The 2017 $M_W$ 8.2 Chiapas, Mexico Earthquake: Energetic Slab Detachment

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Key Points:

- The 2017 $M_W$ 8.2 Chiapas normal faulting earthquake beneath the Tehuantepec gap involved lithospheric-transecting rupture of the thin Cocos slab.
- Seismic, tsunami and GPS data indicate that the rupture extended ~100 km unilaterally to the northwest along strike and from ~30 to 70 km in depth.
- Relative to megathrust earthquakes, subduction zone intraslab faulting is more energetic, resulting in strong ground shaking for the 2017 event.
Abstract

On 8 September 2017, a great ($M_w$ 8.2) normal-faulting earthquake ruptured within the subducting Cocos Plate ~80 km landward from the Middle American Trench beneath the Tehuantepec gap. Iterative inversion and modeling of teleseismic and tsunami data, and prediction of GPS displacements indicate that the steeply dipping rupture extended ~180 km to the northwest along strike toward the Oaxaca coast and from ~30 to 70 km in depth, with peak slip of ~13 m. The rupture likely broke through the entire lithosphere of the young subducted slab in response to down-dip slab pull. The plate boundary region between the trench and the fault intersection with the megathrust appears to be frictionally coupled, influencing location of the detachment. Comparisons of the broadband body-wave magnitude ($m_b$) and moment-scaled radiated energy ($E_R/M_0$) establish that intraslab earthquakes tend to be more energetic than interplate events, accounting for strong ground shaking observed for the 2017 event.

1 Introduction

Along the stretch of the Middle American Trench offshore of southern Mexico from 94°W to 96°W, the Tehuantepec Ridge is subducting at about 7.5 cm/yr (Fig. 1). The dip of the underthrust Cocos slab transitions from shallowly dipping beneath Mexico to the northwest to steeply dipping beneath Central America to the southeast (Ponce et al., 1992). There is no record of a confidently-identified large underthrusting earthquake on the plate boundary in this region, so it has been designated as the Tehuantepec Gap for many decades (e.g., Kelleher et al., 1973; Kelleher & McCann, 1976; Singh et al., 1981; Nishenko, 1991), with very uncertain seismic potential. This region was struck by a large earthquake on 8 September 2017 [15.036°N, 93.907°W, 56.7 km deep, 04:49:20.0 UTC, US Geological Survey National Earthquake Information Center (USGS-NEIC), https://earthquake.usgs.gov/earthquakes/eventpage/us2000ahv0#origin]. Rather than being a plate boundary thrust event, which might have filled the seismic gap, the faulting mechanism and depth indicate an intraslab normal-fault rupture. The moment magnitude estimates from the USGS-NEIC ($M_{ww}$ 8.1) and the global Centroid-Moment Tensor (gCMT) Project ($M_w$ 8.2; http://www.globalcmt.org/CMTsearch.html) and the ~200 km long distribution of early aftershocks...
indicate a rare great intraslab earthquake located beneath the broad continental slope offshore of southern Mexico (Fig. 1). The hypocenter estimate in the Mexican SSN catalog [14.85°N, 94.11°W, 58 km deep, Servicio Sismológico Nacional, National Autonomous University of Mexico, http://www.ssn.unam.mx/, SSN (2017)] is located about ~30 km southwest of the USGS-NEIC location (Fig. 1).

Shaking from the earthquake was devastating in southern Mexico, with at least 98 fatalities, mostly in Oaxaca, and 41,000 homes damaged. Peak tsunami waves 1 to 1.75 m in amplitude were recorded at Salina Cruz and in Chiapas. The offshore faulting location prevented shaking from causing even more severe damage. Large shallow (<70 km deep) intraslab normal faulting has previously struck beneath land under Mexico, causing major destruction, such as in 1858 (M ~7.7; Singh et al., 1996), 1907 (Oaxaca, M ~7.6), 1931 (Oaxaca, M ~7.6; Singh et al., 1985), 1957 (Guerrero, M ~7.6), and 1999 (Oaxaca, Mw 7.5; Singh et al., 2000), as well as beneath the broader offshore continental slope along Guatemala (1957, M ~7.7) and El Salvador (2001, Mw 7.7; Vallée et al., 2003).

