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SLIP BUDGET AND POTENTIAL FOR A M7 EARTHQUAKE IN CENTRAL CALIFORNIA

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Abstract. The slip rate budget of the San Andreas fault (SAF) in central California, which is approximately 33 mm/yr, is accounted for by a change in the slip release mechanism along the fault. In the NW section of the fault, between Bear Valley and Monarch Peak, creep apparently accounts for the slip budget with the seismicity contributing negligibly. The section at Parkfield marks the transition from a creeping to a locked fault trace. Since the M8 1857 earthquake five M6 earthquakes have occurred but have not completely accounted for the slip budget. Southeast of Parkfield, the SAF has been locked since 1857. From Cholame to Bitterwater Valley this section now lags the deep slip by the amount of slip released in 1857; consequently faulting in this section could occur at the time of the next Parkfield earthquake. If this earthquake releases the slip deficit accumulated in the transition zone and in the locked zone, the earthquake will have a moment-magnitude M7.2.

Introduction

The deep slip rate of 34 mm/yr constrained by geological estimates [Sieh and Jahns, 1984] provides a slip budget for the SAF in central California. To determine the potential for large earthquakes on the SAF in central California, we look at the slip release relative to the slip budget for three segments of the fault; the creeping section NW of Parkfield, the transitional Parkfield section, and the locked trace SE of Parkfield (Figure 1). The geodetic data for the NW segment shows this section of the fault to be creeping at approximately 33 mm/yr [Thatcher, 1979] and it is believed that this segment is not storing elastic energy. At Parkfield five M6 earthquakes have occurred since 1857 [Bakun and McEvilly, 1984] and SE of Parkfield at least the trace of the SAF has been locked since the great (M8) earthquake of 1857. Both geodetic and seismic data for the Parkfield section [Segall and Harris, 1987; Archuleta and Day, 1980] are consistent with the idea that the Parkfield section does not release all of the slip budget during M6 earthquakes. In this paper we show that the geodetic data indicate that the 30 km segment SE of Parkfield is locked at depth. We assume that this has been true since 1857. Given this assumption along with a conservative estimate for plate velocity, we show that this segment has accumulated a slip deficit equal to the slip released in the great 1857 earthquake. Thus we consider the possibility that the next Parkfield earthquake will release not only all of the accumulated slip deficit on the Parkfield segment but also trigger faulting on the 30 km segment SE of Parkfield. If this occurs, the next Parkfield earthquake will be a M7.2.

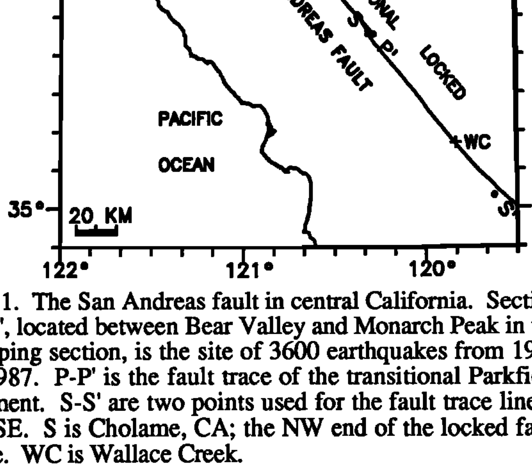

Fig. 1. The San Andreas fault in central California. Section A-A', located between Bear Valley and Monarch Peak in the creeping section, is the site of 3600 earthquakes from 1969 to 1987. P-P' is the fault trace of the transitional Parkfield segment. S-S' are two points used for the fault trace line to the SE. S is Cholame, CA; the NW end of the locked fault trace. WC is Wallace Creek.

