

A Progress Report On

MASE: Shallow Subduction in Central Mexico

R. Clayton, Sept, 2006

Summary

The objective of the MASE (Middle America Subduction Experiment) is to construct a geodynamical model of the subduction process. The Middle America Trench was chosen as the first example because of the relatively simple plate geometry (a linear margin with near normal subduction) and a significant along-strike slab-dip variation. The initial deployment along the Acapulco to Tampico transect in central Mexico is designed to investigate the case of shallow subduction.

The main results to date are:

- The discovery that the slab underplates the continental crust to a distance of 200 km from the trench. This result is interesting because there is no geologic or geodetic indication of coupling in this zone – the coupling that is measured geodetically is confined to the initial 75 km near the coast where the slab is dipping down. There is also no fluid signature in the magnetotelluric (MT) data (Figure 7) of the flat-slab portion of the line.
- The relative attenuation in the mantle under the Mexican Volcanic Belt (presumed location of the mantle wedge) is a factor of 2 higher than the surrounding mantle (Figure 4).
- Modeling studies indicates that a shrinking low-viscosity mantle wedge can lead to flat-slab subduction as observed (Figure 8).
- A slow earthquake appears to be in progress on the southern 200 km of the MASE line (Figure 6). The last slow event occurred in 2002. This one started in March, 2006.

The next steps in the project are to determine the structure of the slab from the receiver function multiples and to integrate this into a velocity/structure model for the region. This will then be used to develop a specific input model for the geodynamic modeling. The MASE line will be moved east to the Oaxaca/Veracruz region, just west of the Tehauntepec Ridge, to sample a moderate dip example.

Introduction

The MASE project has been underway since the beginning of 2005. It is a multi-disciplinary study that involves seismology, geodesy, geology, geochemistry, geodynamical modeling, and electrical methods. The project is also multi-institutional with scientific participation coming from the Tectonics Observatory (TO) at Caltech, the Institutes of Geophysics and Geology at UNAM in Mexico City, the CENS project at UCLA, and the Center for Geosciences at UNAM in Jurquilla. The specific participants and the areas of research are listed in a later section. The initial efforts have focused on the flat-slab region of the Acapulco transect. The plan is to move the TO-station

component of the array to a transect through Oaxaca-Veracruz which will cross the slab at a point of moderate dip (20 degrees).

The field experiments are designed to determine the essential parameters for a geodynamical model. These parameters include the slab geometry, the temperature of the mantle wedge and slab, the viscosity of the mantle wedge, and the coupling between the slab and over-riding plate. The main field effort is the seismic array, and it is fortunate that the initial study area (Acapulco to Tampico) is the site of an extensive GPS monitoring program, and a previously deployed large-scale MT survey. There are also several stations in Mexico's National Seismic Network (SSN) in central Mexico that provide earthquake locations. There has been extensive geologic mapping along the transect by the geologists at UNAM as well as a geochemical database integrated with a GIS system.

Seismic Studies

The seismic array has been fully deployed for approximately one year along the Acapulco to Tampico transect. The array consists of 100 broadband instruments spanning a distance of 550 km (approximately 5-6 km station spacing). This is a dense survey designed to provide sufficiently detailed ground coverage that the basic parameters that are important for modeling the subduction zone can be determined. Half the instruments are from the TO and the other 50 are from the CENS (Center for Embedded Network Systems) project at UCLA. Together this array constitutes one of the most unusual and interesting seismic deployments that will spawn a number of side studies because of the density of stations. The 50 TO instruments are scheduled to be moved to a moderate dip example along the Oaxaca-Veracruz transect in early 2007.

The analysis of the seismic data is utilizing a number of techniques to determine the essential parameters. Receiver functions (RF) are the primary technique to determine the large-scale structure (location of the boundaries) of the crust, mantle and slab. The results to date are shown in Figures 2 and 3. The first 200 km of the slab is underplating the continental crust as is shown in Figure 2. This is one of the clearest images of underplating. The image also indicates that the continental crustal attenuation near the trench is due to uplift and not undersided erosion.

