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Horizontal subduction and truncation of the Cocos Plate beneath central Mexico

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[1] Based on analysis of data from a trans-Mexico temporary broadband seismic network centered on Mexico City, we report that the subducting Cocos Plate beneath central Mexico is horizontal, and tectonically underplates the base of the crust for a distance of 250 km from the trench. It is decoupled from the crust by a very thin low viscosity zone. The plate plunges into the mantle near Mexico City but is truncated at a depth of 500 km, probably due to an E-W propagating tear in the Cocos slab. Unlike the shallow slab subduction in Peru and Chile, there is active volcanism along the Trans Mexican Volcanic Belt (TMVB) that lies much further inland than regions to either side where subduction dip is not horizontal. Geodynamical modeling indicates that a thin weak layer such as imaged by the seismic experiment can explain the flat subduction geometry. **Citation:** Pérez-Campos, X., Y. Kim, A. Husker, P. M. Davis, R. W. Clayton, A. Iglesias, J. F. Pacheco, S. K. Singh, V. C. Manea, and M. Gurnis (2008), Horizontal subduction and truncation of the Cocos Plate beneath central Mexico, *Geophys. Res. Lett.*, *35*, L18303, doi:10.1029/2008GL035127.

1. Introduction

[2] The Middle America Trench (MAT) in central Mexico is a natural laboratory for examining subduction because this process generates a range of dip angles with the western and eastern sections exhibiting normal to steep angles, while the central section beneath Mexico City appears to be shallow. This is despite a monotonic increase in plate age and subduction velocity toward the south [*Singh and Pardo*, 1993; *Pardo and Suárez*, 1995]. The variation in subduction angle is based mainly on seismicity and focal mechanisms, but seismicity is sparse and concentrated between the trench and the coast. To date no seismic images of the slab have been obtained, and the complete absence of a Wadati-Benioff zone beneath the TMVB has meant that the geometry of the slab in the region is unknown. The location and properties of the slab are important for understanding the tectonic evolution of this subduction system.

[3] Understanding flat subduction is also important for tectonic reconstruction. For example, models of the evolution of western North America during the Laramide orogeny (40–80 Ma), prior to Basin and Range extension (30 Ma), invoke flattening of the Farallon slab from the west coast to the Rocky Mountains to explain inland migration of the volcanism. The slab was thought to underplate the crust with coupling that thickened the crust in the Rocky Mountains and Great Plains [e.g., *Bird*, 1988; *Saleeby*, 2003]. However, this model has been questioned, because xenoliths from the Laramide have depths indicating the presence of a significant mantle wedge at the time of inferred underplating [*Riter and Smith*, 1996]. Given these controversies, it is of interest to examine an analog of Farallon flat slab subduction that is presently occurring in Mexico, along with its coupling to the overriding plate and related geological features.

[4] A 100-station broadband array (the Meso-American Subduction Experiment or MASE array) was deployed during 2005–2007 across central Mexico. The array extended from Acapulco on the Pacific coast to Tempoal, near the Gulf of Mexico in the north, passing through Mexico City (Figure 1). We present images that show, for the first time, a slab that horizontally underplates the base of the continental crust, with very little mantle lithosphere and no room for asthenosphere. The slab then dips into the mantle, but is truncated at depth probably due to a slab tear in the Cocos plate.

2. Determining the Slab Structure

[5] Converted teleseismic waves recorded by the MASE array were used to determine the structural interfaces using the receiver function (RF) method (auxiliary material[1]). The crust-mantle interface is clearly delineated in the RF image (Figure 2) along with some sub-horizontal mid-crustal features. The northern portion of the profile shows a single strong Moho interface between the continental crust and mantle wedge, that is a positive velocity transition with depth. The southern portion, detailed in Figure 2, shows a horizontal interface that has a distinct negative transition over a positive one. This feature is a thin low-velocity zone between the lower continental crust and the slab, which is likely to be altered oceanic crust or a mantle wedge remnant. Its thickness is estimated to be 10 ± 3 km, but

