Source areas of the Acapulco-San Marcos, Mexico earthquakes of 1962 (M 7.1; 7.0) and 1957 (M 7.7), as constrained by tsunami and uplift records

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Abstract. A reliable location of the rupture areas for the earthquake doublet of 1962 (11 May, M 7.1; 19 May, M 7.0) and the earthquake of 1957 (M 7.8), which occurred in the Acapulco-San Marcos region, is essential for the assessment of the width and location of the strongly coupled patch along the plate interface and for the evaluation of possible rupture scenarios of future earthquakes in the Guerrero seismic gap. We analyze tsunamis recorded by tide gauges at Acapulco and Salina Cruz. A re-examination of the Acapulco record shows permanent uplifts of 15 ± 3 cm and 7 ± 3 cm during the 11 May and 19 May 1962 earthquakes, respectively. No detectable permanent uplift was found for the 28 July 1957 event. To model the tsunami records we select appropriate focal mechanisms, initial rupture dimensions (L and W), and average dislocations on the fault. By trial and error, we optimize the dimension and location of the rupture area so that the synthetic tsunami fits the residual tsunami waveform. In the case of the 1962 events, the predicted uplift is fitted to the observed uplift. The surface projection of the rupture areas of the 11 and 19 May 1962 earthquakes mostly lies onshore, NW and SE from Acapulco, respectively. The estimated uncertainty in the rupture length and its offshore extension is about 5 km. For the 1957 earthquake we model the tsunami at Acapulco as well as at Salina Cruz. The results suggest that the NW limit of the 1957 rupture area was 30($\pm$5) km SE of Acapulco and L = 90($\pm$20) km. The offshore extension of the rupture was less than $\sim$10 km.

1. Introduction

The Guerrero seismic gap extends from about 99.0°W to 101.2°W. It may be divided in two segments: the NW segment (henceforth called the NW Guerrero gap) extending from ~100°W to 101.2°W, and the SE segment, from 99.0°W to 100.0°W (henceforth denoted as the SE Guerrero gap), roughly coinciding with the presumed rupture lengths of the 28 July 1957 (M = 7.8[3]) and the 15 April 1907 (M = 7.7) earthquakes. The last sequence of large/great thrust earthquakes, which probably ruptured the entire Guerrero gap, occurred in 1899 (M = 7.9), 1907 (M = 8.0), 1908 (M = 7.5, 7.2), 1909 (M = 7.6, 7.0) and 1911 (M = 7.6) (see, e.g., Singh *et al.*, 1982; Anderson *et al.*, 1989; Singh and Mortera, 1991; Kostoglodov and Ponce, 1994; Anderson *et al.*, 1994). Since the 1957 earthquake, only two events with M $\geq$ 7.0 have occurred in the Guerrero gap, both in 1962 (11 May, M = 7.1; 19 May, M = 7.0). These events were located near the border between the NW and the SE Guerrero gaps, close to Acapulco. The size of the 1962

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[3]Magnitude M has been computed from M_o using the formula: M = (2/3) log M_o–10.67. M_o for events before 1963 has been taken from Anderson *et al.* (1989), unless specified otherwise.

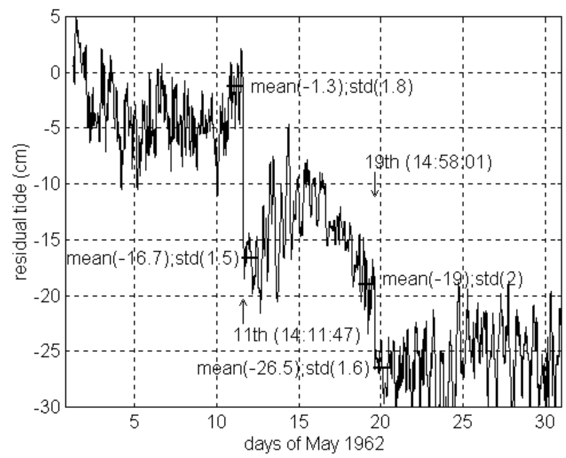

Figure 1: May 1962 residual tide in Acapulco. Arrows indicate the origin time (GMT) of the 11 and 19 May 1962 earthquakes. The length of horizontal dashes indicates the time over which mean values were obtained. Mean sea level values and standard deviations are given for each horizontal line.

events (seismic moment $M_o < 1 \times 10^{27}$ dyne cm) was too small to fill the Guerrero gap (Anderson *et al.*, 1994).

