11 WCEE

Copyright © 1996 Elsevier Science Ltd
Paper No. 887. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SHALLOW DEPTH OF SEISMOGENIC COUPLING IN SOUTHERN MEXICO: IMPLICATIONS ON THE MAXIMUM SIZE OF EARTHQUAKES IN THE SUBDUCTION ZONE

GERARDO SUAREZ AND OSVALDO SANCHEZ

Instituto de Geofísica, Universidad Nacional Autónoma de México, México D.F. 04510 México

ABSTRACT

Studies of locally recorded microearthquakes and the centroidal depths of the largest earthquakes analyzed using teleseismic data show that the maximum depth of thrust faulting along the Mexican subduction zone is anomalously shallow. This observed maximum depth of approximately 25±5 km is about half of that observed in most subduction zones of the world. A leveling line that crosses the rupture zone of the 1985 Michoacan earthquake was revisited afer the earthquake. The comparison between the observed coseismic uplift with dislocation models of the seismogenic interplate contact that extend to depths ranging from 20 to 40 km show that the maximum depth at which seismic slip took place is about 20 km. A similar result is obtained from the postseismic deformation observed after the October 9, 1995 Jalisco earthquake. Inversion of this data to determine the slip distribution on a realistic fault indicate also that for this large earthquake coseisimic slip did not exceed a maximum depth of 20 km. This unusually shallow and narrow zone of seismogenic coupling apparently results in the occurrence of thrust events along the Mexican subduction zone that are smaller thatn would be expected for a trench subducting a relatively young slab at a rapid rate of relative motion. A comparison with the Chilean subduction zone shows that the plate interface in Mexico is scaled in half. Thus it appears that the narrow plate contact produced by this particular plate geometry in Mexico is the controlling variable defining the size of the largest earthquakes in the Mexican subduction zone.

KEYWORDS

Mexico, Chile, subduction, seismogenic coupling, coseismic deformation.

INTRODUCTION

Several studies have shown the the Mexican subduction zone exhibits an unusually shallow depth of seismogenic coupling. The maximum depth of seismogenic coupling is understood as the deepest edge on the plate interface that is capable of rupturing seismically during a large earthquake. This observation has been well documented by the study of the largest subduction earthquakes in Mexico. Whereas in most subduction zones of the world the maximum centroidal depth of shallow thrust interplate events is about 40±10 km, in Mexico the hypocentral depth of the largest earthquakes never exceeds 25 km (e. g., Chael and Stewart, 1982; Tichelaar and Ruff, 1993; Pacheco et al., 1993; Ruff and Miller, 1994).

Similar values of the maximum depth of thrust faulting events are observed from studies of locally recorded microearthquakes. Suárez et al. (1990) showed from data recorded by a local permanent network in the Guerrero region that this type of events were consistenlty shallower than 20 km. This observation has been corroborated by the aftershock studies of the most important earthquakes that have occurred recently in the subduction zone (Ponce et al., 1979; Singh et al., 1980; Valdes et al., 1982; Havskov et al., 1983, UNAM Seismology Group, 1986; Zuñiga et al., 1993), where the deepest thrust faulting events recorded are also shallower than about 20 km.

Although the seismic information suggesting this unusually shallow depth of seismogenic coupling in Mexico is abundant, no geodetic information had been available to confirm this observation in the Mexican subduction zone. Without this information the question may be raised whether beneath this shallow depth of seismic coupling there is a zone that slips slowly and asesimically during large earthquakes. Fortunately, a leveling line perpendicular to the rupture zone of the 1985 Michoacan earthquake and the observed coseismic displacements observed after the October 9, 1995 Jalisco event now provide the geodetic confirmation for the shallow depth of coupling observed from the seismic data.

