COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./DUE DATE:
NSF 12-598 06/01/16

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EAR - GEOPHYSICS

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California Institute of Technology

Awardee Organization Code (IF KNOWN):
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NAME OF PRIMARY PLACE OF PERF:
California Institute of Technology

IS Awardee Organization (Check All That Apply):
☐ SMALL BUSINESS
☐ FOR-PROFIT ORGANIZATION
☐ MINORITY BUSINESS
☐ WOMAN-OWNED BUSINESS
☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT:
Imaging the Eastern Trans-Mexican Volcanic Belt

REQUESTED AMOUNT
$ 178,638

PROPOSED DURATION (1-60 MONTHS)
24 months

REQUESTED STARTING DATE
12/01/16

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
☐ BEGINNING INVESTIGATOR (GPG 1.G.2)
☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.i)
☐ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date
PHS Animal Welfare Assurance Number
☐ HUMAN SUBJECTS (GPG II.D.7) Human Subjects Assurance Number
Exemption Subsection or IRB App. Date
☐ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
☐ COLLABORATIVE STATUS
☐ NOT A COLLABORATIVE PROPOSAL

FUNDING MECHANISM:
Research - other than RAPID or EAGER

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Page 1 of 3
PROJECT SUMMARY

Overview:
The eastern Trans-Mexican Volcanic Belt (TMVB) is an enigmatic narrow zone (100 km wide) that lies between two regions that differ in their subduction style. On the flat-subduction side the Cocos slab underplates the continental crust to for 300 km before steeply plunging into the mantle to a depth of 500 km. On the normal-subduction side the slab dip is 30 degrees but it is truncated at 150 km depth by a clearly imaged, but unexplained structure dipping in the opposite direction. There is also some indication that this structure may continue to the SE to at least Nicaragua. The seismicity shows that there is a trench-perpendicular tear in the slab in this region that is likely the cause of the very high topographic gradient across the zone, and possibly the Veracruz Basin (VB) that lies just to the east of the zone. The VB also is the start of an 800-km long gap in volcanism between the TMVB and the Central American Volcanic Arc. Understanding the structure and flow through this region is important to integrating these two subduction systems together. In the last decade, some 30 new broadband seismic stations have been installed in the zone, and these will allow us to construct a structure and velocity model for region, and to determine the flow directions from seismic anisotropy.

Intellectual Merit:
Lateral flow of mantle material is now recognized as an important mechanism for slab rollback. In the eastern TMVB belt, a trench-perpendicular tear has created a window that could potentially move material from both the forearc and wedge side of the slab in central Mexico laterally along the trench system to east. This could explain the volcanic arc there. However, the south dipping structure that has been imaged on east side will complicate this by created a much more restricted flow region. Identifying the role os this structure in this region, as well as its extent further along the Central American subduction system well be important for developing an overall subduction model this system. A model for the transition zone along with flow directions obtained from seismic anisotropy may help explain this. The south dipping structure is a candidate to explain the truncation of the Cocos slab, which has no other explanation. Confirming that this structure also exists in the transition zone would help establish this a viable mechanism to explain this phenomena Central America.

Broader Impacts:
This project will provide scientific training for a Mexican PhD student at Caltech. This project is of great interest to the scientists at UNAM, and will help continue an intellectual engagement that started a decade ago. This will bolster the student’s job opportunities in Mexico. There has been a lot of progress in recent years in understanding the TMVB and the subduction system in central Mexico. If we can connect this research to southern Mexico and Central America by determining the transition between the two, we will be closer to integrating the whole subduction system.
# TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.B.2.