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NW of Parkfield; A creeping segment of the SAF

NW of Parkfield the SAF appears to exhibit block motion with a slip rate of at least 33 mm/yr [Thatcher, 1979]. It is also a segment delineated by intense microseismicity. To see how earthquakes contribute to the slip budget, we looked at the seismicity recorded from 1969-1987 [Rick Lester, written comm., 1987] for a 36 km long section of the fault between Bear Valley and Monarch Peak (Figure 1). We selected 3600 well-located events within 5 km of the fault plane, with the largest event an M4 earthquake. We calculated the relative velocity, v, of the two sides of the fault using

$$v = \sum_{i=1}^{3600} M_{0i} / (\mu A_{fp} t) \quad (1)$$

[Brune, 1968], where M_{0i}, the seismic moment is determined from magnitudes using relationships for central California [Bakun,1984], A_{fp}, the fault plane area is 540 km^2 (36 km long x 15 km deep), μ, the shear modulus is 3.0×10^{10} nt/m^2, and t, the time is 18 years. We obtained a plate velocity of 2.9×10^{-2} mm/yr, negligible compared to a plate velocity of 33 mm/yr. This velocity assumed the 540 km^2 was covered by the 3600 earthquakes. To approximate the actual source area of these earthquakes we determine a source radius r and area for each earthquake based on M_0 and $\Delta\tau$, the stress drop [Brune, 1970, 1971]:

$$A = \pi r^2 = \pi \left(\frac{7 M_0}{16 \Delta\tau} \right)^{2/3} \quad (2)$$

Assuming $\Delta\tau$ equal to one bar [Archuleta et al.,1982], for earthquakes in this range of magnitudes and non-overlapping areas the earthquake-covered fault plane area was 386 km ^{2}.

This leads to an earthquake contribution velocity of 4.1×10^{-2} mm/yr, again a negligible rate compared to the plate velocity and not significantly different from the earlier estimates. However, this estimate does imply, assuming non-overlapping areas, that the 3600 earthquakes recorded over 18 years almost covered the area of the fault plane in the creeping section but contributed less than 0.2% of the recorded slip rate.

Parkfield; A transitional segment of the SAF

The Parkfield segment of the SAF, from Middle Mountain to Cholame lies in a transition zone between creeping and locked traces of the fault. This segment has experienced five M6 earthquakes since the great M8 earthquake of 1857, with the most recent event in 1966 [Bakun and McEvilly, 1984]. This segment of the fault has been monitored geodetically since 1959. Segall and Harris [1987], and Harris and Segall [1987] analyzed the geodetic data and found for their best fitting models an average coseismic slip of 0.34 m for the 1966 earthquake and a slip rate of 8 mm/yr for the current interseismic period. Models of the 1966 Parkfield earthquake based on forward modeling of strong ground motion data gave approximately 0.43m of slip [Archuleta and Day,1980]. Because no earthquakes of large moment have occurred on the Parkfield section since 1966, seismicity has contributed little or nothing to the slip budget in this period.

SE of Parkfield; A locked segment of the SAF

The trace of the SAF SE of Parkfield (hereafter referred to as SE of Cholame, where Cholame is at the NW end of the locked fault trace; see Figure 1) has been locked since the great (M8) earthquake of 1857, but no estimate of locking depth has been derived from the data. Although this section of the fault has not been geophysically monitored as intensively as the Parkfield section, seismicity and creep are measured and networks of trilateration lines have been surveyed. Little to no seismicity has been recorded [Jones, pers. comm., 1987] and alignment array measurements have not shown any offset [Burford and Harsh, 1980]. Thus we use trilateration data to estimate the slip rate on this section of the SAF.

The network of trilateration lines SE of Cholame is divided into 2 sub-networks (Figure 2). The San Luis network was surveyed by the CDMG (California Division of Mines and Geology) from 1970-1979 and by the USGS (U. S. Geological Survey) after 1979. Two lines, Red Hill-Twissel and Simmler-Twissel were also surveyed by the USGS in 1973. The Carrizo network has been surveyed by the USGS since 1977.

