Variable Slip Modes in Postseismic Deformation North of the April 16, 2016 Mw 7.8 Pedernales, Ecuador Megathrust Earthquake

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Abstract

The north Ecuador subduction zone has a history of experiencing a range of slip modes including megathrust and other fast slip, slow, and aseismic slip. In 1906, a Mw 8.8 megathrust ruptured 500 km along the north Ecuador/Colombia margin. Parts of this region re-ruptured in events (south to north): '42 (Mw 7.8), '58 (Mw 7.7), and '79 (Mw 8.2). The April 16, 2016 Pedernales megathrust rupture overlapped the '42 rupture. Postseismic deformation following the 2016 event exhibited a range of slip behaviors and associated seismicity. A dense temporary land and offshore deployment augmented permanent stations of the national network (RENSIG) to record postseismic deformation for one year. Aftershocks concentrate spatially in bands or clusters mirroring patterns in background seismicity marking persistent asperities which cause variations in plate coupling. Bands of aftershocks outline the 2016 rupture and two patches of larger slip within the rupture; additional bands are observed to the south and to the north. North of the rupture, bands and clusters are observed near Punta Galera, Atacames, and Esmeraldas. Seismicity near Punta Galera outlines the north edge of a patch of aseismic slip that occurred in the month following the mainshock. One month after the mainshock, Mw 6.7 and 6.9 aftershocks occurred. Calibrated relocations show these are interface events north of the 2016 rupture, downdip of the aseismic slip. On 7/11/ 2016, Mw 5.9 and 6.3 interface events occurred, causing an increase in local seismicity. In June intermittent seismicity began in Esmeraldas, near the 1958 rupture. An earthquake swarm and a transient in GPS data in July 2016 suggests possible slow slip in the region. Relocations of earthquakes in the swarm outline a splay fault in the upper plate. An increase in seismicity near Atacames in December suggests fast slip. Calibrated relocations of the 5 largest events (M 4.7-5.2) and automatic locations of the remaining 246 events show they are upper plate events. In the months following the Pedernales event, fast, aseismic, and slow slip occur north of the rupture. Near Atacames and Esmeraldas upper plate seismicity is predominant.

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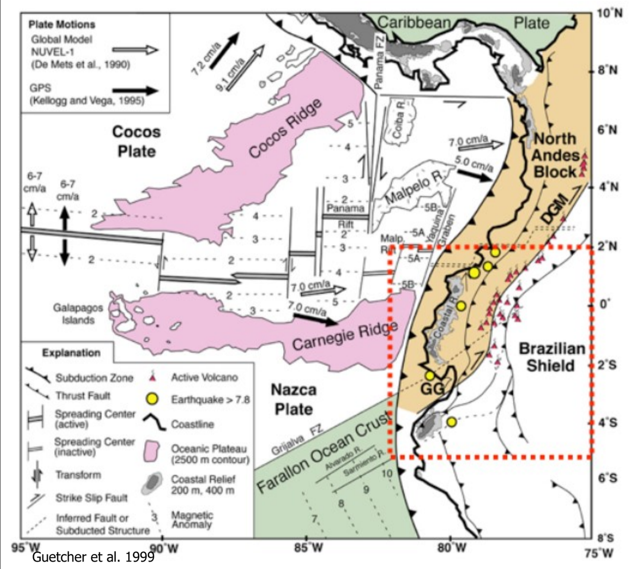
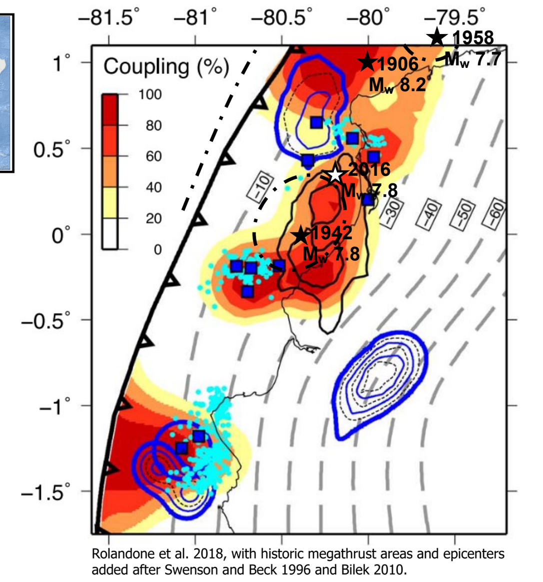
1. Seismo-tectonic Setting of North Ecuador

At the Ecuador subduction zone, significant lower-plate topography is being subducted, creating asperities. Subducting topography includes the Carnegie Ridge hot spot track (of the Galapagos Islands), spreading centers, and seamount chains. The asperities cause heterogeneity in the degree of plate coupling.

