# New constraints on the uplift of October 9, 1995 Jalisco-Colima earthquake ( $M_w$ 8) based on the analysis of tsunami records at Manzanillo and Navidad, Mexico

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## RESUMEN

Se hace una estimación del hundimiento cosísmico en la Bahías de Manzanillo y Navidad mediante el análisis de las observaciones del tsunami obtenidas de dos mareógrafos y de un sensor de presión durante el sismo de Jalisco-Colima del 9 de octubre de 1995 ( $M_w$  8). La posición y magnitud del máximo levantamiento cosísmico mar adentro sobre el plano de falla se determina a partir de la simulación numérica de la propagación del tsunami. Para reproducir el tsunami registrado en Manzanillo y Navidad es necesario suponer un deslizamiento de la falla frente a Manzanillo 2 ó 3 veces menor que el deslizamiento promedio frente a Navidad. Estas nuevas restricciones en los desplazamientos cosísmicos verticales mar adentro y en la costa, obtenidas a partir del análisis del tsunami, podrán ser combinadas con los datos cosísmicos existentes de GPS en la costa y tierra adentro para lograr una inversión detallada de la distribución del deslizamiento sobre el plano de falla.

PALABRAS CLAVE: Sismo de Jalisco-Colima, México del 9 de octubre de 1995, área de ruptura, tsunami, mareogramas.

#### ABSTRACT

Tsunami records registered during the October 9, 1995 Jalisco-Colima earthquake ( $M_w$  8) by two tide gauges and one pressure gauge are analyzed to estimate the coseismic subsidence at Manzanillo and Navidad Bay. Numerical modeling of the tsunami waveform determined the location and magnitude of the maximum coseismic uplift on the fault plane. To fit the observed data, the fault slip offshore from Manzanillo is required to be 2-3 times smaller than the average slip on the fault plane off Navidad Bay. The new constraints on the coseismic uplift distribution obtained combined with the existing coseismic inland GPS data should accomplish a new more detailed inversion of the fault-slip distribution.

KEY WORDS: October 9, 1995 Jalisco-Colima, Mexico, earthquake, rupture zone, tsunami, tide gauge records.

## **INTRODUCTION**

The October 9, 1995 ( $M_{w}$  8.0) Jalisco-Colima earthquake has been extensively studied using local and teleseismic data (Courboulex et al., 1997; Pacheco et al., 1997; Zobin, 1997; Escobedo et al., 1998; Mendoza and Hartzell, 1999), and GPS measurements of the coseismic displacements, obtained directly onshore of the rupture zone (Melbourne et al., 1997). Results from all of these studies are fairly consistent with the notion of highly non-uniform coseismic slip distribution and with the offshore location of the rupture zone; however, they disagree on the position of maximum fault slip (see Figure 1). Tsunami records from Manzanillo Bay (southeastern corner of the rupture zone) and Navidad Bay (approximately center of the rupture) for this earthquake can provide additional constraints on the coseismic uplift and fault-slip distributions; specifically on the offshore location of the maximum coseismic uplift and its magnitude. The offshore location of the maximum vertical coseismic displacement is estimated from the arrival time of the first maximum in the tsunami records, whereas its magnitude is estimated by waveform modeling of the tsunami records. Offshore coseismic displacement, which was obtained by applying a singular value decomposition to the GPS measurements by Melbourne *et al.* (1997), could be significantly improved when employing as well the values of coseismic land subsidence estimated from tsunami modeling. A better knowledge of the coseismic displacement in the Rivera-Jalisco subduction zone is important to understand the seismotectonic structure of this region in order to prescribe an appropriate tsunami initial condition for possible rupture scenarios.

## COSEISMIC SUBSIDENCE IN THE BAY OF MANZANILLO

There are two tide gauges at the tide station in Manzanillo operated by CICESE, NOAA and the Mexican



Fig. 1. a -Map of the region showing offshore locations of rupture zone for the October 9, 1995 earthquake (rectangles) modeled by Zobin (1997), Mendoza and Hartzell (1999), (broadband teleseismic *P* wave inversions), and Melbourne *et al.* (1997), (GPS data inversion). Coseismic fault-slip distributions from: b –Zobin, 1997; c – Mendoza and Hartzell, 1999; d –Melbourne *et al.*, 1997. In b, c and d, annotated isolines are in meters on the rupture planes; the scales are in km: X-scale from NW to SE along the trench, Y-scale from SW to NE from the trench axis; fault planes are aligned along the trench axis according to their actual map location. An evident large discrepancy in the positions of the maximal coseismic slip can be easily seen.

