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TECTONIC SETTING AND SOURCE PARAMETERS OF THE SEPTEMBER 19, 1985 MICHOACAN, MEXICO EARTHQUAKE

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Abstract. Analysis of body waves and long-period surface waves from the September 1985 earthquake in coastal Michoacan, Mexico shows that the event was an interplate subduction event with a low dip angle fault plane (δ=9°) striking parallel to the Mid-America trench (φ=288°) and a small component of left lateral motion (λ=72°) with a point source depth of 17 km, and a seismic moment in excess of 1 x 10^{28} dyn cm. The earthquake was a multiple event, with a second source of identical moment, fault geometry, and depth occurring approximately 26 s after the first. Directivity in the body wave time function indicates that the second event occurred roughly 100 km to the southeast of the first. This suggests that the earthquake first broke the northern portion of the Michoacan gap, propagated with low moment release through the rupture zone of the 1981 Playa Azul earthquake, and then broke the remaining asperity in the southern section of the gap. The seismic moment determined from Rayleigh and Love waves is between 1.0 - 1.7 x 10^{28} dyn cm (M_W = 7.9 - 8.1), the largest moment determined to date for a Mexico subduction earthquake. Comparison of seismograms at Pasadena with records of other large Mexico events shows that the Michoacan earthquake is basically the same size as the 1932 Jalisco, Mexico earthquake, and clearly larger than other significant events in Mexico since 1932. The seismic moment and the time since the last large earthquake in Michoacan (in 1911) fit an empirical relation between moment and recurrence time found for the Guerrero-Oaxaca region of the subduction zone. The large aftershock on September 21 (M_S=7.5) has the same geometry as the mainshock, a somewhat larger source depth (22 km), a simple time function, and a seismic moment between 2.9 - 4.7 x 10^{27} dyn cm (M_W = 7.6 - 7.7).

Introduction

The September 19, 1985 earthquake in coastal Mexico was the most damaging event to date in that country; it cost over ten thousand lives, left hundreds of thousands homeless, and damaged over 800 buildings in Mexico City. Epicentral parameters from the National Earthquake Information Center (NEIC) in Golden, CO are 18.27°N, 102.31°W, origin time 13h 17m 48.1s UT, depth 33 km (fixed), and M_S=8.1. The event occurred along a part of the Cocos-North American plate boundary identified as the Michoacan seismic gap [Kelleher et al., 1973]. The gap had been quiescent since at least 1911, when a damaging magnitude 7 3/4 event occurred there [Gutenberg and Richter, 1954].

Figure 1 shows the aftershock areas of all shallow thrust events in coastal Mexico since 1950 with M$\geqslant$7. Segments of the plate interface immediately adjacent to the Michoacan gap have experienced recent events at short and regular intervals. To the northwest, the Colima area recently had events in 1941 and 1973 (a 32 yr interval), and to the southeast, the Petatlán area in northern Guerrero had events in 1943 and 1979 (a 36 yr interval). An average recurrence interval for the plate boundary of 33± 8 yrs was found by McNally and Minster [1981], although different sub-segments have somewhat different intervals [Astiz and Kanamori, 1984]. South of the Petatlán zone in the middle of the coast, the area void of recent large earthquake activity is the Guerrero seismic gap. The distance from Mexico City to the Guerrero gap is shorter than to any other region along the Mid-America trench. The last major events located in the Guerrero gap were in 1899 (M ~ 8) and 1907 (M ~ 8) [Astiz and Kanamori, 1984].

The Acapulco earthquake (M_S=7.5) occurred in southern Guerrero in 1957 and damaged hundreds of buildings in Mexico City; however the number of structures experiencing complete collapse was far less than for the September 1985 earthquake. South of Acapulco, the plate interface is fairly well filled in with recent large earthquakes. The largest earthquake prior to 1985 was located near coastal Jalisco in 1932 (M_S=8.1), shown by the dashed region in Figure 1.

In 1981, the Playa Azul earthquake (M_W=7.3) occurred in the center of the Michoacan gap. The epicenter of the September 1985 earthquake was located in the northern segment of the Michoacan gap between the 1973 and 1981 aftershock zones. Figure 1 shows the locations of the one-month aftershocks (locations are preliminary from NEIC and are plotted only for events reporting $\geqslant$ 10 arrival times). The aftershocks generally lie between the limits of the 1973 and 1979 aftershock zones, and there is some indication that there was less aftershock activity within the small zone that slipped in the Playa Azul earthquake. The largest aftershock (M_S=7.5) occurred approximately 36 hours after the mainshock on September 21 in the southern part of the gap between the 1981 and 1979 aftershock zones. Activity appears to terminate at the northern boundary of the 1979 zone; however two fairly large late events occurred *south* of the 1979 zone, on September 28 (m_b=5.0) and October 3 (m_b=4.5), in the northernmost region of the Guerrero gap.