Results

We determined the slip rate on the SAF SE of Cholame using station velocities calculated from the rates of line-length change of the frequently surveyed trilateration lines [King et al., 1987]. The station velocities were based on the 'outer coordinate' solution which finds the rotation of the network that minimizes the components of station velocity normal to the SAF. [Prescott, 1981]. The station velocities parallel to the fault for the four well-connected stations in each network are listed in Table I. In Figure 3 we compared predicted station velocities from three models of deep slip rate with observed station velocities. The models were constrained to be locked above 15 km, a depth consistent with maximum hypocentral depths in the region. Because the deep slip rate was best determined by stations furthest from the fault, the station velocities of Berros and Biddle were critical. The rates most consistent with the data were in the range 30-34 mm/yr, similar to geological estimates [Sieh and Jahns, 1984].

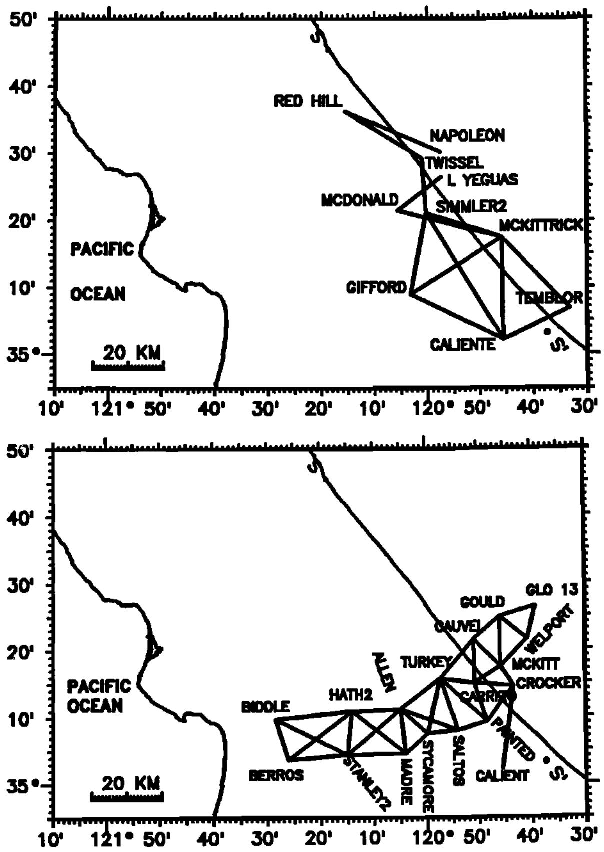

Fig. 2. Two networks of trilateration lines surveyed SE of Parkfield. S and S' are the same as in Figure 1. a) The San Luis network surveyed by the CDMG and the USGS. b) The Carrizo network surveyed by the USGS.

To check our assumption that the fault was locked above 15 km, we examined stations closer to the fault. Unfortunately, the data from stations McKittrick and Simmler, located at about the same distance from our straight line approximation to the actual fault trace, but on opposite sides of the fault did not agree. The approximation affected distances for stations McKittrick and Caliente, which are close to the fault. When we used the actual station-fault distances for the two stations, Caliente's fault parallel velocity increased from 2.5 to 3.1 mm/yr and McKittrick's decreased from 4.9 to 4.2 mm/yr. These distance corrections did not significantly affect the results but also did not resolve

Table I. Fault Parallel Station Velocities

Station	Velocity ($\pm 2\sigma$ mm/yr)	Distance from fault (km)
Berros	14.6±8.2	57.3
Biddle	14.8±8.4	53.0
Hath2	10.2±7.1	34.6
Stanley2	12.6±9.1	43.3
Caliente	2.5±1.4	10.8
Gifford	6.4±2.1	23.9
McKittrick	-4.9±1.1	-6.5
Simmler	2.3±1.5	6.4

Velocities are calculated using an outer coordinate solution and assuming that the SAF strikes 142.5° N.

