SEISMOLOGICAL RESEARCH ISSUES IN THE SAN DIEGO REGION

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INTRODUCTION

What is the nature of earthquake ground motions that can be expected in San Diego's foreseeable future? Although this is the most basic of questions underlying the adequate design of structures to resist earthquakes, answers to this question are disturbingly uncertain. A reasonable assumption is that future earthquake ground motions will be similar to those that have occurred in the past. When compared with San Francisco or Los Angeles, San Diego has historically experienced relatively mild earthquake shaking. Unfortunately, San Diego's written history is very short compared to the time scales of earthquake repetition. Are there sources of earthquakes that may cause damage in San Diego and what is their frequency? Mapping of geologic structures and the study of patterns of small earthquakes are the primary tools for recognizing potentially active faults. There are features in both the geologic structure and the seismicity that are suggestive of major active faults that could pose a serious hazard to San Diego. Furthermore, there is evidence that the rate of occurrence of small earthquakes has increased within the last 5 years when compared with the previous 50 years. However, these features are not well studied or understood.

Even if the potential sources of earthquakes were well understood, the problem of anticipating the range of future ground motions is difficult. The nature of shaking from earthquakes is strongly affected by the nature of seismic wave propagation through complex geologic structures (path effects). Although path effects are likely to be of great importance in San Diego, relatively little specific information is available.

OVERALL TECTONIC SETTING

San Diego is on the eastern edge of a geologic province sometimes referred to as the southern California Continental Borderland. It is a vast geologic province that extends approximately 250 km westward to the edge of the continental margin. It is characterized by large linear bathymetric features that form a series of deep northwest-trending troughs. The great width of this continental margin, together with the series of deep, northwest-trending troughs, makes it unique among world-wide continental margins. In the eastern part of this province, Legg (1985) has inferred that there is a complex system of major right-lateral, northwest-trending faults (Figure 1; Hauksson and Jones, 1988). These faults are apparently connected to major active strike-slip faults in Baja, Mexico (such as the Agua Blanca fault). Although there is evidence that these faults are geologically active, there is some debate regarding the slip rates on this system. Humphreys and Weldon (1986) have suggested that there is between 5 and 10 mm per year of total right-lateral slip in the Continental Borderlands province.

Estimating the geologic slip rate on these offshore faults is vital for the estimation of San Diego's earthquake hazard. Global Positioning Satellite (GPS) surveys of time-varying positions of offshore islands (such as San Clemente Island) with respect to the mainland is a very promising technique for estimating the deformation rate on these major faults that run just offshore from San Diego.

SPATIAL PATTERNS OF SEISMICITY

Figure 2 shows the distribution of southern California earthquakes for the period from 1978 through 1988. A number of lineations can be recognized in this map. In some cases these lineations are along well defined active faults (such as the central creeping section of the San Andreas fault). In other cases, lineations are more diffuse and do not correspond to a mapped active fault (for instance the lineations in the southern Sierra Nevada mountains). Furthermore, several of the major active fault segments were void of small earthquakes for this time period. In particular, the sections of the San Andreas fault that were responsible for the M 8 earthquakes in 1906 (not shown on map) and 1857 show virtually no small earthquake activity.

Several seismicity lineations that are of interest to the San Diego area can be recognized in Figure 2. The San Jacinto and Elsinore fault zones are clearly visible, although the seismicity lineations are rather complex in detail. In addition, two broad, poorly-defined, northwest-trending, seismicity zones can be recognized that are relatively close to San Diego. One of these we will