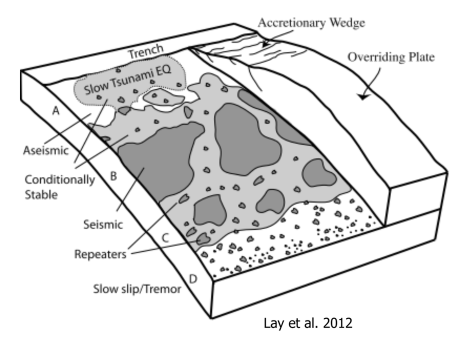
Asperities limit the extents of megathrust ruptures. Large megathrust ruptures break across multiple asperities, such as the 1906 Mw 8.8 event. Subsequent megathrust ruptures have been more limited and have occurred, from south to north in 1942 (M_w 7.8), 1958 (M_w 7.7), and 1979 (M_w 8.2). The M_w 7.8 Pedernales, Ecuador megathrust earthquake occurred April 16, 2016, and re-ruptured part of the 1942 rupture area. Aseismic and slow slip have also been observed in the Ecuador margin.



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

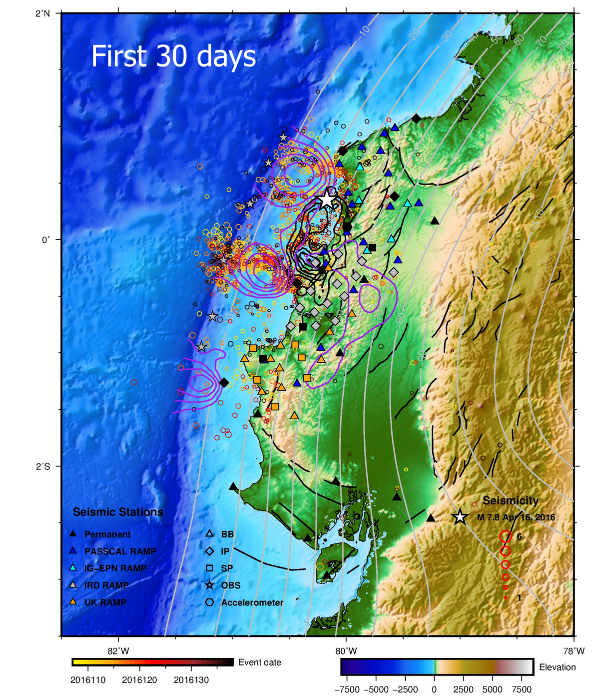


- Variation in plate coupling
- Slow slip identified by GPS (blue lines) and inferred from seismic swarms and repeating events (cyan dots and blue squares)
- Historic megathrust ruptures (black dashed lines)
- Pedernales rupture (solid black lines)

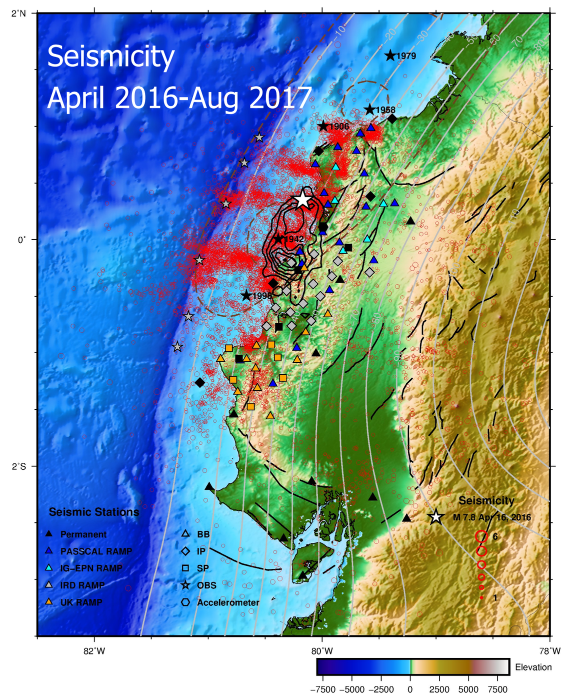


- Variable slip modes occur at subduction zones
- Model shows variations in modes of slip with position on subduction interface