If the average recurrence time for large, subduction earthquakes in Guerrero is of the order of 60–70 yr (Nishenko and Singh, 1987a), then both segments of the Guerrero gap should be in late ultimate mature stages. This fact emphasizes the importance of estimating the size and the location of the future events in the region. An investigation of the rupture areas of previous earthquakes may provide possible clues to assessing the width of the strongly coupled plate interface and, therefore, probable sizes, areas, and location of future events. Unfortunately, due to poor distribution of regional seismic stations, the rupture areas of the doublet of 1962 and the 1957 event cannot be accurately mapped from seismic data alone. Thus, Merino y Coronado *et al.* (1962) located the epicenters of the 1962 doublet offshore, close to the Middle America trench, while Cruz and Wyss (1983) reported an inland location. Nishenko and Singh (1987b), and Gonzalez-Ruiz and McNally (1988) have analyzed the aftershocks of the 1957 earthquake, yet the rupture extent of this event still remains uncertain due to poor quality of the data.

In some cases, tsunamis and coseismic sea level changes recorded by tide gauges can be used to appraise the location and rupture dimensions of large subduction earthquakes (see, e.g., Ortiz *et al.*, 1998). In this study, we obtain new constraints on the locations and rupture dimensions of the earthquake doublet of 1962 and the 1957 event, based on a detailed analysis of the tide gauge data at Acapulco and Salina Cruz.

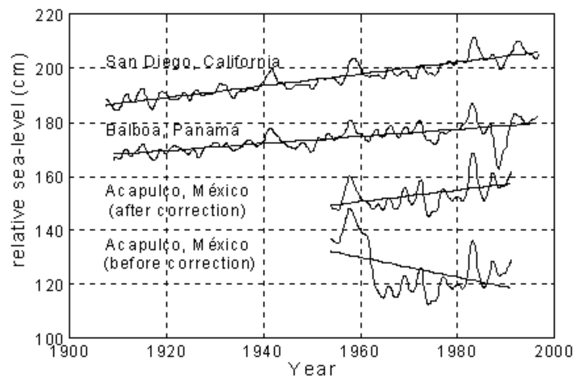

Figure 2: Yearly mean sea level and linear trend computed from the tide record at Acapulco before and after the correction of the shift in the reference level caused by the doublet of 1962. The yearly mean sea level and linear trend from San Diego, California and Balboa, Panama are shown for comparison.

2. Uplift During May 1962 and Long-Term (1952–1975) Sea Level in Acapulco

The vertical uplift of the sea floor at the tide gauge located in Acapulco associated with the 11 May and 19 May 1962 earthquakes as estimated from the daily mean sea level data is 22.7 cm (Grivel, 1967). This uplift was referred to the mean sea level during the periods 1952–1960 and 1963–1966. An uplift estimated by Cruz and Wyss (1983) based on the mean sea level of 10 years before and 10 years after 1962 amounted to 22 cm. It is useful, however, to separate the uplift for each of the earthquakes from the total uplift. An analysis of the residual tide shows a permanent uplift of 15 ± 3 cm and 7 ± 3 cm during the 11 May and 19 May earthquakes, respectively. Figure 1 illustrates the residual tide obtained by subtracting the predicted tide from the observations. The uplifts are obtained from the difference of the mean-residual tide computed 24 hours before and after the earthquakes. The uncertainty is one standard deviation, corresponding to the sum of the variances of the mean before and after the earthquakes. Note that the individual uplift values of 9 cm and 8 cm during the 11 and 19 May 1962 events, respectively, reported by Cruz and Wyss (1983), is less accurate than the values estimated here. No detectable permanent uplift was found for the 28 July 1957 event.

Godin *et al.* (1980) reported a negative long-term sea level trend (∼–1 cm/yr) from the analysis of the Acapulco tide record (1952–1975) and attributed it to a regional tectonic uplift. However, if the shift in the reference level that occurred on 11 May (+15 cm) and 19 May (+7 cm) is taken into account then the resulting trend is positive (∼0.2 cm/yr) and comparable to the trends in the tide records of San Diego, California (0.2 cm/yr) and Balboa, Panama (0.13 cm/yr). The present day average global rate of sea level rise is of the same order, 0.1 cm/yr (Wyrtki, 1990). Figure 2 illustrates

Table 1: Source parameters of the earthquakes of 1962 and 1957 used in modeling of tsunamis.

Event	Depth[a] km	M_o 10^{27} dyne cm	M	L km	W km	Slip[b] (Δu) cm
11 May 1962	12	0.45	7.1	40	35	65(65)
19 May 1962	20	0.32	7.0	35	35	50(30)
28 July 1957	20	5.13	7.8	90	70	165(200)

[a]Depth from the analysis of Uppsala, DeBilt (from Singh *et al.*, 1984), and/or Stuttgart seismograms.

[b]Slip outside the parenthesis is computed from the relation: $M_o = \mu L W \Delta u$ with $\mu = 5 \times 10^{11}$ dyne/cm^2. The value in the parenthesis is the required slip to model the tsunami and the permanent uplift.

the trend and the yearly mean sea level at Acapulco before and after the correction of the reference level.