<table>
<thead>
<tr>
<th>Section</th>
<th>Total No. of Pages</th>
<th>Page No.* (Optional)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover Sheet for Proposal to the National Science Foundation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project Summary (not to exceed 1 page)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Table of Contents</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Project Description (Including Results from Prior NSF Support)</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>(Exceed only if allowed by a specific program announcement/solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>References Cited</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Biographical Sketches (Not to exceed 2 pages each)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Budget (Plus up to 3 pages of budget justification)</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Current and Pending Support</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Facilities, Equipment and Other Resources</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Special Information/Supplementary Documents (Data Management Plan, Mentoring Plan and Other Supplementary Documents)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Appendix (List below.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Include only if allowed by a specific program announcement/solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Appendix Items</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.
Imaging the Eastern Trans-Mexican Volcanic Belt

Introduction

The Cocos Plate is subducting beneath the North American and Caribbean Plates along the Middle America Trench from the triple junction near the Gulf of California to the junction with the Nazca Plate (near Panama). The style of subduction changes along the system in a manner that is not consistent with the monotonic increase in relative plate velocity and age from north to south. The slab alternates between zones of normal and flat subduction, and the volcanic arc has gaps, which indicate that flow is not simply 2D along the trench perpendicular direction. Attempts to explain these changes with variations on the Cocos Plate such as impactors (sea mount chains, ridges) have not been successful (Skinner and Clayton, 2010), at least in central Mexico. To understand the evolution of this complex subduction system, we need to be able to connect the various environments together to model the flow of mantle material between two disparate domains. In this proposal, we focus on the boundary between central and southern Mexico, marked by the end of the Trans-Mexican Volcanic Belt. This is where flat subduction transitions to normal subduction over a narrow zone.

Why is the eastern Trans-Mexican Volcanic Belt (TMVB) of interest? The eastern TMVB is the nexus point of two subduction styles for the Cocos Plate (see Fig. 1 for a map of the region). To the west is flat slab subduction and to the east is normal subduction. Current models of the plate geometry has this as a smooth transition, but the seismicity indicates that there is a trench perpendicular tear in the slab and the surface topography has a very steep west to east gradient. On the west there is a well-developed and active volcanic arc, but to the east is a 800 km gap between the TMVB and the Central American Volcanic Arc where there is little to no volcanic activity. To add a further complication, on the eastern side there is a south-dipping slab-like structure that truncates the Cocos slab at 150 km. There is some indication that this structure continues at least as far to the SE as Nicaragua, but there is no evidence of it on the west. All of these interesting complications come together in the eastern TMVB, for which we have no subsurface model.

Why now? Nearly a decade ago two dense seismic lines defined the subsurface structure on the west and east sides of the eastern TMVB, but at the time there was an extreme paucity of stations in the zone between these two lines. That has now changed with many new stations, including a temporary Mexican array that has been deployed directly over the zone of interest for the past two years and will continue for another year. These new data should now allow us to form an image of the subsurface and construct a crust and upper mantle model in this interesting and complicated area. Better defining the lateral extent of the south-dipping slab seen on the VEOX line, will add credence to that feature, which will help connect the TMVB to the tectonics of Central America. There is also an increased awareness of the importance of the lateral (trench parallel) flow in the mantle wedge as flat slabs rollback, as is the case in central Mexico (Long and Silver, 2008). This means that there should be a significant lithosphere/asthenosphere flow through the eastern TVMB but how this is occurs is not clear. Anisotropy measurements with the new stations will help define this.

In this study, we propose to develop a structural and velocity (Vp and Vs) model for the eastern TMVB based on new stations and algorithms that have appeared in the last decade. All the data for the study is in hand. Our objective is to establish a connection between the tectonics of central Mexico with the rest of Central America.
Tectonic and Geophysical Models for the eastern TMVB

The geological and geophysical setting of the TMVB is well presented in papers by Ferrari et al., (2012) and Manea et al., (2013). Below we briefly summarize the tectonic history in the region.

Subduction in central Mexico has undergone dramatic changes in the past 30 Myrs. Prior to that time, it was a region of normal subduction with a volcanic arc along the coast where its remnants are still evident today. At some point in the Cenozoic, the forearc was shortened by the removal of 200 km of crust that was possibly subducted (Keppie et al, 2012). Then, starting at 29 Ma the slab started to flatten out. The cause of the forearc shortening and slab flattening is not established (Skinner and Clayton, 2010), but one candidate is increased suction due to a low-viscosity layer in the back arc (Manea and Gurnis, 2007). The first manifestation of the flattening was the cessation of arc volcanism along the coast at 29 Ma. This was followed by the reappearance of volcanism at 20 Ma along the northern edge of what is now the TMVB (Ferrari, 2004). This is 500 km from the trench and indicates that the slab had flattened to a very shallow angle. The slab then proceeded to rollback to its present position creating the TMVB. At 10 Ma, the NW end of plate separated, creating what is now the Rivera Plate. This event opened a window in the slab that allowed lateral flow of the mantle into the wedge (Yang et al, 2009). It is thought that this initiated a horizontal tear in the slab that propagated eastward, truncating the slab such that the intact portion of the slab is presently only imaged to 500 km depth (Ferrari, 2004; Perez-Campos et al, 2008). The tear (with accompanying slab melting) can also explain the presence of Adakite volcanics within the TMVB, near Mexico City (Ferrari, 2004).