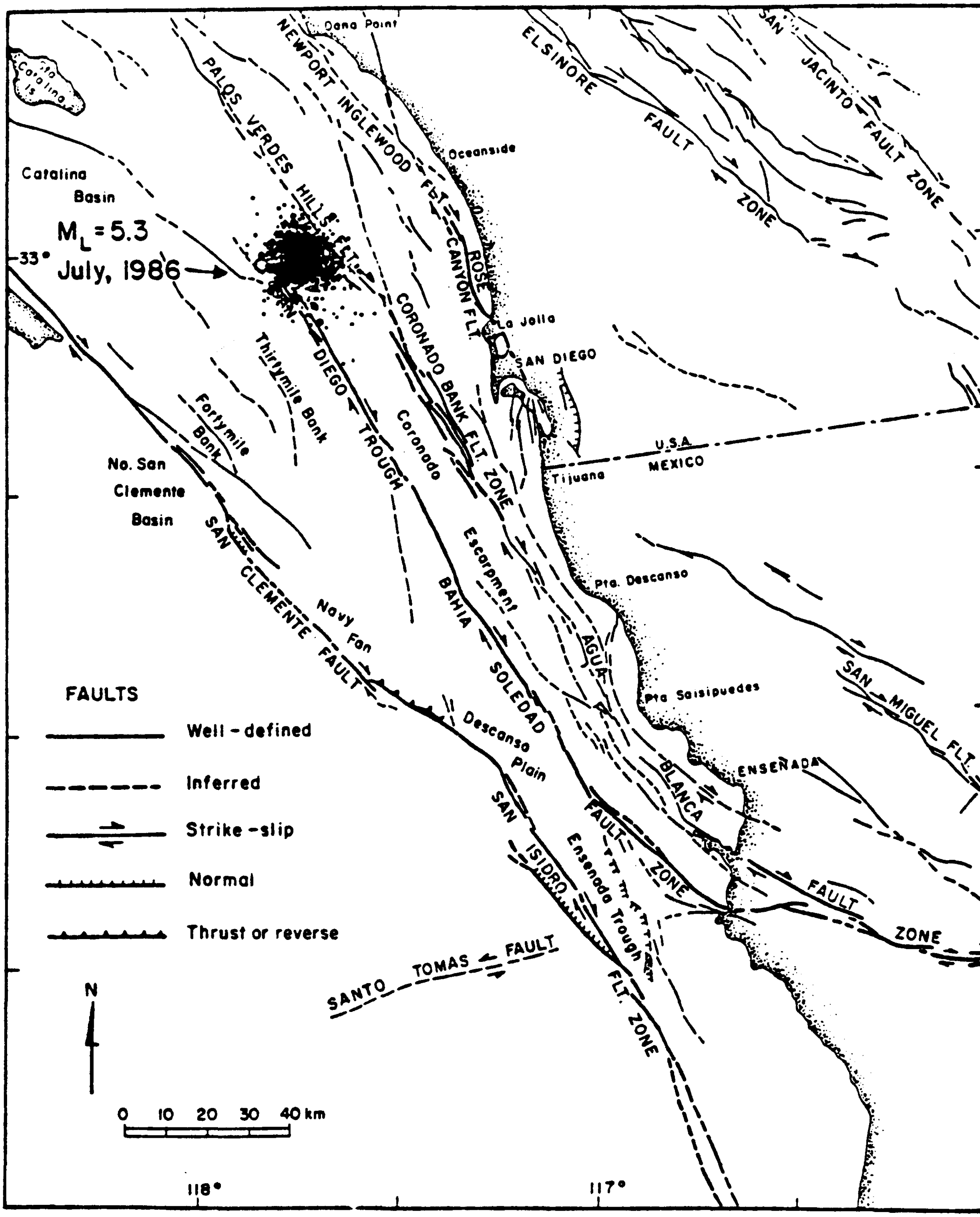

Figure 1. Late Cenozoic faults of the Inner Continental Borderland from (Legg, 1985) together with the aftershocks of the 13 July 1986 Oceanside earthquake. Figure is from Hauksson and Jones (1988).

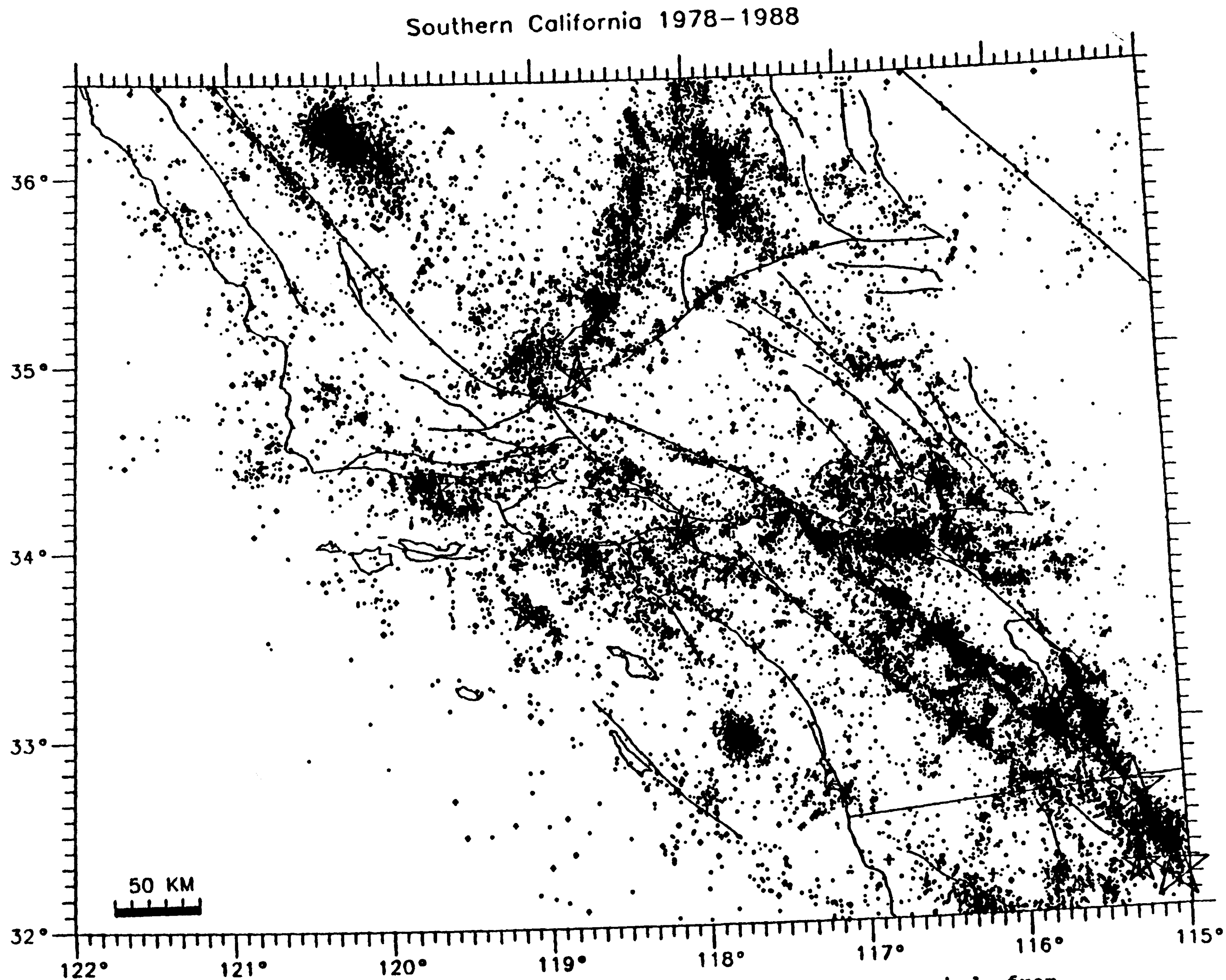

Figure 2. Seismicity of southern California; time period from 1978 through 1988.

call the San Clemente Island seismicity lineation and it roughly coincides with the San Clemente fault zone (Figure 1). This fault zone may connect with the Aqua Blanca fault which experienced magnitude 6.3 and 6.0 earthquakes in 1954. We will call the other apparent seismicity lineation the San Diego seismicity lineation. This feature runs from the San Miguel fault in northern Baja, Mexico, then beneath San Diego and finally offshore towards Catalina Island. Unfortunately, seismographic station coverage is such that earthquake locations are unreliable for most of the events in both of these lineations. The San Diego seismicity lineation does not coincide with any mapped, through-going fault system. The San Miguel fault, which is at the southern end of this lineation, is a major right-lateral fault that experienced magnitude 6.6, 6.4, 6.3, and 6.1 earthquakes in 1956. However, the surface trace of the San Miguel fault has not been found to extend to the northwest beneath San Diego.

