GEOLOGICAL DATA AND SEISMIC-HAZARD ANALYSIS: PAST AND FUTURE

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ABSTRACT

Seismic-hazard analyses during the last [15-20] yrs have increasingly relied on geological data bearing on the seismic history of active faults. The reasons for this trend are the recognition that historical records of seismicity are generally too short to accurately reflect long-term rates of seismicity in many regions, and that available data show earthquakes which occur in regions of shallow seismicity generally have their origins on faults which show geological evidence of prehistoric earthquakes. Towards augmenting a limited historical data set, efforts to both recognize and develop geological methods to infer the past rate of seismicity on active faults have increased. Progress has been greatest in paleoseismic and fault slip-rate studies. Paleoseismic studies yield estimates of the dates of prehistoric earthquakes and fault slip-rate studies furnish information relating to the long-term rate of strain accumulation along faults. However, paleoseismic and fault slip-rate studies generally do not yield direct information regarding the sizes of earthquakes that have occurred in the past and which can be expected in the future. An estimate of the size of expected future earthquakes is fundamental to seismic hazard analysis and, as well, is necessary if earthquake repeat times are to be inferred from fault slip-rate data. In certain instances, estimates of expected earthquake size along a fault may be inferred from geologic or geomorphologic evidence of the amount of coseismic offset in past events, but such inferences are tenuous unless observations are available for many points along a fault. Observed relationships between seismic moment M_o and fault rupture length hold promise for quantitatively estimating the size of earthquakes expected to rupture mapped faults, but estimates of the length of a fault that will rupture are now largely subjective. It is the thesis of this discussion that the greatest promise toward significantly increasing the value of data provided by paleoseismic and fault slip rate studies to seismic-hazard analysis lies in a concerted effort to understand the physical factors that control the length of earthquake ruptures. Such efforts should include a systematic study of the structural and physical factors that have influenced the extent of historical earthquake ruptures and geological studies to determine the timing and offset history at many points along strike of active fault zones.

INTRODUCTION

The input of geological data to seismic-hazard analyses has increased markedly during the last 15-20 years. Several factors have led to this increase. The primary factor is that it is now generally recognized that earthquakes occurring in regions of shallow seismicity and active faulting generally have their origins on faults that show geologically recognizable evidence of prior (Allen, 1975; Sieh, 1978a) and, in certain instances,

similar-sized (Schwartz and Coppersmith, 1984) earthquake displacements in recent geologic time. The large uncertainty attached to seismic-hazard analyses based on the extrapolation of historical records to the future, particularly in regions where the historical record is short with respect to the average return time of earthquakes, has also provided an impetus to integrate geological data into seismic hazard analyses (Anderson, 1979; Wesnousky and others, 1984). The increased effort to incorporate geological data into seismic hazard analyses has led to advances in our ability to recognize and interpret the signature of prehistoric earthquakes as recorded in late Quaternary stratigraphy. In this paper, I will not be concerned with the details of how geological studies of active fault structures may be used to provide quantitative estimates of seismic hazard, since that has been discussed at length in earlier papers (Anderson, 1979; Wesnousky, 1986). Rather, I will briefly comment on what active fault studies currently provide for seismic-hazard analysis and what avenues of approach may likely provide the greatest increase in value of geologic data to seismic-hazard analysis in the near future. And finally, my comments will be concerned only with regions of shallow seismicity and active faulting like those in California and the Western United States.

DISCUSSION

Geological Methods

Fundamental to the increased role of active fault studies in seismic-hazard analysis is the recognition that faults which are seismically active commonly break Quaternary deposits and produce a characteristic and recognizable set of landforms. Hence, faults that break Quaternary deposits and exhibit such landforms are now commonly accepted as sources of seismic hazard, and geological and geomorphological studies are often the primary basis for locating potential seismic sources. In addition to locating seismic sources, geological studies of active faults frequently provide information regarding the long-term level of seismicity on faults.