As yet no direct image of the slab beneath the Trans Mexican Volcanic Belt (TMVB) has been obtained, but as is shown in Figure 3, there is considerable evidence that the multiples (receiver functions that have extra paths or legs in the crust) will be able to provide this missing part. The next step in this analysis is to use velocities provided by tomographic and surface wave studies to "sharpen" the image with better velocity functions. Once this is done, we will be in a position to use the scattering produced at each interface over a number of earthquakes to determine the elastic parameters (V_p , V_s , and density for example). We have also been able to clearly image of the continental Moho and its thickening towards the TMVB (Figure 3).

The RFs can also be used to look deeper in the mantle for structure on the 410 km and 670 km seismic discontinuities. The lower panel of Figure 3, shows a stacked image formed from the RFs from a number of earthquakes is shown. The two major

discontinuities (410 and 670) can be seen along with an apparent discontinuity at 550 km. It is interesting that the 670 appears to decrease in depth under the TMVB.

A complimentary method to the receiver functions is surface waves which are well suited for determining velocities, but not at determining the structure. With this method, the group velocities across the array as a function of frequency are determined from a number of local earthquakes. The initial results are shown in Figure 4, and it is clear that the mantle wedge is a slow shear velocity zone. The location of the Moho in the initial velocity model in the inversion is provided by the RF study.

One of the most important parameters to determine is the viscosity, particularly the distribution of low viscosity in the mantle wedge. Viscosity is measured indirectly by seismic methods by determining the attenuation. An examination of teleseismic P and S waves recorded on the MASE array shows very little variation in attenuation along the transit probably because of the small size of the wedge and by the limited frequency content of teleseismic body waves. However, local events have much higher frequency content and they do show a significant variation along the line. The results of determining the attenuation from local earthquakes are shown in Figure 5. Fixing the Q to be constant in the wedge allows the slab to be estimate at 20 degrees under the TMVB. When the geometry of the slab is determined by RFs, the Q measurements will then be used to determine the lateral variations in attenuation as a proxy for viscosity.

Tomographic studies will also provide estimates of V_p and V_s velocities. These studies are just beginning because of the difficulty in correcting clock errors. The preliminary indication is that the velocity anomaly associated with the subducted slab is small.

Geodetic Studies and Slow Earthquakes

An existing GPS network on the MASE line that is run by V. Kostroglov of UNAM, has been important for determining the coupling between the subduction process and the upper plate. The surprising result is that there is almost no coupling of the upper plate along the flat-slab portion. This agrees with the seismicity, which is concentrated within 75 km of the trench, and with the morphology which shows no compressional structures that are active in the last 20 my in this region.

The GPS network is also showing that a slow earthquake is now underway in the flat slab portion of the profile. The results are shown in Figure 6. The MASE seismic array will provide an opportunity to monitor the seismicity along the slab during this event. The initial results indicate that there is no appreciable change in the tremor earthquake occurrence associated with the silent earthquake. The last slow earthquake in this region occurred in 2002 and lasted for 9 months. If the same duration occurs this time, the end will coincide with the end of the seismic deployment along the Acapulco line.

Magnetotelluric (MT) Survey

In the 1990's the collaboration of German and Mexican scientists carried out a large scale MT survey along the MASE line. They also did a survey along the Oaxaca-Veracruz line. The results were published in 2006 (Jockinke et al, 2006) and are

important for the MASE study because the MT results are sensitive to fluids and melt. A cross-section is shown in Figure 7, and shows that there is no evidence of fluids in the flat slab region. The anomalies near the trench are likely related to a serpentinization process. The largest anomalies are under the Mexican Volcanic Belt (MVB). The farthest south of the anomalies are interpreted to be due dehydration of the slab. The anomalies further to the north are thought to be due previous dehydration episodes when the slab was in that position.

