We examine the along-strike transition from flat to steeper subduction in Oaxaca, Mexico to provide a better understanding of what controls the slab morphology. Prior studies have suggested the slab tends to tear along the transitions in dip as the slab rolls back. We determine the slab geometry based on local seismicity, nonvolcanic tremor (NVT), and slow slip utilizing a deployment of broadband seismometers and continuous GPS receivers distributed in and around Oaxaca. We construct depth contours of the subducting slab surface down to 100 km, which illustrate that the transition from flat to steeper subduction occurs rapidly via a sharper flexure than previously recognized. The prior catalog of NVT in Oaxaca is extended using the same method and additional stations that extend further west. The band of NVT follows the new slab contours, widening towards the west with the downdip extent gradually moving inland. The amount of NVT also correlates with the strength of an ultra slow velocity layer. There are no gaps in seismicity, NVT, or slow slip across the rapid transition in slab dip, further supporting the notion that the slab is not currently torn in the updip region. We propose that the sharp flexure is possible in this region due to bending moment saturation that leads to greater curvature in both the down-dip and along-strike directions. A similar set of observations in southern Peru suggests this is a viable alternative to tearing that accommodates the large strains from variable rates of slab rollback.
NEW PERSPECTIVE ON THE TRANSITION FROM FLAT TO STEEPER SUBDUCTION IN OAXACA, MEXICO, BASED ON SEISMICITY, NONVOLCANIC TREMOR, AND SLOW SLIP

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This Thesis titled

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IN OAXACA, MEXICO, BASED ON SEISMICITY, NONVOLCANIC TREMOR, AND
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1. Introduction

The Mexico subduction zone is an ideal location for studying subduction processes because of along-strike variations in dip of the subducted Cocos plate (Fig. 1). Based on relocated hypocenters of local earthquakes, Pardo and Suárez [1995] first described the subducted slab as having a subhorizontal segment bounded by more steeply dipping segments: ~50° near the Rivera-Cocos plate boundary and ~30° near the Isthmus of Tehuantepec. Flat slab regions are not uncommon, as they occur in 10% of modern convergent margins [Gutscher et al., 2000]. However, what causes the flat slab geometry is still uncertain. Recent studies used receiver functions and seismic velocity tomography to further describe the flat slab as horizontally underplating the North American plate at a depth of 45 km for a distance of ~ 250 km from the trench in the Guerrero region, before descending steeply (~75°) beneath the southern margin of the Trans Mexican Volcanic Belt and truncating at a depth of 500 km [Pérez-Campos et al., 2008; Husker and Davis, 2009; Kim et al., 2010]. This unusual subduction geometry suggests the slab is in rollback mode [Pérez-Campos et al., 2008], which is confirmed by the age progression of volcanism migrating trenchward [Ferrari, 2004].

While many studies have examined the overall geometry of the flat slab, few have looked at the along-strike transitions from flat to steeper subduction. Some of those studies have suggested the slab tends to tear along the sharp transitions in slab dip as the slab rolls back [Bandy et al., 2000; Dougherty et al., 2012; Stubailo et al., 2012; Dougherty and Clayton, 2014]. Along the western transition from flat to steeper subduction, studies based on waveform modeling and seismic anisotropy analysis suggest the Cocos plate is currently tearing along the projection of the Orozco Fracture Zone by a process similar to that which occurred during the Rivera and proto-Cocos plate tearing event 10 MA [Bandy et al., 2000; Dougherty et al., 2012; Stubailo et al., 2012]. Along the eastern transition from flat to steeper subduction, Dougherty and Clayton [2014] propose a less developed or young tear exists in the downdip portion of the Cocos plate. The coincidence of the sharp transition in dip, the abrupt end of the Trans Mexican Volcanic Belt, the boundary between regions of ultra slow velocity layer (USL) and no USL, and a margin of a zone of decreased seismicity suggests a change in plate structure, which Dougherty and Clayton [2014] interpret as evidence of a possible tear (see Dougherty and Clayton [2014] for more observations).

The updip portion of the plate along the eastern transition in dip appears to still be continuous given that a diffuse weakening USL occurs closer to the coast [Dougherty and Clayton, 2014]. A USL is thought to represent a fluid-saturated portion of the oceanic crust, forming a high pore fluid pressure layer [Song et al., 2009] or upper oceanic crust that is highly heterogeneous and composed of mechanically weak hydrous minerals (talc) that might be under high pore pressure [Kim et al., 2010]. The presence of a USL in a region likely indicates continuity within the upper subducted slab, as hydrous minerals and pore fluid of the USL would be difficult to maintain across a discontinuity in the slab [Dougherty et al., 2012].