A more detailed view of the seismicity of the San Diego region from 1977 to 1989 is shown in Figure 3. The seismicity along the Elsinore fault zone can be seen in the northeast corner of the map. In addition, the San Diego and San Clemente seismic lineations can be seen, but it is clear that they do not define a single line of earthquakes. The large blot of earthquakes in the center of the map is an unusual group of earthquakes called the Oceanside sequence. The largest earthquake in this sequence occurred on 13 July 1986 and had a magnitude of 5.3. Despite the relatively modest size of the mainshock, significant aftershock activity is still occurring in this region three years after the mainshock. Although the general tectonic lineations in the region of the Oceanside earthquake are suggestive of northwest-trending strike-slip faults, the mainshock appears to have been thrusting on a fault plane striking to the northwest (Hauksson and Jones, 1988).

Figure 3 also shows several clusters of small earthquakes that have occurred in the immediate vicinity of San Diego Bay and also about 10 km offshore. Although there has been insufficient study of these events to identify which faults they have occurred on, we can say that their location, and at least several focal mechanisms, are compatible with the interpretation that there has been seismicity on the Rose Canyon fault. As will be discussed in the next section, these clusters of seismicity seem to have become active in only the last 5 years.

Many fundamental questions are unanswered about seismicity in the San Diego area. What is the detailed nature of seismicity within the broad San Clemente Island and San Diego seismicity lineations? There is a hint of short north- and northeast-trending lineations within these zones. What are the focal mechanisms of these earthquakes and what does it imply about state of stress? Much could be done with existing data from the Cal-tech/USGS Southern California Seismic Network to better resolve some of these issues. However, the density of seismic stations in this region is relatively low and there is currently no information available about seismic arrivals on the ocean floor. Data from ocean bottom seismometers could be very valuable in helping to map the patterns of small earthquakes in the San Diego region.

INCREASED RATE OF ACTIVITY

It has been a popular belief that if one wants to live in a California city that is immune from earthquakes, San Diego is the place; that is until the last 5 years. The rate of earthquakes in the region surrounding San Diego had been historically low until a rash of earthquakes began in 1984. Heaton (1987) documented what appears to be an increase in the rate of activity beginning in 1984. In this section we briefly describe this rate increase.

In Figure 4, we show the limits of a geographic box that we will call the San Diego region. Earthquake activity (magnitude greater than 2.3) within that box for the time period from 1975 through April 1989 is also shown. In Figure 5, the cumulative number of earthquakes in the San Diego region, larger than magnitude 3.5, are shown for the time period from 1932 through April 1989. We believe that the Caltech earthquake catalog is complete at this magnitude level. An increase in the rate of earthquake occurrence can be seen starting in about 1984. On 17 June 1985, three earthquakes with magnitudes of approximately 4 occurred beneath San Diego Bay. Seismicity continued at a rate higher than the historic level until it increased again after the M 5.3 Oceanside earthquake of 13 July 1986.

The Oceanside earthquake sequence has been unusually rich in aftershocks with a very slow decay with time. Many of the earthquakes in Figure 4 are parts of individual sequences of earthquakes. If several sequences of earthquakes fortuitously occur one after the other, then this can cause an apparently alarming change in the seismicity rate, which is actually due to random chance and the fact that earthquakes have aftershocks. Therefore, in Figure 6 we show a plot of cumulative number of earthquakes since 1932 in which aftershocks have been removed using an algorithm given by Reasenberg (1985). Even with aftershocks removed, it is clear that the rate of earthquake occurrence increased significantly in about 1984. It also appears that, except for Oceanside aftershocks, there have not been earthquakes greater than 3.5 in the last two years. However, the rate of smaller earthquakes in the San Diego region has remained high, even during the last two years. In Figure 7, we show the cumulative number of earthquakes greater than magnitude 2.3 for the time period from 1975 through April 1989. The earthquake catalog is complete at this lower magnitude for this time period because of better station coverage and data