The TMVB is a prominent feature in central Mexico (see Figure 1). The active arc, which is presently a series of large stratavolcanoes along the southern edge of the belt, ends abruptly at the eastern end of the TMVB with the volcano Pico de Orizaba (the highest point in Mexico). On the western end, the Colima volcano marks the point where the Rivera Plate separated from the Cocos Plate at 10 Ma (Ferrari, 2004). In between the flat slab, which at the longitude of Mexico City is horizontal and underplates the continental crust at 45 km depth. The system is evolving with the slab rolling back to the south and taking the active arc with it. It is also breaking up along trench perpendicular tears. The western end of this system was examined in detail with the MARS seismic network (Yang et al, 2009; Suhardja et al, 2015). In this study we focus on the evolution of the eastern end of the TMVB.

The eastern TMVB is in between two dense seismic surveys that provide an image of the crust, slab, and upper mantle. The results of the MASE line (400 km to the west) (Figure 2) show that the Cocos slab is horizontal for 300 km and then descends steeply into the mantle at a 70-degree dip just north of the arc. The Moho through both the forearc and backarc is approximately flat at a depth of 45 km. The slab has evolved to its present position by rollback from its initial location, some 150 km to the north. Its unique geometry of underplating the continental crust means that fluids expelled from the slab are directly injected into the crust, without being transported away by an intervening asthenosphere. The fluid rich lower crust has reduced velocities as shown by a surface wave study by Iglesias et al (2009), which if empirically converted to reduced density,
can support the 2 km topography of the TMVB by a Pratt mechanism. The presence of the fluids in the lower crust is confirmed by magnetotelluric survey by Jodicke et al (2006).

The second seismic line (VEOX line) approximately 200 km to the east of the end of the TMVB (Figure 3) shows that the slab dips normally at 30° to a depth of 150 km (Kim et al, 2011; Melgar and Perez-Campos, 2011). At that point, it appears to be cut off by a more prominent south-dipping structure (SDIP), which itself descends to a depth of 250 km. There is no established tectonic role for this structure but Kim et al (2011) propose that it is part of a collision process that brought the Yucatan block to Mexico. The SDIP structure has only been seen on the VEOX line (Kim et al, 2011, 2014) and its lateral extent is not known. There is some weak evidence in the receiver functions from the few SSN stations that it continues to SE (Kim et al, 2011), but at the time there were no stations between VEOX and the TMVB, and so we could not see if it was present to the west. Now as is evident in Fig 1, there are several new stations, so we will get a better idea of the lateral extent of this structure. In a study by Rogers et al (2002) that is summarized in Figure 5, the Cocos slab appears to be truncated to 100-200 km in depth from the VEOX line all the way to Nicaragua. Since the SDIP structure appears to be cutting of the Cocos slab along the VEOX line, it is conceivable that this process could be present along a considerable portion of Central America, or at least that it might have initiated a lateral tear. There is also some evidence for this type of reverse structure is in Panama (Camacho et al, 2010). Note that the small volcanic fields between the TMVB and the Central American Volcanic Arc are in a better position to be related to the SDIP structure than the Cocos slab.