Navy. The primary tide gauge (acoustic gauge) and the backup gauge (pressure gauge) record the sea level at one sample every 6 minutes, from averaging one-second samples. A preliminary analysis of the records at both gauges indicates an increase in sea level after the earthquake. Figure 2 shows the raw, 6-minute averaged data from both gauges. The datum of both instruments at the epoch of the 1995 earthquake was controlled by 7 benchmarks in a radius of 0.5 km from the gauges. The differential levels of the benchmarks, measured 7 days after the earthquake, indicate that the increase in sea-level can be taken as evidence of coseismic land subsidence in the surrounding area of the tide station.

A reliable estimation of the subsidence from the tide record requires the following considerations. Taking the predicted tide as a reference level, the residual tide, which is obtained by subtracting the predicted tide from the observed one (Figure 3a), shows the presence of low-frequency fluctuations (periods longer than 10 days). These fluctuations of sea-level can mask the effect of subsidence when computed as the difference between the mean sea levels before and after the earthquake using the entire data set.

## Uplift of October 9, 1995 Jalisco-Colima earthquake

An enlarged view of the residual tide (Figure 3b) shows a gradual increase in sea level during the first 8 hours after the earthquake. The subsidence could be underestimated if the first 8 hours of data after the earthquake were included in the computation of the mean sea level. Therefore, a subsidence of 11.8±1.3 cm (11.2±2.0 cm, Kostoglodov et al., 1997) is estimated by subtracting the average of the mean residual tide computed over the first 12 hours before the earthquake, from the average of the mean residual tide for the period from 12 to 24 hours after the earthquake. The mean residual tide is obtained by filtering out the tsunami oscillations from the residual tide. The uncertainty in the subsidence is computed as one standard deviation of the mean residual tide over the period from 12 to 24 hours after the earthquake. Figure 4 illustrates a rather good agreement between the tide record and the predicted tide before the earthquake.

The slow increase in sea level after the earthquake (over a period of 8 hours) can be explained by considering that the tide station is located inside a coastal inlet with a narrow entrance (Figure 5). During the first tsunami period, and in some of the subsequent oscillations, the ebb is greater than



Fig. 2. Raw 6 minutes averaged sea-level data from the primary (acoustic) and the secondary (pressure) tide gauges operating at the tide station in Manzanillo. The origin of the time axis is taken as the origin time of the earthquake. The mean sea-level change after the earthquake can be noted in both records. Comparison of both records indicates a good quality of the data.



Fig. 3.  $\mathbf{a}$  – The residual tide at Manzanillo showing low frequency fluctuations in the sea-level.  $\mathbf{b}$  – An enlarged view of the residual tide at Manzanillo. The mean residual tide (smooth line) indicates a slow increase in the sea-level during the first 8 hours after the earthquake. The origin of the time axis is defined as the origin time of the earthquake.



Fig. 4. The tide record and the predicted tide (smooth line) at Manzanillo showing a good agreement between the predicted tide and the tide record before the earthquake. The origin of the time axis is defined as the origin time of the earthquake.



Fig. 5. A sketch of the Manzanillo bay. The location of the tide station is indicated by the filled circle.

the flood (Figure 4). Thus, the time on which the equilibrium level is reached is retarded by the inlet. In the absence of tsunami oscillations, the water would reach equilibrium level in less than one hour.

# COSEISMIC SUBSIDENCE IN THE BAY OF NAVIDAD

Two pressure gauges (SBE42 and SBE43) with sampling rates of 1 minute were deployed in the Bay of Navidad, 2 km offshore at the depth of 30 m, moored above a depth of 50 m. Comparing the records at the two gauges, before and after the earthquake, the coseismic subsidence was estimated at 32 cm (Filonov, 1997). Using the same procedure as in Manzanillo, our estimation of the subsidence from the SBE42 record is 40.0±2.3 cm (44±3 cm, average from both SBE42 and SBE43 records, Kostoglodov et al., 1997). Figure 6 illustrates the SBE42 tide record and the residual tide. In this case, the equilibrium water level does not show any lag as in the case of Manzanillo. The time stamp of the SBE42 record was corrected by -14 min by comparing the time of the record against the time of the predicted tide, whereas the time of the predicted tide was corroborated by recent sea level measurements in the Bay of Navidad.