The most well-known advances in assessing the long-term seismicity on faults have been made in the area of paleoseismology; the documentation of the dates of prehistoric earthquakes based on structural and stratigraphic analysis of sediments that have been repeatedly disturbed by earthquakes and, generally, exposed by the excavation of trenches across fault traces or liquefaction features (Sieh, 1978b; Wallace, 1981, Obermeier and others, 1985; Talwani and Cox, 1985). To my knowledge, the first such successful analysis was presented by Clark and others. (1972) for their study of the 1968 Borrego Mountain earthquake fault trace. They ascertained that the same fault ruptured in similar- sized events on the average of each 150-200 years during the last few thousand years. The importance of this study is magnified when it is realized that the historical record in Borrego Mountain region extends back in time 100 years at best (Toppozada and others, 1981). Now it is not uncommon to establish specific dates of earthquake ruptures that have occurred on faults during the last several thousand years (Sieh, 1978, 1984 [San Andreas fault]; Swan and others, 1980 [Wasatch Fault zone]; Tanna Fault Trenching Research Group, 1983 [Tanna Fault]; Obermeier and others, 1985 [Charleston area]; Rockwell and others, 1985 [Elsinore Fault]). Withstanding any uncertainties, these efforts have led to a far greater understanding of seismic hazard in the respective regions than could be gained solely from historical data.

Significant progress has also been made in geological methods to assess the long-term slip rate of active faults. Slip-rate estimates, the consequence of recognizing geo-

logical and geomorphological features of known age that are offset a given distance by a fault, have now been estimated from offset features that include, among others, Holocene stream channels (Sieh and Jahns, 1984), fluvial deposits (Adams, 1980), glacial moraines (Plafker and others, 1978), soils (Machette, 1978), and volcanic rocks (Dokka, 1983). Summaries of slip-rate determinations and the data on which they are based have most recently been summarized by the Research Group for Active Faults of Japan (1980), Sieh (1981), and Clark and others, (1984). The parameter of seismic moment M_o, a measure of earthquake size like magnitude, but which may be directly related to physical parameters that describe the earthquake source, such as fault length and coseismic slip, has further enabled quantitative estimates of long-term seismicity rates from geologic estimates of fault-slip rate, in terms of the *seismic- moment rate* (Wesnousky, 1986).

Contributions and Limitations of Geological Data to Seismic Hazard Analysis

Estimation of Earthquake Location

Within the context of seismic-hazard analysis, it appears that that geological studies currently play a most complete role in the identification of seismic sources. The geologic signature of active faults can be relatively easily documented by trained geologists. Moreover, the common coincidence between recent earthquake ruptures and preexisting and mappable Quaternary faults leads to confidence that maps of Quaternary faults and related fold structures provide a good indicator to the locations of future earthquakes. Such information forms the foundation on which seismic-hazard analyses are built.

Estimation of Earthquake Repeat Time

Paleoseismological or trenching studies provide the most direct measure of the past occurrence rate of moderate to large earthquakes on faults. However, the success of such studies is dependent on a unique set of geological conditions leading to preservation of a detailed stratigraphic record at sites along a fault. It is by no means certain that such sites exist along all active faults. Rapid urbanization is also eliminating many sites which would be conducive to paleoseismological analysis. Withstanding these problems, the potential of paleoseismological studies is yet largely untapped along most fault zones and future studies will certainly contribute more information to seismic-hazard analyses.

Fault slip-rates also give a measure of the long-term rate of activity of a fault and seem a more common result of active fault studies than stratigraphic constraints on the time that past earthquakes occurred. The fault slip-rate $\dot{u}$ is equal to U/T, where U is the geologically documented offset across the fault of a rock unit of age T. With knowledge of the fault length L and width W, the *seismic moment rate* $\dot{M}_o$ of the fault may also be estimated to equal $\mu LW\dot{u}$ (Brune, 1968), where μ is crustal rigidity. The average repeat time T between earthquakes on a fault is commonly interpreted from measures of $\dot{u}$ or $\dot{M}_o$ based on the equation

$$T = U^{exp}/\dot{u}^{g} \qquad (1a)$$

or

$$T = M_o^{exp}/\dot{M}_o^{g}, \qquad (1b)$$

where U^{exp} and M_o^{exp} are the values of coseismic offset and seismic moment expected to occur on the fault of interest, respectively (Wallace, 1970, Wesnousky and others, 1983). Thus, further assumptions regarding the size of earthquake expected to rupture the fault are necessary to convert measures of $\dot{u}$ or $\dot{M}_o$ to estimates of earthquake repeat time (RT).