The TMVB ends abruptly at its eastern end, with the volcano Pico de Orizaba. Curiously there are two active volcanoes behind Orizaba (in the trench perpendicular direction). To the east of the TMVB lies the Veracruz Basin (VB), which a 6-km deep sedimentary basin formed in the Miocene. The topographic gradient from the TMVB (+2km) to the basement of the VB (-6km) over a horizontal distance of 100km is one of the steepest in the world. There is also a gap of 800 km in the volcanic arc between the TMVB and the Central America Volcanic Arc. There are a few small volcanoes in the gap (notably Las Tuxtlas and El Chichon) but they are small and farther inland than would be expected with the Cocos slab. Slab contours determined by seismicity (Pardo and Suarez, 1995) show that the slab transitions smoothly between the lines down to the 150 km contour level, but deeper than that, it is unclear what happens. Figure 4 shows the two end-member profiles that must somehow join near the eastern end of the TMVB.

The slab roll-back that has built the TMVB has proceeded a distance of 150 km over the past 20 Myrs. This requires a substantial movement of mantle material from the front to the back of the slab. Rather than accomplishing this with a path around the lateral extremities of the slab, the slab appears to be tearing such that it opens windows for the mantle to short cut the path. This processes originated with the separation of the Rivera Plate from the Cocos Plate at 10 Ma, and now two younger tears are developing to the west and east of the flattest part of the slab (a line from Acapulco to Mexico City) (Dougherty et al, 2012; Dougherty and Clayton, 2014). The SE tear is along a line that separates the TMVB from the Veracruz Basin (see Figures 1 and 4), and may be a possible explanation for the topographic gradient.

The structure transitioning through the eastern TMVB has several implications. The first is the lateral flow (trench parallel) due to the rollback of the flat slab. The flow of material
from the wedge to the fore-arc side of the slab is accomplished by edge flow around the ends or through internal tears in the slab. Seismicity studies by Dougherty (2012 and 2014) show there are two tears, one 200 km to the west of Mexico City and the other coincident with the eastern end of the TMVB. Surface wave anisotropy (Stubailo et al, 2013) indicates there is edge flow through the western tear. The question is, is there flow through the eastern tear, and if so does some of this flow also continue further to the east? If so it might explain the absence of arc volcanism to the east of the TMVB, where there is an 800 km gap in the main arc volcanism. It is interesting to note that the small volcanoes in the gap (e.g. Las Tuxtlas, El Chichon) better follow the SDIP structure than the Cocos Plate as far the 100-km rule is concerned, that is, volcanoes exist when the slab reaches 100-km depth.

The proposed structural and velocity model of the transition zone across the eastern TMVB needs to resolve or predict the following phenomena:

1. **Slab tear.** The down dropped side creates the topographic hole for the Veracruz Basin and the rupture creates the pathway for the volcanoes at the end of the TMVB. This does not explain the abrupt end of the arc, nor the SDIP structure.
2. **Slab truncation.** The slab on the western side extends to 500 km, while on the east side it is truncated at 150 km.
3. **South-dipping slab (SDIP).** The SDIP structure seen on the VEOX seismic line disappears between the VEOX and MASE lines. The logical place for this is at the eastern end of the TMVB.
4. **Lateral flow along the wedge.** The model needs to show how material is transported from and through the transition structure.

**Data Sources**

The eastern edge of the TVMB lies between the MASE and VEOX seismic arrays, which are dense linear arrays deployed 2005-2007 and 2007-2009 respectively. Over the past decade, the Servicio Sismologico Nacional network of Mexico (SSN) has established 12 new stations in the area around these lines. In addition the network (OXNET) run by Michael Brudinski of Miami University has deployed 10-12 stations in the area, and most recently a new temporary array GECO (GEometry of COcos Plate) has deployed 12 broadband sensors in this area. This array was funded by an award from Conacyt (Mexican NSF) of which the author is an unfunded co-PI. The location of all the stations is shown in Figure 1. The MASE, VEOX, SSN, GECO, UV and part of the OXNET datasets are already in hand. Taken together, they provide a reasonably dense set of broadband stations to image the mantle beneath the eastern edge of the TMVB.
Techniques to Be Used in the Seismological Analyses

To obtain a better image of the transition between the flat and normal dipping portion of the slab, we plan to use a variety of seismic techniques. Here we list several that we will apply, but depending on the results and resolution, the techniques will be modified. We have several years of experience with using the techniques.

