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State of Stress in Seismic Gaps Along the San Jacinto Fault

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INTRODUCTION

Data from the Southern California Seismic Network have been extensively used to map spatial and temporal variations of seismicity (for example, Hileman et al., 1973; Green, 1983; Webb and Kanamori, 1985; Doser and Kanamori 1986; Nicholson et al., 1986). A recent study by Sanders et al. (1986) clarified some of the important features of historical seismicity along the San Jacinto fault of southern California, one of the most prominent being the Anza seismic gap. Thatcher et al. (1975) investigated the spatial distribution of large earthquakes along the fault and indicated that a 40-km-long section from Anza to Coyote Mountain is deficient in seismic slip and can be considered a seismic gap (G1 in fig. 1). Sanders and Kanamori (1984) investigated the seismicity along an 18-km-long section (also often called the Anza seismic gap) centered near the town of Anza, and concluded that this section of the fault is locked and has the potential for a magnitude 6.5 event (G2 in fig. 1).

In this paper, we review the most recent activity along the San Jacinto fault and assess the seismic potential of this fault zone in light of an empirical relation between fault length, seismic moment, and repeat time obtained from earthquakes along active fault zones around the world.

RECENT SEISMICITY ALONG THE SAN JACINTO FAULT

Figure 1, a map of recent seismicity along the San Jacinto fault, does not clearly show the seismic gap. Figure 2 is a cross section of the seismicity along the strike of the fault and includes all the events between points A and A′ in the narrow box shown in figure 1. A similar figure has been presented

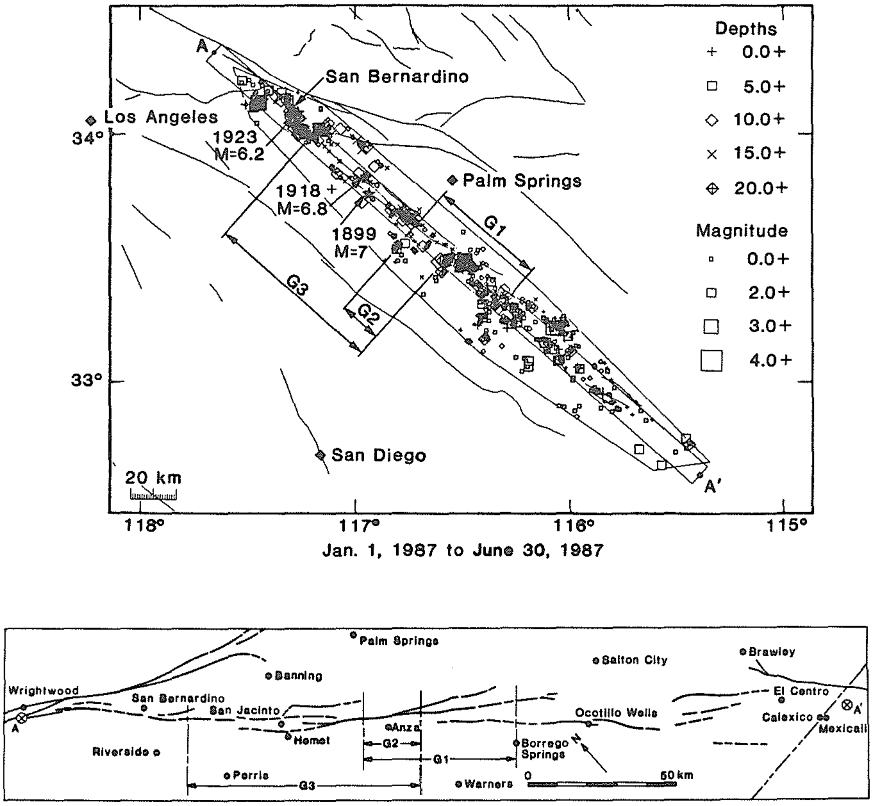

Figure 1. Seismicity along the San Jacinto fault, Southern California, for the period January 1, 1987, to June 30, 1987. The data are taken from the catalog of the Southern California Seismic Network. All the events in the polygon are shown. The narrow box A-A′ indicates the area used for the cross-sectional plot shown in figure 2. Geographical locations of the fault and the gaps are shown in the figure at the bottom.

by Sanders (1986) for an earlier time period. The most striking feature of these displays is the almost complete absence of seismic activity over an 80-km-long section (G3 in figs. 1 and 2) that includes the "Anza seismic gap." The only activity in this quiet zone is at a depth of about 13 km. Doser and Kanamori (1986) interpreted this activity to represent the bottom of the seismogenic zone along the San Jacinto fault.