GEODETIC OBSERVATIONS OF COSEISMIC DEFORMATION IN MEXICO

A first-order leveling line measured by the Instituto Nacional de Estadística, Geografía e Informática (INEGI) runs from the town of Lazaro Cárdenas to Arteaga, and crosses the rupture zone of the Michoacan earthquake of September 19, 1985. This line was levelled in the late 1970's, prior to the earthquake, and the monuments reocuppied in 1990 in collaboration with INEGI. Thus the observed changes in elevation reflect the sum of the preseismic, coseismic, and postseismic deformation of the subduction zone. Coseismic uplift during the 1985 Michoacan earthquake was measured at several points along the coast (Bodin and Klinger, 1986; Corona *et al.*, 1988). A maximum uplift of ~1 m occurred near Caleta de Campo, where the earthquake apparently nucleated (UNAM Seismology Group, 1986). A recent visit to the sites that showed evidence of coastal uplift during the 1985 Michoacan earthquake suggests that today no appreciable postseismic changes in sea level have taken place (<10 cm), and consequently of coastal deformation since the earthquake (Corona, R; personal communication).

In order to compare the changes between the measurements of the two leveling lines, the point farthest inland was fixed (Figure 2); thus we assume that no elevation changes took place at this site, which is ~40 km inland from the coast and far removed from the rupture zone mapped by the aftershock survey (*e.g.*, UNAM Seismology Group, 1986). The results show very small changes in elevation between the two measurements. The largest elevation change observed is approximately 8.5 cm and, in general, the data show subsidence of the coast relative to the previous survey. This observation suggests that most of these relevelled points lie in a zone that suffered little deformation, and are inland of the down-dip termination of the rupture zone. Here, dislocation models predict a changeover in the vertical deformation of the upper plate from coseismic uplift to subsidence.

The observed data were compared with theoretical, one-dimensional dislocation models on an inclined fault embedded in a half space (*e.g.,* Mansinha and Smylie, 1971). The geometry of the fault assumed in the calculations is that observed in the Guerrero region, immediately to the southeast of the 1985 rupture (Suárez *et al.*, 1990) (Figure 1).

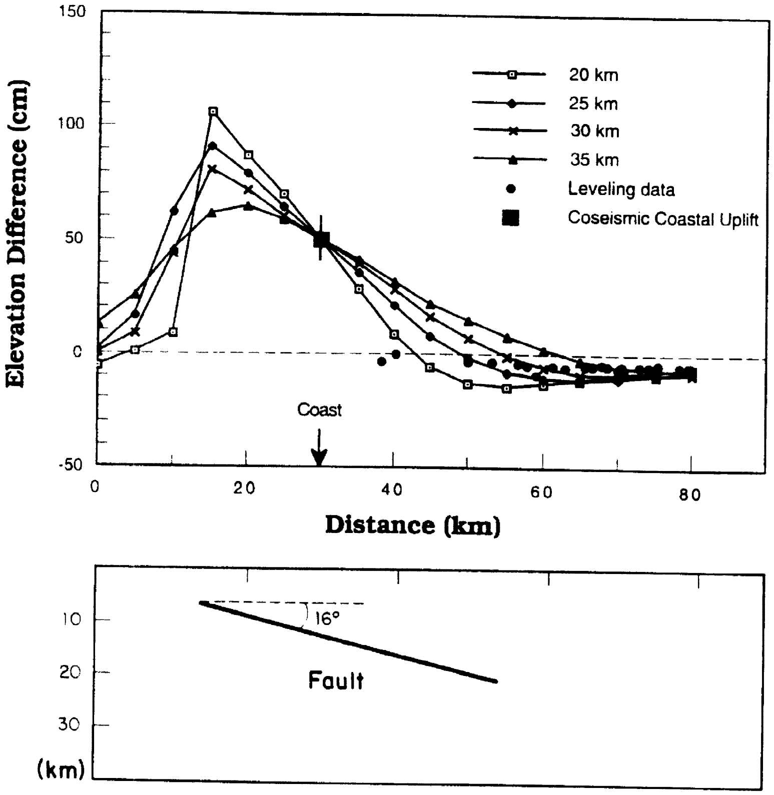

Fig. 1. Comparison of the vertical uplift along a cross-section parallel to the leveling line predicted by four dislocation models that extend to 20, 25, 30, and 35 km. The fault geometry used is the same as that of the zone of interplate contact in

A comparison of the vertical uplift with that predicted by the various dislocation models confirms that the depth of seismogenic coupling is very shallow in central Mexico. The curves corresponding to a maximum depth of faulting deeper than 25 km predict values of uplift that are much larger than those observed in the distance range of 40 to 60 km from the trench. In particular, the two points closest to the coastline indicate that little deformation occurred here, and they match more closely the values predicted by a dislocation model with a maximum depth of faulting of 20 km.