1977-1989

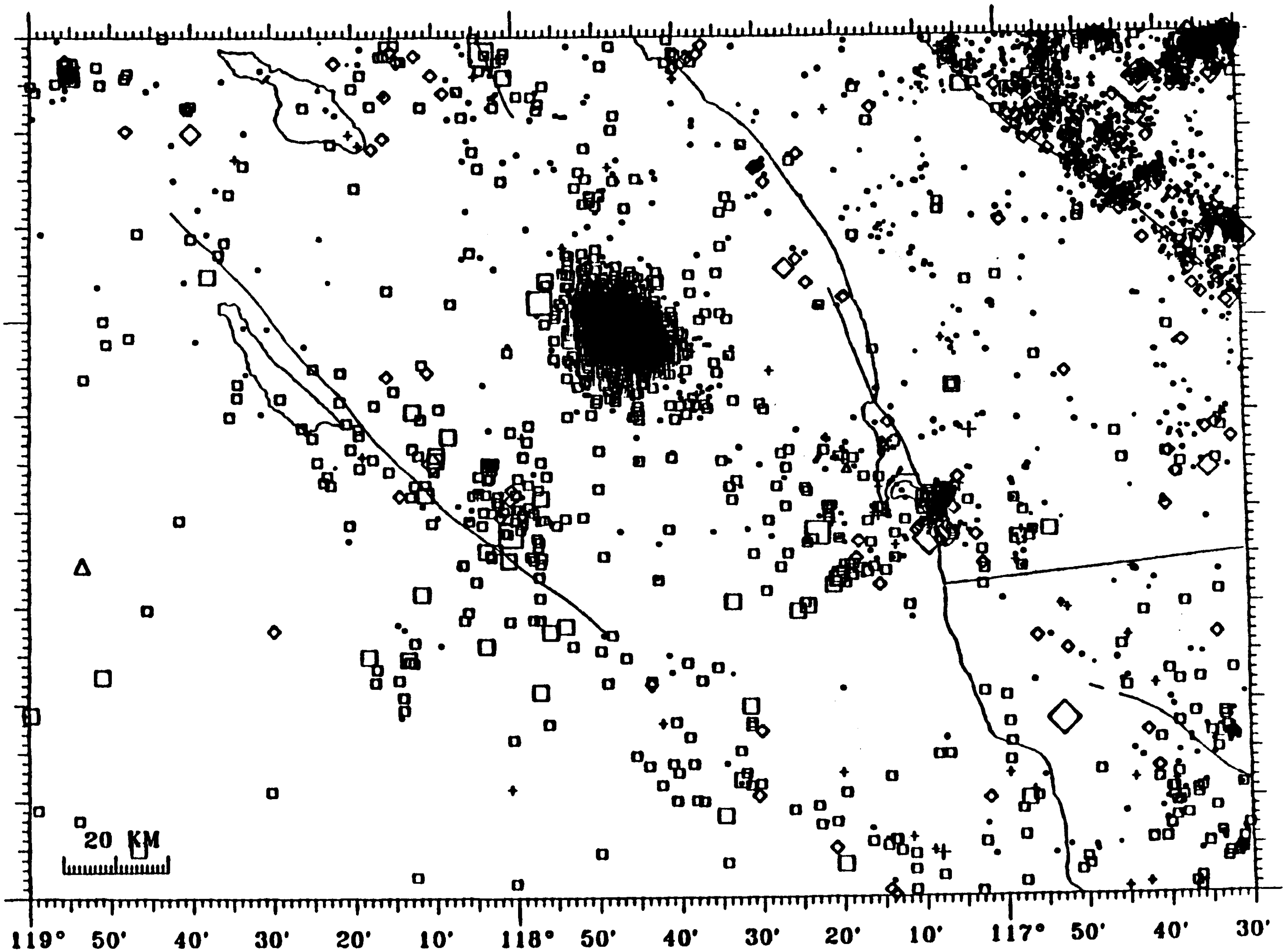

Figure 3. Seismicity of the San Diego region.

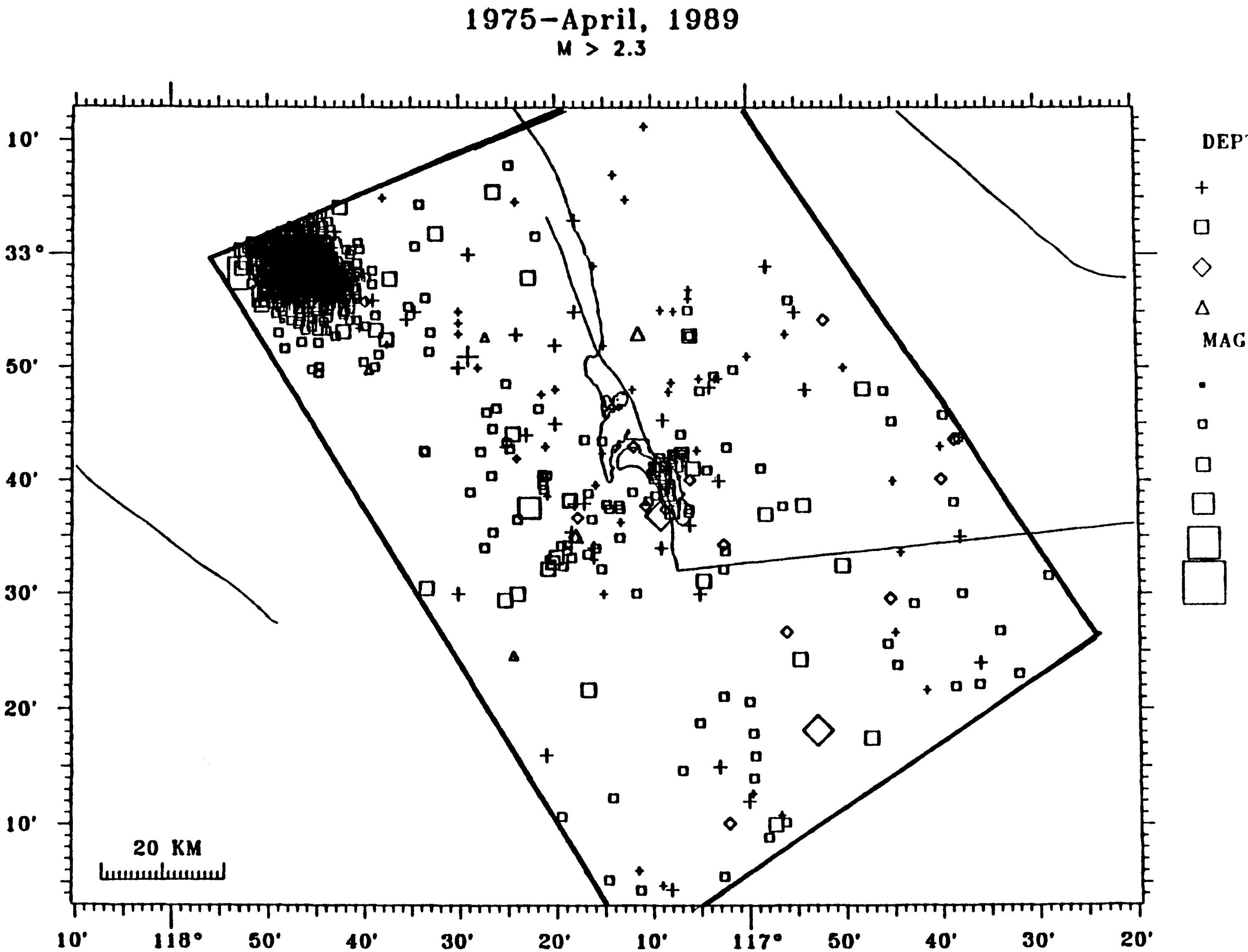

Figure 4. Region for which earthquake rates are shown in Figures 5, 6, and 7.