We examined the seismicity in this zone for the period from July 1983 to December 1986 and found essentially the same seismicity pattern shown in figure 2.

The historical seismicity along this segment was reviewed by Thatcher et al. (1975), Sanders and Kanamori (1984), and Sanders et al. (1986).

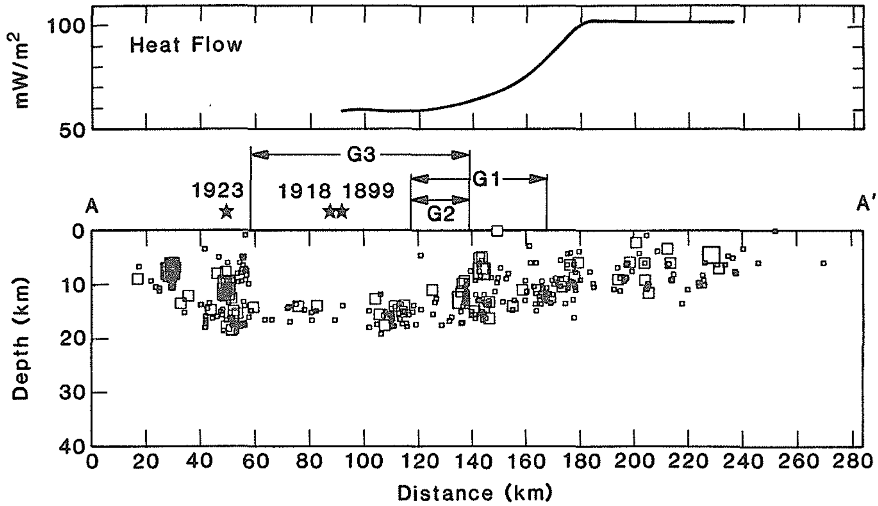

Figure 2. Seismicity cross section along the San Jacinto fault (lower figure). All the events in the box A-A′ in figure 1 are shown. Three gaps, G1, G2, and G3, are indicated. The upper figure shows the variation of heat flow along the San Jacinto fault, taken from Lachenbruch et al. (1985).

Although the exact locations and sizes of the 1899, 1918, and 1923 events are uncertain, it is generally agreed that no large ($M_L > 6.5$) earthquake has occured in the 80-km quiet section at least since 1918.

Another notable feature in figure 2 is the steady increase in the depth of the seismogenic zone, as defined by the deepest activity, from the south to the north. Doser and Kanamori (1986) interpreted this trend in terms of a depression of the geotherm evidenced by a decreasing heat flow. The heat flow along the San Jacinto fault taken from Lachenbruch et al. (1985) is shown in figure 2.

INTERPRETATION

The seismicity pattern shown in figure 2 suggests that strain is building up in the locked fault zone at depths shallower than 13 km. The steady activity at the bottom of the seismogenic zone may be a manifestation of stress accumulation that will eventually cause failure of the overlying locked zone.

A similar seismicity pattern was observed before the 1979 Imperial Valley earthquake ($M_L > 6.5$). Doser and Kanamori (1986) relocated earthquakes along the Imperial fault. Figure 3 shows the cross section of seismicity along the strike of the Imperial fault for a period of about two years before the October 15, 1979, earthquake. The solid curve in the figure outlines the slip

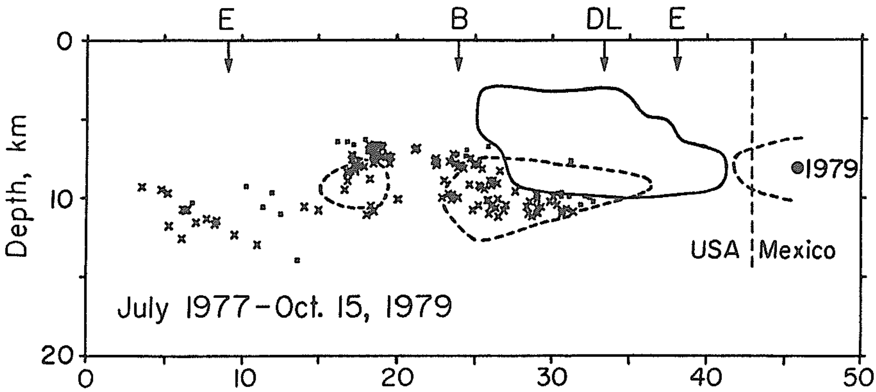

Figure 3. Cross section of seismicity along the strike of the Imperial fault for the period July 1977 to October 15, 1979. The hypocenters with A and B quality listed in the Southern California Network catalog, relocated by Doser and Kanamori (1986), are shown. The regions of the fault outlined by solid and dashed lines represent strike-slip offsets of one meter from the rupture models of Hartzell and Heaton (1983) and Archuleta (1984), respectively. E denotes the ends of the surface faulting and B the intersection of the Brawley fault with the Imperial fault.