3. Estimation of the Rupture Areas of the May 1962 and July 1957 Earthquakes by Numerical Modeling of the Tsunami

The source parameters of the earthquakes are listed in Table 1. We estimated the seismic moments of the 1962 events by comparing surface waves of these earthquakes recorded on Galitzin seismograms at DeBilt with that of the 25 April 1989 earthquake. The 1989 earthquake, whose moment is 2.4×10^{26} dyne cm (Harvard CMT catalog), was located in the nearby region of San Marcos. The estimated M_o values of the 1962 earthquakes are listed in Table 1. The seismic moment of 5.13×10^{27} dyne cm for the 1957 event is taken from Anderson *et al.* (1989). As the first approximation, we estimated the rupture areas, A, from the relation $M = \log A + 4.0$ (Utsu and Seki, 1954; Wyss, 1979; Singh *et al.*, 1980) where A is in km^2. We assumed a common focal mechanism, strike = 296°, dip = 25°, rake = 90°, for all three events. This mechanism is reasonable for thrust events in the region. The rupture areas of the earthquakes are shown in Fig. 3. Although the depths of the three earthquakes, listed in Table 1, differ, we have taken the shallow edge of faults to be located at a fixed depth of 12 km, and oriented parallel to the trench. Thus we are assuming that the geometry of the Benioff zone does not change in the region and that the seismogenic zone begins at a depth of 12 km. The depths of the earthquakes, listed in Table 1, correspond to the area of high seismic energy release. However, slip in each case is assumed to extend up to a constant depth of 12 km. Note that Table 1 also gives the average slip, Δu, required to explain tsunami and, in the case of the 1962 events, uplift data. For the 19 May earthquake, this slip is relatively small (30 cm) as compared to the computed slip from fault area and seismic moment (50 cm). One possible reason for this difference is smaller average slip on the upper part of the fault, which agrees with greater depth of the

