

A DISCREPANCY BETWEEN LONG- AND SHORT-PERIOD MECHANISMS OF EARTHQUAKES
NEAR THE LONG VALLEY CALDERA

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Abstract. The largest events in the 1980 Mammoth Lakes earthquake sequence show a discrepancy between fault mechanisms which are determined on the basis of the local short-period first motions and those determined by modeling of long-period regional and teleseismic waveforms. The short-period solutions are left-lateral strike-slip on north-striking, near vertical planes. The long-periods invariably require a much more moderately dipping fault plane with a significant dip-slip (normal) component. Persistence of disagreements between short- and long-period polarities to teleseismic distances suggests that the source-time functions are complicated and may be responsible for at least part of the discrepancy. In addition, there seems to be a systematic difference between local short-period polarities and teleseismic long-period polarities that is related to travel paths across portions of Long Valley Caldera. It is possible that a low velocity zone related to recent magmatic activity is causing the deflection of local seismic rays, thus distorting the fault plane projection.

Introduction

The 1980 Mammoth Lakes earthquake sequence represents one of the largest seismic strain release episodes in California since the 1971 San Fernando earthquake. During a 48 hour period which began on May 25, there were four events with $M_L > 6$. Aftershock activity continued for over one year, with a large ($M_L = 5.8$) event occurring on September 30, 1981. The strain release of this sequence is complicated. Although the earthquake epicenters straddle a fault system that shows spectacular surface expression of Holocene normal faulting, investigators who have determined the fault mechanisms of the largest shocks on the basis of local short-period first motions suggest that the faulting was pure strike-slip on north-south, steeply-dipping planes (Cramer and Topozada, 1980; Ryall and Ryall 1981a). This contrasts sharply with the modeling of long-period teleseismic body and surface waves by Given et al. (1982), which indicates an oblique-slip mechanism on moderately dipping ($\sim 45^\circ$) north-south planes. Here we investigate this apparent discrepancy between mechanisms determined by the analysis of long- and short-period waveforms.

The general geography of the Mammoth Lakes area is shown in Figure 1. The dominant geologic feature is the Long Valley Caldera which was formed by a violent volcanic eruption 0.7 my ago; active volcanism may have taken place as recently as 450 y ago (Bailey et al., 1976). The position of Long Valley Caldera coincides with a major westward step of the frontal fault system of the eastern front of the Sierra Nevada. The most important fault in the epicentral region is the Hilton Creek fault, which Bailey et al. (1976) estimate to have undergone several hundred meters of pure normal fault displacement since the formation of the Caldera. Also shown in Figure 1 are the epicenters of the events studied in this note. They are the three largest of the events in the 1980 main shock sequence (events B, C and

D in Figure 1), two large aftershocks (E and F), and the 1978 Bishop earthquake (A). A direct association between the Hilton Creek Fault and the 1980 sequence is unlikely; first, the hypocenters are 8 km west of the projected Hilton Creek Fault plane at depth and secondly, the long-period fault mechanisms of Given et al. (1982) are inconsistent with the fault trend. Although the Bishop earthquake is well removed from the Mammoth Lakes events it is interesting because it marks the beginning of an increase of seismicity in the region and it also shows the "frequency dependent" fault mechanism.

Comparison Between the Long- and Short-Period Mechanisms

The primary analysis is simply a comparison of focal mechanisms determined on the basis of local P-wave first motions with those determined by the modeling of the long-period body and surface waves. The short-period mechanisms were taken from work by Ryall and Ryall (1981a) and Cramer and Topozada (1980). The combination of the University of Nevada's local array, CDMG's (California Division of Mines and Geology) local stations and the USGS southern and central California arrays provides fairly dense coverage of the focal sphere for the larger events. The arrivals are fairly clean and impulsive even at Pn distances.