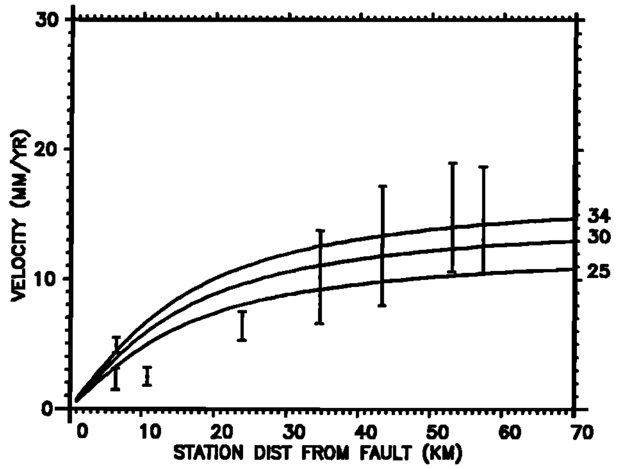

Fig. 3. Fault parallel station velocities (mm/yr) versus absolute distance from the fault plane (km) for the 8 well-connected stations listed in Table I. Curves are predicted velocities for a fault slipping at 25, 30, and 34 mm/yr below 15 km.

the discrepancy between the predicted slip rate and the observations. It is clear that the data do demand that the SAF is locked SE of Cholame. Any increase in the slip rate above 15 km on the fault plane would just increase the difference between the observed and predicted velocities.

Discussion

We have studied the SAF in central California from the creeping section to the locked section. The creeping section, NW of Parkfield does not store elastic energy and has accounted for all of the slip budgeted by the long term slip rate. Although the creeping section experiences thousands of earthquakes over a 20 year period, these earthquakes, which equivalently cover the entire fault plane, do not contribute to the slip rate on the fault plane. The Parkfield segment of the SAF behaves differently. At Parkfield elastic energy is stored, in the form of a slip deficit relative to the budgeted slip, at least over a 20 year period. Most of the energy is then released in M6 events. Since 1857 five M6 events (in 1881, 1901, 1922, 1934, 1966) have apparently ruptured the Parkfield section of the SAF, and have not continued into the currently 'locked' section to the SE [Bakun and McEvilly, 1984]. These five 'characteristic' Parkfield earthquakes all supposedly had similar magnitude and ruptured the same area unilaterally from the NW to the SE. [Bakun and McEvilly, 1984]. Toppozada [1985] has questioned the accuracy of the location of the earliest events and the completeness of the catalog. It is not the intent of this paper to resolve such an issue. Assuming that the sequence of M6 earthquakes did occur on the Parkfield segment, they may not have released all of the stored elastic energy. Sieh [1978] proposed that the great (M8) earthquake of 1857 started with an event in Parkfield, then ruptured about 350 km of the fault to the SE. According to Sieh [1978], the fault slipped about 4 m over the 30 km long section from Cholame to Bitterwater Valley (BV), then increased to about 9 m of slip at Wallace Creek (70 km SE of Cholame, Figure 1). We propose that the next Parkfield earthquake could be much larger than the predicted M6 event, when it releases the entire slip deficit accumulated at Parkfield and triggers faulting on the 30 km long SE segment that last slipped 4 m in 1857.

To examine the potential for a larger (M7) Parkfield earthquake, we have considered the slip budget, which is the deep slip rate of the SAF for Parkfield and for the currently 'locked' section SE of Cholame, the coseismic slip of six M6 Parkfield earthquakes plus interseismic slip, the 1857 slip for the 30 km section SE of Cholame, and, the interseismic slip rate for the 30 km segment.