Geodynamical Modeling

It is generally accepted that dehydration of subducting lithosphere transports fluids into the mantle wedge. Such dehydration of the slab may ultimately cause a decrease in the viscosity of mantle wedge, forming a low viscosity wedge (LVW) on top of the subducting slab. We have found that the incorporation of LVWs significantly improves the realism of modeled slabs. An order of magnitude reduction of the wedge viscosity leads to an increase in slab dip from an initial 30° to 50° after 10 Myr of convergence. We have found two end member states, depending on the maximum depth extent of the LVW (for a viscosity reduction factor of 10). Models with a LVW extending down to 400 km depth show a steep slab geometry (dip $> 50^\circ$), whereas a shallow LVW produces flat slabs, including perfectly flat slabs (dips = 0°). Assuming that slab and sediment dehydration are responsible for lowering the mantle viscosity, the maximum depth extent of the LVW is mainly controlled by the age of the incoming plate and convergence rate. Thus, large variations in LVW geometry and viscosity have significant influence on the slab geometry and volcanic arc evolution through time. According to geochronological data, the onset of the flat slab took place ~ 15 - 20 Ma, after the Farallon plate broke into the smaller Cocos plate (~ 24 Ma). The much younger Cocos plate could have shifted the bulk of slab dehydration to shallower depths. The results of a dynamic model incorporating a shrinking LVW through time and space, with a viscosity at least an order of magnitude smaller than the ambient asthenosphere is given in Figure 8, where a large and rapid change in slab geometry, from a well-developed steep slab to a perfectly flat slab segment located a shallow depth is shown.

During the coming year we will be in a position to significantly improve the realism of the models. The models will include paleogeographic reconstructions of the evolving Farallon, Cocos, North American and Caribbean plates, including the Chortis block that we have assembled with the GPlates software package as well as paleogeographic maps of the oceanic plates. The models are regional cut outs in a spherical geometry, fully time dependent, and incorporate a subducted oceanic crust with a Lagrangian method. The models will predict the full three dimensional geometry of the slab as a function of time. Access to the new CITerra computer will allow us to explore a wide range of cases that will be compared to the MASE lines.

Participants in the MASE Project

- *Robert Clayton*, Prof. at Caltech, Interested in the inversion of the seismic data to determine the parameters important to modeling.

- *Paul Davis*, Prof. at UCLA, Interested in tomography and relation to subduction to volcanic processes.
- *Xyoli Perez-Campos*, Prof. at UNAM, Interested in determining seismic structure with receiver functions.
- *Luca Ferarri*, Prof at UNAM, Interested in the geology of the transect and in models of the subduction process in this region. Also interested in magnetotelluric methods in the region.
- *Dante Moran*, Prof. of Geology at UNAM, Interested in the geology, geochronology and tectonic models for the past history of Mexico and the Caribbean.
- *Arturo Iglesias*, PostDoc in Geophysics at Caltech, Using surface waves to determine the shear-wave velocity structure.
- *Ting Chen*, Graduate student in Geophysics at Caltech, Determining the attenuation structure in central Mexico.
- *YoungHee Kim*, Graduate student in Geophysics at Caltech, Using inversion methods to determine the subsurface parameters.
- *Alan Husker*, Graduate student in Geophysics at UCLA, Doing tomography to determine the P-wave velocity structure.
- *John Eiler*, Prof of Geochemistry at Caltech, Interested in oxygen isotopes along the Acapulco line to determine slab hydration and melt properties.
- *Mike Gurnis*, Professor of Geophysics at Caltech, Developing geodynamical models for the MASE project.
- *Vlad Manea*, PostDoc in Geophysics at Caltech, Building geodynamic models for subduction.
- *Carlos Valdez*, Prof. of Seismology at UNAM, Using local earthquakes to determine the crustal structure.
- *Joann Stock*, Prof of Geophysics and Geology at Caltech, Interested in the geodetic measurements and models.
- *Vladimir Kostroglodov*, Prof of Geophysics at UNAM, Interested in geodetic measurements and models and in slow earthquakes.
- *Fernando Greene*, Graduate student in engineering at UNAM, Seismic structure using receiver functions.
- *Lizbeth Espejo*, Graduate student in engineering at UNAM, Seismic structure using receiver functions.

