5 km below the surface. This range fits with previous interpretations of the depth of the Reelfoot rift basin at approximately 8 km (Nelson and Zhang, 1991). The increase in hit percent in these areas fits with the hypothesis that the Reelfoot rift controls small magnitude seismicity in the region.

The Purple subzone does not show the same increase in hit percent at the intermediate depth layer as the other areas in the region, although sample sizes are small. The Purple subzone also does not show the same decrease in hit percent from the smallest magnitude steps to the moderate magnitude steps of the changing Post-CAT cutoff variable as the other areas in the region. It was hypothesized that the seismicity of the Purple subzone is not as much influenced by the Reelfoot rift as the Complete region and the other subzones, and the CS depth results support this hypothesis. The seismicity in the Purple subzone may be more influenced by characteristics akin to purely SCRs and accretionary belts, similar to AUS and the AK Nonactive subzone, than by well-defined, localized ancient zones of weakness, such as the Reelfoot rift. Ancient zones of weakness in the Purple subzone might be more uniformly distributed than in the zone above the Reelfoot rift.

Australia: Depth Discussion

There are statistically significant increases in hit percent with depth in AUS, but it is not a consistent trend across many catalog pairs in the region. As with other variables, the small samples sizes in the region make complete interpretations difficult, but general analyses are still possible. The hit percents are highly variable between different catalog pairs, but are still in the low-30's to low-70's range consistent with results from the other variable tests for AUS. Particularly for the deep layer, the mid-50's to mid-60's hit percents are also consistent with CS results for intraplate regions from previous studies. The general, although not always significant, increase in hit percent with depth may mean that there are reactivated faults at depths greater than 30 km. This would account for shallow and intermediate depth layers having hit percents more consistent with the H3 hypothesis, and the deep layer having hit percents near the global SCR average of 55%.

California: Depth Discussion

The change in hit percent with depth results which are statistically significant in CA contradict many of the results which are not statistically significant. In all comparisons between depth layers which yielded statistically significant differences, there was a decrease in hit percent with depth. However, (although these changes were not significant) there was an increase in hit percent with depth in three of the five comparisons between the intermediate layer and deep layer in the Complete region, two of the three comparisons between the intermediate layer and deep layer in the North subzone, and three of the five comparisons between the shallow layer and intermediate layer in the South subzone.

The deep layer catalogs in the Complete region and North subzones and the intermediate layer catalogs in the South subzone generally had smaller sample sizes than the remaining layers. In many cases, these sample sizes were too small to meet the five Pre-CAT and five Post-CAT earthquake requirement to consider the result significant. Given the sample sizes, the most relevant changes in hit percent are the decreases between the shallow layer and intermediate layer in the Complete region and North subzone.

The San Andreas fault is a transform boundary which is visible at the surface at many locations. It is possible that it is more common for stored energy to be released at these surface, or near surface, rupture points than it is for the energy to be released at deeper locations. If this is the case, then hit percents could be higher at shallow depths since the locations of many earthquakes are spatially concentrated along the fault. According to this model, earthquake locations at deeper points would be less controlled by the San Andreas, and thus a slight drop in hit percent would be reasonable. The vertical geometry of the San Andreas is not well constrained, but it is estimated to be between about 7 and 18 km deep, depending on the specific location (Norris and Webb, 1990). In CA, the shallow depth layer was set as earthquakes with epicenters less than 15 km below the surface. This range fits with the depth of the San Andreas and supports the hypothesis that releases of energy near the surface of the fault increase hit percents in the shallow depth layer.

Alaska: Depth Discussion

Of the 37 available comparisons in the AK region, 23 showed a significantly higher hit percent in the deeper of the two layers being compared. In the Complete region and Active subzone combined, all 10 comparisons between the shallow layer and intermediate layer (i.e., five catalogs for both of the two areas) showed a statistically higher intermediate depth layer hit percent.

This repeated tendency indicates that, in AK, later occurring earthquakes are located near earlier occurring earthquakes more often at deeper depths than at shallower depths (figure 39). This may mean that the Aleutian-Alaska subduction zone more tightly constrains the hypocenters of earthquakes at depth than it does near the surface. Since the subduction zone is controlling the seismicity of the region, an increase in hit percent at a given depth layer is consistent with the notion that the earthquakes at that depth layer consistently fall along a more defined plane than at other depths. The increase in hit percent with depth in AK is thus consistent with the plate tectonic phenomenon that the seismicity associated with the subduction zone is more confined to the vicinity of the subducting slab at depth than it is near the surface.