zone of the main shock where the strike-slip displacement exceeded one meter (Hartzell and Heaton, 1983). Because of the limited station distribution of the network, the events between DL and the hypocenter, located to the south of the United States–Mexico border, could not be relocated and are not shown in figure 3. This pattern also suggests stress accumulation beneath the locked portion of the Imperial fault.

Given this loading mechanism, we can assess the state of stress in the seismic gaps along San Jacinto fault in the following manner. If we assume that the strain is accumulating on a fault of length L and width W, the accumulated seismic moment M_0 is given by

$$M_0 = \mu VWLT \tag{1}$$

where μ is the rigidity, taken to be 3×10^{11} dyne/cm^2, V is the slip rate, and T is the elapsed time since the last earthquake. If we take the entire 80-km quiet zone (G3) as a locked segment, then $W = 13$ km and $L = 80$ km.

Although the slip rate along the entire San Jacinto fault is not known accurately, Sharp (1981) indicates a minimum Quaternary long-term slip rate of about 8 to 12 mm/year for the segment in the vicinity of Anza. A slip rate of 1 cm/year seems to be a reasonable estimate.

Geodetic studies of King and Savage (1983) indicate an accumulation of

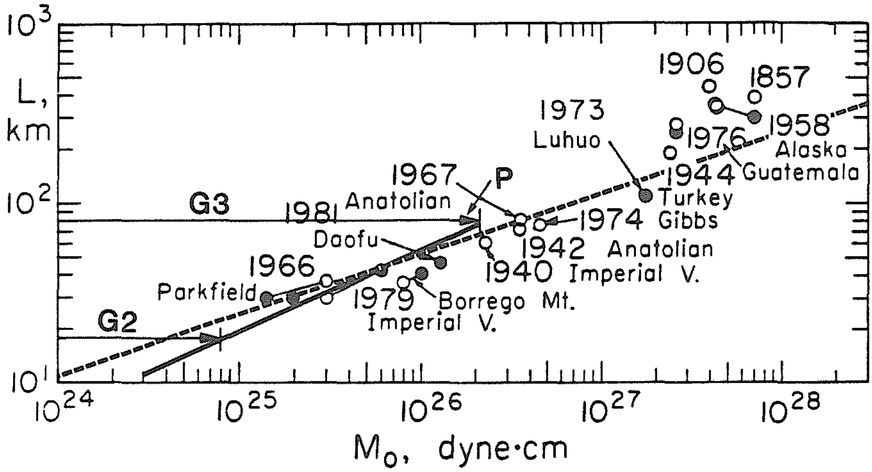

Figure 4. The relation between the fault length and seismic moment of shallow strike-slip earthquakes in active plate boundaries. The dashed line indicates a slope of 1/3 expected for the standard scaling relations. Closed and open circles are the data taken from Kanamori and Allen (1986) and Scholz et al. (1986), respectively. The horizontal lines indicate current strain accumulation in the seismic gaps along the San Jacinto fault.

right-lateral strain in this area at a rate of 0.3 μ strain/year. No surface fault creep has been measured for at least the last ten years along the San Jacinto fault near Anza (Louie et al., 1985; see also Sanders and Kanamori, 1984).

These observations suggest a steady strain accumulation in this gap for at least seventy years since the last large earthquake in 1918. Substituting $T = 70$ years into equation (1), we obtain $M_0 = 2.2 \times 10^{26}$ dyne-cm (corresponding to $M_w = 6.8$) as the minimum accumulated seismic moment along this segment. If the 1918 event did not break this segment, the cumulative moment could be even larger.

The next question is how close the presently accumulated strain is to the ultimate failure strain. We examine this problem on the basis of empirical data obtained from other earthquakes. Kanamori and Allen (1986) examined the relation between the fault length and seismic moment of shallow crustal earthquakes and found that, for a given fault length, earthquakes with longer repeat times have larger seismic moments than those with shorter repeat times. They interpreted this relation in terms of the difference in the strength of fault zones. Fault zones with longer repeat times are stronger than those with shorter repeat times. If we consider only the events with relatively short (less than 500 years) repeat times, a systematic relation can be obtained.