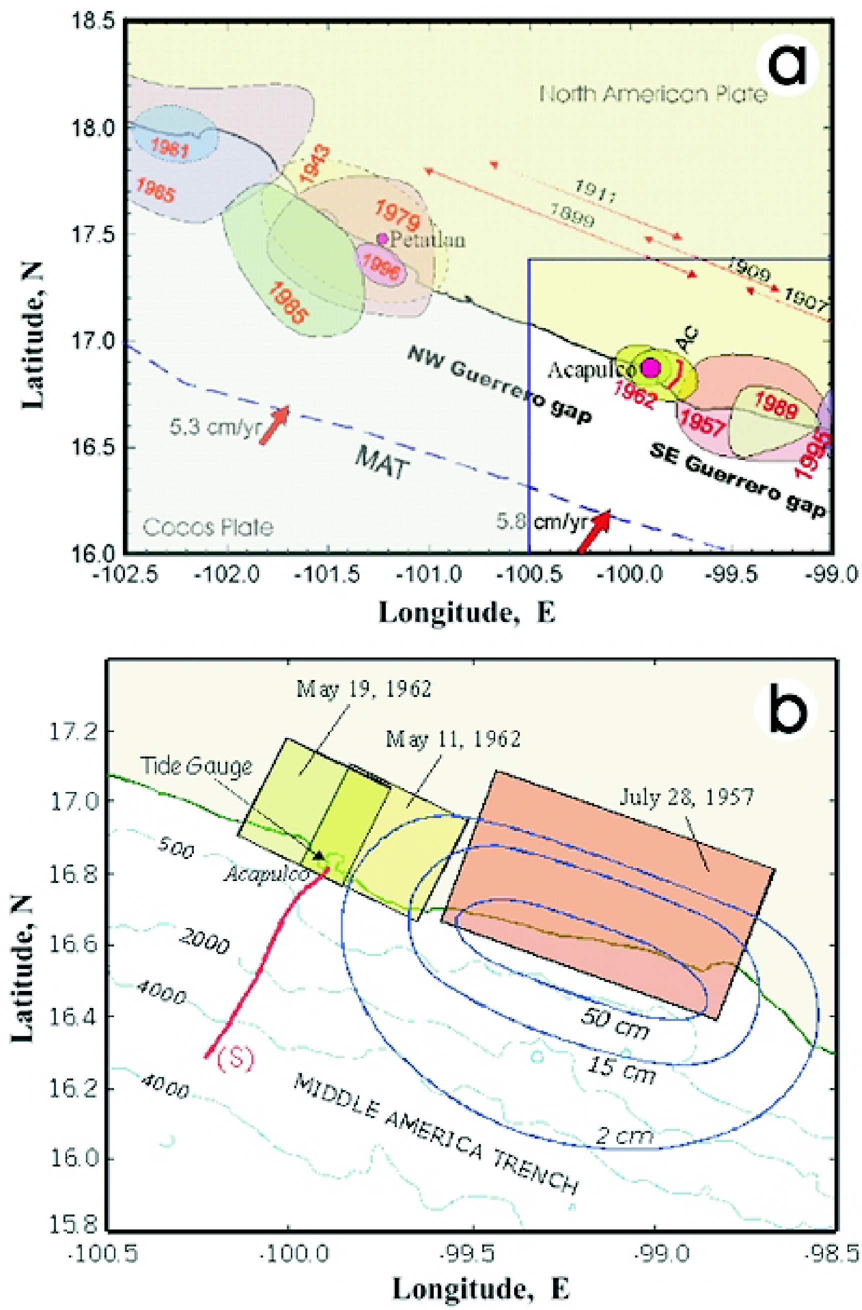

Figure 3: (a) Tectonic setting and the study area. Shaded areas annotated with a year are rupture zones of recent large thrust earthquakes. Thin arrow located inland over the Guerrero gap indicate an approximate extent along the coastal area of the rupture of the large earthquakes in 1899, 1907, 1909, and 1911. Solid arrows are vectors of the Cocos–NA convergence velocities according to the NUVEL 1A model (DeMets *et al.*, 1994). MAT—Middle America trench. Ac—location of the Acapulco leveling line. (b) Rupture areas of the 1962 and 1957 earthquakes estimated by the numerical modeling of the tsunami. The tide gauge is located at the western side of the Bay of Acapulco. The line from the trench to the coast shows the trajectory, S, on which a barotropic wave (tsunami) takes 15 minutes to transverse. Ellipses are the isolines of modeled coseismic uplift for the 1957 earthquake. Thin lines are the isobaths annotated with the depth values in m.

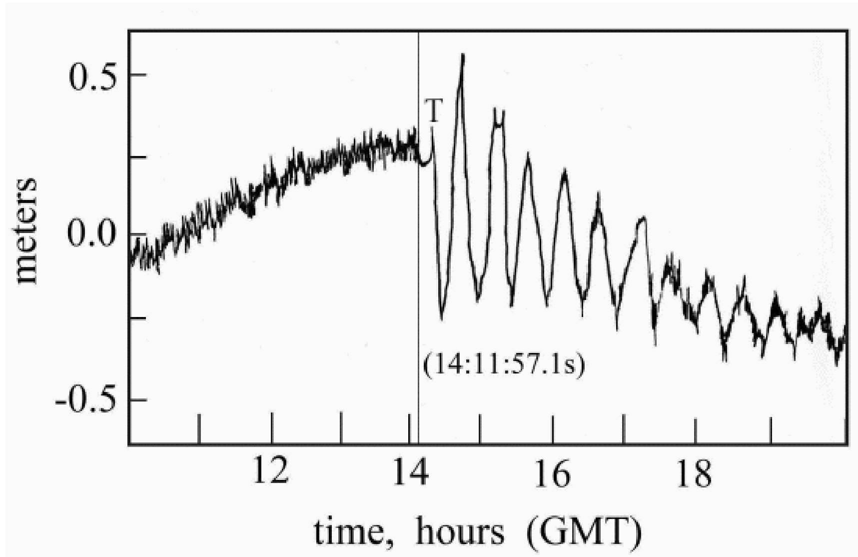

Figure 4: The 11 May 1962 tsunami as recorded at Acapulco. T indicates the first tsunami signal.

source of strong seismic energy release. We note that tsunami generation is highly sensitive to the slip on the shallow part of the fault.

The vertical displacement of the sea floor was computed using the dislocation model of Mansinha and Smylie (1971). For the tsunami initial condition, the sea level change was taken to be the same as the seafloor uplift calculated from the dislocation model. The initial sea level change was assumed to occur at the origin time of the earthquakes.

The propagation of the tsunami was simulated by the following vertically integrated shallow-water equations in a rectangular coordinate system (Pedlosky, 1979):

$$\begin{aligned} \frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} &= 0 \\ \frac{\partial U}{\partial t} + gh\frac{\partial \eta}{\partial x} &= 0 \\ \frac{\partial V}{\partial t} + gh\frac{\partial \eta}{\partial y} &= 0. \end{aligned} \tag{1}$$

In (1), t is time, η the vertical displacement of the water surface above the still water level, g is the gravitational acceleration, h is the still water depth, and U and V are the discharge fluxes in longitudinal (x) and latitudinal (y) directions. The validity of these equations for tsunami propagation is discussed by Ortiz *et al.* (1998).