Long-period waveform modeling provides a much more robust method of determining the overall or "average" source parameters of an earthquake than analyzing the distribution and polarities of short-period P and S-wave first motions. Unfortunately, the earthquake must be fairly large to produce usable long-period records at teleseismic distances. The first event (event B) in the 1980 sequence produced very good surface waves on the global digital seismograph network (IDA and GDSN) and usable body waves on the WSSN network. This combination allowed us to perform a source parameter inversion at periods of up to 200 seconds. The proximity of the second and third events in the 1980 sequence (events C and D) to the first event allowed us to do a relative waveform inversion of the surface waves (see Given et al., 1982). The remaining three events (A, E and F) were too small for surface wave analysis, but they produced clear long-period Pn and PL records at regional distances (3° to 12°). The portion of the seismogram containing Pn and PL, referred to as P_{nl} , is relatively insensitive to fine crustal structure in the pass-band of a long-period WSSN instrument. Because the gross crustal structure of the western U.S. is known, the P_{nl} wavetrain can be inverted for the source orientation (see Wallace et al., 1981). This procedure was used to determine the source parameters of these last three events.

Figure 2 shows a comparison of the short and long-period mechanisms for the three largest events in the 1980 sequence and the Bishop event. For the first event in the sequence both the long and short-period first motions are shown in detail. Also in this case the nodal planes determined from the long-period waves are superimposed on the short-period data. The largest discrepancy between the long and short-period polarities is in the northeast quadrant. Although the series of stations due south of the epicenter are also mismatched with the long-period mechanism, the travel path is along the axis of the Sierra Nevada and it is possible that the earth velocity model used to determine the take-off

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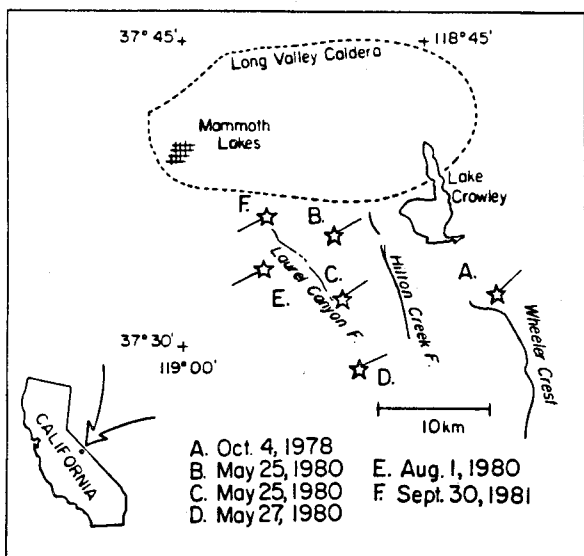


Fig. 1. Location map of Long Valley Caldera region. The stars denote the epicenters of the events in this report. The lines from each star point in the direction of the T axis determined from the long period focal mechanism.

angles is inadequate. This would allow the first motion data points to move in or out on the focal sphere and therefore they are not grossly inconsistent. Also, note that the short-period mechanism also disagrees with this series of arrivals. If the north-south plane is picked for the fault, there are two main differences in the mechanisms: (1) the long-period mechanism is much more moderately dipping, and (2) it requires a significant component of dip-slip (normal) fault motion. The same applies to the other two events in the mainshock sequence. In the case of the Bishop earthquake the inconsistency between the long and short-period mechanisms is in the northwest quadrant. If the east-west plane is chosen for the fault, then the only significant difference between mechanisms is the large dip-slip component at long-periods.

Figure 3 shows a comparison of the PnL data for the Bishop earthquake with synthetics calculated for the long-period (solid nodal lines on the focal sphere) and short-period (dashed nodal line) fault mechanisms. The oblique-slip mechanism fits better at all azimuths, especially in the northwest quadrant. COR, LON and MSO would have the wrong polarity for the strike-slip model.

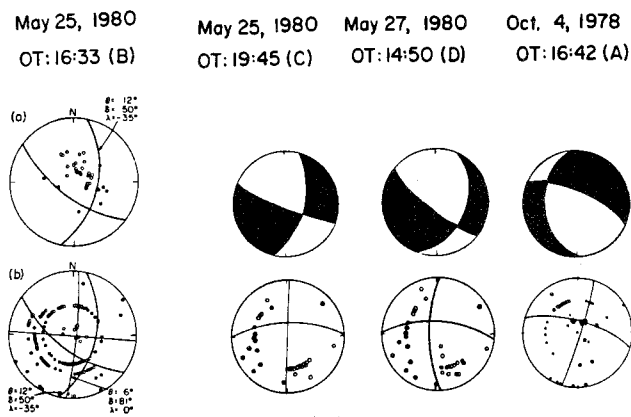


Fig. 2. A comparison between the long period mechanisms (top row) and short period first motion mechanisms (bottom row). For event B the long period arrivals are shown on the top focal sphere. Both the long and short period nodal lines are shown on the short period first motions for event B. The short period mechanism for C and D are taken from Cramer and Topozada (1980), and A is taken from Ryall and Ryall (1981a).