# LOCALIZATION OF THE MAXIMUM COSEISMIC SEA-FLOOR UPLIFT



In the dislocation model of Mansinha and Smylie

Fig. 6. **a** – The raw 1 minute (not averaged) data from the pressure gauge SBE42 compared against the predicted tide (smooth line) in the Bay of Navidad. **b** – The residual tide shows the increase in the sea level after the earthquake; the smooth line represents the mean residual tide. The origin of the time axis is defined as the origin time of the earthquake.



Fig. 7. **a** – Residual tide at Manzanillo (thin line connecting circles at 6 minutes interval), and the synthetic tsunami (thick line). **b** – Residual tide from the SBE42 in the Bay of Navidad (line with circles at 2 minutes interval), and the synthetic tsunami (thick line). **b** – Residual reproduce the tsunami arrival time and the amplitude of the first relative maximum in both records. The origin of the time axis is defined as the origin time of the earthquake.

(1971), the maximum uplift due to the rupture is located above the shallow edge of the fault plane. If we assume that the instantaneous sea-level change due to the rupture can be taken to be the same as the sea-floor uplift during the earthquake, then the arrival time,  $\tau$ , of the first peak in the tsunami record corresponds to the travel time of the nearest maximum seasurface uplift. Therefore, the location of the maximum coseismic sea-floor uplift can be estimated from

$$d = \int_{0}^{\tau} \sqrt{gh(S)dt} \quad , \tag{1}$$

by taking the time  $\tau$  for any long wave traveling to the tide gauge along the path, *S*, prescribed by Snell's Law.

In equation (1), d is the distance along the path, g represents the gravitational acceleration, t is time and h is the still water depth along the path. Figure 7 shows that the first peak in the tide record of Manzanillo occurred 19±3 minutes after the origin time of the earthquake (15:36:29.4 given in

the Harvard CMT solution), and the first peak in the SBE42 record occurred 9±0.5 minutes after the earthquake. Using equation (1), for a wide range of trajectories, the offshore ends of both paths (Figure 8), that simultaneously fit the arrival time to Manzanillo and Navidad, fall on the contour of ~2000 m depth, ~24 km from the trench axis. The location of the maximum sea-surface uplift estimated from the tide record of Manzanillo is (18.6808°N, 104.6818°W), whereas the similar estimation for the tide record of Navidad is (18.8677°N, 104.8875°W). The offshore bathymetry was taken from the Navigational Chart SM400 scale 1:750,000 (1996a), whereas for the shallow regions the bathymetry was taken from Charts SM513, scale 1:25,000 (1996b) and SM514, scale 1:5,000 (1998).

# ESTIMATION OF THE MAXIMUM OFFSHORE UPLIFT BY NUMERICAL MODELING OF THE TSUNAMI

Assuming that the earthquake can be modeled as a bur-



Fig. 8. Map of the region and location of rupture area (rectangle) assumed in the numerical modeling of tsunami. Thin lines are the isobaths annotated with the depth values in meters. The filled star on the southeastern edge of the rupture area indicates the starting point of the rupture. The lines from the coast, perpendicular to the isobaths, show the paths, S, on which a barotropic wave (tsunami) would propagate to Manzanillo and Navidad. The ends of the paths at the depth of 2000 m, mark the maximum coseismic uplift of the sea-surface.

ied rectangular thrust fault, we search for the location of the shallow edge of the fault which fits the estimated location of the maximum coseismic sea-surface uplift. To model the tsunami, the magnitude of the slip, considered constant on the fault plane, was varied to reproduce individually the amplitude of the first peak in the tsunami records of Manzanillo and Navidad. In the dislocation model we considered a rectangular thrust fault of length L = 160 km, and width W = 60km, with its shallow edge at a depth of 10 km, oriented parallel to the trench with an azimuth of 309° (Harvard CMT solution), dip of 16° (Bandy et al., 1999; Harvard CMT solution), and rake of 90°. The length of the rupture, starting from the point of the rupture initiation (18.79°N, 104.47°W), was estimated from an aftershock study (L = 170 km, W =70 km, Pacheco et al., 1997), from a study of the rupture process ( $L = 150 \pm 10$  km, Courboulex *et al.*, 1997), and from tsunami data ( $L = 160\pm 20$  km, Ortiz *et al.*, 1998). The width of 60 km was chosen in order to reproduce the estimated coseismic land subsidence in Manzanillo and Navidad using the dislocation model of Mansinha and Smylie (1971). Figure 8 shows the assumed rupture area in the numerical modeling of the tsunami.