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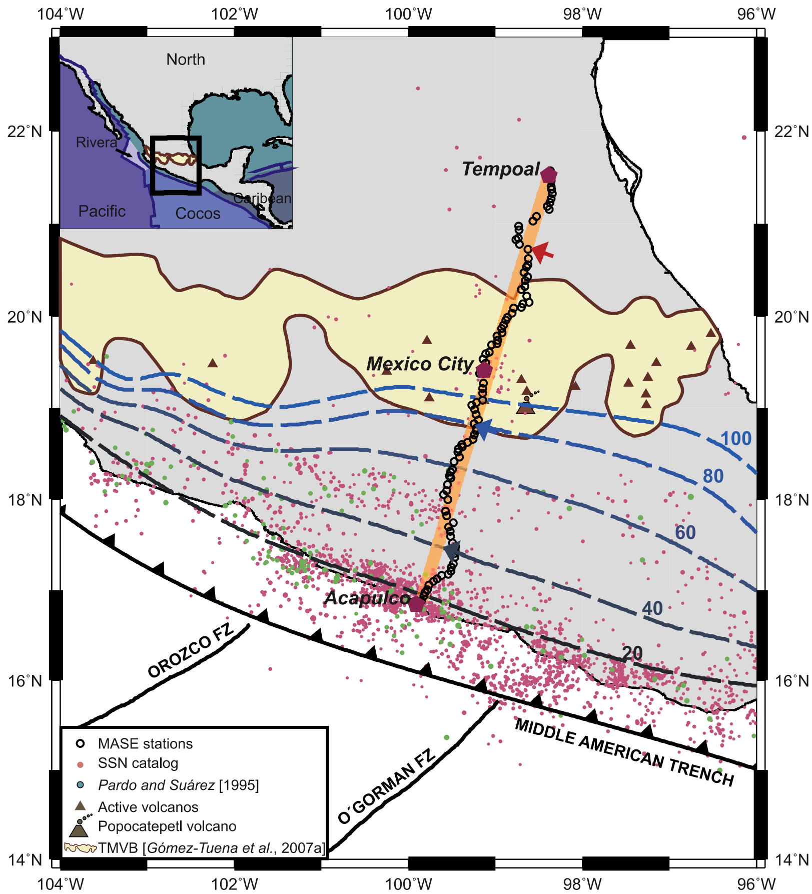

Figure 1. MASE seismic array. Slab isodepth contours from *Pardo and Suárez* [1995] are in blue dashed lines. The dots represent epicenters of M>4 earthquakes, reported by the Servicio Sismológico Nacional (SSN; in pink) from December 2004 through June 2007 and those re-located by *Pardo and Suárez* [1995] (in green). The thick orange line represents the profile of Figures 2 and 3. The arrows indicate the beginning (dark blue) and end (light blue) of the flat segment, and the tip of the slab (red).

resolution is limited by the resolvable frequencies of the earthquakes used in modeling. Velocity models inferred from RFs are shown in Figure 2. They require an impedance contrast provided by a low-velocity oceanic crust possibly overlaid by a thin layer of low-velocity mantle.

[6] Relative traveltime variations determined from teleseismic events were used to obtain a tomographic image of the *P*-wave velocity deviations from a layer model [*Husker*, 2008]. This is a complementary technique to RFs in that it is sensitive to dipping structures but not very sensitive to the horizontal ones. The results in Figure 3 show that the slab dives into the mantle just to the south of the TMVB with a dip of ~75°. It continues to a depth of 500 km at a distance of 400 km from the coast, where the tomography indicates that the slab ends. With this geometry, the currently active volcanoes, such as Popocatepetl, are located 80 to 210 km above the top of the plunging slab [*Gómez-Tuena et al.*, 2007a].