The Aleutian-Alaska subduction zone is estimated to reach depths of 100 to 120 km, depending on the specific location along the arc (van Stiphout et al., 2009). In AK, the intermediate depth layer was set as earthquakes with epicenters between 25 and 140 km, and the deep layer was set as earthquakes with epicenters greater than 140 km. The Wadati-Benioff zone, an area of deep seismicity in subduction zones, has been estimated at up to 400 km in the region (Ruppert et al., 2007). These ranges fit with the deepest portion of the subduction zone and support the hypothesis that the releases of energy are confined to the subducting slab at depth, but are more spatially scattered near the surface.

It is also believed that the clustering of earthquakes in Wadati-Benioff zones tends to focus and taper with depth, due to a narrow region of disturbance as the origin (Scalera, 2008). This would support the hypothesis that hit percents at deep depths in AK are higher than hit percents at shallow depths. If the deep layer earthquakes are at or near the Wadati-Benioff zone, then their hypocenters should be more focused than those near the surface, and Post-CAT earthquakes will be located near Pre-CAT earthquakes more often.

The hit percents within the Complete region and Active and Nonactive subzones are similar to those hit percents seen for the changing Post-CAT magnitude cutoff in their respective regions. The Complete region has hit percents in the mid-60’s to upper-90’s, the Active subzone has hit percents in the mid-40’s to mid-90’s, and the Nonactive subzone has hit percents in the mid-20’s to mid-90’s. This distribution of hit percents is further evidence that the process of covering 33% map area in the Complete region increases its hit percents, as compared to in the Active subzone, even though there are few earthquakes in the northern portion of the map. The Nonactive subzone is analogous to previously tested SCRs, and the Active subzone is the most characteristic of hit percents in the area.

Depth Comparison: Intraplate Regions v. Plate Boundary Regions

Hit percents in CA, the Complete AK region and Active subzone, and areas of the NMSZ appear to be influenced by the depths of the tectonic feature controlling them. These features include the San Andreas fault system in CA, the Aleutian-Alaska subduction zone in AK, and the Reelfoot rift in the NMSZ. The depths at which these features are located vary based on the region. When considering AUS, areas in the NMSZ which do not include large portions of the Reelfoot rift, and the AK Nonactive subzone, hit percents are more varying and generally lower than the areas containing major tectonic features.

The base of the seismogenic zone (i.e., where seismicity can occur in a region), defined as the onset of crystal-plastic deformation (i.e., flow) at the brittle ductile transition will be located at different depths for different regions (Scholz, 2002). The specific depth is influenced by tectonic setting, in particular the thermal structure of the lithosphere. For example, the seismogenic zone is expected to be deeper in subduction zone type boundaries than in transform fault type boundaries. Cold lithosphere is brought to depth in subduction zone type boundaries, also lowering the isotherms.

8.4. Time Progression

When using the same Pre-CAT, little to no evidence of a change in hit percent with time was observed in the regions analyzed. It is possible that the specific results obtained are more a product of the specific catalog pairs chosen than of anything fundamental about the time progression variation in hit percents. However, the lack of any consistent trend in the data, even with many trials, indicates that hit percents remain constant through time in a given region, at least for the time scales tested here.

New Madrid Seismic Zone: Time Progression Discussion

In the NMSZ, hit percents with a changing Post-CAT appear generally consistent, although there are statistically significant differences between the zero time gap trial in each set and the non-zero time gap trials. However, these significant differences often occur at the same Post-CAT steps for different Pre-CATs (e.g., table 2a). This indicates that the change in hit percent is a characteristic of the particular Post-CAT that repeatedly yields a significant difference in hit percent, not evidence of a fundamental change in hit percent with time.

Of the 12 available comparisons in the Complete NMSZ and the Black and Yellow subzones between the zero time gap Post-CAT in a given set and the 2000-2004 Post-CAT (i.e., four comparisons for each of the three areas), nine showed a significantly higher hit percent for 2000-2004. Of the 15 available comparisons in the Complete NMSZ and Black and Yellow subzones between the zero time gap Post-CAT in a given set and the 2005-2009 Post-CAT (i.e., five comparisons for each of the three areas), 10 showed a significantly higher hit percent for 2005-2009. This tendency was also true when the 2000-2004 and 2005-2009 Post-CATs were combined, because the Complete NMSZ and Black, Yellow, and Blue subzones all showed a significant increase in hit percent in the 10 year segment trial when comparing the 1990-1999 to 2000-2009 Post-CATs.

If hit percent consistently increases or decreases at a certain time interval from the Pre-CAT, that would be evidence that hit percent is not consistent though time in the region. If a peak or trough in hit percent is repeatedly observed with a particular time gap between the Pre-CAT and Post-CAT, it may mean that later occurring earthquakes are located near earlier occurring earthquakes at the highest or lowest rate, respectively, given that time gap. If a peak in hit percent is repeatedly observed at a particular Post-CAT, however, it more likely means earthquakes in that particular catalog occur near previous earthquakes at a higher rate than in other catalogs.