Equations (1) were solved using an explicit central finite-difference scheme in a set of interconnected grids (Goto *et al.*, 1997; Liu *et al.*, 1995). In the

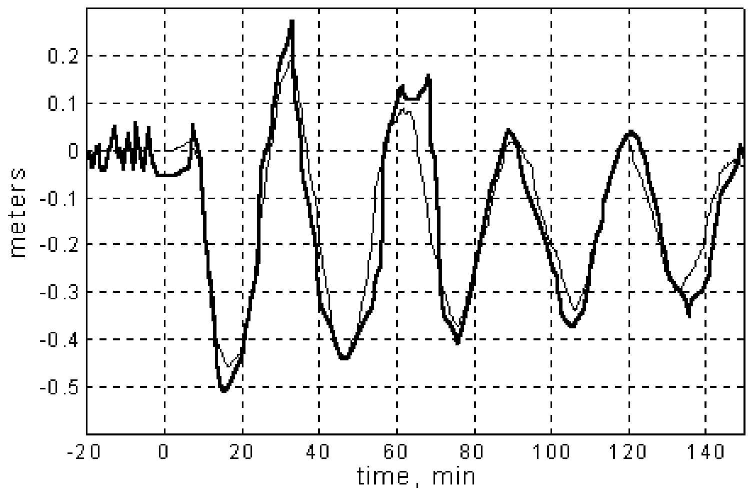

Figure 5: The 11 May 1962 tsunami at Acapulco: Residual tide (thick line); synthetic tsunami (thin line). The origin of the time axis corresponds to the origin time of the earthquake.

computation, the time step was set to 1 s, a grid spacing of 27 seconds was used for the whole region, whereas a grid spacing of 3 seconds was used to describe the bottom relief of the Bays of Acapulco and Salina Cruz. An intermediate grid spacing of 9 seconds was used to interconnect the computational grids. The sea bottom relief was digitized from local navigational charts (SM, 1993–1997).

The rupture area of the 11 May earthquake was constrained by the time of the first tsunami signal identified in the tide record at $\tau = 9$ minutes after the origin time of the earthquake [14:11:56.1] (marked T on Fig. 4). By considering the time τ for any long wave traveling from the point of maximum uplift (which approximately occurs above the shallow edge of the fault plane) to the tide gauge along the trajectory, S, prescribed by Snell's Law, we found $d = 12$ km among a wide range of trajectories. Consequently, the projection of the rupture area should be localized roughly centered on the coast. The distance d was computed from the equation:

$$d = \int_0^\tau \sqrt{gh(S)}dt \ , \tag{2}$$

where g represents the gravitational acceleration, t is time, and h is the still water depth along the trajectory.

The first tsunami signal is most likely not caused by the background noise of the record (which is ~16% of the tsunami amplitude) since the synthetic 11 May tsunami (Fig. 5) also shows the arrival of a small positive wave and reproduces adequately the periodic-damped oscillations seen in the record.

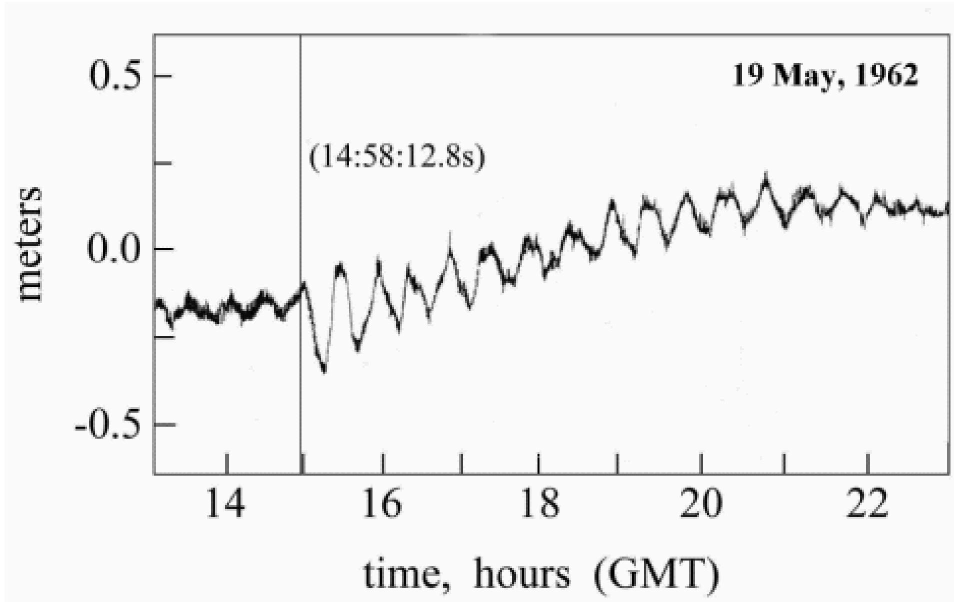

Figure 6: The 19 May 1962 tsunami recorded at Acapulco.

The background noise in the record of the 19 May tsunami (Fig. 6), which is ~30% of the tsunami amplitude, makes it difficult to discriminate the first tsunami signal. However, considering the ebb in the tide record at 7.5 minutes after the origin time of the earthquake [14:58:12.8] as a positive identification of the tsunami signal, we may conclude that the rupture area is located closer to the gauge than that of the 11 May rupture. The synthetic waveform of the 19 May tsunami (Fig. 7) starts decreasing slowly, reproducing the ebb and the periodic-damped oscillations of the recorded tsunami. In the numerical simulations, the location of the fault planes was constrained by matching the uplift predicted by the dislocation model at the tide gauge location to the uplift estimated from the tide records.