Surface wave tomography: A study by Iglesias et al (2010) provided a detailed shear-wave velocity along the MASE line using Rayleigh waves. They were able to identify a slow velocity layer in the lower crust, which when converted to density, can support the elevation of the TMVB via a Pratt mechanism. A 3D study by Stubailo et al (2013) provides a regional scale shear-wave velocity model for central Mexico (see Figure 9 for an example), in which the anisotropic fast directions are consistent with trench-parallel flow in the mantle wedge. More recent studies by Gaite et al, (2015) and Spica et al (2015) have increased the resolution of the shear-wave velocity model by using both earthquakes and ambient noise correlations, but there is still insufficient resolution to tie the lower crust to the sudden end of the TMVB.

We have redone the surface wave study with the enhanced ray coverage provided by the GECO, OXNET and expanded SSN network. An example is shown in Figure 10, where the abrupt end of the TMVB is evident in phase velocity maps at 47 sec (approximately 50 km depth). To further increase the resolution, we plan to use C3 correlations (Stehly et al, 2008) between the MASE and VEOX lines using the permanent SSN stations as common stations. With this technique, correlations between stations that did not record contemporaneously can be generated by first correlating the stations with a set of stations that recorded at both times, and then correlating and stacking the resultant correlations. This has been done successfully between the MASE and MARS arrays by Spica (2015), and he has generously provided the correlations to this study. Also to the increase the depth resolution and extent, we plan to use earthquakes to provide longer periods. To this end we have gathered 50 teleseismic events that were recorded by a substantial number of stations with paths traversing the eastern TMVB.

Receiver Function Imaging: We will use standard receiver function methods that we have used in previous subduction studies in Mexico and Peru. The coverage at the eastern TMVB will be much better now with the GECO, UV and OXNET stations. We will look in particular for a tear in the slab and see how far west the SDIP structure seen on the VEOX line can be detected to the west, and how it changes shape as the Cocos slab flattens out. Examples of receiver function analysis are shown in Figures 2 and 3. We found in our analysis of the data from Peru, that crustal multiples are often very useful for determining the structure when there is interference coincident with the primary conversion (Ma and Clayton, 2015). We will test their application in this study.

Anisotropy: The key to detecting mantle flow under the eastern TVMB through a tear in the slab is the determination of the fast direction of anisotropy. With the new stations that are available, we will use S-wave splitting measurements to determine anisotropy (Long and Silver, 2008; Soto and Valenzuela, 2013), such as shown in Figure 8. In addition, the surface waves analyzed above will be used to measure the fast directions (see Figure 9 for an example). These will need to be well tested with synthetic checkerboard examples to make sure apparent the anisotropy isn’t being generated by lateral heterogeneity. We will also use the differences between radial- and transverse-
component receiver functions to look for anisotropy above the Moho and slab interfaces. An example of this is shown in Figure 8.

*Body-wave tomography:* The study of Chen and Clayton (2012) provided images of $V_p$, $V_s$, $V_p/V_s$, $Q_p$ and $Q_s$ in central Mexico using body waves from both local and teleseismic events. The images were well resolved along the MASE and VEOX lines where the ray density was high, but suffered in quality between the two arrays between where the ray paths were sparse. Results along the VEOX line are shown on the right side of Figure 3. We plan to redo the study, including the new stations. An original study was able to confirm the presence of the SDIP structure, it is hoped that the new station coverage will help determine its location to the west of the VEOX line.

*Full waveform inversion:* The velocity (surface and body waves) and structure (RF’s) will be combined into a 3D model for eastern TMVB. Using this as an initial model, along with the number local and regional earthquakes we will refine the model with reverse-time or adjoint tomography. This is an expensive, time-consuming step and will only be done if a suitable initial 3D model can be generated.

**Expected Outcomes**

The goal of this study is to find the transition structure between the TMVB and normal subduction and the south-dipping structure (SDIP) seen on the VEOX line. We believe that we can do this by extending the structure on the VEOX line to the west using the new stations, and the velocities determined by surface wave analysis to determine how far east from the MASE line the slab remains coupled to the continental crust. The flow directions obtained from the anisotropy measurements should then constrain how material is moving from to the south as the slab in central Mexico rolls back. This may explain the gap in volcanism to the east of the TMVB. We expect to determine the structure and velocities of the crust and upper mantle (lithosphere and asthenosphere) in this region and to make a 3D velocity model.