3. Discussion

[7] The Cocos plate is subducting below central Mexico at ~6 cm/year [*DeMets et al.*, 1994]. From this relative motion and the evidence of little or no room for continental mantle asthenosphere along the flat-subduction segment, one would expect the slab to be highly coupled to the overriding plate, giving rise to potentially large earthquakes. However, GPS observations [*Franco et al.*, 2005] and GPS data inversion of a silent seismic event of 2001 [*Iglesias et al.*, 2004] suggests the flat segment is not strongly coupled. Based on thermal arguments, *Manea et al.* [2004] suggest that the low coupling is related to metamorphism of slab minerals. Furthermore, large earthquakes have not been observed along the flat segment. They occur only on the plate interface updip from the point where Cocos plate commences unbending, ~10 km inland from the coast. The flat segment shows little inslab seismic activity and the diving slab into the mantle is completely devoid of earthquakes. If anything, the overriding plate seems to be in extension, which is consistent with focal mechanisms of the little seismicity observed within the overriding plate [*Singh and Pardo*, 1993]. Over longer time-scales this state of stress is confirmed by several authors [e.g., *Nieto-Samaniego et al.*, 2006; *Morán-Zenteno et al.*, 2007] who report that there are no compressional features in the region that have formed in the past 20 Ma. All this is consistent with our seismic observations of very low velocity and presumably low viscosity at the interface.

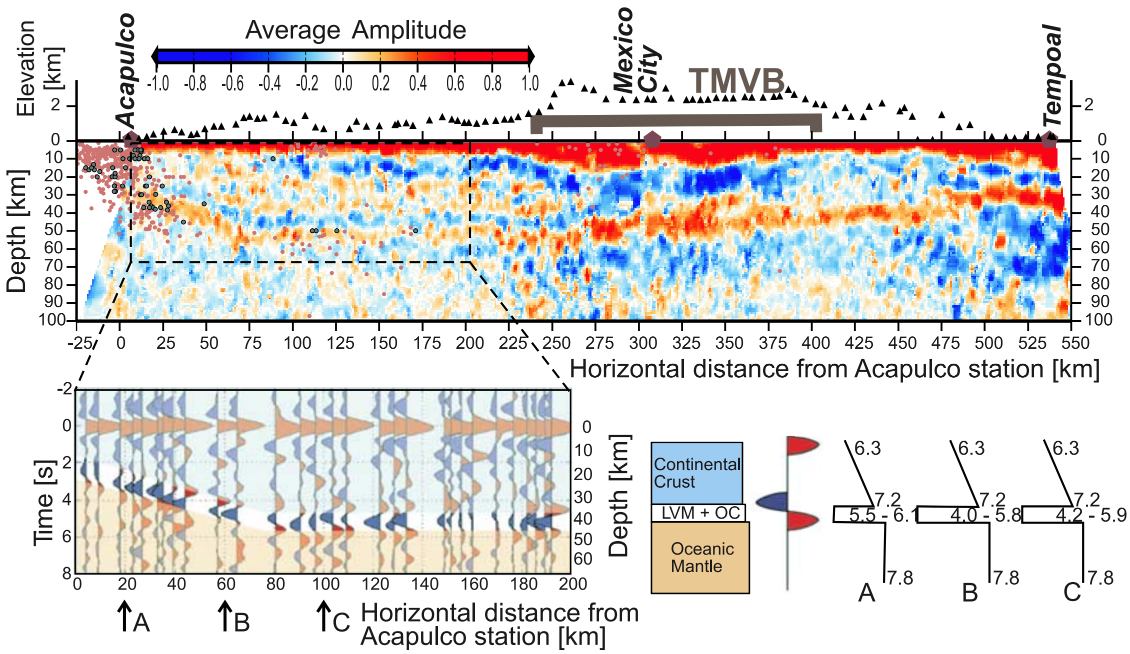

Figure 2. Receiver function images. The black triangles denote the position of the stations along the profile with elevation exaggerated 10 times. The thick brown line denotes the extent of the TMVB. Seismicity (SSN: pink; *Pardo and Suárez* [1995]: green), within 50 km of the MASE profile, is shown as dots. The bottom left plot shows RFs for one teleseismic event along the flat slab portion of the slab; the bottom middle plot illustrates the corresponding model (LVM = low velocity mantle and OC = oceanic crust). Compressional-wave velocity models A, B, and C shown in the bottom right plot were determined from waveform modeling of RFs. They correspond to the structure at A, B, and C of the bottom left plot.