It had been suggested by Singh et al. [1980] that the M=7 3/4 event in 1911, located in the Michoacan area by Gutenberg and Richter [1954], was actually about 200 km further northwest in Jalisco, and that the lack of other large earthquakes in the historical record in the Michoacan area could signify a "permanent" seismic gap. Coincident with the Michoacan gap, the Orozco fracture zone intersects the Mid-America trench for about 150 km. Previous to the September 1985 earthquake, the Michoacan area, with its seismic quiescence and subducting fracture zone, was similar to the southern Oaxaca area, where the Tehuantepec Ridge is subducting, and where there are no large earthquakes in the historic record. One possibility suggested to explain the seismic quiescence in these areas was that features such as the Orozco fracture zone and the Tehuantepec Ridge may be locally affecting the subduction process, such that the area is subducting aseismically, or more slowly than adjacent regions of the plate boundary [Singh et al., 1980; McNally and Minster, 1981; LeFevre and McNally, 1985]. Alterations of subduc-

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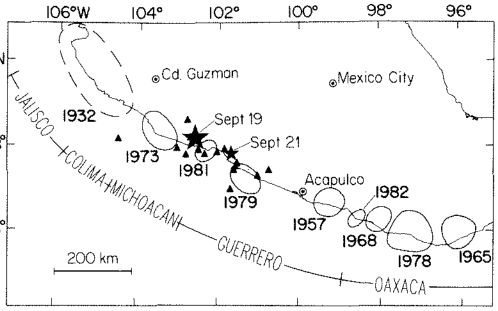

Fig. 1. Map of central Mexico showing the aftershock areas (ellipses) of subduction events since 1950 with M>7. The September 1985 earthquake is plotted as a filled star, and its M_S = 7.5 aftershock as a smaller star. Other symbols are the one-month aftershocks, whose locations are preliminary from NEIC. The dashed region is the aftershock area of the M_S = 8.1 Jalisco event [Singh et al., 1985]. References for other aftershock areas are in Astiz and Kanamori [1984].

tion characteristics are observed in other circum-Pacific regions where areas of topographically anomalous seafloor are subducting [Vogt et al., 1976].

The intensity pattern of the 1911 event was similar to the 1985 Michoacan event, suggesting a similar epicenter. The literature reports that the "center of disturbance" (e.g., deaths, damage to homes, and strong shaking) was near Ciudad Guzman in Jalisco, about 260 km from Gutenberg and Richter's epicenter [Branner, 1912; Figueroa, 1959]. The 1985 event also caused fatalities and structural collapse in Ciudad Guzman. Like the 1985 event, the 1911 event caused deaths in Mexico City; the reported intensity there was VIII, the largest of any earthquake during 1900-1959. For comparison, the intensity in Mexico City from the M_S 8.1 1932 Jalisco event was only V [Figueroa, 1959]. Examination of Gutenberg and Richter's epicenter determination for the 1911 earthquake reveals that data from Mexico (three S-P times and one direct P time) were included in their analysis and support a location offshore northern Michoacan.

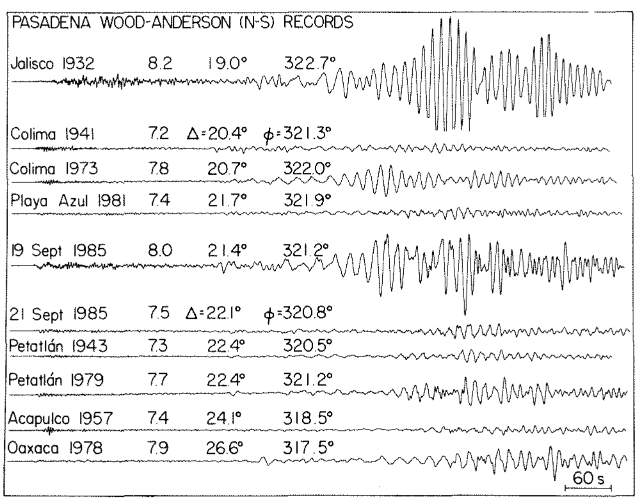

Fig. 2. N-S component records of large thrust events in Mexico from the Wood-Anderson intrument in Pasadena. Events are ordered geographically from northwest (top) to southeast (bottom). Amplitudes are indicative of magnitude since events have similar depths and mechanisms. The September 1985 earthquake is larger than all other events excluding the 1932 Jalisco earthquake. M_S values determined from the surface wave amplitudes are shown.