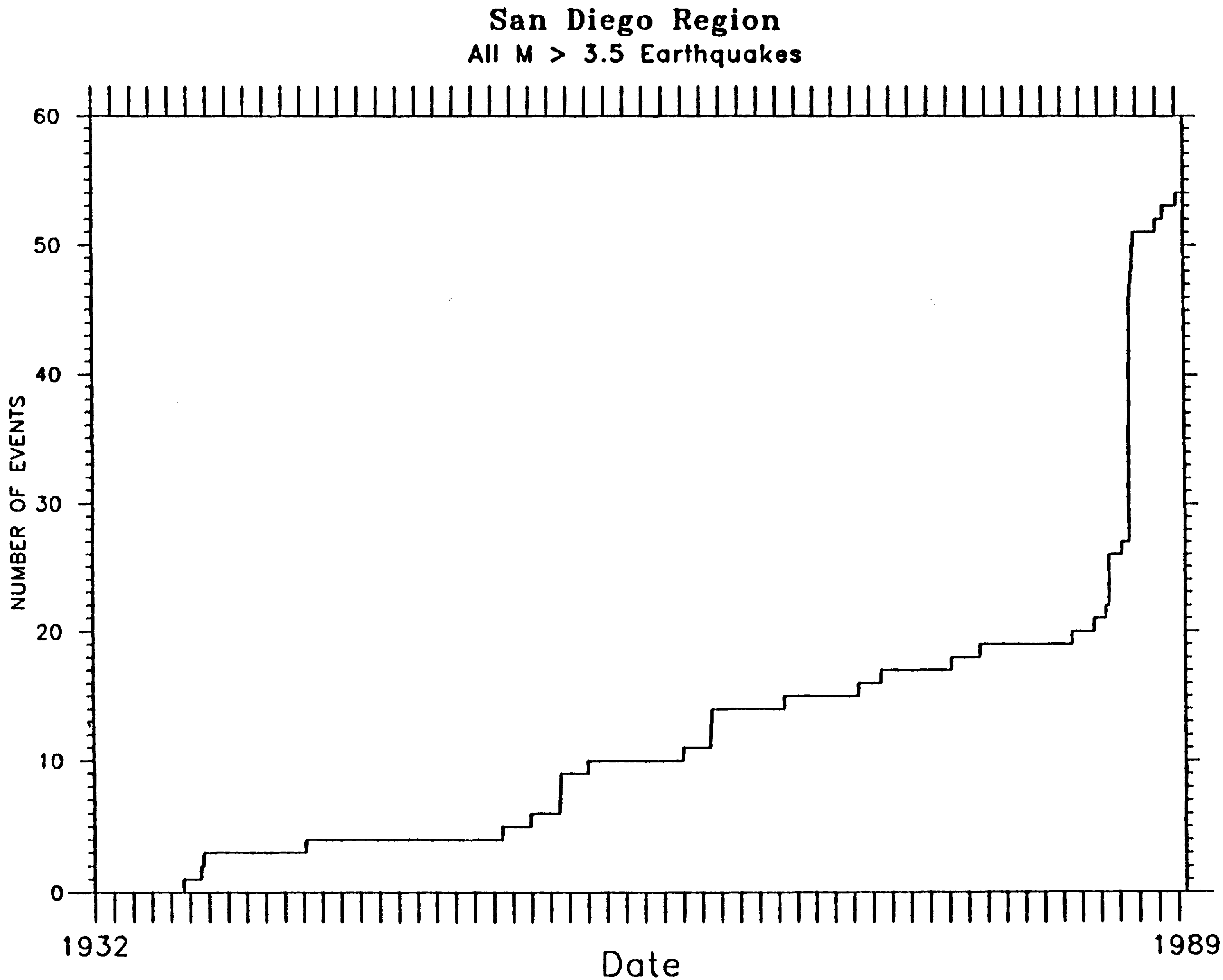

Figure 5. Cumulative number of earthquakes (including after-shocks) greater than M 3.5 from 1932 through April 1989 and in the region defined in Figure 4.