The hit percents are consistent with those observed for other variable tests in the NMSZ. The Complete region and Black and Yellow subzones have the highest hit percents in the mid-90’s to upper-90’s. The Blue and Purple subzones have hit percents in the mid-70’s to mid-90’s and mid-40’s to upper-80’s, respectively. The Purple subzone yields hit percents more akin to AUS and previously tested intraplate regions than does the rest of the NMSZ. This is again evidence that the factors controlling the seismicity of most of the NMSZ region are not the same as the factors controlling the seismicity of the Purple subzone.

Australia: Time Progression Discussion

Hit percents in AUS do not show a consistent pattern with the changing Post-CAT. They are similar to, or lower than, hit percents from SCRs from previous studies. There are some trials in the Complete region and West subzone with enough Pre-CAT and Post-CAT earthquakes to be statistically significant with hit percents less than 33%. The East subzone has extremely low hit percents in many cases, but does not have enough Pre-CAT or Post-CAT earthquakes for these trials to be significant.

There are 10 hit percents in the Complete region less than 33% with at least 16 Pre-CAT and 21 Post-CAT earthquakes. The lowest of these hit percents is 17%, with four hits out of 23 Post-CAT earthquakes forecasted by 16 Pre-CAT earthquakes. There are nine hit percents in the West subzone less than 33% with at least 14 Pre-CAT and 14 Post-CAT earthquakes. The lowest of these hit percents is 12% with six hits out of 49 Post-CAT earthquakes forecasted by 14 Pre-CAT earthquakes.

These hit percents are lower than expected, even for an SCR, but they do not show a consistent trend in terms of change in hit percent with time. Out of 24 comparisons between the zero time gap trial in a set and the non-zero time gap trials, there are six statistically significant differences in both the Complete region and West subzone and zero statistically significant differences in the East subzone. Of the 12 significant differences, eight show a decrease in hit percent from the zero time gap trial to the non-zero time gap trial, and four show an increase in hit percent from the zero time gap trial to the non-zero time gap trial. There is not an observable pattern as to the number of years in the time gap between the Pre-CAT and Post-CAT which produces an increase or decrease in hit percent.

Hit percent results that are less than the 33% CS map area suggest that hypothesis H2 of figure 1 (future earthquakes occurring where past earthquakes have not occurred) may be characteristic of the region under investigation. Such low percentages of hits have not been observed in previous CS studies. Low values for hit percents might then be an indication that we have discovered regions (i.e., AUS, or subregions of AUS) that are characterized by H2. Alternatively, we may be seeing a statistical fluctuation here, i.e., in any statistical analysis, low values are expected due to scatter. Which of these two possibilities is the true phenomenon occurring in AUS can only be discerned through further study of future earthquakes.

California: Time Progression Discussion

There is no clear trend in hit percent with changing Post-CAT years in CA, although there are several comparisons between the zero time gap trial in a set and the non-zero time gap trials which yield statistically significant differences in hit percent. These differences include higher hit percents for the zero time gap Post-CAT and higher hit percents for the non-zero time gap Post-CATs. There is no consistency in the number of years in the time gap between the Pre-CAT and Post-CAT where these differences occur. This is evidence that the significant differences are more likely statistical fluctuations and/or artifacts of the specific catalogs analyzed, rather than any fundamental indication that hit percents do not remain essentially constant through time.

One set of trials which, visually, appears to have a downward trend of hit percent with the changing Post-CAT is the 1975-1979 Pre-CAT set (figure 31b). In the Complete region, the 1995-1999, 2000-2004, and 2005-2009 Post-CATs have statistically lower hit percents than the 1980-1984 Post-CAT. However, the decreases in hit percent observed at these 15, 20, and 25 year time gaps between the end of the Pre-CAT and the beginning of the Post-CAT are not matched in the other sets of trials. The Complete region 1970-1974 Pre-CAT shows a significant decrease in hit percent after a 15 year time gap, but that follows a significant increase in hit percent after a 10 year time gap. The Complete region 1980-1984 Pre-CAT shows a significant decrease in hit percent after a 5 and 10 year time gap, but there is no difference between the hit percents of the 1985-1989 Post-CAT and those Post-CATs associated with a 15 and 20 year time gap. The 15 year time gap Post-CAT for the Complete region 1985-1989 Pre-CAT set of trials has a higher hit percent than the zero time gap Post-CAT.