Outreach and Education

The deployment of seismic instruments has only been possible by installing the majority station in schools that range from kindergartens to universities. Prof. Xyoli Perez-Campos at UNAM has used this opportunity to instruct the students on earth science and on earthquakes in particular. She developed a program for senior engineering students at UNAM that has them developing various type of teaching materials and then going out to the schools and giving presentations. This is timely because the experiment is taking place during the 20th anniversary of the 1985 Michoacan earthquake that was widely felt along the survey line, and caused major destruction in

Mexico City. Figure 9 shows the engineering students visiting one of the schools hosting a MASE station. Three UNAM students Lizbeth Espejo, Luis Edgar Rodríguez, and Fernando Greene were given the Premio al Servicio Social "Dr. Gustavo Baz Prada" award, which is a university wide award given for outstanding social service.

The MASE project involves 2 Graduate students at Caltech, 2 at UNAM, and 2 at UCLA. Two PostDocs at Caltech, both graduates from UNAM are also involved.

Future Plans

In early 2007, we plan to move the TO broadband instruments to a line that crosses the states of Oaxaca and Veracruz (see Figure 10). The slab dip in the region is approximately 20 degrees. There is an existing GPS network (somewhat sparser than on the Acapulco line), and an MT survey has been conducted in this region. The administrative structures and scientific collaboration that we have established with the Acapulco line will be the same with this transect.

Meeting Presentations:

Backbone of America Conference, Mendoza, April 4-7, 2006

Clayton, R., X. Pérez-Campos, A. Husker, A. Iglesias, Y. Kim, V. Manea, P. Davis, L. Ferrari, M. Gurnis, V. Kostoglodov, D. Moran Zentano, S. Singh, and J. Stock. Flat Slab Subduction in Central Mexico as Determined by the MASE Project

Union Geofísica Mexicana (UGM) Fall, 2006

Clayton, R., X. Pérez-Campos, P. Davis, A. Iglesias, Y. Kim, T. Chen, A. Husker, F. Greene, and L. Espejo. Seismic Results From the MASE Trans-Mexico Survey.

Pérez-Campos X., R. Clayton², F. Greene³, and L. Espejo. A receiver function image on how Cocos subducts beneath North America.

American Geophysical Union (AGU) Fall, 2006

Special Session "Flat Slab Subduction in Central Mexico" organized by R. Clayton, P. Davis and L. Ferrari.

Kim, Y., F. Greene, L. Espejo, X. Pérez-Campos, and R. Clayton, Receiver Function Analysis of the Middle American Subduction Zone in Central Mexico.

Iglesias, A., R. Clayton, J. Pacheco, S. Singh, X. Pérez-Campos, and C. Valdés-González, Preliminary results of high-frequency surface wave tomography along MASE line.

Kostoglodov, V., K. Larson, and S. Franco-Sanchez, Seismotectonics of Central Mexico Subduction Zone From Crustal Deformation Studies.

Pérez-Campos, X., L. Rodríguez, L. Espejo, F. Greene, T. Reyes, E. Solano, A. Iglesias, and R. Clayton, MASE: a Great Opportunity for Outreach to the Rural Communities in Mexico.

Manea, V and M. Gurnis, Central Mexican Subduction zone evolution controlled by a low viscosity mantle wedge.

Pérez-Campos, X., R. Clayton, P. Davis, A. Iglesias, A. Husker, and C. Valdes-Gonzalez, MASE: A seismological perspective of the sub-horizontalsubduction of the Cocos Plate under North America.

Clayton, R. and T. Chen, Body-Wave Attenuation Structure in Southern Mexico.

Manea, M. and V. Manea, Flat slabs seen from above: aeromagnetic data in Central Mexico.

Ferrari, L., Cenozoic evolution of the central part of the Mexican subduction zone from geologic and geophysical data – in the eve of the result from the MASE experiment.