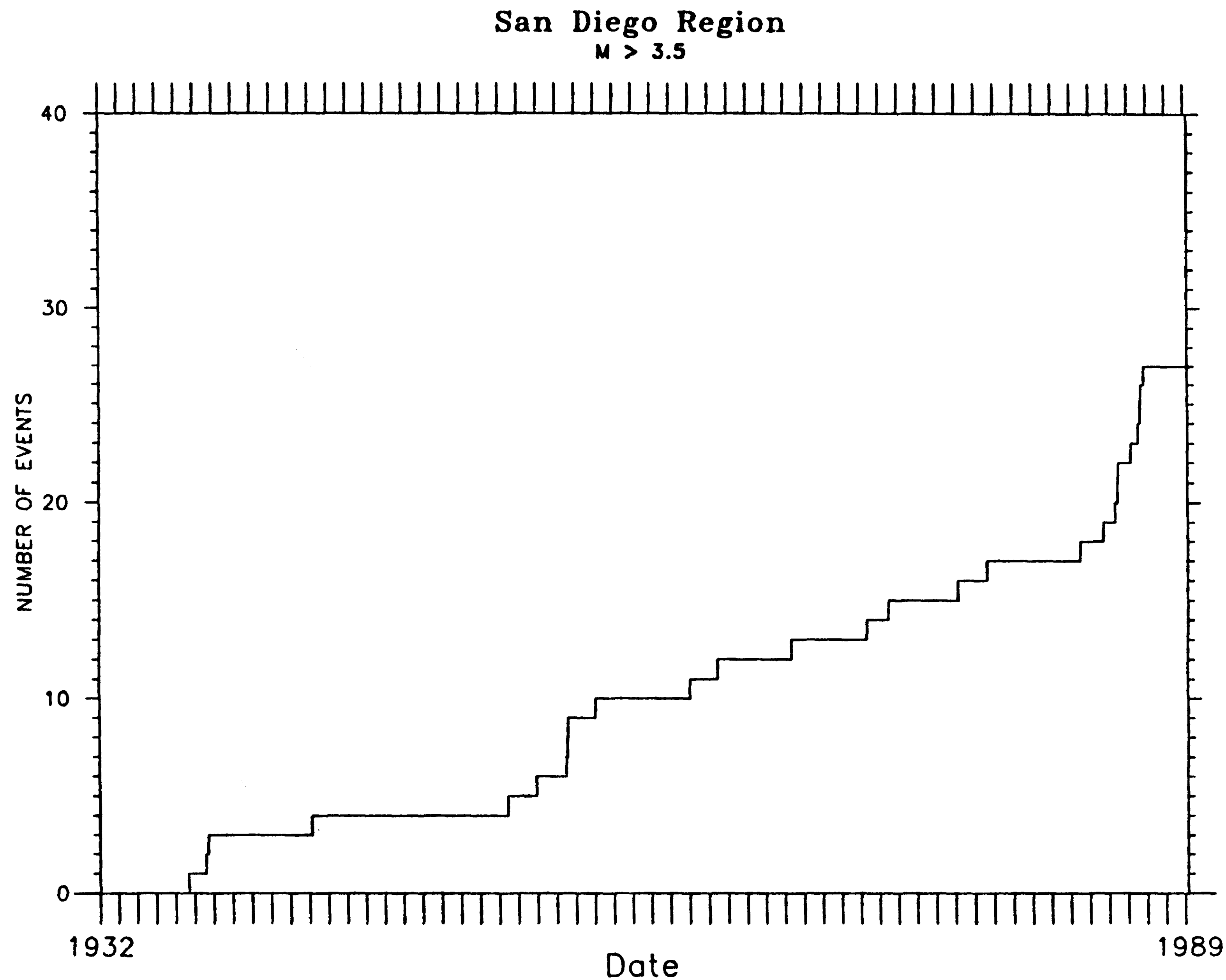

Figure 6. Cumulative number of earthquakes (excluding aftershocks) greater than M 3.5 from 1932 through April 1989 and in the region defined in Figure 4.

processing techniques. Prior to 1984, there were about 8.5 sequences per year in the San Diego region, and since 1984, the rate has been fairly steady at 17 sequences per year.

Neither the physical mechanism for this rate change nor its significance for seismic hazard are understood. Curiously, a similar increase in the rate of earthquakes has occurred in the region of the Los Angeles and Santa Monica basins beginning in 1986 (Jones and Reasenberg, 1989). Thus, it appears that the rate of earthquakes has increased along the continental margin from the Transverse Ranges south to the International Border. Presumably, this increased activity is related in some way to strain accumulation levels or rates. However, geodetic data from periods prior to introduction of GPS systems (about 1985) are inadequate to resolve strain rates in the borderlands region.

PREDICTING GROUND MOTIONS

Even if the magnitudes and distances to future San Diego earthquakes were known, there would still be considerable uncertainty about the nature of the ground motions that would occur. In Figure 8, we show a collection of response spectra from horizontal ground motions record at distances near 50 km from strike-slip earthquakes of about magnitude 6.5. The records have been scaled slightly to correct for deviations in distance and magnitude. Obviously, there is a very large degree of scatter seen. The largest motion is over ten times larger than the smallest one. Is there any way to parameterize a site besides distance to an earthquake of a given magnitude? In Figure 9, we show response spectra that are from several different earthquakes, but recorded at the same sites. It is clear that the particular site can have a profound effect on the nature of seismic shaking.

Study of distributions of ground shaking have shown that site response (or path effects) are determined by several conditions. In the case of very low rigidity materials (such as the soils beneath Mexico City, the San Francisco bay muds, or perhaps soils in the San Diego Bay), important amplifications and harmonic resonances can occur. In the case of the 1985 Michoacan (Mexico) earthquake, such amplification and resonance in the near-the-surface clays interfered constructively with resonance vibrations of buildings of approximately 20 stories with disastrous results. However, there is also convincing evidence (e.g. Liu and Heaton, 1984) that the propagation of surface waves within large sedimentary basins (such as the Los Angeles basin) can profoundly affect ground motions.