In the North subzone, the 1985-1989, 1990-1994, 1995-1999, 2000-2004, and 2005-2009 Post-CATs all have statistically lower hit percents than the 1980-1984 Post-CAT. Again, there are no similar decreases in hit percent at the 5, 10, 15, 20, and 25 year time gaps between the end of the Pre-CAT and beginning of the Post-CAT observed in the other Pre-CAT trials. All time gaps for the North subzone 1970-1974 Pre-CAT set of trials have higher hit percents than the zero time gap 1975-1979 Post-CAT, including significant increases in hit percent for the 5, 10, and 30 year time gaps. There are no significant differences in hit percent between the zero time gap trial and the non-zero time gap trials in the North subzone 1980-1984 or 1985-1989 Pre-CAT trials.

The lack of a repeatable pattern in these statistically significant differences, coupled with the essentially constant hit percents through time of the other trial sets, is further evidence that the factors controlling the seismicity of CA are approximately constant throughout the region and through time. There was no measurable effect on hit percent with the increasing minimum magnitude cutoff of the Post-CAT, and this was attributed to the seismic energy being regularly released along the San Andreas and related faults across the region. With Oligocene to Miocene initial movement along the fault, and continued movement of the Pacific and North American Plates, it is reasonable to assume that these energy releases along these throughgoing fault lines are constant not just spatially, but also temporally.

Alaska: Time Progression Discussion

Many of the comparisons between the zero time gap trial in a set and the non-zero time gap trials have statistically significant differences in hit percents. Most of these differences are a lower hit percent for the non-zero time gap, although there is not a consistently decreasing trend (i.e., hit percents from a non-zero time gap trial are often lower than hit percents for the zero time gap trial, but a hit percent from a non-zero time gap trial is not necessarily lower than the preceding trial with a shorter time gap).

In the Complete AK region, 15 of the 24 comparisons show a significant difference in hit percent between the given non-zero time gap Post-CAT and the zero time gap Post-CAT. Of these significant differences, 11 are lower hit percents for the non-zero time gap trial, and four are lower hit percents for the zero time gap trial. Of the 34 hit percents used to make those comparisons, all are between 87% and 97%, and 23 out of 34 are at least 94%. This indicates that even though there are several statistical differences, the hit percents of the region fits with those found in the previous tests of other variables.

In the Active subzone, nine of the 24 comparisons show a significant difference in hit percent between the given non-zero time gap Post-CAT and the zero time gap Post-CAT. Of these significant differences, six are lower hit percents for the non-zero time gap trial, and three are lower hit percents for the zero time gap trial. Of the 34 hit percents used to make those comparisons, all are between 69% and 81%, and 21 out of 34 are at least 75%. These hit percents again fit with the results from tests of other variables. The Complete region and Active subzone have similar patterns in hit percent, but the Complete region has slightly higher hit percents. This is likely due to the increased radius needed to cover 33% of the entire map area, although the northern portion of AK has little to no seismicity.

In the Nonactive subzone, 14 of the 24 comparisons show a significant difference in hit percent between the given non-zero time gap Post-CAT and the zero time gap Post-CAT, and all 14 are lower hit percents for the non-zero time gap trial. Of the 34 hit percents used to make those comparisons, 22 are between 63% and 79%. These results are slightly higher than those found from tests of other variables, but are lower than both the Complete region and Active subzone, as is expected for an area which approximates an SCR.

There are several examples where the trend of hit percents is the same for the Complete region and both subzones, which may indicate that the results are predominantly an artifact of the chosen catalogs (as opposed to anything temporally, spatially, or tectonically fundamental). The 1975-1979 Pre-CAT shows the same pattern of increases and decreases in hit percent from one Post-CAT trial to the next in all three areas (figure 32b), including a trough at the 1985-1989 Post-CAT and a peak at the 1995-1999 Post-CAT. The 1985-1989 Pre-CAT also shows the same patters for all three regions (figure 32d), including a trough at the 2000-2004 Post-CAT.

Time Progression Comparison: Intraplate Regions v. Plate Boundary Regions

Hit percents appear to remain nearly constant through time, on the time scales analyzed in this study, in both the intraplate and plate boundary regions. Hit percents in CA, the Complete AK region, and the AK Active subzone are generally consistent with previous CS results for plate boundary regions. Hit percents in AUS are relatively low compared to previous CS results for intraplate regions, although the data vary highly and have several values which fall in the expected range based on previous results. Hit percents in areas in the NMSZ which do not include large portions of the Reelfoot rift, and the AK Nonactive subzone, are consistent with previous CS results for intraplate regions. Hit percents in areas of the NMSZ which include the Reelfoot rift are similar to results from other variable tests for the region, and consistent with or higher than previous CS results for plate boundary regions.