Thus the 1985 Michoacan earthquake appears to have had seismic slip down to a maximum depth of ~20 km (Figure 3); this anomalously shallow depth of strong coupling agrees with the deepest thrust faulting events observed in the coast of Guerrero (Suárez *et al.*, 1990), where the geometry of the subduction zone is well constrained.

Coseismic displacements were measured by reocuppying a network of geodetic markers before and after the occurrence of the October 9, 1995 Jalisco earthquake ($M_W = 7.8$). The measurements were taken using the Global Positioning System (GPS) constellation of satellites. The Jalisco GPS network was first occupied in March of 1995 and remeasured a six days after the October earthquake (Melbourne et al., 1996).

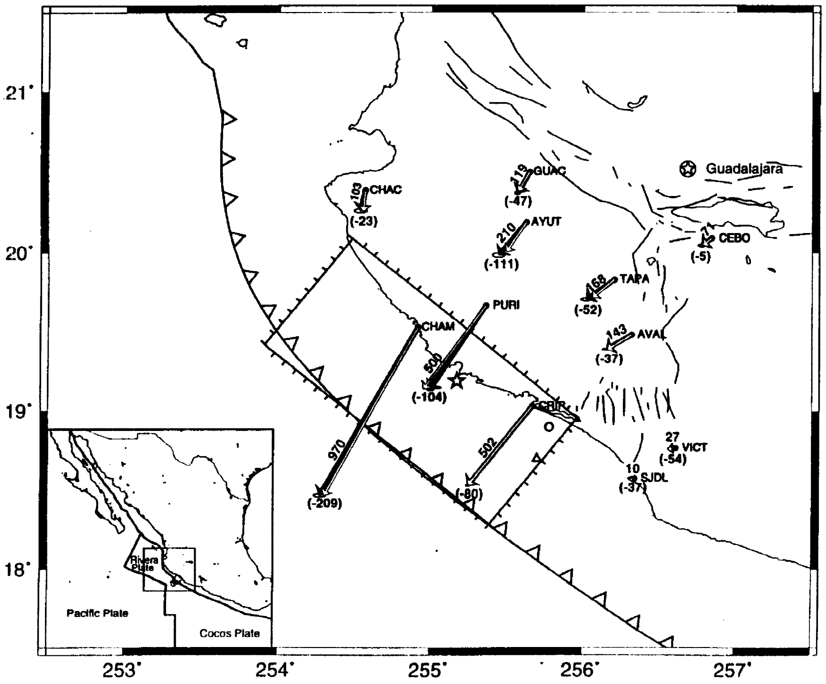

Fig. 2. Coseismic displacement for the October 9, 1995 earthquake. GPS measurements are shown as black vectors with displacements described in mm. Ellipses represent the 95% confidence intervals. The thin white vectors are predicted by the slip distribution of the fault shown on Figure 3. After Melbourne et al. (1996).

The coseismic displacements show subsidence and extension decreasing uniformly away from the trench. A maximum horizontal displacement of 986±14 mm was measured at a station CHAM along the coastline (Figure 2). The deformation decreases gradually towards the interior of the continent. All stations show coseismic subsidence decreasing away from the trench. Subsidence values were corroborated with the tide gauge data observed in Manzanillo. The GPS-derived subsidence is of 80±14 mm which compared to the 74±10 mm observed with the tide gauge show the accuracy of the GPS measurements.

The distribution of the slip on the fault plane was estimated by inverting the three component GPS vectors for slip along an *a priori* fault with a specified number of subfaults. The fault plane has a total along-strike length of 200 km, a down-dip width of 100 km, dips at 16° , and is subdivided into 200 subfaults, each 10x10 km^2. The slip distribution indicates that nearly all of the slip occurred within the upper 18 km of the surface with a maximum displacement of 5 m. (Figure 3). This observations again confirm that even in the case of large earthquakes such as the October Jalisco earthquake, seismic displacement along the main plate contact never exceeds a maximum depth of 18 km.