The 2017 event is the largest intraslab event documented along the Mexican subduction zone, and it is challenging to evaluate the seismic potential for such events given that the strain budgets in the slab are poorly known. Temporal patterns of intraslab seismicity have been examined for coupled and uncoupled subduction zones (Astiz & Kanamori, 1986; Christensen & Ruff, 1988; Astiz et al., 1988; Dmowska et al., 1988; Lay et al., 1989; Mikumo et al., 2002; Ye et al., 2012). For weakly coupled regions, great intraslab normal faulting may occur near the trench or in the outer rise, e.g., the 1977 Mw 8.3 Sumba earthquake (Spence, 1986; Lynnes & Lay, 1988), or after a shallow megathrust has ruptured, as for the 1933 Mw 8.4 Sanriku earthquake (Kanamori, 1971) or the 2007 Kuril Mw 8.1 earthquake (e.g., Lay et al., 2009). If there is strong coupling of the megathrust that has not recently failed, great intraslab normal faulting may occur down-dip of the coupled zone, as for the 1977 Mw 8.1 Tonga earthquake (Christensen & Lay, 1988).

The Tehuantepec Ridge has significant bathymetric expression and the buoyant ridge intersects the coast where there is a major landward shift of the coastline and a very broad submerged continental shelf. GPS stations in Chiapas are thus located at large distance from the shallow megathrust, unlike along Oaxaca where the offshore distance to the trench is
small. The plate boundary in the Tehuantepec Gap has relatively few interplate thrust fault solutions in the gCMT catalog (Fig. 1, Supplemental Figure S1), with most locating seaward of the aftershock pattern for the 2017 event. There is more interplate thrusting along the megathrust along Oaxaca to the northwest, and offshore of the southernmost Chiapas coast east of 94°W. This region is also tectonically complicated by the northwestward extension of the Caribbean plate and the oblique trend of the Caribbean-North American plate boundary through central Guatemala and offshore over the region of the 2017 rupture. The Caribbean plate appears to be leaving a forearc block behind as it moves eastward, complicating the upper plate deformation pattern. Franco et al. (2012) allow for this and infer a fairly high interplate coupling, >0.6, offshore of Chiapas as far west as 95.5°W, spanning the region above the 2017 rupture zone, in contrast to relatively low coupling to the southeast offshore Guatemala and El Salvador.

The rupture characteristics of the 2017 Chiapas earthquake are determined here to evaluate tectonic implications of this event and to address the severity of the strong shaking associated with the source radiation.

2. Analysis of the Source Process

Global long-period W-phase data are inverted for a point-source representation of the 2017 earthquake to constrain the faulting geometry, centroid depth, and seismic moment (Kanamori & Rivera, 2008). We use 182 channels from 71 Federation of Digital Seismic Network stations filtered in the frequency band of 2 to 5 mHz. The best-double couple for the solution has strike 313°, dip 77.7°, and rake -95.5°, with seismic moment of 2.57 x 10^{21} Nm (M_w 8.21), a 26.0 s centroid time shift for an assumed symmetric triangular source time function, and a centroid location of 15.340°N, 94.309°W at 50.5 km depth (Fig. S2). The centroid depth resolution for the W-phase inversion is limited, so we enhance the sensitivity to centroid depth by evaluating the misfit in the predicted fundamental mode Rayleigh wave signal that follows the W-phase window for vertical component recordings using the W-phase inversion solutions for specified depths. The Rayleigh wave misfit is also minimized at 50.5 km, with a broad region of low misfit from 45 to 65 km (Fig. S2).
Given the tendency for USGS-NEIC locations to be biased in the slab-dip direction for
subduction zones (Fig. S1c), we measure the first-arrival times from regional seismograms to
relocate the hypocenter. A grid search indicates an optimal location at 14.940°N, 93.940°W
(Fig. S3), which is between the initial USGS location (subsequently updated to near our
preferred location) and the SSN location, placing the hypocenter below the edge of the
continental slope (Figs. 1, S3). The depth is not resolved in the relocation, and we fix it at 60
km, similar to the other solutions.

Using the relocated position, we perform a teleseismic short-period (0.5-2.0 s) P wave
back-projection for data in westernmost North America (Fig. S4), using the method of Xu et al.
(2005). The resulting image indicates unilateral rupture propagation toward the northwest,
extending into Oaxaca, with overall rupture speed of ~3 to 4 km/s. We found that back-
projections for seismic networks in eastern North America, Europe and a global configuration
did not provide robust images.