Estimation of Earthquake Size

It is perhaps in the estimation of earthquake size that geological studies of active faults currently play their weakest role in seismic hazard analysis. Estimates of earthquake size are necessary to calculate the area which will be subjected to strong ground motions due to rupture of a fault. Further, estimates of earthquake return time from fault slip-rate data are critically dependent on estimates of the expected earthquake size (equation 1). Stratigraphy exposed along a trench wall or geomorphological features offset by a fault can sometimes provide information regarding the amount of offset that occurred coseismically at that site (Sieh and Jahns, 1984). However, such measures are generally limited to a small portion or site along a fault's entire length. An estimate of the offset along the entire length of a fault is desirable to correctly assess the size of past earthquakes. Recent earthquake ruptures show that variability of coseismic slip along faults can be very large. As a result, large uncertainty must be attached to estimates of earthquake size from point measurements of coseismic offset along a fault. Furthermore, many fault slip-rate studies report an estimate of fault slip-rate but are apparently unable to provide data regarding the coseismic offset of past earthquakes. Historical earthquakes may also provide direct evidence of the capability of the faults on which they occurred. However, it is my experience that, more commonly, empirical relations between earthquake magnitude M or moment M_o and rupture length l derived from recent earthquakes (fig. 1) must be relied upon to estimate the expected size of earthquakes on mapped faults, with the inference that the size of an earthquake will be proportional to the mapped fault or fault segment length.

The estimation of earthquake size from mapped fault length is simple in concept but difficult in practice. The difficulty stems from observations that earthquakes do not necessarily rupture the entire extent of the faults on which they occur. The great 1857 and 1906 California earthquakes are a well-known example of this behavior, each only rupturing 350-400 km of the total 1,000 km length of the San Andreas fault. Arising from this observation is the critical problem of identifying the segments of faults which will be the most likely source of future earthquakes. When coupled with the scatter observed in the empirical relationships between earthquake size and fault rupture length used to infer the expected size of future earthquakes (fig. 1), the uncertainty regarding estimates of the segments of faults expected to rupture during future earthquakes can translate into uncertainties in estimates of earthquake size and repeat time which are unacceptably large and not practically useful. The uncertainties are conveniently illustrated by a brief examination of the Elsinore Fault zone in southern California (fig. 2).

The Whittier-Elsinore Fault strikes southward from Los Angeles a distance of about 250 km. Displacement across the fault is primarily right-lateral. It may be inferred from the relations in fig. 2 that rupture along the entire 250 km length of the Elsinore fault would produce average displacements of 2.5-7.0 m (Wesnousky, 1986). A recent interpretation of offset geomorphic features along the southern Elsinore indicates the repeated occurrence of several earthquakes during the Holocene with coseismic offsets averaging about 1.4 m (Pinault and Rockwell, 1984), less than would be expected from a complete