8.5. Relationship with Previous Cellular Seismology Results

The results of this study are shown as part of a more complete picture summarizing hit percents from all regions analyzed by CS so far in figure 40a (Kafka, 2012). For the histogram in figure 40a, a representative result was chosen for each region analyzed to date. There is a recognizable separation between typical hit percents in intraplate regions versus in plate boundary regions. Based on the representative trials chosen, there is a lower mean hit percent in intraplate regions (67%) than in plate boundary regions (85%). This is further evidence that major, presently active, tectonic features in plate boundary regions increase the likelihood of later occurring earthquakes being located near earlier occurring earthquakes.

In figure 40b, the representative trials chosen for the regions from this study are indicated. The NMSZ, which is hypothesized here to act more like a plate boundary region than an intraplate region, in terms of CS results, falls in the highest hit percent bin for intraplate regions (i.e., 90-100% hits). This bin is more typical of plate boundary regions. AUS, which is hypothesized here to act as an SCR, in terms of CS results, falls in typical hit percent bins for intraplate regions (i.e., 50-70% hits). CA and AK, which are hypothesized here to act as plate boundary regions, in terms of CS results, fall in typical hit percent bins for plate boundary regions (i.e., 70-90% hits). The regions studied here, in conjunction with previous CS results, indicate that past earthquakes tend to delineate zones where future earthquakes are likely to occur, but that tendency may be more pronounced in plate boundary regions than in intraplate regions.

An earthquake catalog has been compiled for China dating back to 646 B.C.E. (see Liu et al., 2011). This is important to future CS studies because it mitigates some of the effects of possible random fluctuations in hit percent due to short time spans discussed above in the

Assumptions and Known Problems section. Prior to the availability of the China database, the longest available earthquake catalogs that were considered complete were several decades long. On these time scales, it is difficult to determine if changes in hit percent through time are a fundamental characteristic of a particular region or an artifact due to the duration of time over which the analyses were able to be completed. Figure 40c (adapted from Kafka, 2012) shows where preliminary CS results from the China catalog fall in relation to previous CS results. These results span a wide range, but fit into the common hit percent bins associated with intraplate regions. Further tests need to be completed on the China catalog so that its place in relation to other CS results will be more fully understood, but the length of the catalog makes it a valuable tool on which to perform CS with less uncertainty due to a short time duration catalog.