The numbers to the right of each synthetic give the ratio of moment determined from that station to the average moment. The stability of this ratio can be used as a measure of the correctness of the fault mechanism. The order of magnitude larger scatter in the ratios for the strike-slip model compared to the oblique-slip model further supports the long-period mechanism.

Local short-period first motion solutions have not been published for the two aftershocks (events E and F) which we have also investigated. Although these events have substantially smaller moments (5 to 10 times smaller) than the main shocks, they also exhibit the moderately dipping oblique faulting. This suggests that these aftershocks are the result of the same stress regime which caused the main shock sequence, and the discrepancy between long and short-period fault mechanisms probably continues at least to these smaller moments. Table 1 summarizes the source parameters which have been determined in this study. All six of the events in the caldera area have very consistent P and T axes. The T axes are shown in Figure 1. It is interesting to note that the T axes which would be determined from the short-period solutions are not grossly different from those in Table 1. On the other hand, the substantial plunge of the P axes is indicative of a dip-slip component of motion.

The mechanism of an additional earthquake was determined by the inversion of PnL data. This event occurred in Huntoon Valley, about 60 km northeast of the Mammoth Lake epicenters. It was included in this analysis since it was close enough to Long Valley to test the hypothesis that some sort of regional distortion of the long-period waveforms is present, and at the same time it is far enough away to be free of the near source structural complications. The fault mechanism which was determined is essentially pure strike-slip on steeply dipping planes, which is in agreement with the local dipping short-period first motion mechanism (U. Vetter, personal communication 1982). This strongly suggests that differences in short- and long-period mechanisms is a phenomenon localized to the region around Long Valley. Note the clockwise rotation of the P and T axes of the Huntoon Valley event relative to the Mammoth Lakes events (Table 1).

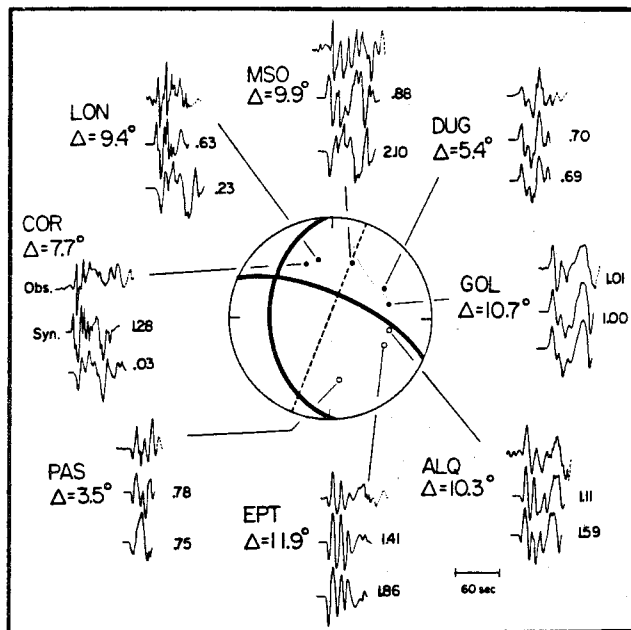


Fig. 3. A comparison between observed (top trace at each station) waveforms for event A and synthetics calculated for the oblique-slip (middle trace) and strike-slip (bottom trace) models. The solid nodal lines give the oblique solution, while the dashed are for the strike-slip. The numbers to the right of each synthetic give the ratio of the moment determined at that station to the average moment.