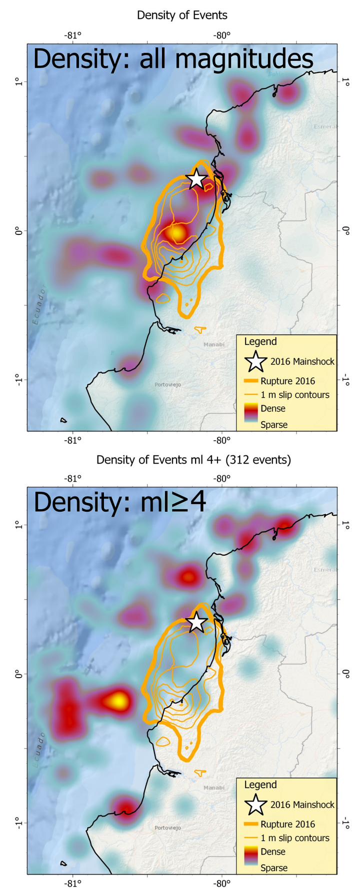
2. Aftershock Distribution



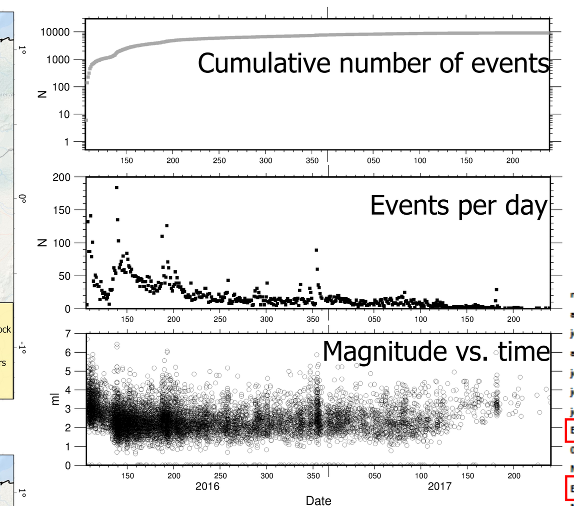
- International aftershock deployment included 66 stations including OBS
- Mainshock and coseismic slip contours (black) from Noquet et al. 2017
- Aseismic afterslip contours in first 30 days from Rolandone et al. 2018 (purple)
- Note aftershocks in first 30 days correlate with aseismic and slow slip



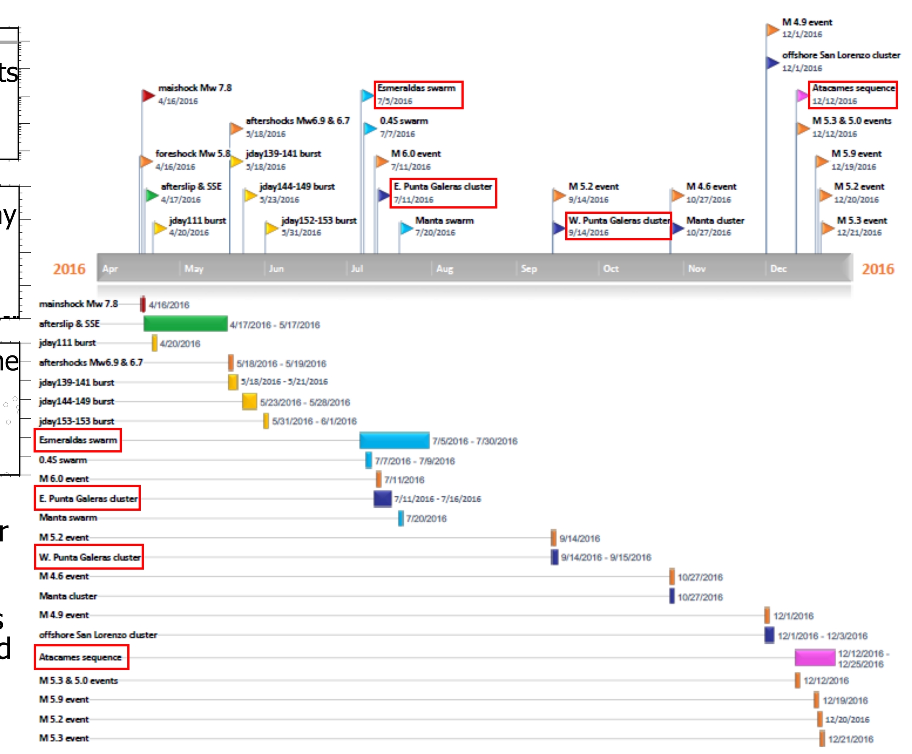
- Mainshock and coseismic slip contours (black) from Noquet et al. 2017
- Historic ruptures—brown dashed ellipses (Bilek 2010, Swenson and Beck, 1996)
- Note distinct clustering of event locations