The USL is also thought to be a key contributor to the process of episodic tremor and slip that has been discovered along the Mexico subduction zone [Payero et al., 2008; Song et al., 2009; Brudzinski et al., 2010; Kostoglodov et al., 2010] as the high pore fluid pressures would be expected to greatly reduce the effective normal stress on the plate interface, promoting episodic slow slip [Liu and Rice, 2005, 2007] and dynamic triggering of tremors [Rubinstein et al., 2007]. Slow slip events (SSE) consist of transient, aseismic fault slip lasting up to weeks or months that is often coincident with low-level seismic vibrations termed non-volcanic tremor (NVT) that appears to represent a swarm of low-frequency earthquakes [Dragert et al., 2001; Obara, 2002;
Both of these phenomena are thought to occur along the deepest portion of the plate interface transition zone (~30-50 km) [Dragert et al., 2001; Obara et al., 2004; Brown et al., 2009]. For this reason they can also be used as indicators of slab continuity, as gaps in tremor have been correlated to tears in the downgoing slab [Ide et al., 2010; Abbott and Brudzinski, 2015].

The increases in seismic and geodetic instrumentation deployed in recent years have allowed for improved characterization of seismicity in many subduction zones. Local seismic studies of small magnitude earthquakes provide high-resolution images of seismogenic zones, hence providing the opportunity to better study the configuration of a subducted slab [e.g., Nishizawa et al., 1990; Hino et al., 1996; Husen et al., 1999; Shinohara et al., 2005]. The Oaxaca segment is a prime region to study slab geometry due to its relatively rapid convergent rates (50-70 mm/y), unusually shallow subduction angles, and well-studied seismic history [Kostoglodov and Ponce, 1994]. In particular, the relatively short (~50 km) trench-to-coast distance brings the seismogenic and transition zones ~250 km inland, providing a chance to pursue detailed studies of the plate interface. In this study, the eastern transition from flat to steeper subduction in Oaxaca, Mexico (Fig. 1) is examined in greater detail using high resolution seismic data to provide a better understanding of how the slab morphology changes during slab rollback. We determine the geometry and continuity based on local seismicity, NVT, and slow slip utilizing a deployment of broadband seismometers and continuous GPS receivers distributed in and around Oaxaca.

2. Data and Analysis

The joint seismic-GPS network includes seven portable Guralp CMG-3T three-component broadband seismometers installed in and around the state of Oaxaca in June 2006 (Fig. 2). The original purpose of the network was for detecting and monitoring NVT and microseismicity signals along the Oaxaca segment [Brudzinski et al., 2010], but the network is useful for monitoring local seismicity as well. The seismic stations are distributed inland along the Oaxaca segment covering an area of ~300 km east-west and 200 km north-south with nominal ~80 km spacing, and pockets of higher density GPS instrumentation [Brudzinski et al., 2007; Correa-Mora et al., 2008, 2009]. Two additional stations were established in 2008 in eastern Guerrero. Five broadband seismic instruments from the permanent National Seismological Service (SSN, Servicio Sismológico Nacional) array in Mexico were used as well. This study focuses on the spatial and temporal behaviors of seismic activity along the Oaxaca segment for the purpose of determining the slab configuration beneath Oaxaca.

Our characterization of seismicity patterns along the Oaxaca segment began with the organization and analysis of seismic data from the six years of recording (June 2006 – March 2012) using the Antelope software package. We initially calculated our locations using the global iasp91 velocity model and then utilized the 1D velocity model from Brudzinski et al. [2010] modified from Valdes et al. [1986] developed for the Oaxaca region. The comparison of locations from the two velocity models resulted in a median difference of 3 km horizontally and 5 km vertically. The results we present use the locally-derived velocity model from Brudzinski et al. [2010]. Our analysis followed the approach of Abbott and Brudzinski [2015]. We began the processing of the seismic data by applying a multi-frequency short-term average vs. long-term average (STA/LTA) detector (dbdetect) on all vertical component waveforms. We used default antelope parameters, including overall signal-to-noise ratio detection threshold of 5 and short/long window lengths of 5 s / 50 s, 2 s / 20 s, and 1 s / 10 s for filters of 0.5-1.2 Hz, 0.8-3.0
The detections were investigated using the spatial grid search based associator and event locator (dbgrassoc). Nearly all the default parameters were employed, including the use of residual thresholds for association of P and S waves at 10 s and 20 s, respectively. The lone exception to our use of default parameters was that the minimal allowable number of stations was adjusted to 6 at this stage in the processing based on our network configuration. We found these detection and association parameters provide an appropriate balance between minimized missed events and multiple detections on a single event.

