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The geodetic signature of the M8.0 Oct. 9, 1995, Jalisco subduction earthquake

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Abstract. The October, 1995 Mw 8.0 Jalisco subduction earthquake has provided a thorough geodetic observation of the coseismic subduction process. An 11 station regional GPS network located directly onshore of the rupture demonstrates consistent vertical subsidence verified by tide gauge data and southwest-directed extension, with measured displacements reaching 1 meter. Unusually shallow and non-uniform faulting is required to explain the displacements. We determine that up to 5 meters of slip occurred within the upper 15 km of the thrust fault zone and 2 meters possibly as shallow as 8 km, and that slip was likely distributed in two main patches. The paucity of continental sediments in this subduction zone could be responsible for the anomalously shallow faulting.

Introduction

The October 09, 1995, Mw 8.0 subduction zone earthquake located near Manzanillo, Mexico, was well recorded by an 11 station regional GPS network located directly onshore of and bracketing the epicentral region, giving a detailed geodetic view of the subduction process. The largest event in 60 years along the active Northern Middle America subduction zone, this earthquake produced widespread coastal subsidence rather than the uplift characteristic of most large subduction events [Tsuji et al, 1996; Tabei et al, 1996; Savage, 1983; Thatcher, 1984]. Through inversion of the geodetic data we find that the cause of the anomalous behavior is extremely shallow faulting. This earthquake broke the uppermost regions of the subduction zone, and much of the slip occurred at depths usually considered to be unlikely to undergo brittle failure, typically those above 10 km and characterized by unconsolidated wet sediments which deform by gradual creep [Byrne et al, 1988; Marone and Scholz, 1988]. We hypothesize that the relative lack of continental derived sediments within the Northern Middle America subduction zone allows the anomalously shallow seismic front.

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GPS Observations

The Jalisco GPS network was first occupied in March of 1995, seven months prior to the Mw 8.0 earthquake of October 09, 1995[1]. Fifteen stations were occupied with dual frequency P-code receivers for three days each, with the exception of one coastal station at Manzanillo, which was occupied for 9 days. Following the earthquake, the network was re-occupied six days after the mainshock, and 11 stations were re-measured over the following week. The GIPSY-OASIS II software [Lichten and Border, 1987] and ephemerides and satellite clock corrections provided by the Jet Propulsion Laboratory for the International Geodynamics Service [Zumberge et al, 1995] were used to reduce the data to absolute displacements within the ITRF'94 reference frame [Zumberge et al, 1996]. Average station coordinate repeatabilities (scaled such that χ^2=1) from the first occupation were 4, 8 and 14 millimeters in North, East and Vertical components.

A maximum displacement of 986±14 mm was measured at station CHAM, and a minimum of 39±15mm was measured at station SJDL (Table 1, Fig. 1). All stations show coseismic subsidence, with amplitude decreasing away from the epicentral region. The site CRIP is located on the coast at Manzanillo, near a continuously monitored tide gauge. Data from this gauge, when compared with tide gauge data from Acapulco and Puerto Vallarta, indicate 74 ±10(2σ) mm of subsidence at Manzanillo between the time of the earthquake and 7 days later. The GPS-derived offset, measured 6 days after the event, shows 80±14 mm (2σ) of subsidence, in good agreement with the tide measurements.

The coseismic displacements are not likely to be significantly contaminated by non-coseismic signals. Any inter-seismic strain associated with the roughly 2 -

[1]National Earthquake Information Center(NEIC), Electronic report of revised Harvard CMT solutions, October, 1995

Table 1. Measured and modeled displacements, in millimeters. Errors are 2σ. N,E,V represents North, East, and Up; NE_Cor is correlation between north and east measurements.

Station	GPS Displacement							Model Displacement and Residuals					
ID	N	Nerr	E	Eerr	V	Verr	NE_Cor	N	Nres	E	Eres	V	Vres
AVAL	-72.2	3.2	-124.7	16.4	-37.8	33	0.187	-75.2	3	-120.8	-3.9	-16.7	-21.1
AYUT	-160.8	8.8	-137	25	-111	87.6	0.026	-144.6	-16.2	-99	-38	-13.4	-98
CEBO	-34	5.2	-50.5	14.4	-5	37.8	0.075	-34.4	0.4	-45.4	-5.1	0.9	-5.9
CHAC	-99.8	8.2	-25.6	25.8	-23.1	54.4	0.194	-103.1	3.3	-10.8	-14.8	-30.6	7.5
CHAM	-836	6.4	-479.1	24	-209	47.2	0.25	-836.3	0.3	-457.3	-21.8	-253.9	44.9
CRIP	-392.8	2.2	-315.2	7	-80.3	14.8	0.073	-392.8	0	-314.8	-0.4	-79	-1.3
GUAC	-104.6	5.4	-59.3	12.6	-47.5	34	0.285	-95.4	-9.2	-57.1	-2.2	-3	-44.5
PURI	-417.9	4.6	-274.6	13.2	-104	30.6	0.17	-417.2	-0.7	-308.2	33.6	-180.5	76.5
SJDL	0.6	5.4	-10	18.2	-37.5	28	0.142	-7.6	8.2	-24	14	-17.5	-20
TAPA	-99.6	6.4	-138	22.8	-52.3	48	0.015	-92.2	-7.4	-106.9	-31.1	-9	-43.3
VICT	-3.2	2.4	-27.8	8	-54.3	22.4	0.172	-8.2	5	-37.1	9.3	-12.4	-41.9