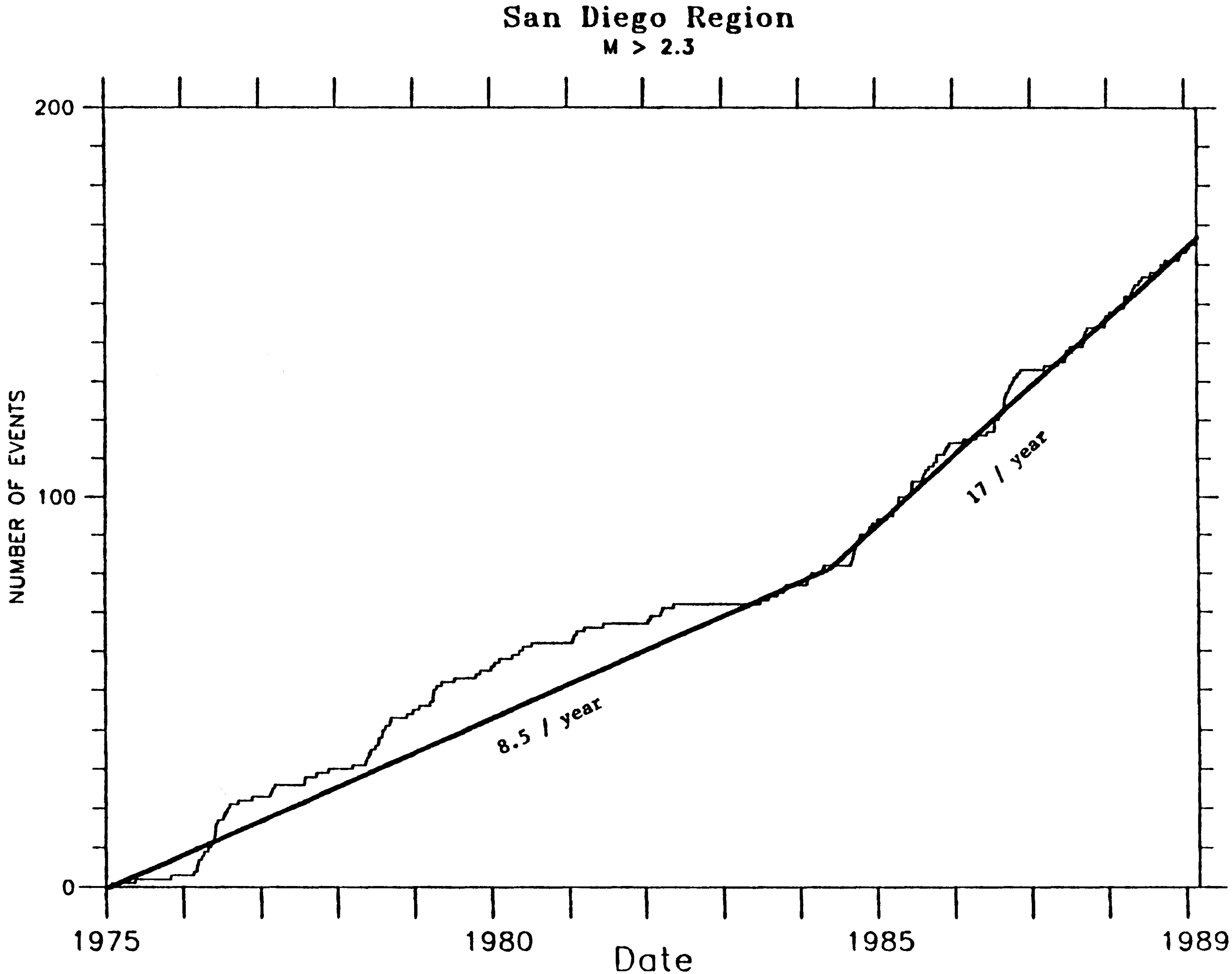

Figure 7. Cumulative number of earthquakes (excluding aftershocks) greater than M 2.3 from 1975 through April 1989 and in the region defined in Figure 4.

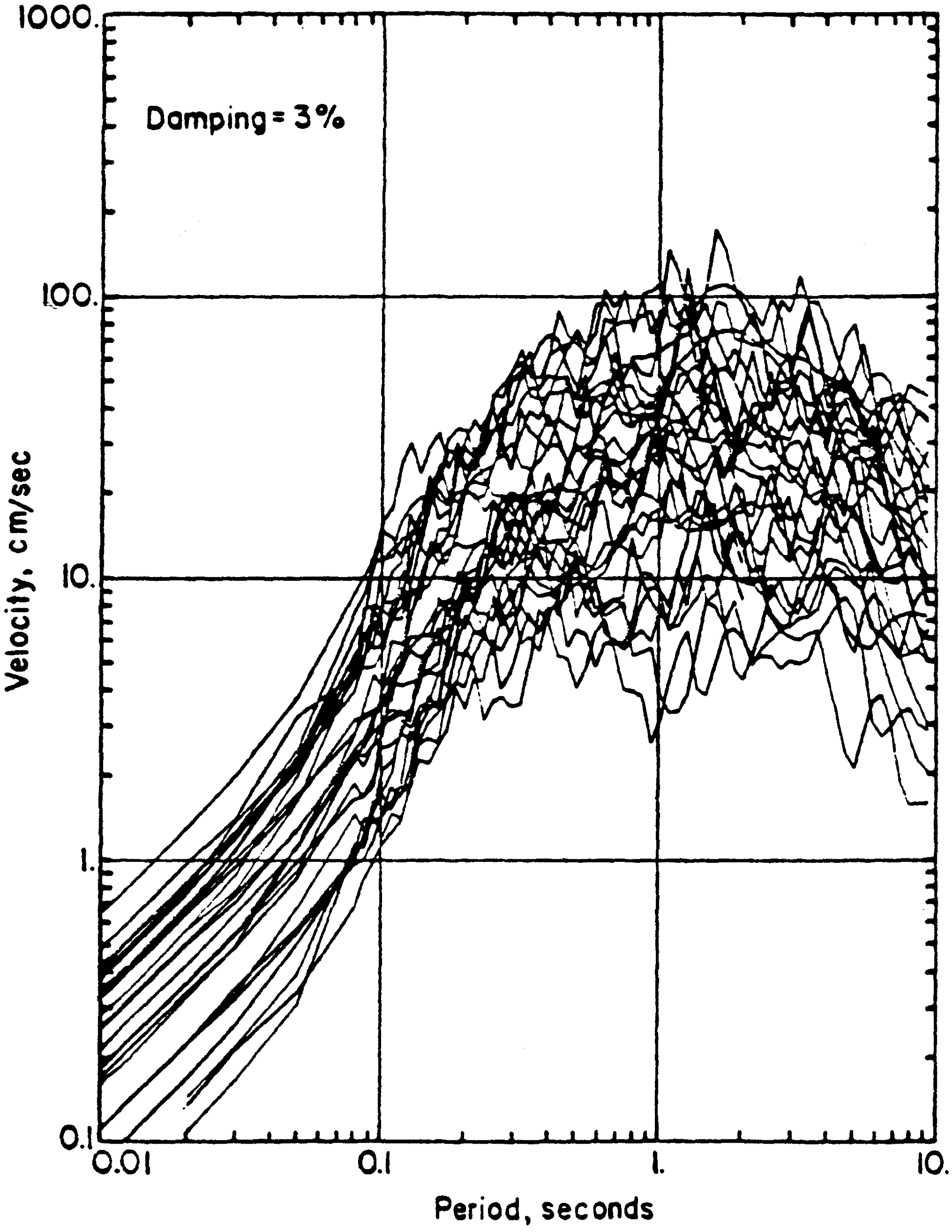

Figure 8. Response spectra (3% damped) for horizontal components of 15 records from strike-slip earthquakes that are scaled to a distance of 50 km with a magnitude of 6.5. This composite plot shows the type of scatter that is typical of ground motions that are recorded at a given distance and magnitude (from Heaton and Hartzell, 1988).