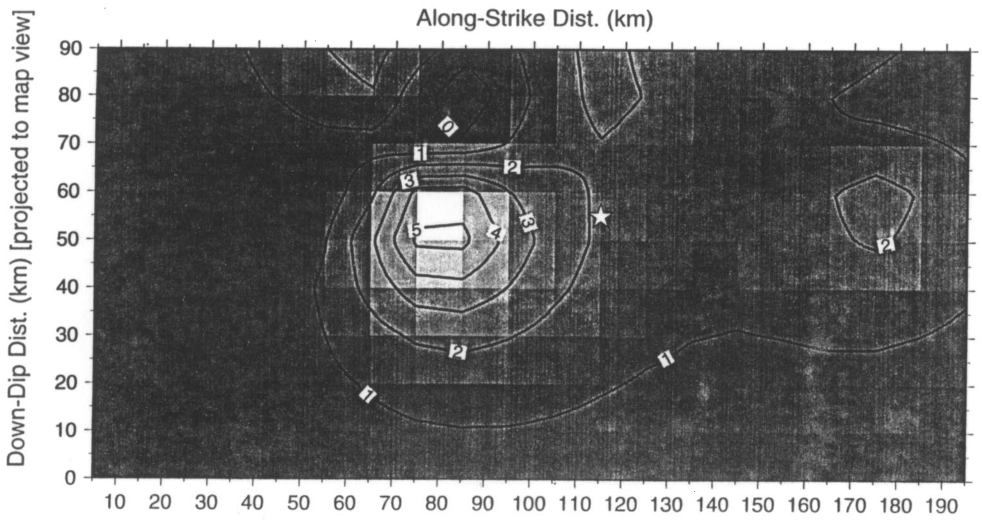

Fig. 3. Distribution of slip on the plate interface. Contours indicate the thrust-slip amplitude in meters. The distribution of slip indicates that it did not exceed a maximum depth of 18 km and that it is concentrated in two patches separated by 95 km. The star indicates the location of the epicenter. After Melbourne et al. (1996).

MAXIMUM DEPTH OF COUPLING AND THE MAXIMUM SIZE OF EARTHQUAKES

The results of coseismic deformation observed both in Michoacan and in Jalisco during two great earthquakes agree with the seismicity information which indicates a shallow seismogenic zone that extends to a depth of only 25 km. This depth is approximately half of what is observed in most subduction zones of the world (Tichelaar and Ruff, 1993; Pacheco et al., 1993). Besides the Mexican subduction zone, only the Rat Islands and the South Sandwich Islands show a maxmimum depth of seismogenic coupling which is not in the order of 50 km.

It is of interest to compare the results of the Jalisco earthquake to those obtained after the large Chilean earthquake of July 1995. In that case, a GPS network similar to that described for the Jalisco region was revisited after the occurrence of a large subduction earthquake (Ruegg et al., 1996). The resulting dislocation model of the fault which fits the observations indicates that coseismic slip took place down to a depth of approximately 50 km, in clear contrast with the deformation observed after the earthquake in Jalisco a few months afterwards. Although at first glance the plate boundaries in Chile and Mexico show very similar tectonic characteristics, it is striking that the depth extent and the resulting down-dip width of the Chilean subduction zone is about twice as large as that observed in Mexico.

Therefore, the major difference between these two apparently similar subduction zones is that the particular geometry of the Mexican subduction zone results in a width of strong seismogenic coupling that is only half of that observed in Chile (Tichelaar and Ruff, 1991; Suárez and Comte, 1993). This appears to be the key parameter controlling the size of the largest earthquakes in both subduction zones. The smaller than expected magnitude of Mexican earthquakes appears then to be the result of this relatively narrow interplate contact (Suárez and Sánchez, 1996).

Although the mechanism that produces this shallow depth of coupling is still unknown, there appears to be a correlation between this shallow depth of seismogenic coupling and the size of the largest earthquakes that occur in the Mexican subduction zone. The smaller than expected maximum magnitude of Mexican earthquakes appears to be the result of a shallower, and consequently narrower, zone of interplate coupling that limits the size of the faults that rupture during a particular earthquake, which in turns limits the size of the largest earthquakes. This observation may explain why the largest observed earthquakes in the Mexican subduction zone do not exceed a moment magnitude of about 8.2, whereas in similar subduction zones such as the Chilean coast, earthquakes as large as M_W of 8.7 or 9.6 have been observed in the past 100 years.