Figure 4 shows the relation between fault length L and seismic moment

M_0 of shallow strike-slip earthquakes with repeat times less than 500 years in the world. The open and closed circles indicate the data taken from Scholz et al. (1986) and Kanamori and Allen (1986), respectively.

The seismic moments accumulated in the two segments (G2 and G3) of the San Jacinto fault are indicated in the figure. As the time elapses, the accumulated moment increases along the horizontal line drawn for the given fault length. If the strength of the San Jacinto fault zone is comparable to that of other fault zones, the fault should break when the head of the arrow (point P) reaches the moment value defined by the average trend of the data. Since the seismic moment is generally considered to be proportional to the seismic-wave energy released in earthquakes, we use the term "energy" below in place of "moment."

Figure 4 shows that the strain energy presently accumulated along the longer gap (G3) is at least comparable to the average of the ultimate strain energy that can be stored in an 80-km fault segment. In this sense, one can conclude that this gap is close to failure. We note, however, that the empirical data indicate a factor-of-two spread in strain energy, suggesting that strain accumulation can continue for another seventy years or so without breaking this gap.

Another possibility is that the strain is not uniform along the gap because of varying slip histories, so that only a part of the gap may break in a smaller earthquake. We can estimate the accumulated strain for this case using equation (1), but some ambiguity exists in the width W. The empirical relation shown in figure 4 suggests that W is not constant, but is approximately proportional to L (see Scholz, 1982; Kanamori and Allen, 1986). Equation (1) then suggests that the accumulated energy is proportional to L^2. In figure 4 we show a straight line with a slope of 1/2 passing through point P. This line determines the level of strain accumulation for gaps with different lengths. For example, for the shorter Anza gap (G2) $L = 18$ km, and the accumulated moment is about $M_0 = 1 \times 10^{25}$ dyne-cm ($M_w = 5.9$). If a gap with $L = 40$ km breaks, then $M_0 = 5 \times 10^{25}$ dyne-cm ($M_w = 6.4$).

CONCLUSION

A comparison of the size of the gap and the elapsed time since the last large earthquake with fault length-moment relations of shallow strike-slip earthquakes suggests that the strain energy accumulated in the 80-km seismic gap along the San Jacinto fault is comparable to the ultimate strain energy that can be stored there. However, the ultimate strain per unit volume of the earth's crust depends on the strength of the fault zone. The empirical relation indicates approximately a factor-of-two variation in the strength for faults in active plate boundaries. This range translates into a factor-of-two variation in repeat time. It is therefore possible that strain accumulation could continue for another seventy years or so without causing an earthquake.

Other possible scenarios include: 1) The present slip rate along the San Jacinto fault is much smaller than 1 cm/year, and it takes much longer than seventy years to accumulate enough strain to break the gap. 2) The depth of the seismogenic zone is significantly greater in this segment than elsewhere along the San Jacinto fault, as evidenced by the decrease in heat flow, resulting in an increase in the overall strength of the fault zone and in the repeat time. 3) The 1899 and 1918 earthquakes did not completely break this gap, and the accumulated strain is larger than indicated in figure 4. In this case, the gap is closer to failure than indicated by figure 4. 4) The 40-km-long gap may fail in several smaller earthquakes.

Despite this uncertainty inherent in the empirical methods, the information obtained from detailed analyses of seismicity and earthquake rupture processes provides an important clue to the state of stress in a seismic gap with respect to its ultimate strength.

Earthquake prediction on the basis of empirical methods like the one presented above, and many others currently used, is obviously of limited accuracy. Nevertheless, it provides a physical framework for further experiments. In the case of the seismic gaps along the San Jacinto fault, high-resolution seismicity studies have delineated the geometry of the gaps and the currently seismogenic zone, which has enabled us to determine the physical condition of the fault (Sanders and Kanamori, 1984; Doser and Kanamori, 1986). Detailed analysis of the rupture parameters of earthquakes in similar tectonic environments provides a tool to measure the level of strain accumulation relative to the ultimate strain.

Obvious next steps involve more physical measurements. Since earthquakes are ultimately caused by strain accumulation, continuous monitoring of the strain field in the gap area is crucial. Also, since fault ruptures appear to initiate from the bottom of the seismogenic zone, studies of spatial and temporal variations of source characteristics of the events near the bottom of the seismogenic zone are important.

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