The propagation of the tsunami was simulated using the non-linear shallow water equations (Goto *et al.*, 1997):

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 ,$$

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x} \left(\frac{V^2}{D}\right) + \frac{\partial}{\partial y} \left(\frac{UV}{D}\right) + gD \frac{\partial \eta}{\partial x} + \frac{gm^2}{D^{7/3}} U\sqrt{U^2 + V^2} = 0,$$
(2)

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x} \left( \frac{UV}{D} \right) + \frac{\partial}{\partial y} \left( \frac{V^2}{D} \right) + gD \frac{\partial \eta}{\partial y} + \frac{gm^2}{D^{7/3}} V \sqrt{U^2 + V^2} = 0.$$

In equations (2), *t* is time,  $\eta$  is the vertical displacement of the water surface above the still water level, *g* is the gravitational acceleration, and *h* is the still water depth.  $D = (\eta + h)$  is the total water depth. *U* and *V* are the discharge fluxes

# Table 1

Coseismic uplift during the October 9, 1995 Jalisco-Colima earthquake ( $M_w$  8) as the result of tsunami modeling at Manzanillo and Navidad

Location	Latitude, °N	Longitude, °W	Uplift, cm
SBE42 - Navidad	19.1710	104.7464	- 40±2.3
Offshore - Navidad	18.8677	104.8875	+165±20
Tide gauge - Manzanillo	19.0640	104.2978	- 11.8±1.3
Offshore - Manzanillo	18.6808	104.6818	+55±3

in longitudinal (x) and latitudinal (y) directions, and m is Manning's roughness which is set to 0.025.

Equations (2) 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 computation, the time step was set to 1 sec and a grid spacing of 27 sec was used for the whole region, whereas a grid spacing of 3 sec was used to describe the shallow areas and the inland topography. As an initial condition, the sea-level change due to the rupture was taken to be the same as the instantaneous seafloor uplift computed by the dislocation model.

The maximum coseismic sea-surface uplift at the end of the path, starting from Manzanillo, is estimated to be 55±3 cm, whereas at the end of the path, beginning from Navidad, the maximum is 165±20 cm. The uncertainty corresponds to one standard deviation of the residual tide in Manzanillo and Navidad before the earthquake. The 8-hour delay at Manzanillo required for the water level to reach the equilibrium does not affect the amplitude of the synthetic tsunami. In fact, as it was discussed earlier, tsunami oscillations (period of ~30 minutes) are the cause of this delay. The magnitude of the slip was set to 1.5 m to model the tsunami at Manzanillo, whereas a slip of 4 m was necessary to model the tsunami at Navidad. Figure 7 shows a comparison of the synthetic and the recorded tsunamis at Manzanillo and Navidad. In the numerical simulations, a delay of ~2 minutes in the arrival time is produced by moving the fault plane 5 km offshore from the given location in Figure 8. Therefore, due to the sampling rate of the records, we may assume an uncertainty of less than ±5 km in the location of the maximum uplift offshore Navidad, and an uncertainty of ±8 km in the location of the maximum uplift offshore Manzanillo.

# DISCUSSION AND CONCLUSION

The detailed analysis of the tsunami records at Manzanillo and Navidad from the October 9, 1995 Jalisco-Colima earthquake ( $M_w$  8) and the numerical tsunami modeling provide a new independent constraint on the location

coseismic inland GPS data (Melbourne *et al.*, 1997) to carry out a further inversion of the full (land-ocean) displacement data set. It is rather difficult to use our tsunami modeling infer-

ences to distinguish between different models of the faultslip distribution (Figure 1). While we assumed a constant and homogeneous fault-slip in the tsunami modeling to fit the observed data, different slip values should be accepted for Navidad and Manzanillo. Actually the average fault-slip off Manzanillo is less than that one off Navidad. For now, based on these results we can only qualitatively conclude that the fault-slip distribution of Mendoza and Hartzell (1999) is apparently more consistent with the tsunami data than other inversions.

and magnitude of the maximum coseismic uplift (Table 1).