REFERENCES

Bodin, P. and T. Klinger (1986). Coastal uplift and mortality of intertidal organisms caused by the September 1985 Mexico earthquakes, *Science*, **233**, 1071-1073.

Chael, E.P. and G.S. Stewart (1982). Recent large earthquakes along the Middle America Trench and their implications for the subduction process, *J.. Geophys. Lett.*, **87**, 329-338.

Corona-Esquivel, R., F. Ortega-Gutiérrez, J. Martínez-Reyes, E. Centeno-García (1988). Evidencias de levantamiento tectónico asociado con el sismo del 19 de septiembre de 1985, en la región de Caleta de Campos, estado de Michoacán, Univ. Nal. Autón. México, Inst. Geología, Revista, **7**, 106-111.

Havskov, J., S.K. Singh, E. Nava, T. Domínguez, M. Rodríguez (1983). Playa Azul, Michoacán, Mexico, earthquake of 25 October 1981 (Ms=7.3), *Bull. Seismol. Soc. Am.*, **73**, 449-457.

Mansinha, L. and D.E. Smylie (1971). The displacements fields of inclined faults, *Bull. Seismol. Soc. Am.*, **66**, 204-206.

Melbourne, T., I. Carmichael, C. De Mets, K. Hudnut, O. Sánchez, J. Stock, G. Suárez, and F. Webb (1996). Shallow faulting and regional subsidence in the October 1995 Jalisco earthquake, submitted to *Science.*

Pacheco, J., L.R. Sykes, and C.H. Scholz (1993). Nature of seismic coupling of the subduction type, *J. Geophys. Res.*, **98**, 14,133-14,159.

Ponce, L., K.C. McNally, J. González, A. del Castillo, and E. Chael (1979). The 29 November, 1978, Oaxaca earthquake: Foreshock activity, *Geofis. Int.*, **17**, 267-280.

Ruegg, J.C. and others (1996). The $M_W = 8.1$ Antofagasta (North Chile) earthquake of July 30, 1995: First results from teleseismic and geodetic data, submitted to *Geophys. Res. Lett.*

Ruff, L.J. and A.D. Miller (1994). Rupture process of large earthquakes in the northern Mexico subduction zone, *Pure Appl. Geophys.*, **142**, 102-171.

Singh, S.K., J. Havskov, K. C. McNally, L. Ponce, T. Hearn, and M. Vassiliou (1980). The Oaxaca, Mexico, earthquake of 29 November 1978: A preliminary report on aftershocks, *Science,* **207**, 1211-1213.

Suárez, G., T. Monfret, G. Wittlinger, and C. David (1990). Geometry of subduction and depth of the seismogenic zone in the Guerrero gap, Mexico, *Nature*, **345**, 336-338.

Suárez, G. and D. Comte (1993). Comment on "Seismic coupling along the Chilean subduction zone" by B.W. Tichelaar and L.R. Ruff, *J. Geophys. Res.*, **98**, 15,825-15,828.

Suárez, G., and O. Sánchez (1996). Shallow depth of seismogenic coupling in southern Mexico: implications for the maximum size of earthquakes in the subduction zone, *Phys. Earth Planet. Int.*, **93**, 53-61.

Tichelaar, B.W. and L.J. Ruff (1993). Depth of seismic coupling along subduction zones, *J. Geophys. Res.*, **98**, 2017-2037.

UNAM Seismology Group (1986). The September 1985 Michoacan earthquakes: Aftershock Distribution and History of rupture, *Geophys. Res. Lett.*, **13**, 573-576.

Valdés, C., R. P. Meyer, R. Zuñiga, J. Havskov, and S.K. Singh (1982). Analysis of the Petatlan aftershocks: numbers, energy release and asperities, *J. Geophys. Res.*, **87**, 8519-8527.

Zúñiga, R., C. Gutiérrez, E. Nava, J. Lermo, M. Rodríguez, and R. Coyoli (1993). Aftershocks of the San Marcos earthquake of April 25, 1989 (Ms=6.9) and some implications for the Acapulco-San Marcos seismic potential, *Pure Appl. Geophys.*, **140**, 287-300.