Guided by the faulting geometry from the W-phase inversion, our relocated hypocenter,
and the kinematic constraints from the back-projection, we invert for finite-fault rupture
models using teleseismic broadband P-wave displacements and SH-wave velocities (Fig. 3)
using linear least square inversion based on Hartzell & Heaton (1983) and Kikuchi & Kanamori
(1992), as updated by Ye et al. (2016a, b). We use a planar fault extending asymmetrically
toward the northwest, parameterizing each subfault to extend 10 km along strike and 7.5 km
along dip, with a source time function having 14 2-s rise-time triangles offset by 2-s each,
allowing up to 30 s subfault durations. The teleseismic data can be fit very well for
predominantly unilateral models with rupture expansion velocities of 3 to 4 km/s and total
rupture lengths of 160 km or longer, for the USGS, SSN or our preferred source locations. To
improve the constraint on absolute location of the faulting and the overall rupture length and
rupture speed, we model deep-water tsunami recordings and a preliminary open data set of
GPS coseismic displacements. Figure 2 shows the final rupture model that we obtain and
Figure 3 shows the fit to the teleseismic observations for this model.

We obtain this final model by iterative modeling of 5 ocean-bottom pressure sensor
recordings from NOAA DART buoy stations (Fig. 4), which recorded very clear deep-water
tsunami waveforms. In modeling the tsunami recording we use NEOWAVE, a shock-capturing
non-hydrostatic model based on the staggered finite-difference formulation (Yamazaki et al., 2009; 2011a). The governing, nonlinear shallow-water equations are coupled with a pressure Poisson equation for the depth-averaged vertical velocity, which accounts for weakly-dispersive tsunami waves. The time-varying deformation of the seafloor is resolved by a vertical velocity term that makes the calculation fully consistent with the kinematic finite-fault slip model. Two two-way nested grid levels are used to represent the 30 arc-sec GEBCO_08 bathymetry near the coastal source region and 2 arc-min bathymetry over the eastern Pacific.

We follow an iterative modeling strategy similar to prior successful applications (e.g., Yamazaki et al., 2011b; Lay et al., 2013; Bai et al., 2017), inverting the seismic data for a finite source model, predicting the tsunami observations, deducing necessary modifications of the under-constrained seismic inversion parameters (fault dimensions, absolute fault placement) and iterating to convergence on a self-consistent source representation that provides good fit to both sets of observations. We focus on placement of slip along-strike and absolute placement of the model. The shallow continental shelf is effective in trapping tsunami energy. The initial arrivals at the DART stations primarily come from the uplift on the continental slope (Fig. 4a). The stations provide a 180º coverage of the tsunami to constrain the fault placement (Fig. 4b). Using the initial USGS-NEIC location we found very poor prediction of the tsunami waveforms and deduced that the source must locate closer to the shelf break. We also found poor predictions of the tsunami for the SSN location. Using our relocated hypocenter from regional travel times in between the USGS-NEIC and SSN locations (Fig. S3), we find significant improvement in the tsunami waveform fits (Fig. 4c).

A suite of models for varying choices of strike, dip, hypocentral location, fault length, rupture velocity, and subfault source duration defines the range of parameters compatible with both seismic and tsunami observations. Rupture models with fault lengths <150 km provide satisfactory fits to both data sets. However, the GPS displacements for stations in Oaxaca provide additional constraints on the northwestward extent of faulting (Fig. 4a). We therefore seek models consistent with all three data types by extending the rupture to near the Oaxaca coast, matching the strength and direction of the displacements at stations OXTH, OXUM, TNSJ, TNNP, and TNCY using the elastic half space solution of Okada (1985). The rupture model in Figure 2, obtained entirely from seismic inversion, predicts the horizontal
displacements well for the Oaxaca stations (Fig. 4a), and gives excellent fits to the seismic
data accounting for 88% of the signal power (Fig. 3), and to the tsunami waveforms (Fig. 4c).
The preferred model has a rupture expansion speed of 3.5 km/s, resolved to about ± 0.5
km/s, a fault model extending 185 km northwestward from our relocated hypocenter to
below the Oaxaca coastline (Fig. 1a), with strike of 313° and dip of 77.7°. We found acceptable
models for strike and dip varying by a few degrees, so we settled on the solution with our $W$-
phase geometry, ensuring consistency with long-period seismic waves as well. The moment
rate function has a dominant pulse 40 s in duration, with energy later than 50 s originating
near the Oaxaca coast, about 180 km from the source. The late slip abuts the edge of our
model, but extending the model further over-predicts the geodetic displacements. It is
plausible that the late slip is on a separate fault plane, possibly with different geometry, so it is
not well-constrained and is not critical to the fit of the seismic and tsunami data. However,
there is certainly a need for minor slip near the coast to match the Oaxaca GPS data. The
seismic moment of our final model is $2.56 \times 10^{21}$ Nm, with a centroid time of 29 s, compatible
with the $W$-phase solution. The slip-weighted static stress drop for the final model is 18 MPa
using the procedure from Ye et al. (2016a).