Table 1: Source Parameters

Event	Date	OT	Lat	Long	Depth	Moment	Θ	δ	λ^\dagger	P		T	
										ϕ	γ	ϕ	γ
A Bishop	10/4/78	16:42	37.493	118.673	8.0	5.7×10^{24}	290°	70°	235°	-21°	51°	45°	18°
B Mammoth Lakes #1	5/25/80	16:33	37.609	118.846	9.0	2.9×10^{25}	12°	50°	-30°	165°	46°	64°	11°
C Mammoth Lakes #2	5/25/80	19:45	37.562	118.838	15.3	1.3×10^{25}	15°	50°	-10°	161°	34°	57°	21°
D Mammoth Lakes #3	5/27/80	14:50	37.506	118.826	14.2	1.1×10^{25}	22°	42°	-19°	178°	43°	66°	22°
E Mammoth Lakes	8/01/80	16:38	37.554	118.896	5.0	1.5×10^{24}	11°	40°	-34°	176°	53°	63°	17°
F Mammoth Lakes	9/30/81	11:53	37.588	118.887	8.0		14°	50°	-28°	166°	45°	64°	12°
Huntoon Valley	9/07/80	04:36	38.048	118.558	5.5	9.6×10^{23}	67°	85°	-15°	-158°	14°	114°	7°

\dagger Θ gives the strike of the fault measured clockwise from the north, δ gives the fault dip. Dip direction is always to the right of the strike direction. λ is the rake; rake is the angle of motion of the hanging wall relative to the foot wall (eg. right lateral strike-slip has a rake of 180 , while pure normal faulting has a rake of -90). P and T are the most and least compressive stress axes respectively. ϕ is the azimuth and γ is the plunge.

Discussion

There are two basic mechanisms that can cause the frequency dependence of the fault parameters in the Long Valley Caldera area demonstrated above; (1) distortion of the radiation pattern by structure and (2) complexity of the source. The simplest structural model would be to have deflection of short-period seismic signals due to a low velocity region within the caldera. Steeples and Iyer (1976) used teleseismic P wave delays to map a volume beneath the caldera in which the average P-velocity is 15 percent lower than that of the surrounding crust. This low velocity zone extends in depth from approximately 5 - 25 km. Hill (1976) reported a series of late arrivals in a refraction experiment across Long Valley which he interpreted as a reflection from a depth of 7 - 8 km. This reflection could represent the roof of a magma body. There is evidence that the magma body is still an active feature. Savage and Clark (1982) present level line data which shows a broad uplift centered over the resurgent dome in the western part of the caldera. This uplift occurred sometime between 1975 and September 1980. Ryall and Ryall (1981b) observed S-wave screening for some of the aftershocks of the 1980 sequence which have travel paths through the caldera. They interpret these observations to indicate a zone of partial melting at depth greater than 8 km. These different observations taken together strongly suggests that there may be a zone of substantially reduced velocity in the caldera. Sassa (1936) observed the deflection of P-waves up to 30° in azimuth for travel paths which crossed the Volcano Aso, Japan. The inconsistent first motions for the event B (see Figure 2, NE quadrant) correlate with travel paths across a segment of the caldera; a low-velocity structure in this part of the caldera would distort the radiation pattern in the observed manner. If we consider recording stations which are at Pn distance and that the low velocity zone distorts both the azimuth and take-off angle we can constrain the size of the velocity contrast which is required to produce the observed effect. It is simplest to assume that the low velocity zone has a very deep root; then the velocity contrast must be on the order of 35 percent. For the Bishop earthquake, the travel paths are again across the same region of the caldera and the velocity contrast which is required is approximately the same. Although a 35 percent velocity contrast is large, (especially compared to Iyers and Steeples' 15 percent) this number is based purely on geometric deflection, and diffraction effects could reduce the necessary velocity contrast.

The data also suggest that source complexity may be a factor in the discrepancy between the short- and long-period mechanisms. This is demonstrated in Figure 4 which compares the long and short-period waveforms for the same station for event B. For both records the first arrivals are well above the noise but show opposite polarity. The same phenomenon is observed at PNT ($\sim 14^\circ$) and FRB ($\sim 39^\circ$). These stations have azimuths which are approximately due north of the epicenters. Since the effect of deflection due to a near source velocity anomaly would have relatively little effect on teleseismic signals, these observations suggest complexity in the source-time function. Comparison of the arrival times between instruments indicates that the short-periods may arrive a fraction of a second earlier than the long-periods but this probably is not significant. The reversal of polarity is also observed