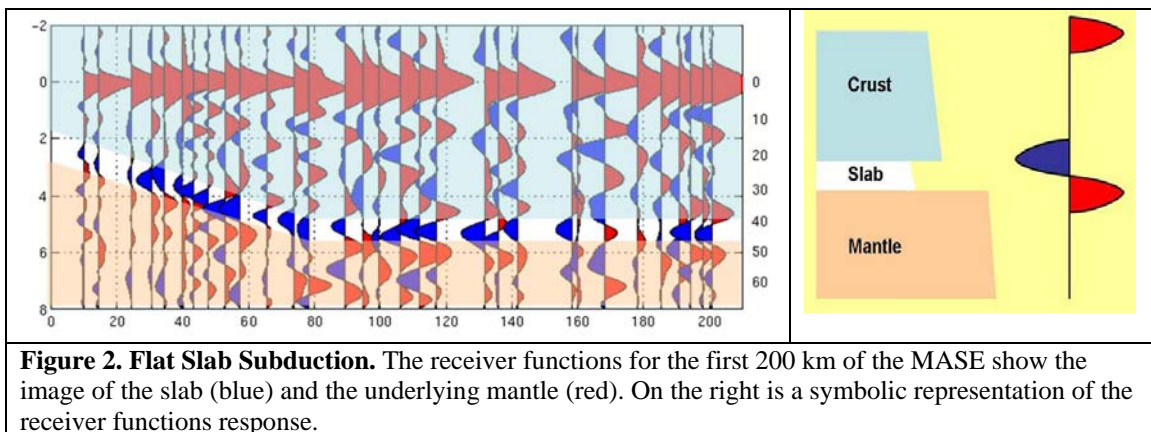
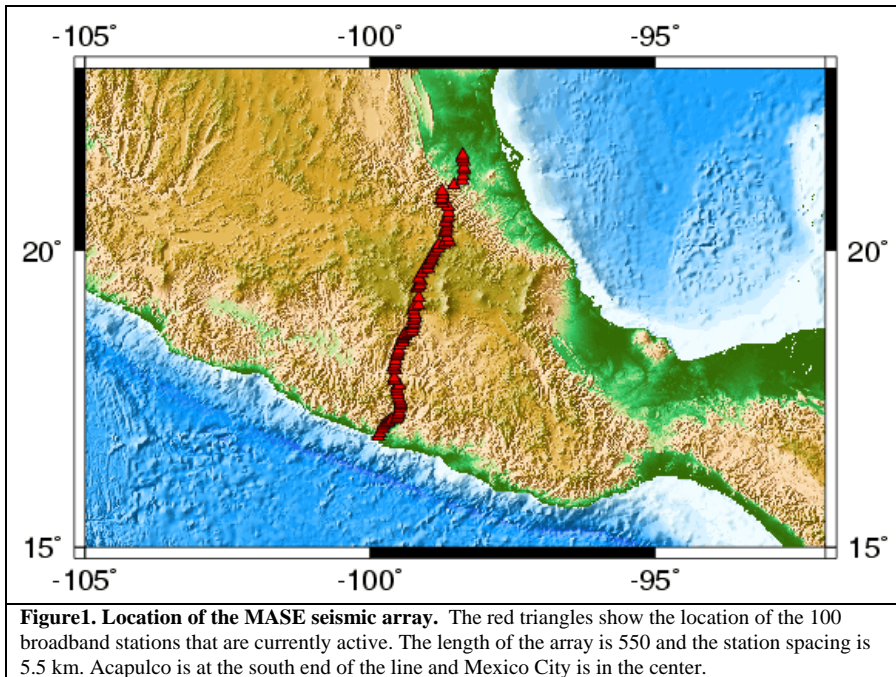
Rubin, K., G. Zellmer, Z. Jurado-Chichay, D. Moran-Zenteno, and D. Pyle, The Subduction Component at Volcan El Jorullo: Young but Subdued.