The 28 July 1957 tsunami, recorded by the tide gauges in Acapulco and Salina Cruz, are shown in Figs. 8 and 9, respectively.

The preliminary localization of the rupture area of the 28 July 1957 earthquake, west of Acapulco, was based on the epicenter location given by Merino y Coronado (1957). Starting with the first guess given in Table 1, the NW and SE extremes of the fault length were varied so that the initial observed and synthetic tsunami signals in Acapulco and Salina Cruz agreed with each other. The NW limit of the rupture area is 30 km SE of Acapulco while L remains 90 km. The rupture area was shifted with respect to the coastline to reproduce the resonance pattern of the observed tsunami. The estimated offshore extension of the rupture is less than 10 km. Figures 10a–c show the synthetic tsunami signals at Acapulco and Salina Cruz.

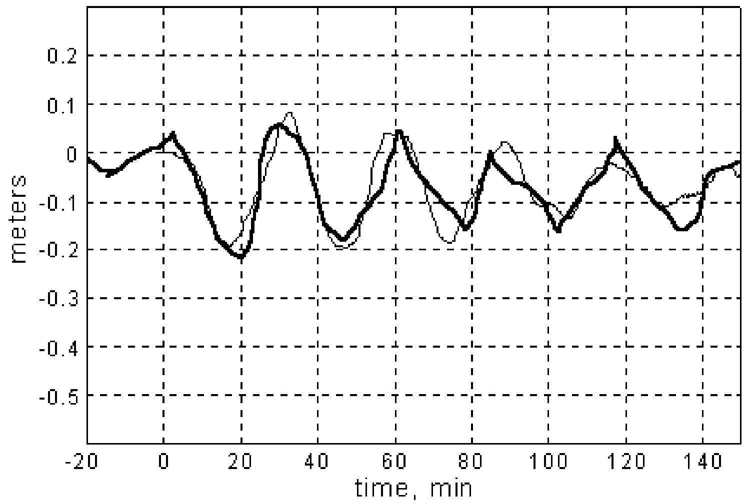

Figure 7: The 19 May 1962 tsunami at Acapulco: Residual tide (thick line); synthetic tsunami (thin line). The origin of the time axis is taken as the origin time of the earthquake.

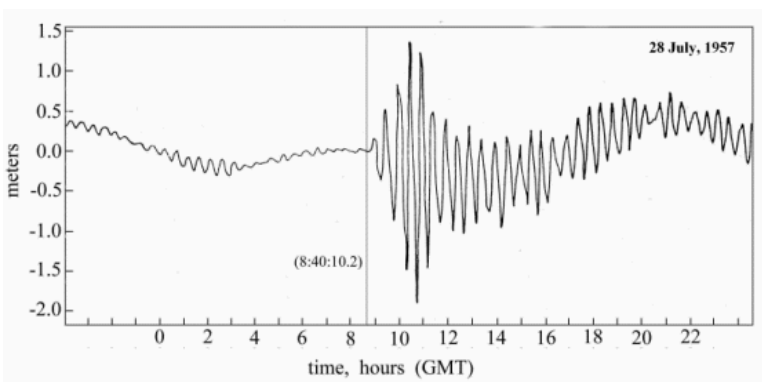

Figure 8: The 28 July 1957 tsunami as recorded at Acapulco.

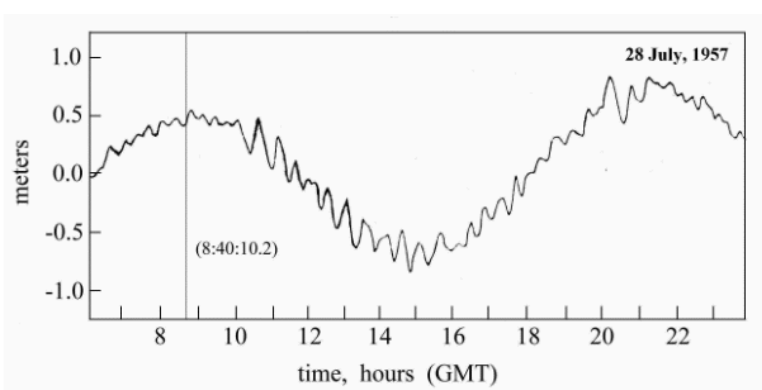

Figure 9: The 28 July 1957 tsunami as recorded at Salina Cruz.