**Broader Impacts**

With this study, we will attempt to connect two parts of a subduction system that are beside each other, but are very different in their structure and dynamics. Among the observations that we believe will be explained by understanding this transition is the very steep topographic gradient between the TMVB and the Veracruz basin, and the pronounced change in arc volcanism. It should also help explain the origin (and function) of the enigmatic SDIP structure that is seen under the VEOX line, which may be part of a phenomena that causes the apparent truncation of the Cocos slab in Central America.

This proposal will fund the PhD research of Jorge Castillo-Castellanos, a Mexican citizen with a Master’s degree from UNAM. It will be one component of his PhD thesis at Caltech. He did his Master’s thesis at UNAM on seismic anisotropy along the MASE line, and is familiar with the tectonic evolution of the region. While a student at UNAM, he also participated in the deployment of the GECO array. This project will allow him to build on this knowledge and maintain intellectual contact with his colleagues and mentors at UNAM, which will be helpful for future job prospects in Mexico.

**Collaborators**

This project has a number of unfunded collaborators from Mexico. In particular, Prof. Xyoli Perez-Campos at UNAM and Director of the Servicio Sismológico Nacional (SSN) will collaborate on the generation of receiver functions, and Prof. Arturo Iglesias at
UNAM and Director of the Instituto de Geofisico will help with surface waves. Prof. Raul Vanezuela will collaborate on SKS splitting. This group is also the source of the SSN, GECO and UV data.

Results From Prior NSF Support
EAR-1045683: Collaborative Research: The Peru Subduction Experiment (PeruSE), a Seismic Investigation of the Role of Water in the Lithospheric Dynamics of Subduction Zones, joint with Paul Davis at UCLA, $171,853, 03/01/11-02/28/2014.

Intellectual Merit
Under this award, we performed body and surface wave tomography and receiver functions using a 150-stations broadband network located in southern Peru. The main results are summarized in Figures 11 and 12. The goal was to examine the transition zone from normal to flat subduction and to compare the results to the subduction system in central Mexico. The results show a normal subducting slab to the south that smoothly transitions to a flat slab that is located approximately 25 km beneath the continental Moho. The remarkable feature of the flattened slab is that it follows the topography of the continental Moho, including an upward rise that occurs approximately 400 km inland from the trench. This indicates that suction is the dominant force in the slab flattening. There is also some indication that there is a subducted seamount from the Nasca Ridge in the flat slab system, and this may be the mechanism that forced the system into a suction-dominated system. By comparison to the flat subduction in central Mexico, the slab in Mexico underplates the continental Moho, and there is no counter-part to the Nasca Ridge (a subducted impactor).

Broader Impacts
The study contributed to the PhD of 4 students (Kristen Phillips, Stephen Skinner, Sara Dougherty and Yiran Ma) at Caltech, and resulted in 7 published papers: Phillips et al, 2012; Skinner and Clayton, 2013; Ma et al, 2013; Ma and Clayton, 2014; Dougherty and Clayton, 2015; Kim and Clayton, 2015; Ma and Clayton, 2015. The data from the survey (PeruSE, 2013) is available from IRIS.

An earlier study, EAR-0609707, contributed a large portion of the data and background for this proposal. It contributed to the PhD of three students (YoungHee Kim and Ting Chen at Caltech and Diego Melgar at UNAM), and the datasets MASE (2007) and VEOX(2010). The main results of this study are the slab structure along the MASE and VEOX lines (Kim et al, 2010, 2011, 2012, 2013, 2014; Chen and Clayton, 2013). The results are summarized in Figures 2-4.
Figure 1. Location Map for Central Mexico. The orange region is the Trans-Mexico Volcanic Belt (TMVB). The slab depth contours are shown with black dashed lines, with the red dashed line showing the edge of the slab. The white symbols are the seismic stations used in the study. The yellow, purple and light blue dashed lines show tears in the slab. The focus of this study is along the light blue dashed line.