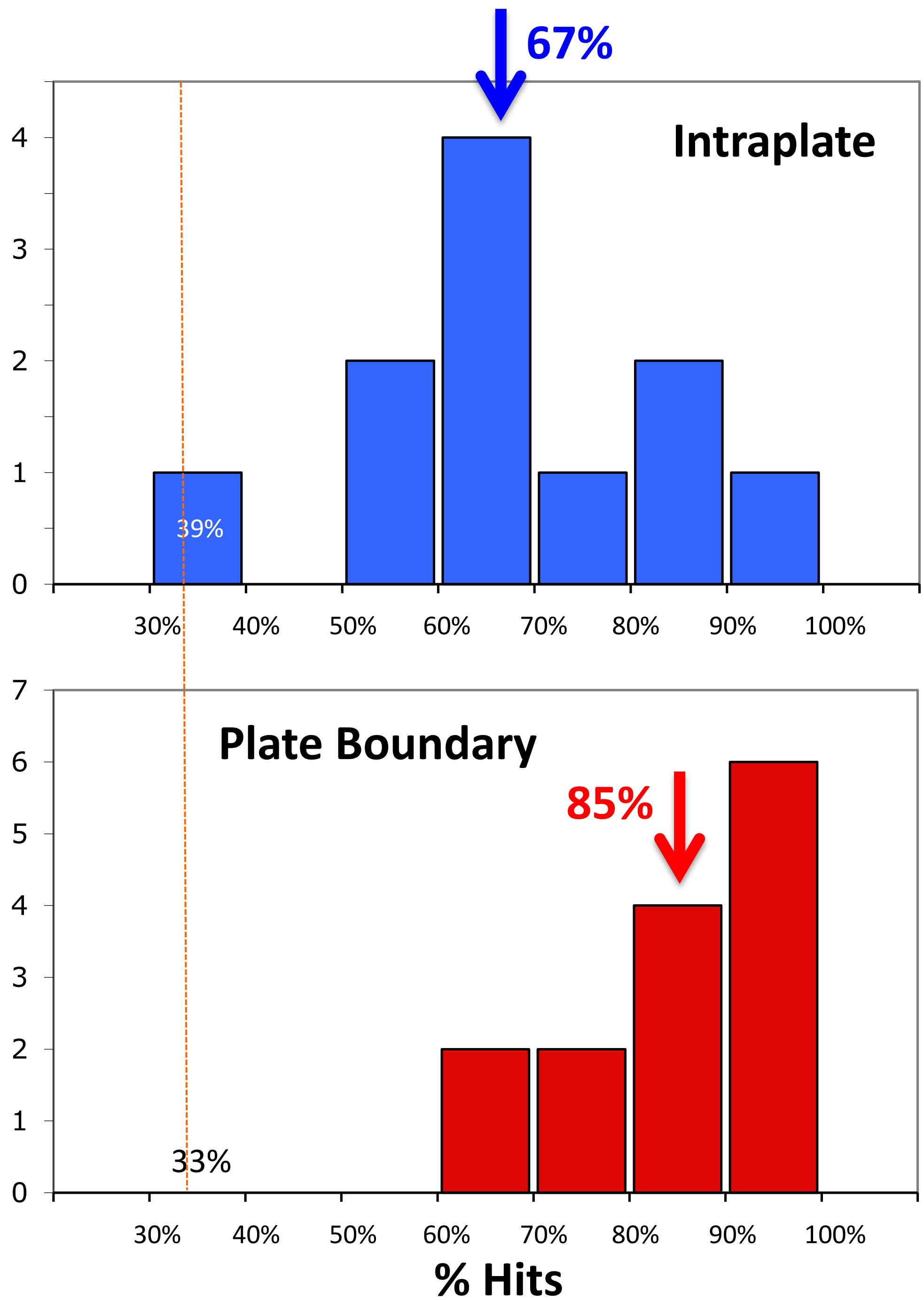


Figure 40a. Frequency of representative hit percents for different tectonic regions analyzed in past CS studies and this study. All results for 33% map area, denoted by orange dashed line. Means of intraplate regions (67%) and plate boundary regions (85%) indicated by blue and red arrows, respectively.