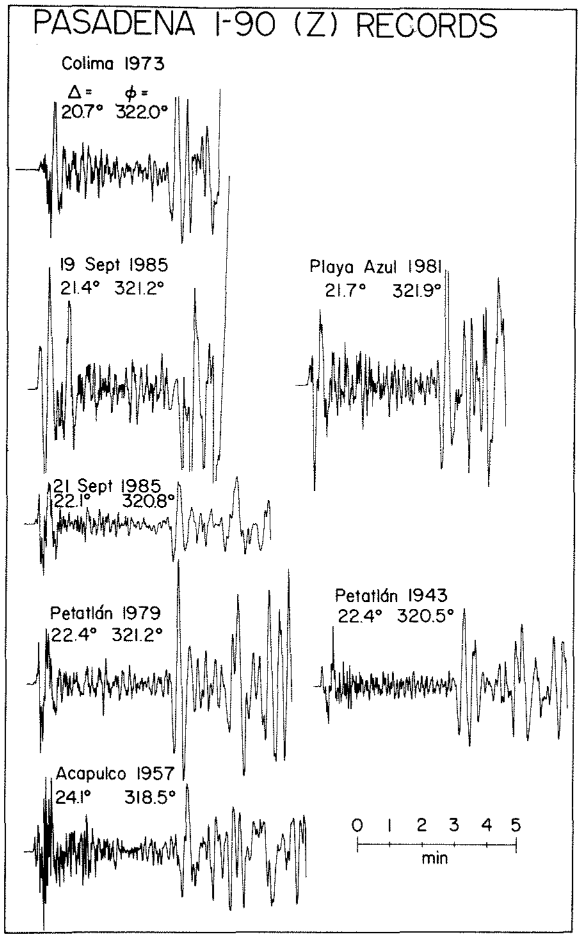

Fig. 3. Records of the same events on a broadband vertical intrument. Waveforms are remarkably similar between events, except for the September 19, 1985 Michoacan record, which shows a second arrival within 1 min of the P wave, indicative of source complexity.

Pasadena Seismograms from Large Mexico Earthquakes

Records from instruments at the Seismological Laboratory in Pasadena, CA from the largest subduction events in Mexico were gathered for comparison in different period bands. Figure 2 shows about 12 minutes of the north-south component of the horizontal Wood-Anderson instrument. Although surface wave amplitudes are affected by the source depth and mechanism, most of these events have similar depths (16-20 km) and mechanisms (reverse faulting on a low angle plane parallel to the trench) [Chael and Stewart, 1982; Singh et al., 1984]. Thus amplitude differences should be indicative of differences in magnitude. Figure 2 shows three basic sizes of events. The 1932 Jalisco earthquake has offscale surface waves, and the 1985 Michoacan earthquake surface waves are nearly as large. The Colima 1973, Petatlán 1979, and Oaxaca 1978 are comparatively sized events. The Colima 1941, Petatlán 1943, Playa Azul 1981, Michoacan September 1985 aftershock, and Acapulco 1957 earthquakes have the smallest amplitudes. The Acapulco earthquake is anomalous in having a large body wave pulse compared to its surface waves. M_S values determined from the Wood-Anderson records are shown in the Figure.

Figure 3 shows records from the broadband vertical Benioff instrument (T_p=1 s, T_g=90 s). This instrument was not installed at the time of the 1932 earthquake. The records show the P wave, S arrival at approximately 4 min, and beginning of the surface wave. The most remarkable feature is the similarity of the waveforms between events, indicating similar source parameters and time functions. The notable exception is the Michoacan mainshock, which shows a late arrival less than 1 min behind the characteristic P waveform, indicative of a complex time function. The Acapulco earthquake has an unusual amount of high frequency, but the overall waveform has the same shape as the other events.

Source Parameters from Body Wave Modeling

P waves from the earthquake recorded globally on long-period vertical instruments can be modeled by a time function of 2 trapezoidal sources of equal duration and moment about 26 s apart at 17 km source depth and an overall thrust geometry on a low angle plane ($\delta=9^{\circ}$, $\varphi=288^{\circ}$, $\lambda=72^{\circ}$). Figure 4 shows observed and calculated waveforms for 11 WWSSN stations and one GEOSCOPE station, as well as the focal mechanism and P wave first motion data. The seismic moment from the body wave modeling is 8.3 x 10^{27} dyn cm. The slip direction of this mechanism is 37°, precisely the local direction of motion of the Cocos plate at the epicentral location calculated from its pole of rotation.