We estimate the average source spectrum for the 2017 earthquake using the spectrum of
slip model moment-rate function for frequencies less than 0.05 Hz and averaged P wave
spectra after corrections of radiation pattern, geometrical spreading and attenuation for
higher frequencies. The decay rate, $\sim 1.3$, from $\sim 0.1-1$ Hz, is lower than the average decay rates
$\sim 1.6$ for large interplate events (Ye et al., 2016b), suggesting increased high-frequency source
radiation. The radiated energy is $2.56 \times 10^{16}$ J, following the procedure described by Ye et al.
(2016b), giving a relatively high moment-scaled value of $2.38 \times 10^{-5}$.

4 Discussion

The seismic waves from the 2017 earthquake are relatively enriched in short-period
energy, and we place the event in the context of other intraplate events relative to interplate
ruptures in Figure 5. Here we determine the classic broad-band body wave magnitude ($m_b$
(Gutenberg, 1945) measured at periods of $\sim 3.7$ s (7.79) and $\sim 7.3$ s (7.83) after converting
broadband P waves to Wiechert seismometer responses with dominant periods of 3.5 s and
10 s, respectively, for consistency with old events (Utsu, 2002; Bormann and Saul, 2009). The 2017 event lies along the trend of $m_b$ versus $M_W$ for intraplate ruptures, which is about 0.35 magnitude units higher than the parallel trend found for typical interplate ruptures, and much higher than for tsunami earthquakes (Fig. 5a). The use of the classic magnitude measure allows comparison with the 1931 Oaxaca and 1933 Sanriku normal faulting events, with the 2017 value locating on the same trend. The moment-scaled radiated energy, which can only be robustly estimated for recent events, is also consistently higher than for most interplate events (Fig. 5b).

The large size of the Chiapas rupture suggests fracture of the entire Cocos lithosphere along the Tehuantepec Ridge. The lithosphere is ~25 Ma, so the brittle portion is expected to be on ~30 km (Manea & Manea, 2006). The large-scale variation in dip of the slab may influence the stress state locally (Ponce et al., 1992), but the stress is dominated by down-dip tension, consistent with the steeply dipping normal fault for the 2017 event. We view the rupture as more likely to represent breaking of the plate than bending of the upper portion of the brittle lithosphere due to the size and extent of the rupture. While the depth extent is not precisely resolved by our data, the rupture appears to extend from ~30 to 70 km, sufficient to locally detach the lithosphere. The location relative to the trench is similar to that for the 1931 Oaxaca earthquake, which is down-dip of a locked portion of the megathrust (Singh et al., 1985). We infer that the seaward portion of the megathrust up-dip from where the 2017 rupture plane intersects it is partially locked, based on the occurrence of minor thrusting activity in this region and the regional geodetic inference of slip deficit (Franco et al., 2012). However, the lack of historic large megathrust ruptures in the relatively narrow strip of megathrust slip deficit raises the possibility that the coupling is either very heterogeneous due to the bathymetric structure of the subducting ridge, reducing the size of ruptures in the region, or the buoyancy is such that the region is undergoing high-stress creep rather than stick-slip motion. In either case, the existence of shallow slip-deficit may have concentrated slab-pull stress at the lower edge of the locked zone, influencing the 2017 location, rather than allowing extensional stress to concentrate near the trench to produce great normal faulting there.
5 Conclusions