To confirm the reliability, estimate the accuracy of the automated event location procedure, and determine a satisfactory uncertainty threshold, we manually reanalyzed over 4,000 events spanning over twelve months of data. For this test, the analyst individually confirmed or adjusted associations and arrival times on waveforms filtered above 5 Hz until a stable source location was obtained. When we compared hypocentral locations for common events between the original (i.e. automated) and manually reanalyzed catalogs, we found that the mean spatial differences between the corresponding events in the two catalogs were only 5 km horizontally and 7 km vertically. In other words, by limiting the automated catalog to only those events with good recordings, we achieved similar results between the catalog of manually identified seismic events and the catalog of automated seismicity, with far less time needed to construct the automated catalog. Based on this result, we then utilized the automated location procedure on all six years of data and focused on hypocenters located above 100 km depth (Fig. 2) as temperatures may be too high for brittle failure below this depth [Manea et al., 2006; Husker and Davis, 2009]. The slab contours we establish in this paper suggest that the limited amount of well-constrained seismicity below 100 km we observe is likely due to that deeper part of the slab occurring north and outside of our seismic network.

NVT source locations were determined following the same procedure as the initial study of NVT in Oaxaca [Brudzinski et al., 2010]. Tremor locations performed for this study were from 2010 to 2012. We focused on using the new western stations installed in eastern Guerrero to improve the spatial distribution of NVT in that region. We combined the new tremor locations with those from Brudzinski et al. [2010], which were from June 2006 to September 2007. NVT envelope waveforms were analyzed with a semi-automated process for identifying prominent energy bursts, and analyst-refined relative arrival times were inverted for source locations. For further detail on the NVT analysis procedure, see Brudzinski et al. [2010]. We did not solve for source locations of slow slip episodes in this study, as a catalog of slow slip episodes in Oaxaca was recently compiled [Graham, 2013] utilizing the GPS stations deployed in conjunction with the seismic stations used in our study.

3. Seismicity and Shape of the Subducted Slab

The analysis to construct a six-year catalog of seismicity in Oaxaca produced over 14,000 earthquake locations and provided a clearer image of the subducted slab down to 100 km depth (Fig. 2) than previous studies [Pardo and Suárez, 1995; Pérez-Campos et al., 2008; Kim et al., 2010; Melgar and Pérez-Campos, 2011]. Seismicity below 70 km is focused towards the eastern half of the study region while events below 70 km in the western half are generally absent, making the continuity and geometry in the western half not well constrained below these depths. However, we believe the seismicity in the east is sufficient enough to aid in our interpretation of the slab below these depths. The further inland distribution of deeper (>30 km) seismicity towards the west and the narrower distribution towards the east supports findings from Pardo and Suárez [1995], Pérez-Campos et al. [2008], and Kim et al. [2010] that there is an along-
strike transition from flat to steeper subduction beneath Oaxaca. This transition in dip along-strike is also clearly illustrated in both cross-sections perpendicular to the trench and along-strike (Fig. 3). However, our study examines the nature of this transition more closely based on detailed examination of seismicity across this dip change.

To better constrain the geometry of the slab, we sought to make new slab depth contours. We constructed a series of north-south cross-sections for every 0.2° longitude and sought to fit a line to the top of the seismicity representing the upper slab surface (Fig. S1). We chose to make contours based on these narrow north-south cross-sections as it provided the best way to ensure we did not miss any events while generating the contours. We restricted our attention to earthquakes below 25 km depth as that depth approximately marks the downdip extent of the seismogenic zone in southern Mexico [Pardo and Suárez, 1995; Pacheco and Sigh, 2010]. Events below 25 km were most likely to be intraslab earthquakes within the subducting plate, whereas shallower events were more likely to be associated with the plate interface or the upper continental plate. We also refined the catalog by removing outliers that did not have at least one other event within 20 km horizontally or vertically. The seismicity in each cross-section was divided into 5 km depth ranges, and slab surface points were calculated using the furthest earthquake distance from the trench in the corresponding longitudinal range and the bottom of the 5 km depth range. To account for hypocentral uncertainty, choosing the bottom of the depth range is somewhat conservative and leaves a handful of earthquakes above the slab surface. Slab surface transects were constructed by connecting the points in each cross-section, and finally to the trench. Slab depth contours were constructed by connecting common depth points across all cross-sections and smoothing the resulting line to account for hypocentral depth uncertainties. The comparison of contours calculated from the two different sets of hypocenters from the global and regional velocity models resulted in a median spatial difference of 7 km, which is an estimate of our contour location uncertainty.