5 cm/year Rivera-North America plate convergence [DeMets and Stein, 1990; Kostoglodov and Bandy, 1995] during the seven months between network occupations should be small compared to the coseismic offsets measured. Similarly, long-term tectonic strain within the rift zone around the network is measured in millimeters/year and should also be quite low [Allan, 1986; Nieto-Obregon et al., 1985; Ferrari and Rosas, 1996].

The pattern of displacement is qualitatively consistent with a purely elastic response to thrust faulting along a shallowly dipping plane offshore the GPS network. The orientation of the displacement vectors varies smoothly across the network; the site furthest to the northwest (CHAC) has a SSW-oriented vector while at the southern end of the network (SJDL, VICT) the vectors are oriented west, and displacement of stations directly inland of the epicenter point SW, as is expected for a response uncontaminated by imbricate faulting or other local tectonic processes. The small offsets measured at coastal sites furthest from the epicenter show that the network bracketed the deformation field well; SJDL and CHAC have offsets of only 4% and 11% of the largest coastal displacement, measured at CHAM.

Although this earthquake appears from the geodetic measurements to have ruptured the Rivera-North America plate boundary, the nature of the boundary between the Rivera and Cocos plates at the surface is not well determined. The Cocos plate is thought to subduct at up to twice the rate of the Rivera plate [DeMets

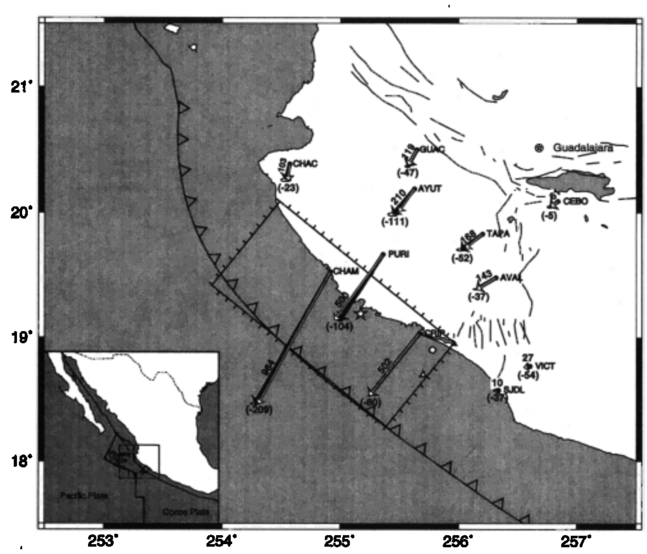

Figure 1. Coseismic displacements for the Oct., 1995, Rivera plate subduction earthquake (Mw=8.0). GPS measurements are shown as solid black vectors, with amount (in millimeters) of horizontal offset written along the vector and vertical offset in parentheses at the vector tip. GPS vectors at stations SJDL and VICT point west. Ellipses represent 2D 95% confidence intervals. Thin white vectors are modeled from slip distribution in Fig. 2. Gridded rectangle is the surface projected model fault plane, and the Harvard and Caltech centroids and the NEIC epicenter are indicated by the star, circle and triangle, respectively. Inset. The Rivera and Cocos plate subduction zones.

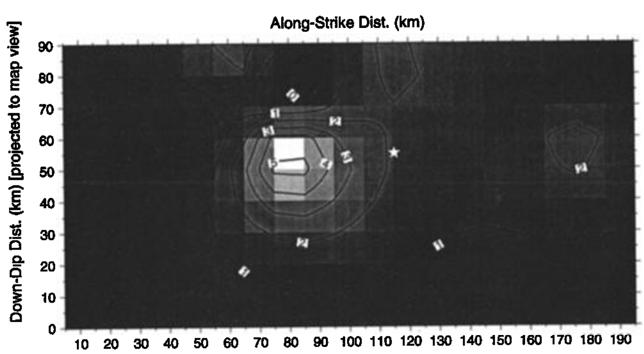

Figure 2. Distribution of slip on the Rivera plate thrust fault. Contours and shading indicate the thrust-slip amplitude (in meters). The model plane has 20 subfaults along-strike and 10 sub-faults down-dip, each 10 km by 10 km. The distribution indicates two distinct slip patches separated by 95 km, in agreement with seismic evidence for a multiple-source event. The star indicates the projected position of the Harvard CMT epicenter.

and Stein, 1990; Kostoglodov and Bandy, 1995], and recent sea floor observations suggest that the boundary is not necessarily a discrete feature but rather a zone of deformation between the East Pacific Rise and the Middle America Trench [Bandy, 1992]. This difficulty in identifying a Rivera-Cocos boundary therefore precludes an absolute determination of which plate interface with North America broke during this event.

