Structural Controls on Postseismic Deformation Following the Mw 7.8 Pedernales, Ecuador Megathrust Earthquake: Insights from Joint Tomographic Inversion and Aftershock Relocation

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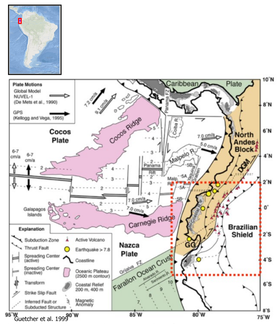
Mariah C. Hoskins*[a], Anne Meltzer[a], Josh Stachnik[a],Hans Agurto-Detzel[b], Alexandra Alvarado[c], Susan Beck[d], Philippe Charvis[b], Yvonne Font[b], Stephen Hernandez[c], Clint Koch[d], Sergio Leon-Rios[e], Colton Lynner[d], Marc Regnier[b], Andreas Rietbrock[e], Mario Ruiz[c]

[a]Lehigh University, Bethlehem, PA; [b]Universite Nice Cote d'Azur IRD Geoazur Nice FR; [c]Instituto Geofisico at the Escuela Politecnica Nacional Quito EC; [d]University of Arizona Tucson, AZ; [e]University of Liverpool, Liverpool, UK

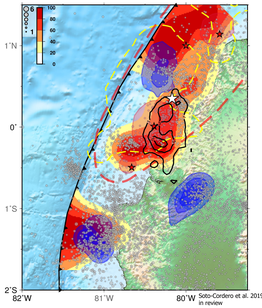
*Contact: mac716@lehigh.edu

1. Seismo-tectonic Setting of North Ecuador

The north Ecuador subduction zone exhibits segmentation in megathrust ruptures and clustering of seismicity through interseismic and aftershock seismicity. In 1906, a M_w 8.8 megathrust event ruptured a 500 km segment, portions of which were re-ruptured in 1942 (M_w 7.8), 1958 (M_w 7.7), 1979 (M_w 8.2) and 2016 (M_w 7.8 Pedernales event). Segmentation between the ruptures is caused by subducting topography and upper plate structure. Upper plate structure in north Ecuador includes major faults, sedimentary basins and accreted terranes. We perform finite difference tomography using aftershocks recorded following the 2016 Pedernales earthquake to investigate the structures controlling the clustering of seismicity and the megathrust rupture in North Ecuador.

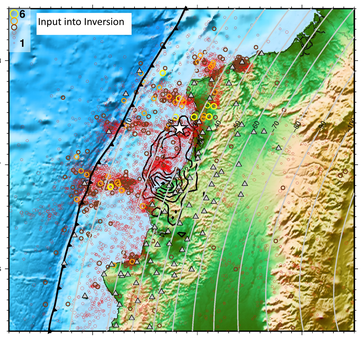


Map showing main tectonic elements
- Nazca/South American plate convergence
- Subduction zone
- Carnegie Ridge
- Spreading ridges
- Volcanic arc



- Variation in plate coupling (white to red) (Chlieh et al. 2014)
- Slow slip identified by GPS (blue shading) (Rolandone et al. 2018)
- Historic megathrust ruptures (red elipses, red dashed line) and aftershock areas (yellow dashed lines) (Kelleher, 1972; Mendoza and Dewey, 1984; Swenson and Beck, 1996)
- Pedernales rupture (solid black lines) (Nocquet et al. 2017)
- Interseismic seismicity (Beauval, et al., 2013; IGEPN)

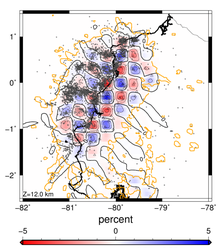
2. Data and Tomographic Inversion Methods

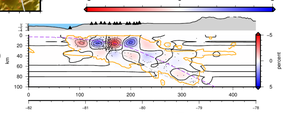


Map of input events colored and sized by magnitude. Pedernales mainshock (white star) and rupture (black contours of coseismic slip) from Nocquet et al. (2017). Stations shown as gray triangles. Slab 2.0 (Hayes, 2018) isodepth contours shown in gray.