We then sought to verify the accuracy of the contours in a series of 10 km depth interval plots (Fig. 4). Again, we note that our conservative approach to account for hypocentral uncertainty results in a handful of earthquakes plotting beyond the slab surface, but overall the contours appropriately mark the inland extent of seismicity for each depth interval. Our approach struggles with the 20 km depth contour of the slab surface without the guidance of focal mechanisms to discern thrust events, but our approach suggests the shallow extent of the 20-30 km depth seismicity follows the trend of the coastline (Fig. 4). The maps also reveal less abundant intraslab seismicity in the west where the slab has a shallower dip. While it is possible for a reduction in intraslab seismicity to reflect a discontinuity in the slab [Dougherty and Clayton, 2014], it could also indicate changes in slab stress. It is thought that a combination of regional stress (slab pull) and a local trigger (dehydration embrittlement) is required to accumulate and release elastic strain in intraslab earthquakes [Hacker et al., 2003; Abers et al., 2009]. However, down-dip extensional stresses generated from slab pull are greatly reduced when the slab is subhorizontal, as the downdip component of slab pull is approximately proportional to the sine of the slab dip [Brudzinski and Chen, 2005]. While dehydration embrittlement still occurs, this reduction of slab pull stress may lead to fewer earthquakes than where the slab is steeper to the east. Another explanation for the reduction of intraslab seismicity in the flat slab region is that the deeper part of the Cocos plate has essentially no rigidity and as a result is unable to transmit any stress to the flat slab [Manea et al., 2013]. In cases where intraslab seismicity in flat slab regions is abundant (i.e. Peru and Chile), the localized source of
stress, typically masked by slab pull, is both necessary and sufficient to generate earthquakes in absence of the dominating source of regional stress [Brudzinski and Chen, 2005].

While Pardo and Suárez [1995] first described the flat slab based on relocated hypocenters of local and teleseismic earthquakes, recent studies have more accurately delineated the geometry of the slab using receiver functions [Pérez-Campos et al., 2008; Kim et al., 2010; Melgar and Pérez-Campos, 2011] and tomography [Husker and Davis, 2009]. Contours generated from Pardo and Suárez [1995] and from the combined results of Pérez-Campos et al. [2008], Kim et al. [2010], and Melgar and Pérez-Campos [2011] are compared to contours generated in this study (Fig. 5) and show a median spatial difference of 30 km and 44 km, respectively. A key reason these differences are large is that our slab depth contours illustrate the eastern along-strike transition from flat to steeper subduction as a sharper transition (Fig. 5) relative to the previous contours. The greater angle of curvature at which the contours bend toward the trench and their closer spacing indicate a sharper flexure of the slab. Pardo and Suárez [1995] contours show a more muted signature of the flat slab with a more gradual transition to steeper subduction (Fig. 5a) compared to the new contours, likely because they were generated using a more limited earthquake dataset of fewer events available at that time based on broader station coverage.

Our contours also differ greatly from the combined results of Pérez-Campos et al. [2008], Kim et al. [2010], and Melgar and Pérez-Campos [2011] that primarily used receiver function analysis to interpret the slab geometry (Fig. 5b). Receiver function analysis uses teleseismic converted waves to effectively characterize seismic velocity discontinuities below the seismic stations [Yamauchi et al., 2003; Kim et al., 2010]. Pérez-Campos et al. [2008], Kim et al. [2010], and Melgar and Pérez-Campos [2011] used linear seismic arrays perpendicular to the trench with dense spacing for high resolution imaging of the subducting slab directly below along a pair of transects west and east of our study region, but yields significantly lower resolution in between the arrays where the station coverage is reduced. Our seismicity analysis using a broad array across the target region does not suffer from this limitation, so we interpret that our slab depth contours more accurately capture the subducting slab geometry across the transition from shallow to steep dip.