- Densest cluster of lower-magnitudes between patches of greater coseismic slip within rupture
- ml ≥ 4 events cluster outside rupture area, especially to west and north

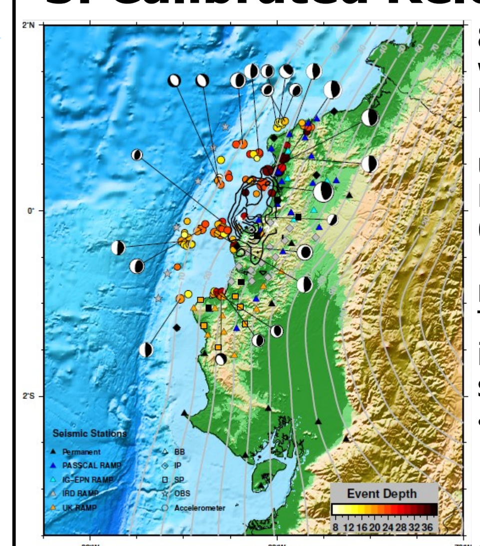


- Step increases in cumulative number of events correspond to short periods of high daily seismicity
- Apparent increase in trend of events per day from jd 2016130-140 related to instrument deployment
- Note decay in events per day and magnitudes with occasional burst of activity and large-magnitude events
- Bursts of increased activity jd 2016139, 187, 193 & 354 correspond to regions discussed in sections 4-6.



Post-mainshock seismicity is characterized by distinct behaviors (fast earthquakes and earthquake swarms) clustered in space and time. Timeline shows temporal relation of large-magnitude events and sub-sequences. Events and sub-sequences occurring in the north (highlighted by red boxes) discussed in sections 4-6.

3. Calibrated Relocations

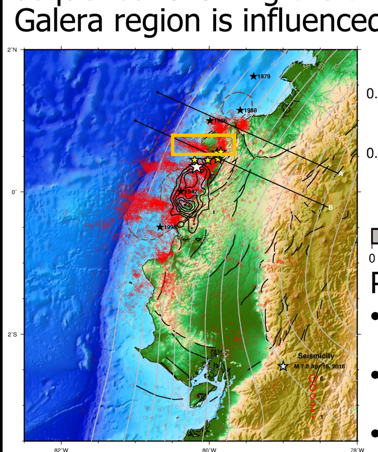


89 aftershocks of M > 4 with focal depths < 50 km and azimuthal gap < 240°, were relocated using the Hypocentroidal Decomposition method (Jordan and Sverdrup, 1981) of multiple-event relocation procedure. The relocation problem is separated in two sections:
- Calculation of the absolute location of the hypocentroid of the event cluster
- Relative location of the individual events within the cluster

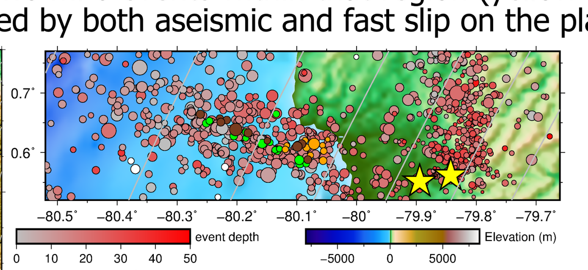
Main Observations
- Similar to ml ≥ 4 aftershock automatic locations, relocated events concentrate outside the mainshock rupture area and are spatially clustered.
- Moment tensor solutions for 23 of the relocated aftershocks indicate predominance of thrust events.
- 3 events (2 west of the rupture and 1 south) show extensional, while a few others show non double-couple mechanisms, indicating a variety of processes.

4. Punta Galera

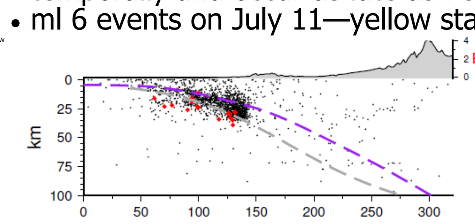
Seismicity in the Punta Galera region consists of a western and eastern cluster with distinct characteristics. Seismicity in the western cluster is within a region of aseismic afterslip (see first map in section 2) and contains events with similar waveforms. This region also experienced increased seismicity following nearly ml 6 events. The eastern portion of the Punta Galera region experienced the main increase in seismicity as a local aftershock sequence following the two ml 6 events within that region (yellow stars in map below). Seismicity in the Punta Galera region is influenced by both aseismic and fast slip on the plate interface.