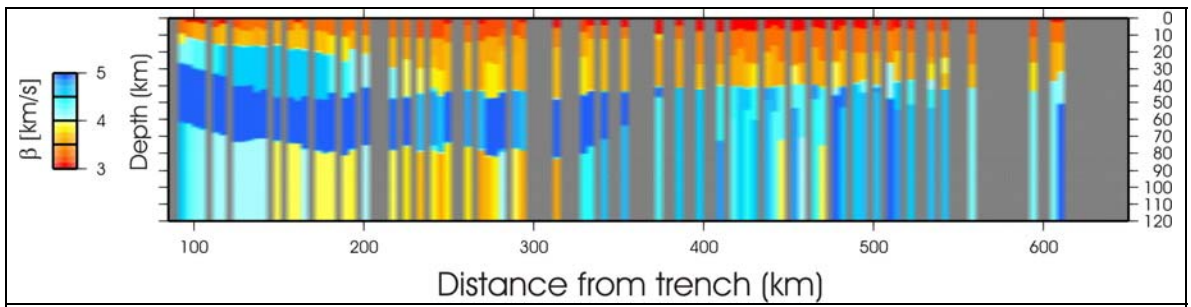
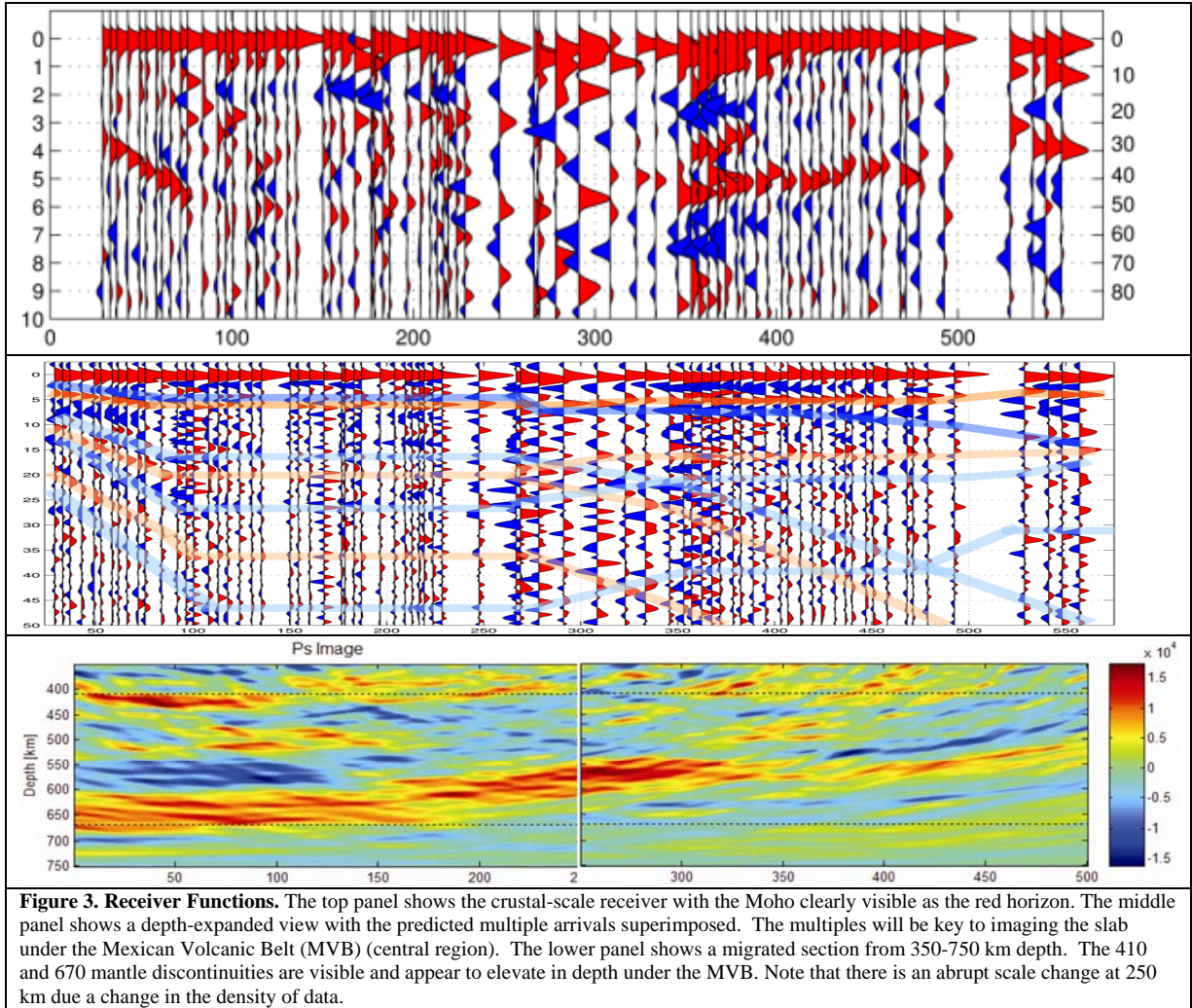
Husker, A. and P. Davis, Seismic Tomography of the Cocos Plate.