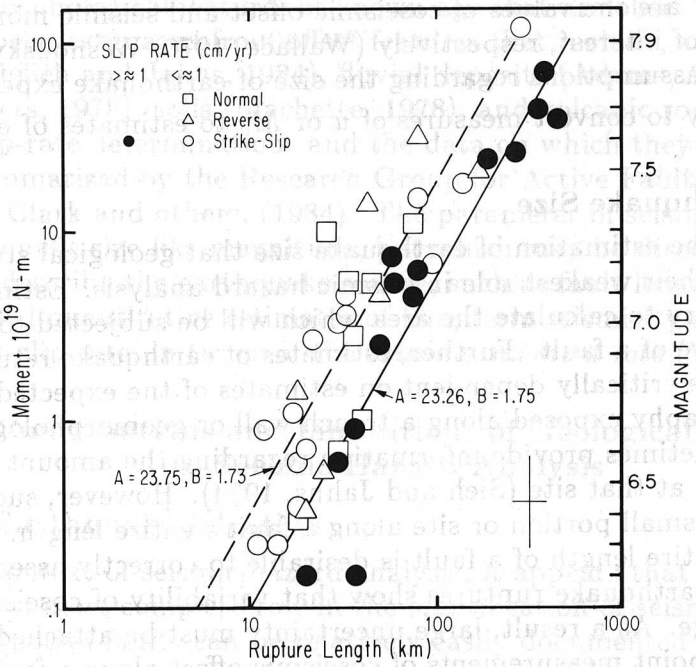

Figure 1. Seismic Moment M_o versus fault rupture length L for a set of historical earthquakes compiled by Wesnousky (1986). Solid symbols indicate earthquakes on major plate boundary faults generally characterized by a slip-rate of about 1 cm/yr or greater. Earthquakes on faults with lesser slip rates are shown by open symbols. Solid and dashed lines of form $logM_o = A + B \times logL$ are fit through the solid and open symbols, respectively. The vertical and horizontal bars of the cross in lower right corner of plot correspond to a factor of 3 in M_o and 50 percent in L, respectively. Estimates of earthquake size and repeat time in figure 3 are determined with the relationship shown by the solid line.

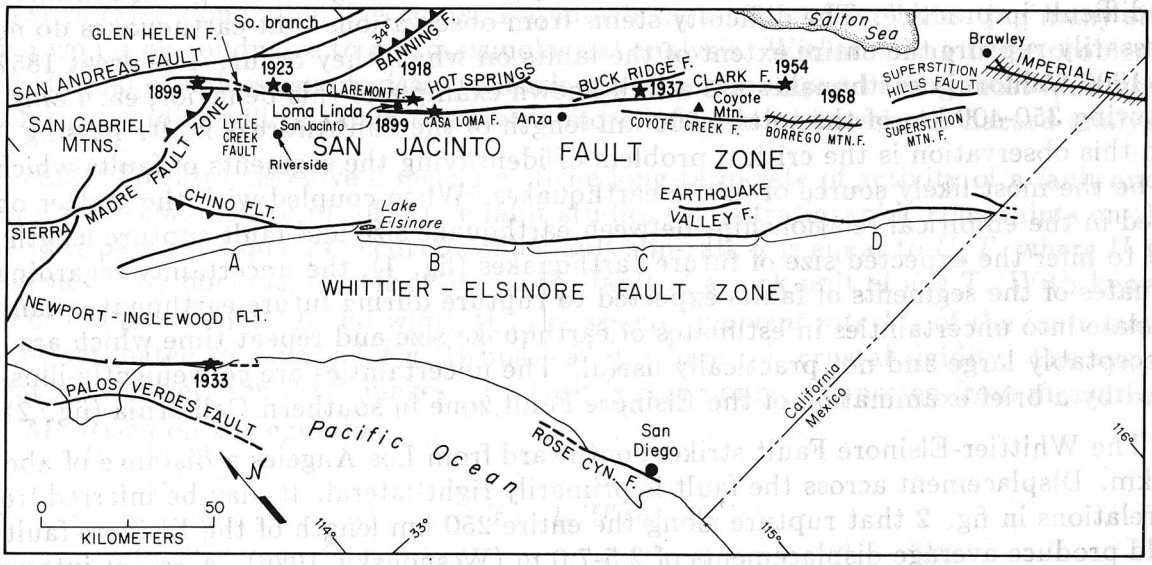

Figure 2. Location of Whittier-Elsinore fault zone in southern California. Labeled brackets show segments of fault which are divided on the basis of major steps or bends in the fault trace. Stars with dates are location of major historic earthquakes.

rupture of the fault zone. Historical data indicate that the Elsinore has not broken in its entirety during the last 150 years (Toppozada and others, 1980). Isoseismal data is, however, compatible with the occurrence of a moderate M=6.0 earthquake along the northern end of the fault zone in 1910 (Toppozada and Parke, 1982). It is entirely possible then, if not likely, that the Elsinore fault zone does not typically rupture in entirety during single earthquakes but, rather, breaks in sequences of lesser size events which are limited to specific segments of the fault zone. The possibility could be addressed by implementation of a suite of paleoseismic studies along strike of the Elsinore. Such a data set is not currently available nor is it certain that a sufficient number of sites suitable for paleoseismological analysis exist to provide such a data set. Estimates of earthquake size and repeat time must currently be based on data describing fault slip-rate and estimates of the length or segment of fault expected to rupture during the earthquake. The sensitivity of seismic hazard analysis to estimates of expected fault rupture length are, in part, schematically illustrated in fig. 3.