Method
- Joint inversion for earthquake relocation and 3D velocity model
- Finite difference tomography method of Roecker et al. (2006)

Data
- Aftershocks recorded by Ecuador national network (RENSIG) and international aftershock deployment
- 6,608 events with 94,280 P and 64,852 S arrivals
- Aftershocks focus in bands and clusters.



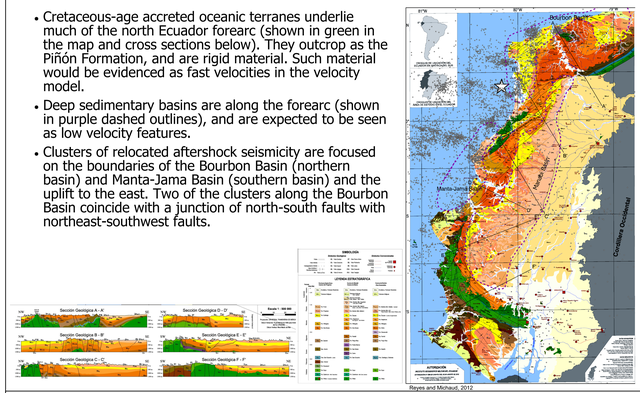


Depth slice (top) and cross section (bottom) through checker board model. Orange contour shows region with 10+ rays.

Checkerboard resolution test
- Synthetic models created of 12 km checkers with +-5% perturbations
- Recovery of synthetic checkerboard shows good resolutions at the 12 km-scale, with some smearing of features, particularly toward the edges of the resolvable area.
- Best resolution in top ~35 km.

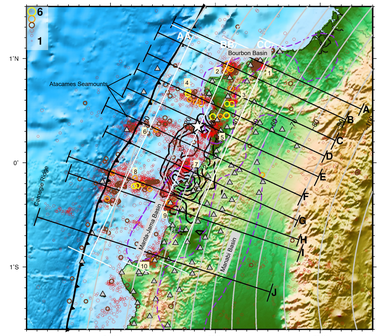
3. Geologic setting and Relocated Seismicity

- Cretaceous-age accreted oceanic terranes underlie much of the north Ecuador forearc (shown in green in the map and cross sections below). They outcrop as the Piñón Formation, and are rigid material. Such material would be evidenced as fast velocities in the velocity model.
- Deep sedimentary basins are along the forearc (shown in purple dashed outlines), and are expected to be seen as low velocity features.
- Clusters of relocated aftershock seismicity are focused on the boundaries of the Bourbon Basin (northern basin) and Manta-Jama Basin (southern basin) and the uplift to the east. Two of the clusters along the Bourbon Basin coincide with a junction of north-south faults with northeast-southwest faults.



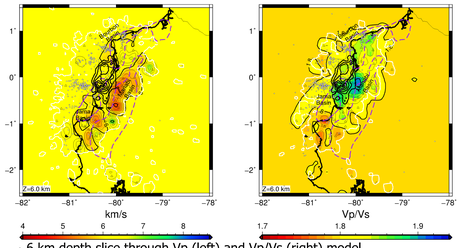
4. Joint Inversion for Earthquake Relocation and Velocity Model

- Relocation of earthquakes in the joint inversion results in bands of seismicity collapsing to discrete clusters (for comparison, see section 2).
- Clusters co-locate with clustering in interseismic seismicity (section 1).
- Clusters of seismicity (numbered 1, 3, 9, and 10) locate along the boundary between basins and the Costal Ranges.
- Clusters of seismicity outline the subducting Atacames Seamounts (6) and subducting topography on the Carnegie Ridge (8).
- The cluster within the rupture area between the patches of greater slip (7) became more focused in the relocation, as did the cluster on the north side of the rupture (5).
- Clusters 1 and 2 consist of upper plate events, mostly occurring within swarms.