Inversion

To estimate the distribution of thrust-slip on the rupture plane we invert the data using singular value decomposition (SVD) after [Larsen [1991]] and Hudnut et al [1996]. We find that a uniform slip model cannot adequately fit the three large displacements at CHAM, PURI and CRIP without an excessively large seismic moment; using a smaller fault plane situated so as to best fit CHAM and PURI produces a very poor fit at CRIP. The SVD method, whose limitations we discuss below, inverts the three component GPS vectors (accounting for uncertainties) for slip along an *a priori* fault with a specified number of subfaults. For the fault we use a single plane consistent with the Harvard CMT solution for this event as well as the fault geometry inferred for the region by Pardo and Suarez [1995] from local and teleseismic data. The fault plane (Fig. 1, Fig. 2) has an along-strike length of 200 km, a downdip width from the trench of 100 km, a dip of 16° and has 200 10x10 km subfaults. We placed no constraints on the amount of slip at the edges and employed no smoothing outside of the averaging intrinsic to singular value decomposition; in this inversion there are 8 singular values. It should be noted that because stations CHAM, PURI and CRIP contain roughly 80% of the total offset measured in the network, these three stations dominate the inversion.

Discussion

The slip distribution (Fig. 2) indicates that nearly all of the slip occurred within the upper 18 km of the surface, with a maximum of 5 meters at 15 km depth and 2 meters of slip as shallow as 8 km. The most robust aspect of the inversion is this lower depth limit of faulting; it is insensitive to small variations in either the dip, the area of the fault plane, or the number of independent subfaults, and is primarily a result of the geometry of the subduction zone and its proximity to the coast. Qualitatively, the boundary between coseismic uplift and subsidence for slip along a shallow-dipping thrust fault delineates a trench-parallel axis, or hingeline, whose position lies near the surface-projected down-dip terminus of fault rupture. To match the coastal vertical subsidence measured in Jalisco, the majority of slip on the fault must be located sufficiently far offshore that the deformation hingeline also lies offshore, i.e., such that only subsidence is produced on land. As the northern Middle America trench near Jalisco is located at a relatively close 65-80 km from the coast, or half that of Chile and other major subduction zones [Thatcher, 1984], fault slip located sufficiently far offshore to produce the measured subsidence is therefore constrained to lie within the upper reaches of the fault. Tests of the *a priori* fault parameters cause only minor deviations from the slip distribution presented here, and in particular, extending the fault plane further to the southeast produced negligible slip there.

The SVD inversion also shows two distinct slip regions, one offshore of station CHAM and another at the same depth but 95 km to the southeast, offshore of CRIP. Although these two slip concentrations are consistent with seismic interpretations of a 100 km rupture length [Kikuchi 1995] and a major sub-event separated in time from the mainshock by approximately 35 seconds[2] (implying a slip-patch separation distance of 90-115 km for a rupture velocity between 2.5 to 3 km/s), it should be noted that the inversion cannot uniquely resolve the along-strike shallow slip. The slip patch directly offshore CRIP reflects the fact that there are no stations near CRIP which could better constrain the inversion. Furthermore, slip in the uppermost regions of the fault is poorly constrained due to a lack of GPS stations offshore. The SVD inversion therefore gives a reliable lower depth limit to faulting and attempts to resolve the first order slip distribution in the shallow portions of the fault; however, additional data is needed for increased resolution.

The slip distribution agrees with previous studies showing a shallow seismogenic zone in the Middle America Trench extending only to a depth of 25±5 km; this depth is roughly half of that observed in most subduction zones of the world and appears to control the maximum earthquake size here [Suarez and Sanchez, 1996]. The narrow locked portion of the fault could be controlled in part by sediment supply. The Jalisco-Colima coast has no large river systems through which a high continental sediment flux can reach the trench, and there is little to no accretionary prism offshore and therefore presumably relatively little subduction of hydrated sediments compared to other convergent margins with deeper seismogenic zones. Faulting mechanisms tying brittle failure in subduction zones to sediment rheology and supply [Marone and Scholz, 1988] predict a shallower seismic front in subduction zones which receive less sediment.

Sediment rheology provides a consistent explanation for the up-dip limit of seismicity offshore Jalisco but the shallow down-dip limit is more likely to be controlled by temperature. The temperature of the down-going slab has been suggested by several studies to be the primary controlling factor on the down dip extent of the locked portion of subduction zones [Tichelar and Ruff,

[2]NEIC

1993, Hyndman and Wang, 1993]. As the down-going slab offshore Jalisco is relatively thin, the temperature-controlled transition from velocity-weakening to velocity-strengthening in the fault constitutive properties within hydrothermal environments can occur at shallower depths in this subduction zone compared to the global average.

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