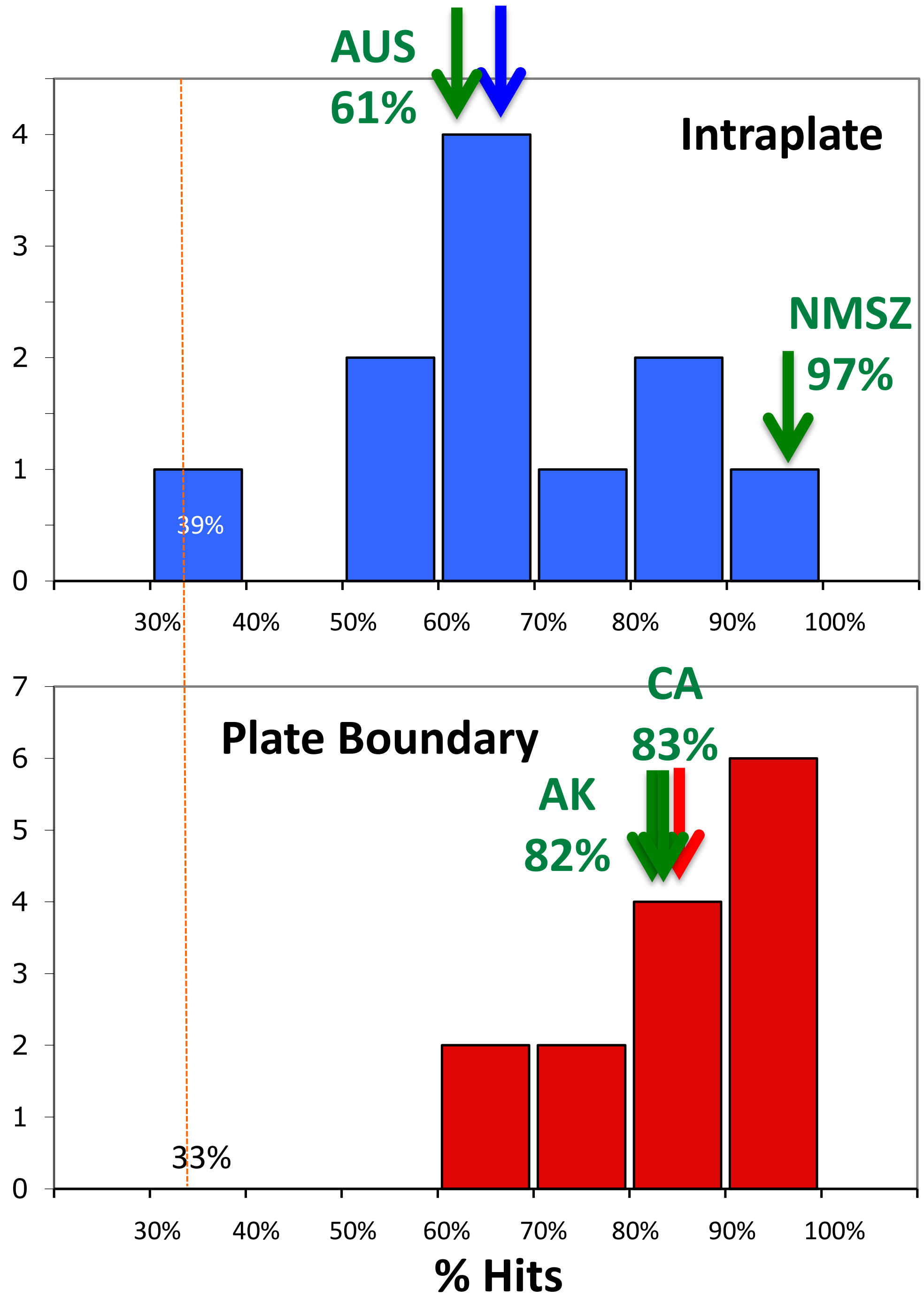


Figure 40b. Frequency of representative hit percents for different tectonic regions analyzed in past CS studies and this study. All results for 33% map area, denoted by orange dashed line. Means of intraplate regions (67%) and plate boundary regions (85%) indicated by blue and red arrows, respectively. Representative trial chosen for NMSZ: Complete region, 1974-1999 (Pre-CAT)/2000-2010 (Post-CAT), M1.4 minimum cutoff, 7.3 km radius, 1791 Post-CAT earthquakes, 1742 hits, 97% hits. Representative trial chosen for AUS: Complete region, 1990-1994 (Pre-CAT)/2000-2004 (Post-CAT), M4.5 minimum cutoff, 345 km radius, 23 Post-CAT earthquakes, 14 hits, 61% hits. Representative trial chosen for CA: Complete region, 1970-1989 (Pre-CAT)/1990-1999 (Post-CAT), M4.0 minimum cutoff, 19 km radius, 808 Post-CAT earthquakes, 671 hits, 83% hits. Representative trial chosen for AK: Active subzone, 1970-1989 (Pre-CAT)/1990-1999 (Post-CAT), M4.0 minimum cutoff, 11 km radius, 2117 Post-CAT earthquakes, 1743 hits, 83% hits.