This source depth and mechanism are essentially the same as those of all other large Mexico interplate subduction events studied to date. However, the double source time function is unusual. Body wave modeling has shown that most large Mexico subduction events have simple time functions [Chael and Stewart, 1982]. For the few events that show a complex time function, the dominant moment release still occurs in one simple pulse [Astiz and Kanamori, 1984; Singh et al., 1984]. The exception is the 1932 Jalisco earthquake, which had a second event of equal size approximately 30 s after the first, much like the time function of the Michoacan earthquake [Singh et al., 1984]. Earthquakes with larger seismic moments such as in 1932 and 1985 tend to have larger rupture zones, increasing the chance of breaking through several asperities to create a multiple time function.

The time separation t_0 between the two sources was adjusted with azimuth for the best fit between observed and calculated waveforms. The longest time separation was 31 s for stations in northwest azimuths, and the shortest was 21 s for stations in southeast azimuths. Stations with northeast azimuths and southwest azimuths had intermediate separations of 26 s and 29 s respectively. This systematic pattern indicates that the second source was located southeast of the first. If a fault strike parallel to the trench is assumed, the observed variation in t_0 gives a spatial separation of about 100 km. The scenario is that the earthquake first broke the north part of the Michoacan gap, propagated to the southeast with low moment release through the 1981 rupture zone, and then broke the southern segment of the gap.

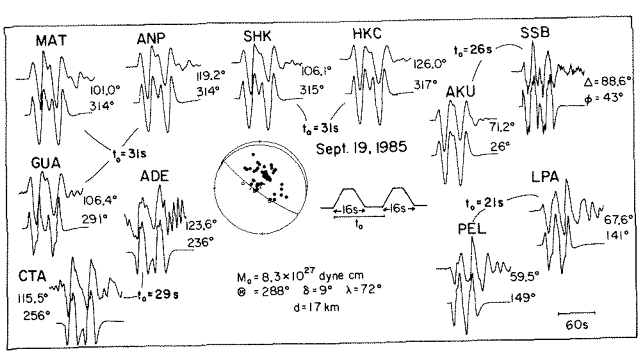

Fig. 4. Observed (above) and calculated waveforms of P waves from long-period WWSSN and one GEOSCOPE stations at teleseismic distances. The observed waveforms are matched with the focal mechanism shown and a point source depth of 17 km, and a two source time function whose time separation t_0 varies systematically with azimuth, indicating source directivity.

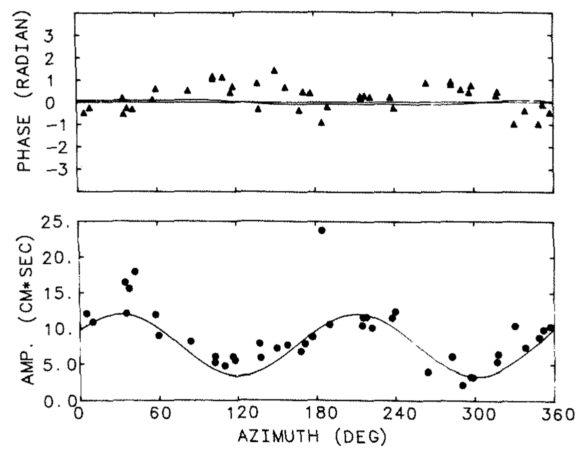

Fig. 5. Observed phase (triangles) and amplitude (circles) spectral values vs. azimuth of Rayleigh wave data compared with the theoretical pattern for the best solution. Spectral values are at 256 s period.

P wave modeling of the aftershock shows a mechanism identical to the mainshock, with a slightly greater source depth (22 km). The aftershock time function is a single trapezoid with duration of 13 s. The seismic moment from the body waves is 1.2 x 10^{27} dyn cm.