4. Spatial Distribution of Nonvolcanic Tremor and Slow Slip

To interpret patterns of NVT in the Oaxaca region, we combined our NVT locations from 2010 to 2012 with those from Brudzinski et al. [2010] from June 2006 to September 2007 (Fig. 6a). The new NVT locations are similar to that of Brudzinski et al. [2010], such that NVT primarily occurs further inland from the region of slow slip. The continuous band of NVT widens towards the west and its downdip extent gradually moves inland, characteristic of the shallowing of the subducting slab. NVT extends further west and inland than previously observed in Brudzinski et al. [2010] as a result of the additional stations added in eastern Guerrero in 2008. Although depths of NVT are not well determined with the approach of Brudzinski et al., [2010], this study and other studies indicate that NVT hypocenters locate on or near the plate interface [e.g., Brown et al., 2009], which is consistent with what we observe (Fig. 3). NVT was also observed to coincide with regions of USL and possible USL determined from Dougherty and Clayton [2014] further supporting that the slab is continuous in the shallow portion (Fig. 6a). The map of NVT shows a less abundance of NVT in the east compared to the west, which we attribute to the transitional, weakening USL zone, where zones of possible USL and no USL overlap, observed by Dougherty and Clayton [2014]. Since a USL is thought to
form from very high pore fluid pressures trapped at the top of the subducting plate, a weaker USL would suggest a reduction in fluids, which in turn could limit the amount of NVT [e.g., Song et al., 2009].

NVT locations can aid in determining the geometry of the slab downdip of the seismogenic zone, because NVT occurs at the deepest portion of the transition zone [Dragert et al., 2001; Obara et al., 2004; Brown et al., 2009] and is a result of fluid flow and fluid processes at the plate interface and within the overlying plate [Audet et al., 2009; Rubinstein et al., 2010]. For this reason, NVT locations were plotted with new slab contours as well as older contours for comparison. Since the depths of NVT are poorly constrained, we focus on the overall pattern and extent of NVT when comparing to the slab contours. The refined slab contours in this study show that the updip and downdip extent of NVT more closely follow the shape of the slab contours across the entire Oaxaca region (Fig. 6b). Even without knowledge of the exact depths of NVT, studies indicating tremor occurs on the plate interface imply that NVT stays in the same depth range across our study region. Where the contours are closely spaced, so are the NVT, as well as where the contours are widely spaced so are the NVT. The apparent depth of the updip extent of NVT also better matches the downdip extent of the seismogenic zone (25 km). The observation that the shape of the new contours better parallels NVT across the entire Oaxaca region suggests that NVT is occurring via similar set of pressure and temperature conditions.

We do not analyze GPS time series directly, because the spatial patterns of SSEs in the Oaxaca region have been previously described in several recent studies [Brudzinski et al., 2007; Graham, 2013; Graham et al., 2014]. We start by examining an amalgamation of all previously documented SSEs that occurred during the time of this study (2006-2012) to use in comparison with the sharp transition in dip (Fig. 6a). In Oaxaca, SSEs occur approximately every 2 years and are located slightly updip from the region of NVT [Brudzinski et al., 2007; Correa-Mora et al., 2009]. Similar to the NVT, SSEs coincide with the region where Dougherty and Clayton [2014] determined the USL to be possible, further confirming that the slab is continuous in this region. To examine the continuity of individual SSEs with regards to the sharp transition in dip, we looked at the along-strike locations of individual SSE over time (Fig. 7).

5. Discussion

Age progression of volcanism migrating trenchward suggests ongoing rollback of the slab since the late Miocene [Ferrari, 2004]. Slab tears in western [Bandy et al., 2000; Dougherty et al., 2012; Stubailo et al., 2012] and eastern [Dougherty and Clayton, 2014] central Mexico are proposed to exist where there is a sharp transition in dip along-strike on either side of the flat slab. These tears may imply the slab is rolling back in segments, given that if rollback begins on only one segment of the plate, the first tear will develop and rollback will continue, which will eventually steepen the initial segment and induce rollback in another segment resulting in the development of a second tear (see Dougherty and Clayton [2014] for an illustration). Both of these tears are thought to be less developed features, not yet extending into the shallow portion of the slab.

In this study we have collected several new pieces of evidence to evaluate whether the eastern tear proposed by Dougherty and Clayton [2014] has reached depths shallower than 100 km and if not, what is allowing such a sharp transition in dip.