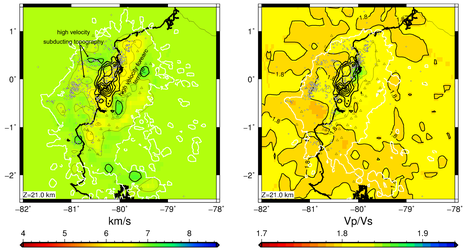


Cross sections through velocity model shown below. Events ML 4+ shown as black circles on cross sections. White contour marks region with 10+ rays (resolvable).

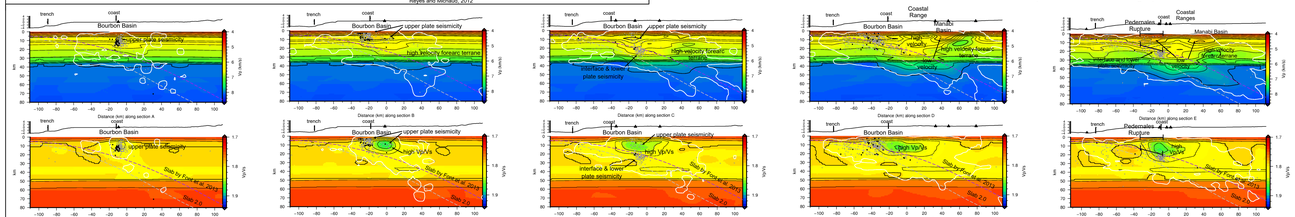
Sedimentary basins shown in purple dashed lines (Reyes 2013). Pedernales mainshock (white star) and rupture (black contours of coseismic slip) from Nocquet et al. (2017). Stations are gray triangles. Slab 2.0 (Hayes, 2018) isodepth contours shown in gray.



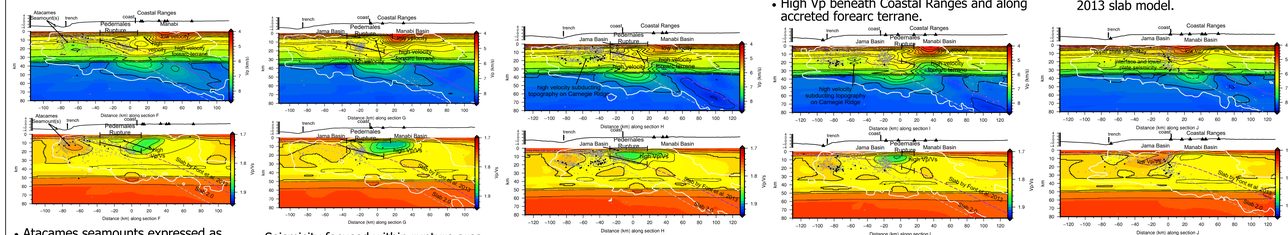
- 6 km depth slice through Vp (left) and Vp/Vs (right) model.
- Low Vp aligns with basins.
- High Vp/Vs aligns with Manabi and Bourbon basins.
- High Vp/Vs features occur above the rupture area.



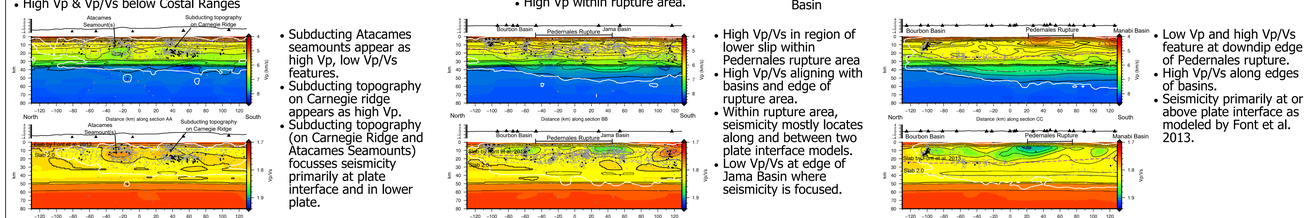
- 21 km depth slice through Vp (left) and Vp/Vs (right) model.
- High velocity features along strike align with accreted forearc terranes.
- Subducting topography evidenced as high velocity features.