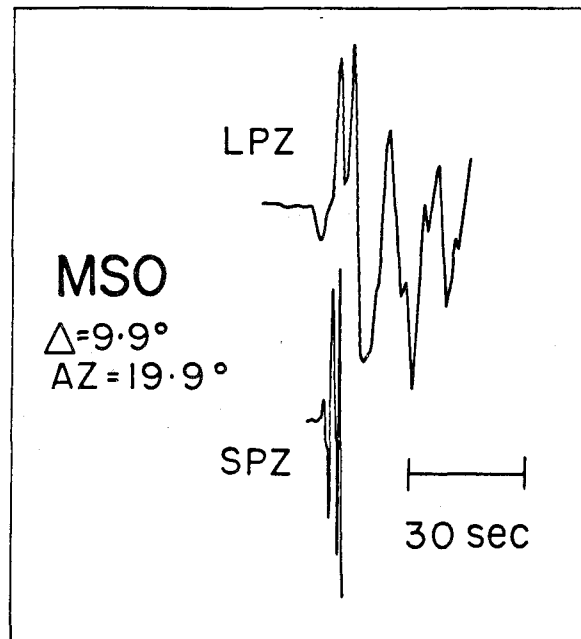


Fig. 4. A comparison of the long and short period P arrivals at MSO for event B.

for the third event in the 1980 sequence (event D) but it is not nearly as clear (the short-period arrival is much smaller).

For an arrival to show up clearly on the short - periods but be completely absent from the long-periods, a complicated time function would be required. The initial short-period waveform represents a very rapid rise time, or a small, high stress-drop event. The cleanness of the long-period dilatational arrival puts a bound on the seismic moment of this small event; it is probably less than 1×10^{24} dyne-cm. The long-period waveforms are the response of the overall faulting episode. In other words, the short-period episodes may represent failure of an asperity (strong patch on the fault) which, when broken, allows the regional strain to be relieved with the mechanism determined from the long-period data.

Although this type of source complexity seems plausible for a single event, it would be difficult to explain the frequency dependence of all the events with the same process. Obviously the difference in polarity at teleseismic distances requires the short-period event to have a different faulting mechanism. Whether this fault mechanism is the vertical strike-slip fault as indicated by the local short-period mechanism depends on the effect of the local structure on these fault plane solutions as discussed previously. If one chooses to minimize the distortion due to structure and suggests that the short-period mechanism represents the breaking of a small asperity then the repeatability of the process must be explained. Savage and Clark (1982) have shown that magma injection beneath the resurgent dome (at the western end of Long Valley) would give rise to a stress-system which has a maximum shear-stress on north-south planes, consistent with left-lateral strike-slip faulting in the vicinity of the hypocenters. The stress-drops that would be expected for Savage and Clark's point source magma injection model are small; a few bars at most. A similar left-lateral shear on north-south planes would be imposed in the hypocentral region of the Bishop earthquake although the stress-drop would be substantially lower. It is possible to develop a model in which a superposition of the stress field from the magma inflation on the regional stress system allows the possibility of a very sharp, but low seismic moment strike-slip beginning followed by a large scale fault movement along a moderately dipping zone of weakness. Although this is a very complicated model, (and for that reason unappealing) it can account for the source mechanism discrepancy, and would suggest a difference between the small and large earthquakes. A less speculative hypothesis would be to suggest that the stress system in this region has small scale heterogeneity and thus, the short-period source-time functions are complicated. The stress heterogeneity and process of magma emplacement could be related causally, although probably not in a systematic fashion.

Conclusions

Recent earthquakes near the Long Valley Caldera display a significant discrepancy between the long- and short-period faulting mechanisms. The short-period first-motion solutions of the large events require vertical strike-slip faulting, while invariably the

long-periods require oblique slip on more moderately dipping faults. At this time it is not possible to isolate the cause of the fault mechanism discrepancy, although it is apparent that the source-time functions are complex. The fact that this discrepancy has occurred over a period of time (since the 1978 Bishop earthquakes) suggests that at least part of the discrepancy may be related to structure. Local short - period arrivals which travel through portions of the caldera north of the epicenters could be systematically deflected. Both a low velocity zone and stress heterogeneity are consistent with other evidence for the recent injection of magma. In such a region as Long Valley, great care must be taken when interpreting short-period fault mechanisms in terms of tectonic significance. The T-axes which are determined from the short-period mechanisms are consistent with those of the long-period mechanisms (both are roughly consistent with the regional stress-field).

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