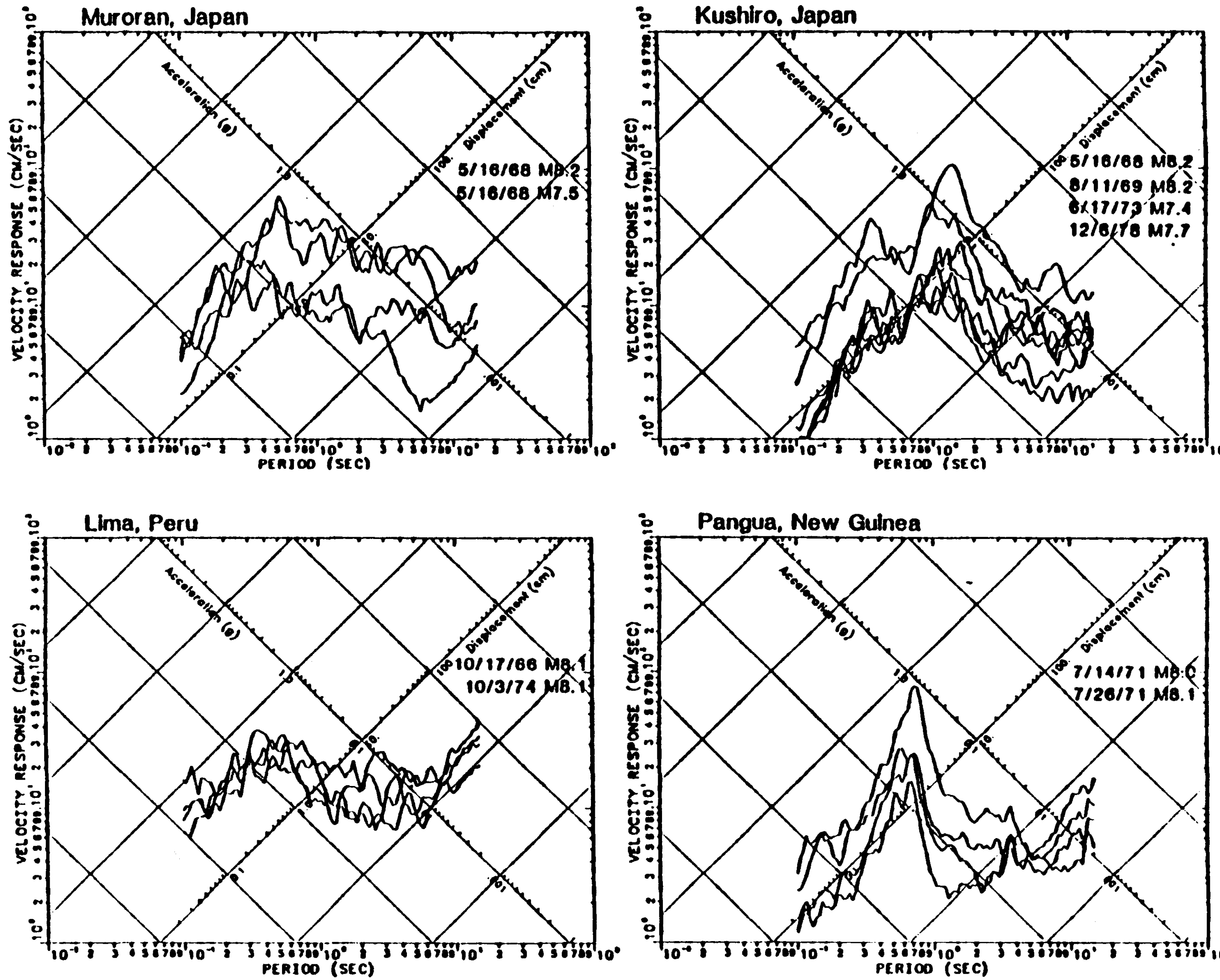

Figure 9. Response spectra (5% damped) of horizontal ground motion from several different earthquakes recorded at the same site. Notice that features in the response spectra are similar from one earthquake to another, thus indicating the importance of path effects (from Heaton and Hartzell, 1988).

Can these wave propagation/site phenomena be predicted before the occurrence of a damaging earthquake? The answer is a qualified yes. In most instances, the same path effects are present in the ground motions that occur in relatively numerous moderate sized earthquakes. By studying the spatial variation in ground motions produced from smaller earthquakes, we can recognize sites that may have dangerous resonances or amplifications. This technique is not yet widely applied in engineering design decisions, but it appears to be very promising. Unfortunately, there seem to be few ground motion recordings of moderate sized earthquakes in the San Diego region.

CONCLUSIONS

There is evidence that significant deformation is occurring on major offshore faults within 50 km of San Diego. There is a poorly defined band of seismicity that coincides with the San Clemente fault. San Diego is within another poorly defined band of seismicity that runs from the San Miguel fault towards Catalina Island. The tectonic significance of these bands is not currently known. Some smaller earthquakes within San Diego Bay may be on the Rose Canyon fault. There is still considerable uncertainty about the distribution of active faults in the San Diego region.

The rate of occurrence of earthquake sequences within the San Diego region seems to have doubled (relative to its historical average) since about 1984. The rate of small earthquakes remains high at this time (June 1989), but earthquakes larger than M 3.5 have not occurred within the last two years, except as aftershocks of the 13 July 1986, M 5.3 Oceanside earthquake. No interpretation of the mechanism for this rate change or its significance for earthquake hazards has been made as of this time.

The effects of wave propagation are of first order importance for estimating ground motions for engineering design purposes. These effects can be anticipated by the study of seismic velocity structures and by the study of ground motions produced from small earthquakes. Very little seems to be currently known about the specific nature of path effects in the San Diego region.

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EDITOR'S NOTE:

San Diego is in an unfortunate in-between situation as far as earthquakes go. Relative to San Francisco or Los Angeles, San Diego really hasn't had many historic earthquakes, it does not have big folded structures, nor a gigantic fault on shore. As a result, it is easy to assume that California seismologists are off looking at the San Andreas fault or the Transverse Ranges and San Diego is not getting much attention. On the other hand, if San Diego were located in the eastern United States it would be considered a major seismic belt--it has had historic earthquakes, it has faults; it would be a classic case study for a place with lots of earthquakes.

The San Andreas system has been well studied and seismologists and geologists know quite a bit about it. The same level of information does not exist for the San Diego region. On maps of seismicity, the San Andreas fault can in some places be located by lines of earthquakes. But over most of the San Andreas fault it cannot, especially where it has had its largest historic *displacement. The presence or absence of small earthquakes doesn't necessarily tell you what's going to happen in terms of large earthquakes. In fact, Dr. Heaton suggested that the areas that had large historic displacements are probably the areas that do not have many small earthquakes. Not having a lot of earthquakes is not a particularly reassuring thing.*

In terms of seismic sequences, something seems to have changed in San Diego in the early 1980's. Prior to 1983 the rate of earthquakes of magnitude 3 or greater was about 8.5 per year. Since 1983 the rate increased to 17 per year. It appears that in this general time period the rate of earthquakes has changed in the entire Continental Borderlands region.