[8] In contrast to other flat subduction zones where the cause for the flattening is thought to be obvious, such as buoyancy from thickened crust [e.g., *Yáñez et al.*, 2002], central Mexico lacks such a feature. In fact, our seismic results indicate normal crustal thickness. Several hypotheses have been suggested as the cause of shallow subduction (auxiliary material); however, to date there has been no definitive explanation; in fact, there is no anomalous behavior of the subduction near Acapulco in terms of plate age or velocity in the last 60 Ma [*Sdrolias and Müller*, 2006].

[9] The history of volcanism has been used to infer the evolving geometry of subduction. Typically volcanism appears above regions where slabs reach a depth of ~100 km and slab dehydration is thought to take place. Originally, like the regions to either side, the volcanic arc in central Mexico was nearer the coast and parallel to the trench consistent with steep subduction. In late Eocene (30 Ma) there was a hiatus, thought to be associated with the flattening process [*Ferrari et al.*, 1999]. At 20 Ma, after a 10-Ma lull, volcanic activity resumed [*Gómez-Tuena et al.*, 2007b]. At ~10 Ma, the western part of the Cocos Plate separated to form the Rivera Plate [*Lonsdale*, 1991; *DeMets and Traylen*, 2000]. It has been suggested that at about this time, a tear developed in the subducting plate, and the eastward propagation of this tear corresponded to the migration of TMVB volcanism, culminating with the lower portion of the Cocos plate breaking off [*Ferrari*, 2004] and foundering. The age progression of mafic volcanism and the presence of oceanic island basalts and adakites in central Mexico [*Ferrari*, 2004] have offered petrological support for this model. The west-east propagating volcanism along the TMVB reached the longitude of Mexico City at about 7 Ma.

[10] The slab image we present in Figure 3 provides kinematic support for the slab tear hypothesis. In the subsequent 7 Ma, at 6 cm/yr, the upper tip of the tear would now be at a depth of > 420 km, which we identify as the slab tip at 500 km from the tomography, suggesting that it broke at a depth of 80 km. This truncation means the negative buoyancy of the older deeper part of the plate is absent. This can explain the absence of a Wadati-Benioff zone, since the stress within the slab could be sub-critical given that the deeper part of the slab has been removed after tearing, coupled with the fact that the slab is young and hot.

[11] Our detection of a low-velocity layer at the interface of a flat slab beneath Mexico suggests a possible solution to the origin of the flat slab itself. The lack of evidence for in plane compression in central Mexico suggests that the interface we have detected seismically is physically associated with either low viscosity or low strength. The motion of the over-riding plate oceanward has long been known to decrease the dip of the slab in dynamic models [*Gurnis and Hager*, 1988]. We suggest that at the time of cessation of volcanism, the dehydration might have been distributed in the mantle wedge lowering its viscosity rather than concentrated at ~100 km. Using a numerical modeling technique