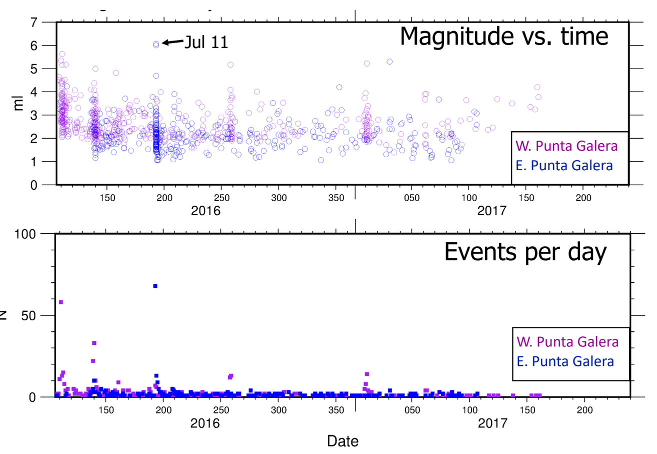
Map showing location of Punta Galera area
- ml 6 events—yellow stars
- Historic rupture areas—brown dashed ellipses
- Afterslip area shown in section 2 overlaps west Punta Galera cluster
- Slab depth contours from Slab 2.0—gray



Punta Galera region seismicity
- 3 families of at least 10 events with similar waveforms—brown, orange, and green
- Events in families are not clustered temporally and occur as late as Feb 2017
- ml 6 events on July 11—yellow stars



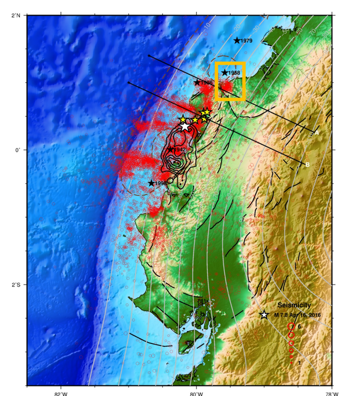
Cross-section from trench to arc
- Calibrated relocated events—red
- Slab interface models: Font et al. 2013—purple, Slab 2.0—gray
- Interface activity occurred as well as upper and possible lower-plate



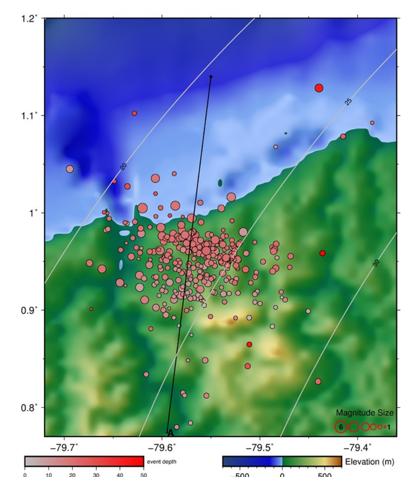
- Note July 11 ml 6 events (jd2016193) and seismicity increase in east cluster
- Seismicity increase in west cluster on May 18 (jd2016139) follows ml 6 events to south (see first map this section)
- Note ml 5 events on jd2016285 and 2017011 and associated minor seismicity increase in west cluster

5. Esmeraldas

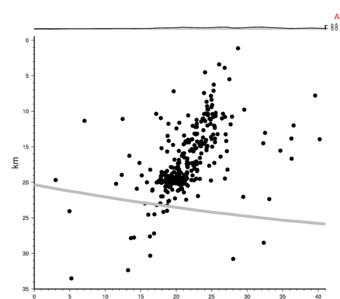
Seismicity in the Esmeraldas area began 2 months after the mainshock, with the majority of activity occurring in a 1 month swarm (see events per day plot below). After the initial pulse of the swarm, a second episode of heightened activity within the swarm follows the July 11 ml 6 events in the east Punta Galera area (see stars on first map). Relocations of events, following manual picks of arrival times for events ml ≥ 2.5, outline an unmapped upper-plate splay fault. Cross-correlation analysis reveals 8 families of at least 6 events with similar waveforms. Families were activated during the July swarm, with most events confined to that time. GPS data shows a transient coincident with the swarm. Seismicity throughout the recording time shows no consistent level. The swarm nature of seismicity (see magnitude vs. time plot), families of similar waveforms, and GPS transient suggest that slow slip and/or fluid flow are main drivers of seismicity in the Esmeraldas area.