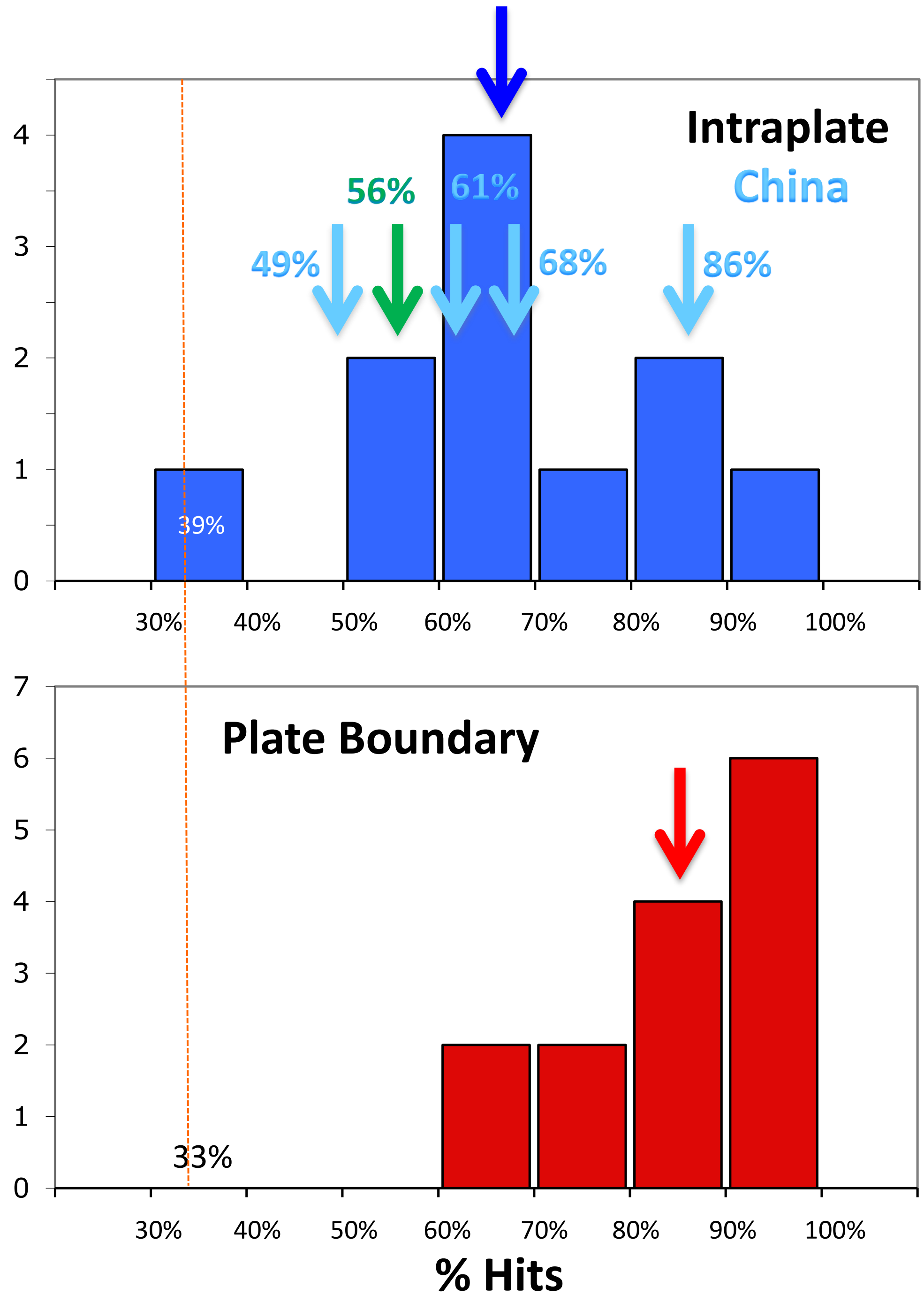


Figure 40c. Frequency of representative hit percents for different tectonic regions analyzed in past CS studies and this study. All results for 33% map area, denoted by orange dashed line. Means of intraplate regions (67%) and plate boundary regions (85%) indicated by blue and red arrows, respectively. Results from China catalog shown as light blue arrows and green arrow. Light blue arrows use 646 B.C.E.-1607 C.E. (Pre-CAT) and century long Post-CATs. 1608-1707 Post-CAT (68% hits). 1708-1807 Post-CAT (86% hits). 1808-1907 Post-CAT (49% hits). 1908-2007 Post-CAT (61% hits). Green arrow indicates trial with 646 B.C.E.-1999 C.E. (Pre-CAT)/2000-2007 (Post-CAT), M4.0 minimum cutoff, 56% hits.

9.0. CONCLUSIONS

The results of this research indicate that past seismicity does tend to delineate zones where future earthquakes are likely to occur, at least in the regions and for the time scales studied here. CS hit percents appear to be complexly affected by several variables, including magnitude, depth, time, and tectonic setting. These variables seem to affect the tendency for later occurring earthquakes to be located near earlier occurring earthquakes to different extents in different regions. The following specific conclusions can be drawn from the results of this study:

1. Hit percents in the NMSZ Complete region and Black, Yellow, and Blue subzones typically ranged from the mid-80's to upper-90's. These areas showed a decrease in hit percent with an increasing minimum magnitude cutoff of the Post-CAT and an increase in hit percent at intermediate depth levels. These results are attributed to the influence of the Reelfoot rift.

2. Hit percents in AUS, the NMSZ Purple subzone, and the AK Nonactive subzone typically ranged from the mid-20's to mid-80's, and these hit percents varied highly. These results are considered most representative of intraplate regions. A number of the hit percent results for AUS were the lowest values of CS hit percents observed to date, and were lower than the 33% map area chosen for the analysis.

3. Hit percents in CA and the AK Complete region and Active subzone typically ranged from the mid-70's to mid-90's. These results were consistent in most cases, although hit percents tended to increase with an increase in depth in the Complete AK region and Active subzone. These results of generally higher hit percents than were found for intraplate regions are attributed to the influences of the San Andreas fault system in CA and Aleutian-Alaska subduction zone in AK. The Complete CA region and the Active AK subzone are considered most representative of plate boundary regions studied here.

4. The sample sizes and time lengths of the earthquake catalogs are the greatest limiting factor to a better understanding of the relationship between the locations of past and future earthquakes, particularly in intraplate regions. Small sample sizes made statistical significance testing difficult for some trials, including tests involving large magnitude earthquakes in the NMSZ, many tests in AUS, and tests involving deep earthquakes in several regions. Longer and more complete datasets, coming from additional time recording with reliable and widespread seismic networks, will provide more information in regards to these conclusions.

These results and conclusions offer useful insights into what can (and can't) be gleaned from Cellular Seismology studies. Understanding the capabilities and limits of Cellular Seismology studies can provide guidance for improving the seismicity-based components of seismic hazard assessments, particularly in terms of the relationship between locations of past and future earthquakes.

10.0. WORKS CITED

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