What characterizes the continuity of oceanic lithosphere over vast areas is its relatively uniform structure and thickness and its ability to act as a seismic waveguide [e.g., Molnar and Oliver, 1969]. In this study, seismicity, NVT, and SSEs are all used to show the continuity of the plate at shallow depths across the transition from flat to steeper subduction. We observed
seismicity to be continuous in the updip portion of the slab (Fig. 4), which is similar to findings from Dougherty and Clayton [2014]. An offset in the alignment of seismicity in map view would be expected if there was a slab tear, as is observed at the Philippine Sea plate beneath Japan [Ide et al., 2010]. We cannot access the continuity of the slab at greater depths (> 100 km), as these events would fall outside of our network. NVT is also shown to occur continuously in the updip portion of the slab where there is a sharp transition in dip (Fig. 6a). If there was a discontinuity in the slab, we would expect to see gaps in NVT [e.g. Ide et al., 2010; Abbott and Brudzinski, 2015] as a tear in the slab would disturb the pressure and temperature conditions necessary to generate NVT [Fagereng and Diener, 2011]. Because the presence of USL is thought to be a key contributor to SSEs [Payero et al., 2008; Song et al., 2009; Brudzinski et al., 2010; Kostoglodov et al., 2010], a continuous subducting plate is required for slow slip to migrate. As a result, SSEs represent another opportunity to evaluate the consistency of a slab as they typically last several months and migrate several 100 km along strike in this region [Brudzinski et al., 2007; Graham, 2013; Graham et al., 2014]. Figure 7 shows that many SSEs have migrated smoothly across this region without interruption. If there were a tear, trapped fluids from hydrous minerals and/or pore fluids would be released disrupting the USL [Dougherty et al., 2012], which would result in the termination of slip propagation.

To get a better idea on the behavior of the slab across the eastern transition in dip in the shallow portion of the slab, slab depth contours were generated based on seismicity from this study. New contours show a sharper transition or a greater flexure of the slab compared to old contours [Pardo and Suárez, 1995; Pérez-Campos et al., 2008; Kim et al., 2010; Melgar and Pérez-Campos, 2011]. We hypothesize that the transition is so sharp, because the subducting plate is close to its yield strength due to bending moment saturation, which reduces the resistance to bending [e.g., Goetze and Evans, 1979]. When the curvature of the plate is very small, the plate mainly undergoes elastic deformation, and any increase in curvature will result in increased bending moment [Kao and Chen, 1996]. As curvature and bending moment increase, large fiber stresses cause permanent deformation in the form of brittle failure and ductile flow in the upper and lower lithosphere, respectively [Kao and Chen, 1996]. At large curvatures, the bending moment approaches an asymptotic value or saturates [Goetze and Evans, 1979], such that the plate can continue to bend as any increase in applied load is relaxed via additional permanent deformation [McNutt and Menard, 1982]. Because there are large uncertainties in estimating lithospheric curvature, Kao and Chen [1996] proposed that bending moment saturation could be determined through a study of the spatial correlation between the configuration of the subducting plate and seismogenic behavior beneath the outer rise and along the plate interface. Specifically, they compiled evidence for bending moment saturation in nearly a dozen locations globally by correlating depressions in seafloor bathymetry, large outer rise earthquakes, and gaps in forearc seismicity. In this scenario, a lack of bending resistance allows for a permanent increase in the plate’s curvature that results in greater extension in the outer rise, more rapid slab dip steepening in the forearc to generate a topographic low, and an aseismic forearc due to less stress transmitted across the interplate thrust zone.

A segment of the subducting slab right in the middle of our study region was identified as bending moment saturated by Kao and Chen [1996] based on the correlation of seismicity and topography patterns. To see if the observations made by Kao and Chen [1996] still hold true in this area of Mexico, we compared their observations with new seismicity determined in this study and searched for any more recent outer rise normal-faulting earthquakes. The gap of forearc seismicity from Kao and Chen [1996] corresponds to low levels of background
seismicity in this study (Fig. 2). The area of reduced seismicity appears to extend slightly further to the west and not quite as far inland as previously thought, refinements that are likely due to availability of local seismic recordings. In Kao and Chen [1996], there are two large previously recorded outer rise normal-faulting events (4 July 1994, M_w ~6.0 [Dziewonski et al., 1995]; 16 September 1972, m_b ~6.0 [Chapple and Forsyth, 1979]) and two historic events (14 January 1903, M_s ~8.3; 29 December 1917, M_s ~7.7 [Duda, 1992]) whose location and magnitude suggest they were very large outer rise normal-faulting earthquakes. One additional outer rise normal-faulting earthquake was found in this region occurring on 10 December 2004 with a M_w 5.2 (Fig. 5c), which was identified by searching the Global Centroid Moment Tensor catalog since Kao and Chen [1996] was published. There are no outer rise normal-faulting events in the catalog in neighboring regions, supporting the conclusion that the seismicity patterns in this along-strike portion of the Mexico subduction zone are unique.