Valdes-Gonzalez, C., C. Cardenas-Monroy, X. Perez-Campos, A. Iglesias, and R. Clayton, Raytracing along the Central Mexico MASE profile with nearby earthquakes.

References

Jodicke, H., A. Jording, L. Ferrari, J. Azate, K. Mezger, and L. Ruokey, Fluid release from the subducted Cocos plate and partial melting of the crust deduced from magnetotelluric studies in southern Mexico: Implications for the generation of volcanism and subduction dynamics, *L. Geophys. Res.*, 111, B08102, doi:10.1029/2005JB003739, 2006.





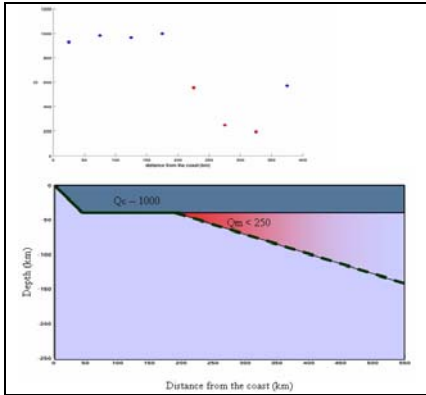


Figure 5. Attenuation Model. The upper panel shows attenuation measurements determined from local earthquakes, and the lower panel shows the inferred model with a low-Q wedge.

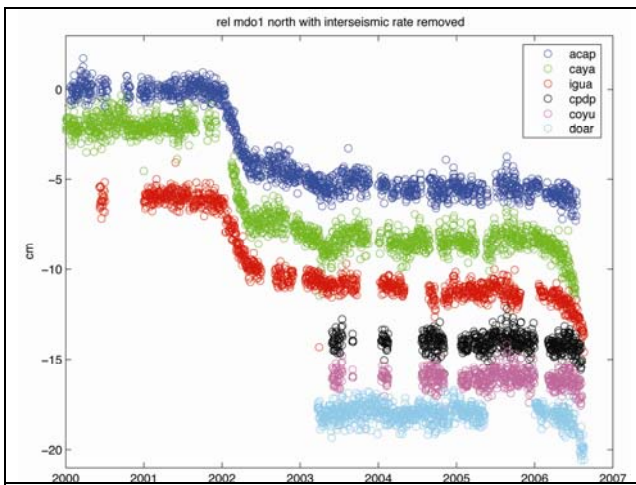


Figure 6. GPS Transient. The north component of GPS shows a slow earthquake starting in March of 2006. The previous such event was in 2002. All station are on the coast near Acapulco except the red one (IGUA), which is 200km inland.