Moment Determination from Long-Period Surface Waves

The seismic moment and fault geometry of the earthquake were resolved from amplitude and phase spectral data of multiple Rayleigh and Love wave passages at 256 s, generally following Kanamori and Given [1981]. The moment tensor source representation was not used due to the complication of some moment tensor components being unconstrained at shallow source depths. Instead, the steeply dipping auxiliary plane was held fixed at the orientation from the first motion solution ($\delta_a=81^{\circ}$, $\varphi_a=127^{\circ}$) and the surface wave data was inverted for the best-fitting values of seismic moment M_0 and slip angle λ_a, using excitation functions for a source depth of 16 km. A data set of 42 Rayleigh wave phases (R_2 through R_4, with 26 phases from the IDA network and 16 phases from GDSN) with a good azimuthal coverage returned a solution with $\lambda_a=91.9^{\circ}$ and $M_0=1.7$ x 10^{28} dyn cm. The parameters for the fault plane are then $\delta=9.2^{\circ}$, $\varphi=295^{\circ}$, and $\lambda=78^{\circ}$. Figure 5 shows the fit between the observed and calculated Rayleigh wave radiation pattern. When 10 Love wave phases were included, the solution was virtually identical ($\lambda_a=92.2^{\circ}$, $M_0=1.6$ x 10^{28} dyn cm). The source process time τ was about 100 s. Inversion of 26 Rayleigh wave phases from the IDA network for the September 21 aftershock, again with the steep plane fixed, returned the same geometry ($\lambda_a=92.9^{\circ}$, or $\delta=9.5^{\circ}$, $\varphi=289^{\circ}$, $\lambda=73^{\circ}$ for the fault plane), a seismic moment of 4.7 x 10^{27} dyn cm, and τ about 60 s.

The constraint on the fixed auxiliary plane forces the inversion to return a very shallow dip (9°) for the fault plane. Although this agrees with the dip determined from body wave modeling, the fault plane representative of the overall moment release may have a somewhat greater dip. For shallow events, the seismic moment from the surface wave inversion depends on the dip angle assumed as $M_{0_{(1)}}/M_{0_{(2)}}=\sin2\delta_{(2)}/\sin2\delta_{(1)}$ [Kanamori and Given, 1982]. Thus for a dip of 15° instead of 9° the moment is smaller by about a factor of 2. In our judgement 15° is a maximum value for dip, and the moment range for the mainshock is 1.1 - 1.7 x 10^{28} dyn cm (M_W = 7.9 - 8.1). For the aftershock, the moment range is 2.9 - 4.7 x 10^{27} dyn cm, or M_W = 7.6 - 7.7.

Relation Between Recurrence Time and Seismic Moment

Astiz and Kanamori [1984] noted an empirical relation between the average seismic moment per region and the average recurrence time per region for large earthquakes in the Mexico subduction zone:

$$\log T = 1/3 \log M_0 - 7.5, \qquad (1)$$

where T is in years and M_0 in dyn cm. Using 1911 as the last event date in the Michoacan gap, their relation predicts a seismic moment of 1.3 x 10^{28} dyn cm for an event in 1985, which is within the moment range found for the Michoacan earthquake. Astiz and Kanamori based their relation on activity in the Guerrero-Oaxaca region of the subduction zone, and noted that it did not hold north of the Michoacan gap; we can now tentatively extend it into the Michoacan area. Equation (1) implies that an impending event in the Guerrero gap would have a large seismic moment ($\approx 10^{28}$ dyn cm). For the purposes of the $T-M_0$ relation, one single M_W=8.0 event would be equivalent to two M_W=7.8 events occurring, say, months apart; however, these two cases may have very different outcomes in terms of damage.

Conclusions

The seismic moment of the 1985 Michoacan earthquake is between 1.1 - 1.7 x 10^{28} dyn cm (M_W = 7.9 - 8.1). Thus the event is comparable with the largest previous event in the Mexico historic record, the 1932 M_S 8.1 Jalisco earthquake.

The seismic moment of the aftershock is 2.9 - 4.7 x 10^{27} dyn cm (M_W = 7.6-7.7).

Source parameters from body wave modeling are fault dip, 9°; fault strike, 288°; slip angle, 72°; and source depth, 17 km, essentially the same mechanism and depth as other interplate subduction events in Mexico.

The earthquake had a complex time function consisting of two equal pulses with the second source approximately 26 s after the first. The second source was resolved to be about 100 km southeast of the first from observed directivity in the body waves. The two-source time function plus the aftershock distribution imply that the earthquake broke the two remaining asperities in the Michoacan gap to the north and south of the 1981 Playa Azul rupture zone.

The longer source duration may have been a factor in the severe damage in Mexico City. Residents of Mexico City told us that while they had felt comparatively strong earthquakes in the past 40 years, the Michoacan event was notable in its unusual length of shaking.

The seismic moment of the event is consistent with an empirical relation between moment and recurrence time for the Mexico subduction zone. The relation implies that an earthquake in the Guerrero gap could have a similar seismic moment (~ 10^{28} dyn cm). Alternatively, the Guerrero gap could break in a series of smaller events within a few years of each other and still be in accord with the empirical relation.

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