Considering the gap in forearc seismicity observed by Kao and Chen [1996] and recent [Chapple and Forsyth, 1979; Dziewonski et al., 1995] and historic [Duda, 1992] outer rise normal-faulting earthquakes align with our interpretation of where the sharp flexure is (Fig. 5c), we suggest that the sharp bend of the slab along-strike offers further evidence that this segment of the plate is bending moment saturated. Kao and Chen [1996] only considered the sharp curvature of the plate in the down-dip direction, but we are suggesting that the physics behind bending moment saturation is not any different if applied to the sharp curvature in the along-strike direction. Since it appears the subducting plate in this portion of the Mexico subduction zone is bending moment saturated, we interpret that the sharp transition in dip along-strike (i.e. the large curvature of the plate) can be attributed to the permanent increase in the plate’s curvature as the plate can continue to bend without requiring much increase in applied moment [McNutt and Menard, 1982]. This case in our study region indicates that bending moment saturation allows the subducting plate to not only have a large curvature in the down-dip direction, but to also have a large curvature in the along-strike direction. Our hypothesis that the sharp along-strike flexure is due to bending moment saturation is consistent with a similar set of observations in southern Peru. Southern Peru also has a sharp transition from flat to steeper subduction [Grange et al., 1984; Cahill and Isacks, 1992; Philips and Clayton, 2014; Dougherty and Clayton, 2015] and is thought to be bending moment saturated based on correlations between topography and seismicity patterns [Kao and Chen, 1996].

The indications that the plate is reaching bending moment saturation may be related to the ongoing process of slab rollback in the Mexico subduction zone. If the plate is rolling back in segments that create large transitions in dip along-strike, it increases the likelihood that at some point during slab rollback the plate will approach its maximum yield strength and reach bending moment saturation. In addition to generating large bending stresses, slab rollback in segments would generate membrane stresses (i.e. stress due to the lithosphere being extended or compressed [Lithgow-Bertelloni and Guynn, 2004]) along those large transitions in dip along-strike. Similar to how a tear would reduce the membrane resistance from a neighboring portion of the slab [Yamaoka et al., 1986] allowing the slab dip to steepen, the permanent deformation of the slab when approaching bending moment saturation would relax any additional load and allow the slab dip to steepen [McNutt and Menard, 1982]. Consequently, regions that have previously achieved bending moment saturation during subduction may not be required to tear in response to the accumulated membrane stress during non-uniform rates of slab rollback.
6. Conclusions

In this study, the geometry of the subducted slab along the Oaxaca segment is determined with the help of a local seismic network. We compile catalogs of seismicity, NVT, and previously documented SSEs to determine the continuity of the slab. We present new slab contours for the subducted Cocos plate beneath Oaxaca, which show a sharper transition from flat to steeper subduction than previous studies.

The extended catalog of NVT in Oaxaca shows a band of NVT widening towards the west and its downdip extent gradually moving inland, characteristic of the flattening of the subducting slab. The improved spatial distribution of NVT correlates better with the newly developed slab surface contours. An intriguing characteristic of the NVT is that the amount of NVT appears to correspond with the strength of the USL. The amount of NVT is the greatest where the USL is observed and there is a less abundance where the USL weakens. While the processes that govern NVT are still a matter of ongoing debate, this observation provides further evidence that fluids play a key role in the generation of NVT.

Patterns of local seismicity, NVT, and SSEs support the idea that the subducting slab is continuous at shallow depths across the sharp transition in dip. We suggest a sharp flexure of the slab accommodates the transition from flat to steeper subduction from central to eastern Mexico as a result of ongoing slab rollback. Slab rollback can be non-uniform such that different segments of the subduction zone are rolling back at different velocities leading to variations in the geometry of the slab, however not much is known about this process [Hale et al., 2010]. In order to accommodate the considerable amount of strain in the slab due to the sharp transition in slab dip, tears within the slab may develop [Miller et al., 2004, 2005; Yang et al., 2009]. Our study region appears to demonstrate an alternative outcome from the large strain – bending moment saturation of the subducting plate. Evidence for bending moment saturation in our study region was previously suggested based on the spatial correlation between the configuration of the subducting plate and seismogenic behavior beneath the outer rise and along the plate interface. Bending moment saturation creates a lack of bending resistance that allows for a permanent increase in the plate’s curvature, producing greater extension in the outer rise, a topographic low in the forearc from more rapid slab dip steepening, and an aseismic forearc due to less stress transmission across the interplate thrust zone. We interpret that the reduced bending resistance also allows a sharp along-strike flexure to accommodate variable rates of rollback without a slab tear. A similar set of observations in southern Peru suggests Oaxaca is not the only region where bending moment saturation is an alternative to tearing.
7. References