- Esmeraldas swarm in upper plate
- Suggestion of high Vp forearc terrane, but resolution is limited
- Atacames swarm in upper plate
- Seismicity at edge of and within high Vp/Vs feature aligning with basin
- High velocity forearc terrane better resolved
- Main seismicity in lower plate
- Seismicity at edge of and within high Vp/Vs feature aligning with basin
- Main seismicity interface & upper plate. Seismicity in lower plate on west side of section.
- Interface seismicity follows Font et al. 2013 slab
- Seismicity at edge of high Vp/Vs feature aligning with basin
- High Vp beneath Coastal Ranges and along accreted forearc terrane.
- Main seismicity beneath high Vp/Vs feature at edge of and within rupture
- Main seismicity locates between slab models and along Font et al. 2013 slab model.



- Atacames seamounts expressed as high Vp, low Vp/Vs feature
- Seismicity focused in front of and behind Atacames seaounts
- Within Pedernales rupture is high Vp/Vs feature
- Rupture termination updip at Atacames seamounts, downdip at forearc terranes (both high Vp).
- High Vp & Vp/Vs below Costal Ranges
- Seismicity focused within rupture area (between patches of greater slip) along interface and in upper and lower plates.
- Low Vp beneath Manabi Basin.
- High Vp/Vs feature within/above rupture and within Manabi Basin.
- High Vp feature within rupture area
- Rupture termination downdip at high Vp forearc terrane
- Seismicity focused around subducting topography (high Vp) of Carnegie Ridge in lower and upper plates.
- Termination of Pedernales rupture at subducted topography (updip) and high Vp forearc terrane (downdip).
- High Vp/Vs within rupture area/basin areas.
- High Vp within rupture area.
- Seismicity focused around subducting topography (high Vp) in lower and upper plates
- Pedernales rupture termination downdip at forearc terrane
- Low Vp aligned with Manabi Basin
- High Vp/Vs aligned with Jama Basin and rupture area, but not Manabi Basin
- Main seismicity in lower plate down dip of high velocity feature.
- Low Vp/Vs beneath southern end of Jama basin.
- Low Vp beneath Manabi basin.



- Subducting Atacames seamounts appear as high Vp, low Vp/Vs features.
- Subducting topography on Carnegie ridge appears as high Vp.
- Subducting topography (on Carnegie Ridge and Atacames Seamounts) focusses seismicity primarily at plate interface and in lower plate.
- High Vp/Vs in region of lower slip within Pedernales rupture area
- High Vp/Vs aligning with basins and edge of rupture area.
- Within rupture area, seismicity mostly locates along and between two plate interface models.
- Low Vp/Vs at edge of Jama Basin where seismicity is focused.
- Low Vp and high Vp/Vs feature at downdip edge of Pedernales rupture.
- High Vp/Vs along edges of basins.
- Seismicity primarily at or above plate interface as modeled by Font et al. 2013.

5. Conclusions

- Joint inversion for 3D velocity structure and earthquake location provides significantly improved precision in earthquake locations.
- Clusters in aftershock seismicity align with clusters in background seismicity.
- High velocity features are seen corresponding to accreted forearc terranes and subducting high topography.
- Sedimentary basins are seen as low velocity features. The Manabi and Bourbon Basins are seen as high Vp/Vs features.
- Subducted topography focuses seismicity.
- Limits of the Pedernales rupture align up-dip with subducted topography in the lower plate and down-dip with accreted forearc terranes in the upper plate.
- Existing features, including basins, accreted terranes, and subducting topographic features are expressed in the velocity model and control megathrust, postseismic, and interseismic deformation across megathrust cycles.

6. Acknowledgements

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