Figure 3 is a schematic map of the Whittier-Elsinore fault. The total 250 km length of the fault is divided into a various number of segments in figures 3a, b, and c, respectively. Available fault slip-rate studies (Wesnousky, 1986) are used to assume that the slip-rate along the entire fault zone is 4 mm/yr. In each case, individual segments of the fault are assumed to rupture in separate earthquakes. The size of earthquake expected on each segment is computed with the empirical relationship between fault length and seismic moment in fig. 1. The repeat time of the expected earthquake on each segment is estimated with equation 1b. Equations from Joyner and Fumal (1985) relating earthquake size–source to site distance–and strong ground motion are then used to estimate the distance from the fault to which peak strong ground accelerations equal to or greater than 0.2 gravity can be expected. Figure 3 illustrates that different assumptions regarding the length of fault expected to rupture during earthquakes yields strongly contrasting estimates of the size and repeat time of earthquake strong ground motions along a fault zone, even when disregarding the uncertainties inherent to fault slip-rate estimates and the uncertainty represented by the scatter in relationships between earthquake size and repeat time (fig. 1). Whereas the uncertainties associated with slip-rate estimates and empirical relations between earthquake size and seismic moment can be addressed in some quantitative fashion, estimates of the expected length of rupture are now primarily subjective. Thus, significant improvement to geological estimates of seismic hazard could be be realized if criteria were documented on which we could make statistically quantifiable estimates of the extent to which a fault will rupture in the future.

CONCLUSIONS

Geological studies of active faults now contribute, to varying degrees, to the asssessment of the expected location, size, and frequency of earthquakes in regions of active tectonics. The common coincidence between recent earthquake ruptures and preexisting and mappable Quaternary faults leads to confidence that maps of Quaternary faults and related fold structures are a good indicator to the locations of future earthquakes. Paleoseismology provides a tool to assess the past occurrence rate of earthquakes on active faults and, hence, a basis to estimate future behavior. Fault slip-rate studies, when combined with estimates of expected earthquake size, provide data bearing on the average expected repeat time of earthquakes on a fault. In certain instances, estimates of expected earthquake size for a fault can be gained by observations of geomorphic evidence of past coseismic offsets along the length of fault. It is more common, however,