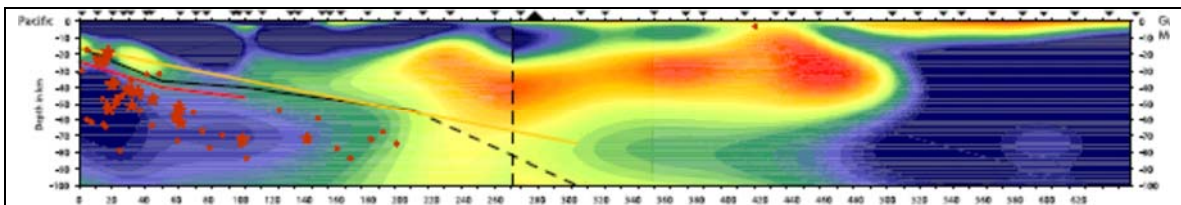


Figure 7. Electrical Resistance. The resistivity determined by the magnetotellurics from the study by Jockinke et al (2006). The bright anomaly at the left is thought to be due serpentinization of the incoming slab, and the next large anomaly to the right may be dehydration. The subsequent anomalies to the right may be related to previous episodes of dehydration.

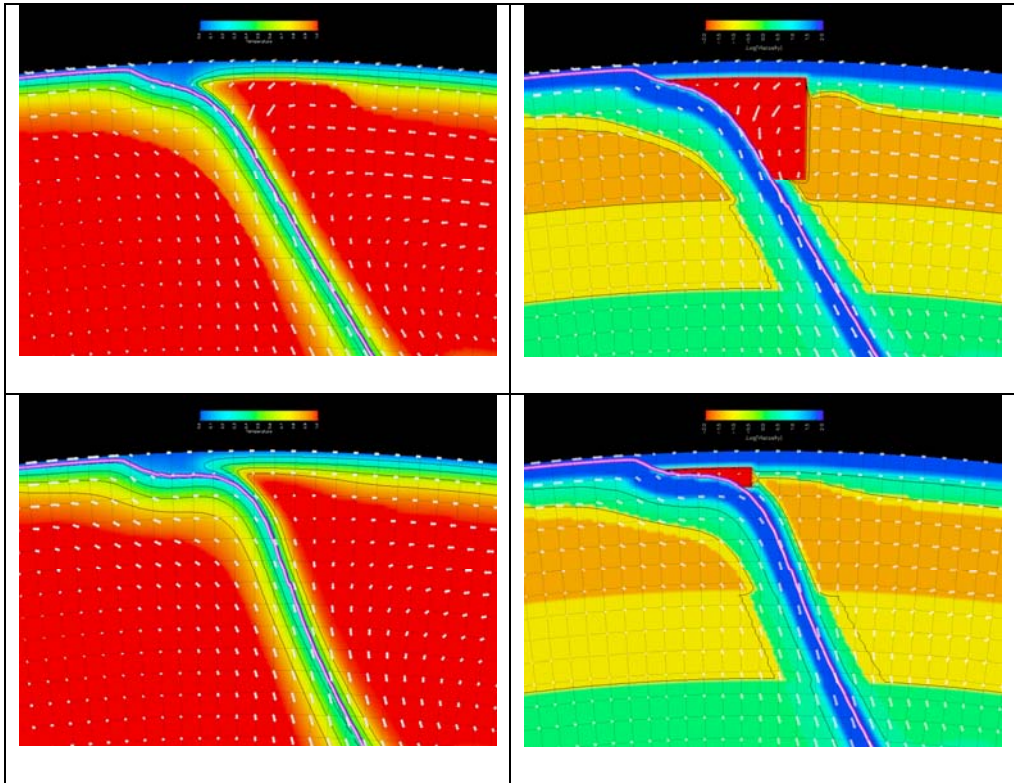


Figure 8. Simulation of Flat Slab Subduction. The upper panels show the results for subduction with a large low-velocity wedge (LVW), with temperature on the left and viscosity on the right. The red zone in the upper-right is the wedge in this case. The lower panels show how flat slab subduction can develop by shrinking the size of the LVW as the subduction evolves.



Figure 9. Outreach. The pictures show engineering students from UNAM making presentations on earth science and earthquake hazard at a school that is hosting a MASE station.