Figure 2. Summary of Imaging along the MASE line (the inverted triangles in Fig 1). The left panel shows the slab diving into the mantle at 70 degrees starting at the southern edge of the TMVB and ending at a depth of 500 km. The right panel shows the detail in the upper 100 km, with the Cocos slab underplating the continental to a point 300 km from the trench. The Moho is approximately flat through the region, despite the 2 km relief of the TMVB, indicating that is supported by a Pratt mechanism. From Perez-Campos et al, 2008).
Figure 3. Summary of Imaging Along the VEOX Line (the upright triangles in Fig 1). The left panel shows a receiver function section and shows a weak image for the Cocos slab, which is more clearly delineated by the earthquakes (green dots). Much stronger and more coherent is a south-dipping slab-like structure (SDIP) (marked by arrows). This structure truncates the Cocos slab at 150 km depth. The two panels on the right also shown this feature with the top-right being a tomography image computed from teleseismic waves, and the bottom-right is constructed from local earthquakes (Chen and Clayton, 2012). The SDIP structure does not have an identified role in the tectonics of the region. From Kim et al (2011) and Clayton and Chen (2012).

Figure 4. Models of the slab structure beneath the MASE line (left) and VEOX line (right). The SDIP structure is labeled as the Yucatan slab in this figure. The challenge in this proposal is to fit these two models together with a structure that spans 300 km laterally. Figure from Chen and Clayton (2012).
Figure 5. Truncated Slab in Central America. The global P-wave tomography cross-sections show the Cocos slab is cut off at depth of 100-200 km. The land portion of line 1 is nearly coincident with the VEOX profile (Figure 3), which shows it is truncation is due to the SDIP structure. This explanation may also apply to the other profiles. Figure adapted from Rogers et al (2002).

Figure 6. Evidence of a slab tear at the eastern end of the TMVB. The left panel (a) shows the seismicity (stars) from 2001 to 2011, and the right series (b-d) shows depth slices along the west, center and right rectangles of the grid on the left. They show the slab changing dip from 0 to 25° as it crosses through the edge of the TMVB. This is summarized in d) where the along-strike dip of the slab is shown. The circles are some of the stations used in the locations. From Dougherty and Clayton (2014).
Figure 7. Map of Ultra Slow Layer (USL). The USL, detected by waveform analysis, extends to the eastern end of the TMVB. This is used as a marker of where the slab appears to underplate the continent and hence is taken to be the location of the tear. A similar feature is observed with a tear to the west of the MASE line. From Dougherty et al, (2012)

Figure 8. Anisotropy Measurements. The left panel shows the fast directions along the MASE line and shows that in the mantle wedge under the TMVB, there is a component of trench parallel flow (Castillo, 2015). The labels F0 denotes trench perpendicular flow, F1 and F2 are corner flow. The right panel shows fast S-wave splitting directions along the VEOX line using local earthquakes and shows even a stronger trench parallel flow (Soto et al., 2013).
Figure 9. Phase Velocity Map. Shown is the Rayleigh phase velocity from Stubailo et al. (2013, along with the fast directions. The crustal results (left panel) show stronger flow parallel to the trench than the flow beneath the crust (right panel).

Figure 10. Preliminary Phase Velocity Maps. Shown are Rayleigh wave phase velocity maps. The left shows velocities in the upper crust and is dominated by the Veracruz Basin (VB) and the Valle of Mexico (VM), while the right shows the velocities in the lower crust and upper-mantle. Note abrupt change in velocities at the eastern end of the TMVB (dashed line) in the right panel.
Figure 11. Prior-Work Peru. Receiver function image (left) and tomographic image (right) of the normal subduction region in southern Peru. MC is a mid-crustal interface interpreted as the western edge of the Brazilian Shield. The inverted triangles are Moho depth estimates from stacked RF multiples. From Phillips et al., (2012).

Figure 12. Prior-Work Peru. Image of the flat slab portion of the Nazca slab based on receiver functions and ambient-noise tomography (left) and a cartoon of the result (right). Note the slab follows the Moho topography, which means that the suction force is dominant in the system. From Ma and Clayton (2015).
References


Ferrari, L., (2004), Slab detachment control on mafic volcanic pulse and mantle heterogeneity in central Mexico, Geology, 32, 77-80, doi:10.1130/G19887.1