Figure 1. Map of the Mexico subduction zone and regional plate tectonic setting. Major earthquake rupture zones are outlined in blue. The black region is Middle Miocene to Holocene volcanism: Trans-Mexican Volcanic Belt (TMVB) [Ferrari et al., 2012]. Slab contours from Pardo and Suárez [1995] are in purple. Solid black lines and dotted lines on the oceanic plates represent magnetic anomalies and fracture zones, respectively. Dashed black lines from west to east mark: Rivera-Cocos plate boundary [Andrews et al., 2011] which is where Yang et al. [2009] suggest a tear; projection of Orozco Fracture Zone along which Dougherty et al. [2012] believe a tear is occurring; the sharp transition in slab dip where Dougherty and Clayton [2014] suggest a tear is occurring down dip. White lines mark state boundaries. The abbreviations are EPR, East Pacific Rise; RFZ, Rivera Fracture Zone; OFZ, Orozco Fracture Zone; MAT, Middle American Trench. Black box marks the focus of this study in the state of Oaxaca (Fig. 2).
Figure 2. Map of seismicity from 2006 to 2012 (colored by depth) for Oaxaca and surrounding regions. Recording stations used in this study are represented by black triangles. Inverted black triangles are part of the National Seismological Service array in Mexico. Boxes show areas of cross-sections in Figure 3. Gap in forearc seismicity observed by Kao and Chen [1996] is encircled by dash-dotted curve.
Figure 3. Cross-sections showing seismicity in Oaxaca and surrounding regions. Cross-sections (a-e) and (f) are oriented downdip and along-strike, respectively. Small black dots represent shallow (<25 km) earthquakes and large black dots represent deeper (>25 km) earthquakes in order to distinguish subducting slab seismicity from seismicity likely related to the upper plate or plate interface. Our slab depth contours are used to estimate the top of the downgoing plate (dashed line). Note the progressive steepening of the subducting plate from west to east. Red dots are NVT hypocenters.
Figure 4. Maps of seismicity (black dots) at 10 km depth intervals. Depth intervals are plotted to verify slab contours (starting with 20 km contour) determined in this study (blue lines). Red triangles are the same as in Figure 1.
Figure 5. Maps of slab contours determined in this study (blue lines) are compared with (a) slab contours from Pardo and Suárez [1995] (purple lines), (b) slab contours based on the collective results of Pérez-Campos et al. [2008], Kim et al. [2010], and Melgar and Pérez-Campos [2011] (orange lines) along with the sharp transition in dip from Dougherty and Clayton [2014] (dashed black line), (c) gap in forearc seismicity observed by Kao and Chen [1996] (encircled by dotted black curve) and recent and historic normal-faulting earthquakes represented by focal mechanisms and open circles, respectively. Red line marks the segment of the slab we interpret to be bending moment saturated based on gap in forearc seismicity and normal-faulting earthquakes align with the sharp along-strike transition in slab dip. Solid blue contour lines are 20 km increments for comparison with previous contours. Dashed blue contour lines show the intermediary depths for better clarity of slab geometry.
Figure 6. (a) NVT locations (red dots) and amalgamation of SSEs [Brudzinski et al., 2007; Graham, 2013; Graham et al., 2014] (green line) plotted with regions where Dougherty and Clayton [2014] determined the USL to exist (blue patch), to be possible (orange patch), and to not exist (pink patch). The region where the possible USL and no USL overlaps is thought to represent a weakening USL region. Region of NVT activity (red line) is compared with (b) slab contours determined in this study (blue lines), (c) slab contours from Pardo and Suárez [1995] (purple lines), and (d) slab contours based on the collective results of Pérez-Campos et al. [2008], Kim et al. [2010], and Melgar and Pérez-Campos [2011] (orange lines).
Figure 7. Along-strike locations of slow slip over time (darker shading indicates more slip). Slow slip events are gathered from earlier studies [Brudzinski et al., 2007; Graham, 2013; Graham et al., 2014]. Dashed box represents the region where the sharp transition in dip from Dougherty and Clayton [2014] intersects the amalgamation of SSEs in Figure 6a.
Figure S1. North-south cross-sections of seismicity in Oaxaca and surrounding regions for every 0.2° longitude from -96° to -98.8°. Black dots represent shallow (<25 km) earthquakes and open circles represent deeper (>25 km) earthquakes in order to distinguish subducting slab seismicity from seismicity likely related to the upper plate or plate interface. Our interpretation of the top of the downgoing plate is shown on each cross-section with a solid line. Note the progressive steepening of the subducting plate from west to east.