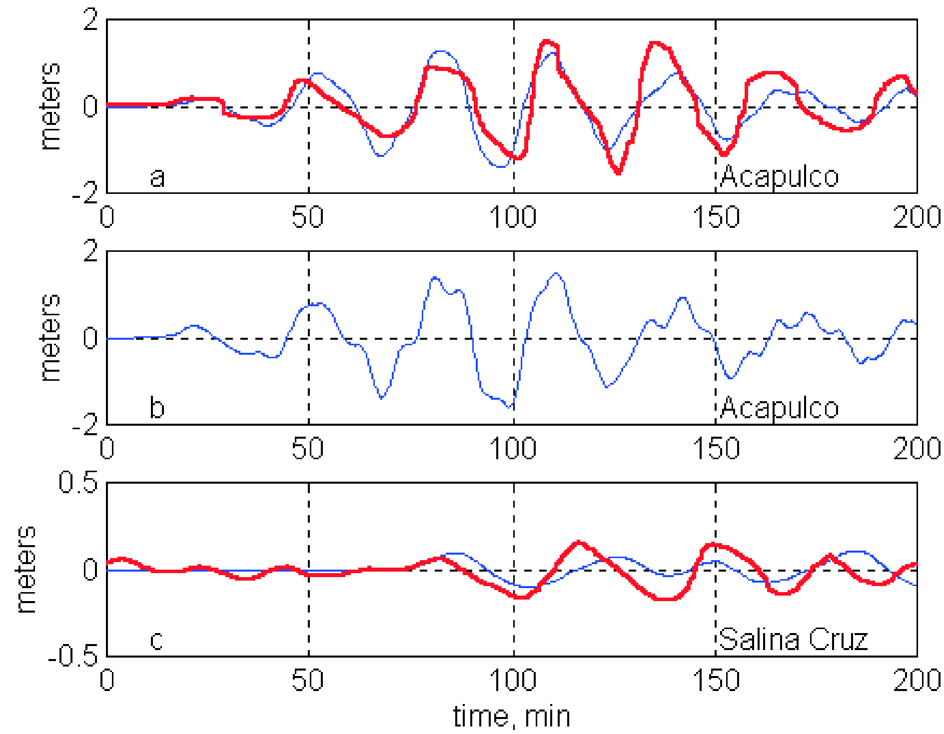

Figure 10: (a) The 28 July 1957 tsunami at Acapulco. Residual tide is shown as a thick line, and synthetic tsunami as a thin line. (b) The 28 July 1957 synthetic tsunami at Acapulco produced by increasing the offshore extension of the rupture by 10 km from the assumed location. The second wave front (short wave length) appears superimposed on the standing wave. (c) The 28 July 1957 tsunami at Salina Cruz. Residual tide is shown as a thick line, and synthetic tsunami as a thin line. In all three frames (a–b) the origin of the time axis is defined as the origin time of the earthquake.

4. Uncertainty in the Results

At the epoch of the 1962 and 1957 Guerrero earthquakes, the tide gauges in Acapulco and Salina Cruz were standard United States Coast and Geodetic Survey analog flotation-type devices, operating in a stilling well of 12 inches diameter and $\frac{3}{4}$ inch intake orifice. The frequency response for this particular type of gauge is such that waves with periods greater than 25 minutes and amplitudes less than 1 meter are not affected by the response of the gauges (Cross, 1968). Therefore, the 1962 and 1957 tsunami records at Acapulco and Salina Cruz need not be corrected for the gauge response.

In the numerical simulations of the 11 and 19 May 1962 tsunamis, a delay of $\sim$2 minutes is produced by moving the fault plane 5 km around the given location. A change of 5 km in the length of the fault plane produces an increase of $\sim$10% in tsunami amplitude. Considering that the time uncertainty in the analog tide records is 1 minute (Grivel, 1967), we may estimate the uncertainty to be less than ±5 km for the location of the fault planes as well as for their lengths.

In the simulations of the 28 July 1957 tsunami, a difference of ±2 minutes in the phase of the synthetic tsunami arrival at Acapulco is produced by moving the NW limit of the rupture ±5 km along the strike, whereas a difference of ±1 minute in the arrival time at Salina Cruz is produced by moving the SE limit ±20 km along the strike. This sensitivity is due to the deeper region of the trench over which the tsunami propagates toward Salina Cruz. On reproducing the resonance pattern observed in the tide record, the most sensitive change in the synthetic waveform occurs by shifting the rupture area with respect to the coastline. By increasing the offshore extension of the rupture, the maximum uplift of water produces a second wave front that, after being reflected on the coast, propagates as a progressive wave superimposed on the standing resonant pattern. The second wave front is not observed in the tsunami record. Figure 10b illustrates the superimposed second wave front produced by increasing the offshore extension of the rupture 10 km from the assumed location, a distance that may be accepted as an uncertainty in the inland-offshore location of the rupture. The resonance pattern at the period of 30 minutes is produced by a standing wave oscillating between the coast and the trench, as it was visualized during the simulations. Damped oscillations at the period of 30 minutes, similar to those observed on the 11 and 19 May 1962 tsunamis, are produced by reducing the transversal length of the disturbed water surface.