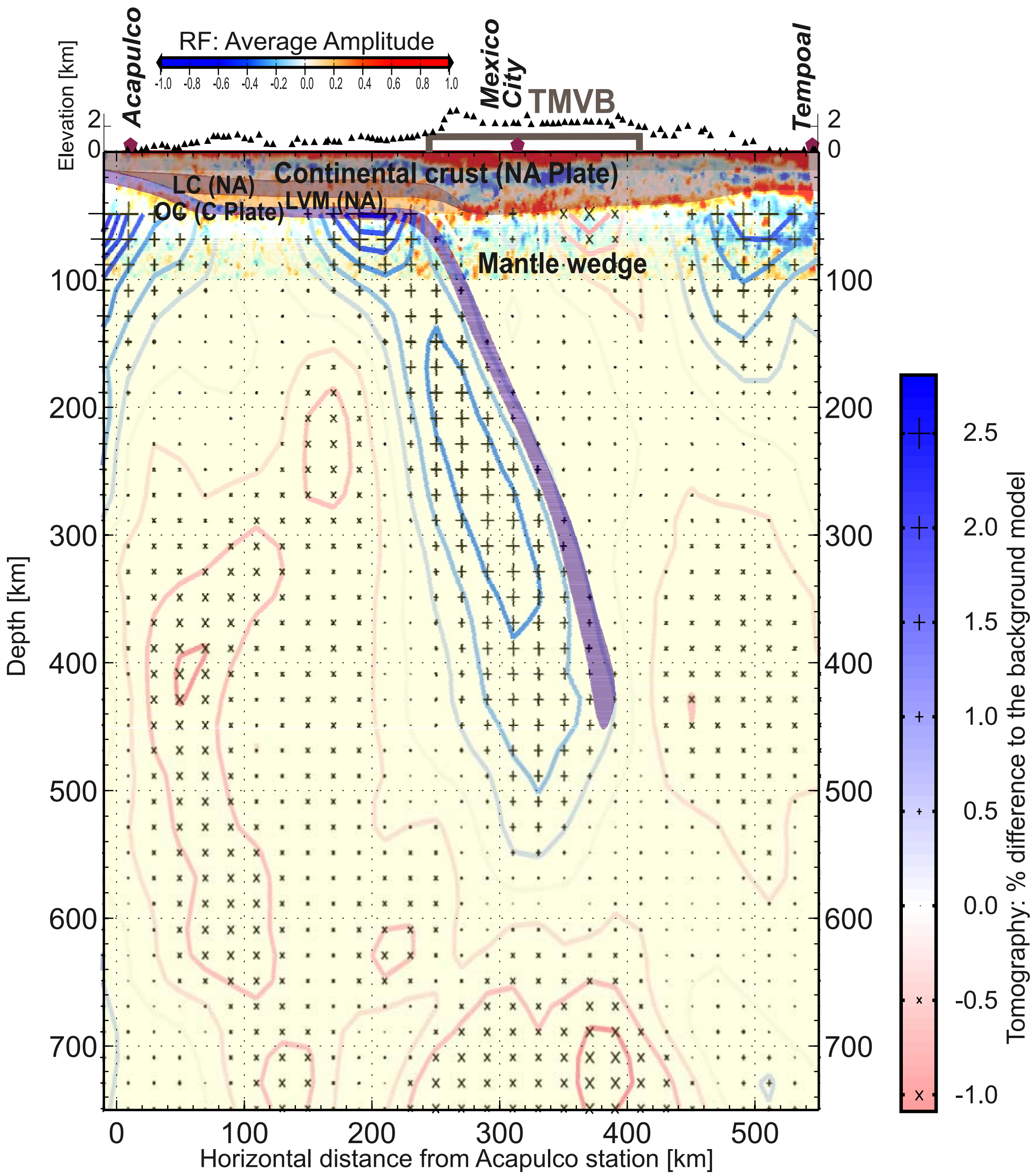

Figure 3. Composite model: tomographic and RF image showing the flat and descending segments of the slab. The key features are the flat under-plated subduction for 250 km, and the location and truncation of the slab at 500 km. The zone separating the ocean crust from the continental Moho is estimated to be less than 10 km in thickness. NA = North America, C = Cocos, LC = lower crust, LVM = low velocity mantle, OC = oceanic crust.