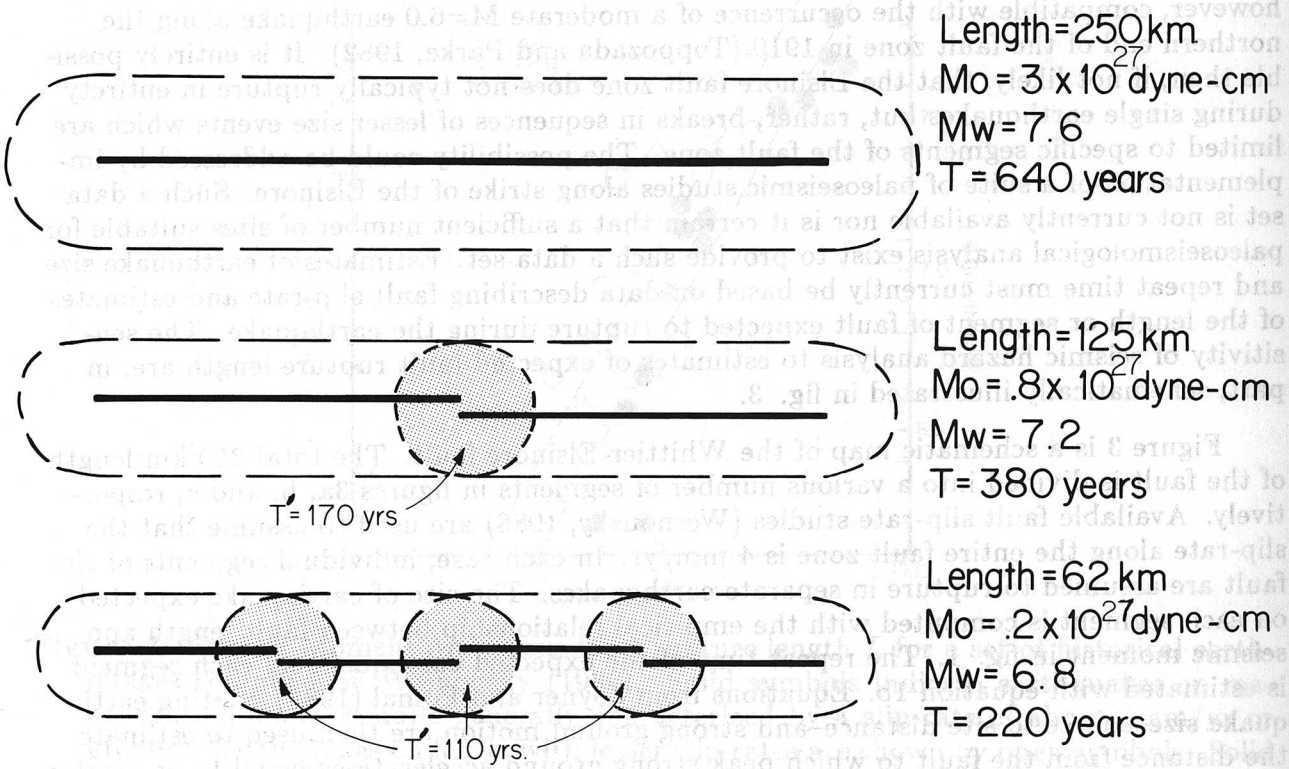

Figure 3. Schematic illustration showing how assumptions of fault segmentation strongly influence geological estimates of seismic hazard along a fault zone. Map view of 250-km fault trace shows fault divided into 250 km, 125 km, and 62 km segments in a, b, and c, respectively. The seismic moment M_o and moment-magnitude Mw expected for earthquakes rupturing individual segments are determined from empirical relationship in figure 1. The return time T of earthquakes on each segment is computed with equation 1b assuming $\mu = 3 \times 10^{11}$ $dyne/cm^2$, fault width $W = 15$ km, and the fault slip rate is 4 mm/yr. The regions expected to experience 0.2-g peak ground accelerations or greater due to earthquakes on each segment are encompassed by dashed lines and computed with the equations of Joyner and Fumal (1985). The return time of 0.2-g ground shaking will be equal to the repeat time T of earthquakes computed for each fault segment in the unshaded regions encompassed by dashed lines. Regions near segment boundaries will be subjected to ground shaking from earthquakes on more than one segment (shaded regions) and, hence, the return time of strong ground motions T' will be less than the repeat time of earthquakes on individual segments. Estimates of the expected return time of ground shaking along a fault zone are thus strongly dependent on the assumed location and length of individual fault segments.

that estimates of earthquake size are made with empirical relationships between earthquake size (magnitude or moment) and fault length. Such estimates thus require some knowledge of the length of fault which will rupture. Since faults do not as a general rule rupture their entire length during an earthquake, estimating the extent to which a fault will rupture during future earthquakes is now largely subjective. In turn, estimates of earthquake repeat time from fault slip-rate data and earthquake size are often associated with unacceptable uncertainties. In this regard, the growing body of observations which suggest that points of structural complexity along faults strongly influence the initiation and extent of earthquake ruptures (Allen, 1968; Segall and Pollard, 1980; Lindh and Boore, 1981; Sibson, 1985; King and Nabelek, 1985) is an exciting and crucial development for seismic-hazard analysis. If systematic relationships can be established between the endpoints of earthquake ruptures and structural complexities along fault strike, much of the subjectivity involved in estimating the rupture length, expected size, and repeat time of earthquakes on mapped faults may be removed. Establishment of any such systematics will require a thorough examination of past earthquake ruptures coupled with extensive paleoseismologic efforts at many sites along particular fault zones. To summarize, it is my opinion that the greatest promise toward significantly increasing the value of data provided by paleoseismic and slip-rate studies to seismic hazard analysis lies in a concerted effort to quantify the extent to which structural and physical discontinuities along fault strike play a role in the rupture propagation process, and to determine whether or not the effects of these features are sufficiently systematic and large that they may ultimately be used with confidence as a predictive tool for assessing the likely length of earthquake ruptures.

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