The slip budget is based on a relative plate velocity of 30 mm/yr. This is a conservative estimate considering the evidence for 33 mm/yr or faster [Sieh and Jahns, 1984, King et al., 1987]. In Table II we add the coseismic and interseismic slip contributions at Parkfield and compare this sum with 3.9 m of slip that would have been accumulated by a plate rate of 30 mm/yr since 1857. Segall and Harris's [1987] preferred geodetic models for the 1966 coseismic slip and 1966-1986 interseismic slip rate gave an average slip over the fault plane of 0.34 m (a maximum value) for 1966 and an average interseismic slip rate of 8.0 mm/yr (11.0 mm/yr maximum) since 1966. Using the 1966 earthquake as a 'characteristic' event, the total coseismic slip released since 1857 has been 1.7 m. Assuming that the current interseismic slip rate on the fault plane has been constant since 1857, the interseismic slip has contributed an additional 1.05 m. The equivalent seismic calculations using 0.43 m per characteristic event give a total slip of 2.15 m, since there has been a negligible interseismic seismicity contribution. With a slip budget of 3.9 m and actual slip of 2.7 m since 1857 the Parkfield section of the SAF now lags the slip budget by at least 1.2 m. This deficit will not be made up with one more (a sixth) 'characteristic' M6 earthquake, and, the case is worse if either the seismic event slip estimate is used or the deep slip rate is faster than 30 mm/yr.

Sieh [1978] estimated about 4 m of slip for the 1857 rupture between Cholame and Bitterwater Valley. Lienkaemper [1987] estimated 6±2 m of slip. South of BV, the slip increased up to 9 m at Wallace Creek [Sieh, 1978]. We do not expect the fault SE of BV to rupture in the next few Parkfield earthquakes, since a deficit equal to the slip released in 1857 has not been accumulated, however, it does appear that 30 km of the locked section SE of Cholame has accumulated the critical slip deficit.

The interseismic slip rate SE of Cholame is the least well controlled parameter. Previous geophysical studies [Burford and Harsh, 1980] showed that the surface is not slipping, but did not give depth information. Our results are among the first to show that the SAF SE of Cholame is locked at depth. This implies that the slip deficit is at least 3.9 m, which is within the lower bounds of slip released in 1857, for the 30 km of the 'locked' zone. Using the logic that once a segment of the fault lags the deep slip by the amount of slip released in the previous earthquake, it can rupture again, then the 30 km SE of Cholame is apparently ready to rupture. We conclude that the next Parkfield earthquake could be significantly larger than the M6 expected. Because the segment SE of Cholame has only now accumulated the critical slip deficit, the current situation is different from any previous time that the Parkfield segment has ruptured.

The seismic moment of an earthquake which ruptures both the 30 km long Parkfield section (average slip 1.2 m) and the 30 km section SE of Cholame (average slip 3.9 m) is 7.0×10^{21} nt-m; a moment-magnitude M7.2 earthquake.

Table II. Parkfield Slip Deficit (m) based on Plate Velocity of 30 mm/yr

Slip (m)	Seismic	Geodetic
1966 Coseismic	0.43	0.34 (0.34)
5 Events Coseismic	2.15	1.69
Since 1857 Interseismic	0.00	1.05 (1.44)
Since 1857 Total Available	3.93 (4.32)*	3.93 (4.32)*
Since 1857 Slip Deficit	1.78 (2.17)*	1.19 (1.58)*

Values in parentheses are maximum values
*Based on plate velocity of 33 mm/yr

We are now in a much different situation than we were in in 1966 when the SAF SE of Cholame did not yet lag the slip budget by 4 m. Now there is the potential for a **M7** earthquake.

Conclusions

The creeping segment of the SAF in central California is well delineated by earthquakes, but this seismicity does not contribute to the overall slip on the fault plane. The Parkfield 'transitional' segment has accumulated a slip deficit of about 1.2 m since 1857 even though moderate earthquakes have occurred. The 30 km long section SE of Cholame is locked to a depth of at least 15 km and has now accumulated at least 3.9 m of slip deficit, which is within the estimates of the slip released in 1857 on this section. As a consequence faulting on this segment could be triggered by faulting during the next Parkfield earthquake. Should the next Parkfield earthquake release all of the accumulated slip deficit in the Parkfield region and the slip deficit in the 30 km section SE of Cholame, the earthquake would be a M7.2 event.

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