5. Discussion and Conclusions

Numerical modeling of the tsunami records from the Acapulco and Salina Cruz tide gauges allowed us to constrain the rupture locations of the large earthquakes of 11 and 19 May 1962, and 28 July 1957. These areas are shown in Fig. 3.

The NW extreme of the rupture area of the 1957 earthquake is located ∼30 km to the SE from Acapulco. In previous estimates, this extreme extended up to Acapulco (e.g., Nishenko and Singh, 1987b; Gonzalez-Ruiz and McNally, 1988). The fault areas of 11 and 19 May 1962 abut the rupture zone of the 1957 earthquake.

It is important to point out that the SW edge of the rupture area for all three earthquakes lies roughly 60 km from the axis of the Middle America Trench. This suggests that the strongly coupled plate interface in this region may not extend offshore by more than ∼10 km. The numerical experiments show that the location of this boundary is tightly controlled by the observed tide gauge data, while the location of the inland boundary and the dip of the fault plane are less critical for the modeling. The position and the width of the rupture zone of 1962 earthquakes coincide remarkably well with the location of the locked (or highly coupled) patch along the subduction interface SE of Acapulco, estimated from the modeling of the observed vertical crustal deformation. Figure 11 shows a comparison between the location of the rupture zones of the 1962 events and the position of the locked zone es-

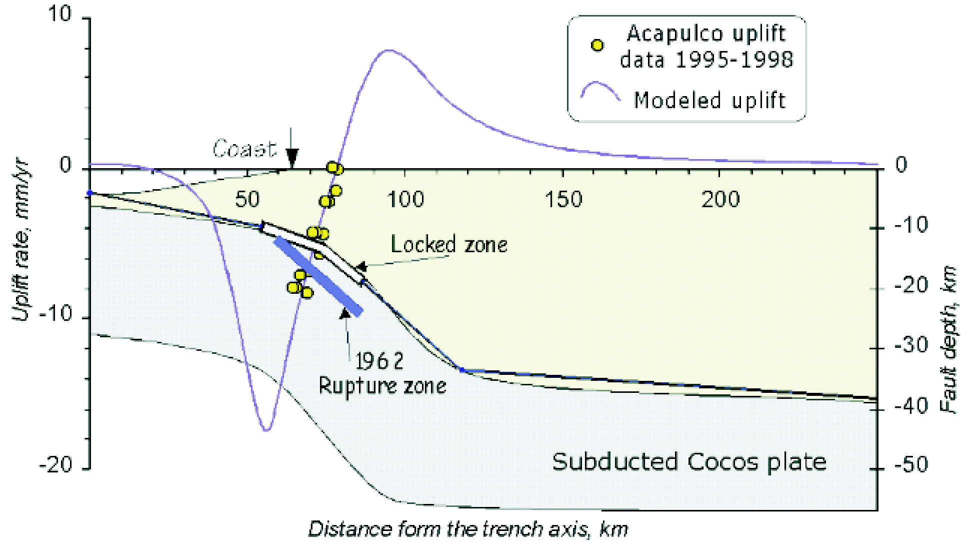

Figure 11: The location of the rupture zones of 1962 events estimated in this study and the position of the locked zone inferred from the modeling of the uplift rate on the Acapulco profile. Configuration of the subduction interface is from Kostoglodov *et al.* (1996).

timated from the modeling of the differential leveling data on the Acapulco profile (Kostoglodov *et al.*, 2000). In that study the 2D elastic dislocation model of Savage (1983) was applied to fit the observed uplift distribution along the leveling line, which is located ∼8 km south from the tide gauge site in Acapulco. The model approximates the seismogenic contact between the oceanic and continental plates as a patch of the subduction interface that is locked. The uplift produced during the interseismic stage is modeled by the linear superposition of steady-state slip at the entire plate interface and supplemental solutions for normal slip on the locked patch. The uncertainty in the absolute uplift of the leveling line results in the ambiguity of the location and size of the locked patch of less than 10 km.

The agreement between the lateral location and the width of the presently locked zone and the rupture areas of 1962 probably suggests that the plate interface zone, extending from the trench to ∼60 km landward, is aseismic (or poorly coupled), at least in the area SE of Acapulco. The same cannot be postulated for the NW Guerrero gap.

Several recent large earthquakes in Mexico have ruptured the plate interface, which lies entirely offshore (e.g., the earthquakes of 21 September 1985, M 7.6, offshore Petatlan; 9 October 1995, M 8.0, Colima-Jalisco; and 25 February 1995, M 7.1, offshore Pinotepa Nacional), suggesting that the width of the coupled zone, at least in some segments, may extend almost to the trench. Based of the available data, we cannot rule out this possibility for the NW Guerrero gap.

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