The 2017 Chiapas earthquake ruptured through the lithosphere of the subducting Cocos slab, essentially detaching the slab locally over an ~ 150 km long region. The event activated faulting just offshore of the Oaxaca coast on either the same fault or another one, and that signal contributed strongly to the GPS deformations in Oaxaca. The $M_w$ 8.2 earthquake is one of the largest recorded events within a subducting plate beneath the megathrust. Geodetic indications of slip deficit and the occurrence of few small interplate thrusting events seaward of where the 2017 faulting intersects the megathrust suggests that the shallow slip-deficit region influenced where stress concentrated to rupture the plate. The rupture is energetic, with high moment-scaled radiated energy and a large $m_B$ (7.8) typical of intraplate ruptures. The enhanced level of short-period energy contributed to the significant shaking damage experienced in southern Mexico.


References


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Figure 1. Tectonic environment and seismicity around the 8 September 2017 Mw 8.2 Chiapas earthquake. (a) Large earthquakes (M ~7+) from 1900 to 1976 from the USGS-NEIC catalog (magenta circles), along with gCMT solutions for M5+ events from 1976 to 2015 (gray focal mechanisms). Stars show epicenters of the 2017 Chiapas mainshock from USGS-NEIC, SSN and our relocation from regional P arrivals. Green focal mechanisms show gCMT and W-phase solutions. Blue rectangle indicates the slip region of our preferred slip model (Fig. 2). Aftershocks with $M \geq 3.5$ from SSN (circles), along with available gCMT solutions, are color coded with source depth. The dashed curves show slab surface depths from model Slab 1.0 (Hayes et al., 2012), with 20-km increments. Arrows indicate the Cocos plate motion relative to a fixed North America plate from model MORVEL (DeMets et al., 2010). (b) Depth profile of the mainshock, aftershock sequence and gCMT focal mechanisms along profile A-A’ (azimuth 35°) within distances of ±175 km. The bold blue line indicates the approximate depth extent of the mainshock from our preferred slip model. The dashed gray curve shows the slab surface along profile A-A’.

Figure 2. Finite-fault slip model inverted from teleseismic P and SH waves for the 2017 Chiapas earthquake. (a) The slip distribution is shown with arrows indicating average rake of each subfault, and slip magnitude being color-coded. A maximum rupture expansion speed $V_r$ 3.5 km/s is used, with 10 s isochrones for the expanding rupture fronts (white dashed curves). (b) The moment-rate function, seismic moment and centroid time. (c) The average source spectrum (red) and a reference $\omega^{-2}$ spectrum (dashed line) with assumed stress parameter of 3 MPa and shear-wave speed of 3.75 km/s. (d) Radiation patterns of teleseismic P and SH waves from the average double-couple focal mechanism. Cyan dots indicate the positions sampled by 74 P waves and 49 SH waves used in the inversions.

Figure 3. Comparison between observed (black) and synthetic (red) teleseismic P displacement and SH velocity waveforms from our preferred slip model (Fig. 2), plotted a function of directivity parameter relative to the fault strike direction (azimuth of 313°). The blue dashed lines in (a) and (b) are reference curves for unilateral rupture to the northwest along the fault strike direction with a speed of 3.0 km/s.

Figure 4. Comparison between observed and predicted GPS and tsunamis for our preferred slip model. (a) Black and red arrows show observed and predicted horizontal static motions at GPS stations. Background color indicates predicted vertical deformation. Data for OXPE, OXTH, ICHS and TNPJ are determined from rapid time series with large uncertainty. The red star and rectangle show the mainshock epicenter and slip region, and cyan vectors show the slip distribution and magnitude.
(b) Tsunami wave peak surface amplitude across the eastern Pacific and regional nested (black rectangle) grids at 2 arc-min and 30 arc-sec resolution. Circles show the location of DART stations used in constraining the slip distribution. (c) Comparison of recorded (black) and computed (red) waveforms (left) and amplitude spectra (right) at DART stations.

Figure 5. Body-wave magnitude ($m_b$) and radiated energy normalized by seismic moment ($E_b/M_0$) plotted as a function of moment magnitude ($M_w$) for earthquakes in different tectonic environments. The red, green and blue dots show intraplate, typical megathrust, and tsunami earthquakes, respectively.
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