in which subducted slabs evolve their structure dynamically, we have parameterized the evolution of low viscosity wedges and channels above subducted oceanic crust [*Manea and Gurnis*, 2007]. In models tailored to the kinematics of the Cocos and North America plates and the age of the downgoing slab, the development of the weak region in the mantle wedge causes the slab to be flat lying as opposed to merely having a small dip (Figure 4) and facilitates the subducting plate to slide beneath the overriding plate with little coupling between the two. The slab geometry in the example shown in Figure 4 evolved to being flat from the initiation of steep subduction at 22 Ma (auxiliary material). The modeling shows that small changes in viscosity, which could be due to differential hydration, can give rise to a flat slab geometry consistent with our seismic observations. Therefore, the development of the flat-lying slab with no in-plane compression in the upper plate may be genetically related to the presence of a low-velocity, low-viscosity layer. This hypothesis implies that the thin channel of low velocity mantle above the oceanic crust is a remnant of the mantle wedge. It is not known why the distributed dehydration was confined to the flat slab

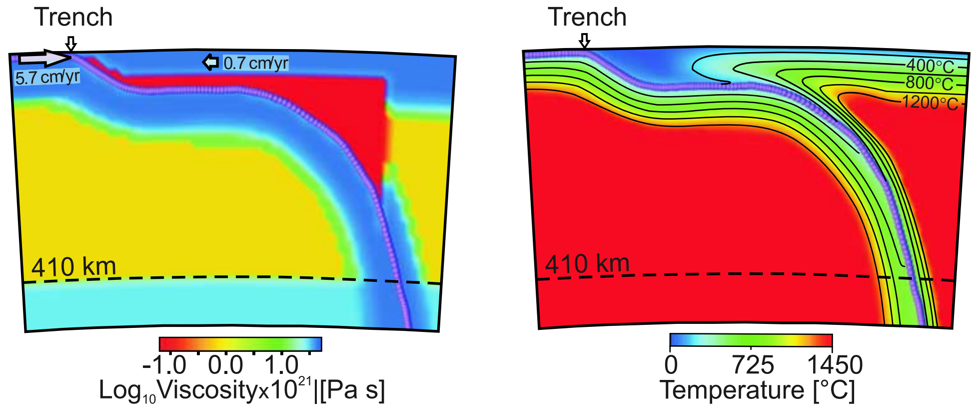

Figure 4. Final configuration for the Middle American subduction zone from dynamic modeling. This was obtained through the coupling of (right) temperature transport and (left) viscous flow using the methods of *Manea and Gurnis* [2007]. The subduction of the oceanic crust is tracked through the advection of particles (purple chain). The initial model involves steep subduction which may correspond to the geometry of the slab 22 Ma (Figure S3). The viscosity of the region above the oceanic crust between 50 and 300 km from the trench is reduced by half compared to normal asthenospheric layers. The velocities of the Cocos and North America plates are imposed as kinematic boundary conditions since 22 Ma (auxiliary material); velocity vectors shown in Figure 4 (left) are present day values.

portion in central Mexico. That it did occur, is based on the cessation and resumption of volcanism.

4. Conclusions

[12] Low coupling explains the absence of earthquakes in the horizontal section just south of Mexico City. Beneath the city itself it is at a depth of 150 km and is aseismic. The steeper part has developed negative buoyancy, and slab rollback is now being observed. The volcanism in the vicinity of Mexico City is normal andesitic volcanism which means that in contrast to the absence of volcanism at shallow subduction in Peru and Chile, where dehydration may be distributed through the wedge, the 250-km horizontal slab segment simply delays the concentrated dehydration process until it reaches 100 km depth [*Jödicke et al.*, 2006].

[13] As a result of our observations and the presence of andesitic volcanism near Mexico City, we present a new model of shallow subduction based on slab dehydration to explain the history of subduction in central Mexico in comparison with the non-volcanic regions of shallow subduction in Chile and Peru. The model proposes three regimes (1) normal subduction and andesitic volcanism with concentrated dehydration at ∼100 km. (2) When dehydration is distributed (0–100 km), volcanism ceases, mantle wedge viscosity decreases and the slab shallows and squeezes out the mantle wedge until it meets the crust. (3) Now at shallow depth, distributed dehydration ceases, and concentrated dehydration resumes at 100 km depth with the resumption of andesitic volcanism. Also, we believe this model can explain the volcanic history of central Mexico.

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