These new results should be complemented with the

An important conclusion inferred from the present and previous works on tsunami modeling is that the tide and pressure gauge records are extremely valuable as additional information to the seismological and geodetic data for studies of large thrust earthquakes in the Mexican subduction zone.

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## BIBLIOGRAPHY

- BANDY, W., V. KOSTOGLODOV, A. HURTADO-DIAZ and M. MENA, 1999. Structure of the southern Jalisco subduction zone, Mexico, as inferred from gravity and seismicity. *Geofís. Int.*, 38, 127-136.
- COURBOULEX, F., S. K. SINGH, J. F. PACHECO and C. J. AMMON, 1997. The 1995 Colima-Jalisco, Mexico, earthquake (Mw 8): A study of the rupture process. *Geophys. Res. Lett.*, 24, 1019-1022.

- ESCOBEDO, D., J. F. PACHECO and G. SUAREZ, 1998. Teleseismic body-wave analysis of the 9 October, 1995 (Mw = 8.0), Colima-Jalisco, México earthquake, and its largest foreshock and aftershock. *Geophys. Res. Lett.*, 25, 547-550.
- FILONOV, A. E., 1997. Researches Study Tsunami Generated by Mexican Earthquake. Eos, Trans. AGU., 78, 3, 21.
- GOTO, C., Y. OGAWA, N. SHUTO and F. IMAMURA 1997. IUGG/IOC TIME Project: Numerical Method of Tsunami Simulation with the Leap-Frog Scheme, Intergovernmental Oceanographic Commission of UNESCO, Manuals and Guides # 35, Paris, 4 Parts.
- KOSTOGLODOV, V., S. K. SINGH, A. GORBATOV, J. F. PACHECO, A. FILONOV and M. ORTIZ FIGUEROA, 1997. October 9, 1985, Mw 8.0 Colima-Jalisco earthquake: New constraints on the coseismic slip distribution, Eos Trans., AGU., 78, 447.
- LIU, P., Y CHO and S. SEO., 1995. Numerical Simulations of the 1960 Chilean Tsunami Propagation and Inundation at Hilo, Hawaii. Tsunami Progress in Prediction, Disaster Prevention and Warning. Y. Tsuchiya and N. Shuto (editors). Kluwer Academic Publishers.
- MANSINHA, L. and E. SMYLIE, 1971. The Displacement Field of Inclined Faults, *Bull. Seimol. Soc. Am.*, *61*, 1433-1440.
- MELBOURNE T., I. CARMICHAEL, C. DeMETS, K. HUDNUT, O. SANCHEZ, J. STOCK, G. SUAREZ, and F. WEBB, 1997. The geodetic signature of the M8.0 Oct. 9, 1995, Jalisco subduction earthquake. *Geophys. Res. Lett.*, 24, 715-718.

- MENDOZA, C. and S. HARTZELL, 1999. Fault-slip Distribution of the 1995 Colima-Jalisco, Mexico, Earthquake, *Bull. Seism. Soc. Am.*, 89, 1338-1344.
- NAVIGATIONAL CHART: SM400 scale 1:750,000, Feb. 1996a, *Secretaría de Marina de México*.
- NAVIGATIONAL CHART: SM513 scale 1:25,000, Feb. 1996b, Secretaría de Marina de México.
- NAVIGATIONAL CHART: SM514 scale 1:5,000, Nov. 1998. Secretaría de Marina de México.
- ORTIZ, M., S. K. SINGH, J. PACHECO and V. KOSTOGLODOV, 1998. Rupture length of the October 9, 1995 Colima-Jalisco earthquake (Mw 8) estimated from tsunami data. *Geophys. Res. Lett.*, 25, 2857-2860.
- PACHECO F. J., S. K. SINGH, J. DOMINGUEZ, A. HURTADO, L. QUINTANAR, Z. JIMENEZ, J. YAMAMOTO, C. GUTIERREZ, M. SANTOYO, W. BANDY, M. GUZMAN and V. KOSTOGLODOV, 1997. The October 9, 1995 Colima-Jalisco, Mexico earthquake (Mw 8): An aftershock study and a comparison of this earthquake with those of 1932. *Geophys. Res. Lett.*, 24, 2223-2226.
- ZOBIN, V., 1997. The rupture history of the Mw 8.0 Jalisco, Mexico, earthquake of 1995 October 9, *Geophys. J. Int.*, 130, 1-9.

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