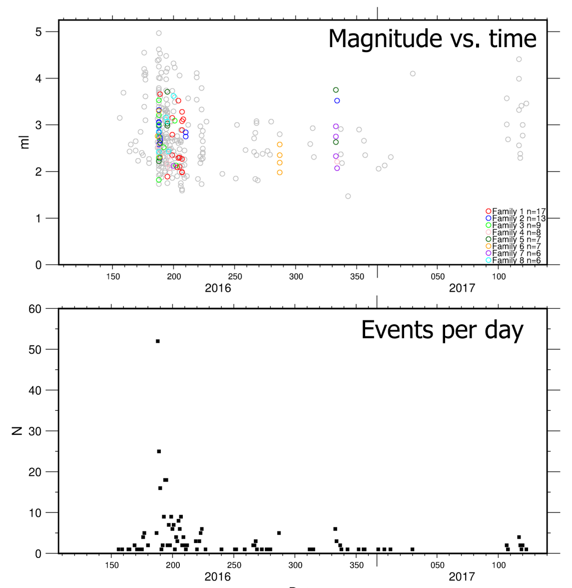
Map showing location of Esmeraldas area
- ml 6 events—yellow stars
- Historic rupture areas—brown dashed ellipses
- Esmeraldas area is by 1958 rupture
- Cross-section line on this map shown in section 6



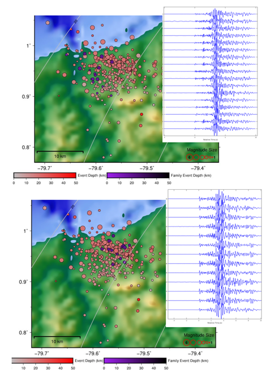
Map of events in the Esmeraldas area
- Locations based on manual arrival picks for events ml ≥ 2.5
- Events cluster east of the Esmeraldas fault (mapped along the river and sub-marine canyon), which likely limited the 1958 rupture area.
- Slab depth contours based on Font et al. 2013 model



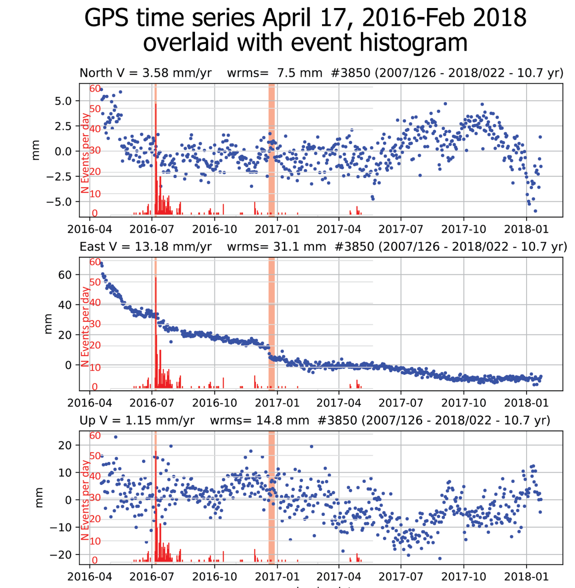
North to south cross-section along line in map above
- Hypocenters outline upper-plate splay fault
- Orientation of cross-section is down dip of splay fault
- Slab interface (gray line) based on Font et al. 2013 model fits well with hypocenter locations



- Note late onset of activity in Esmeraldas area
- Magnitudes of events do not decay systematically
- All families of similar events initiated during July swarm
- 221 of the 318 events in the area occurred July 5-30 (jd 187-211), with 98 from July 5-8
- Pulse of activity within the swarm occurred July 11-13 (jd 193-195) likely related to ml 6 events in Punta Galera area



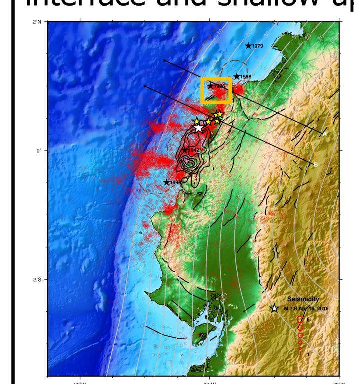
Maps showing two families of events in purple symbols Associated waveforms shown adjacent



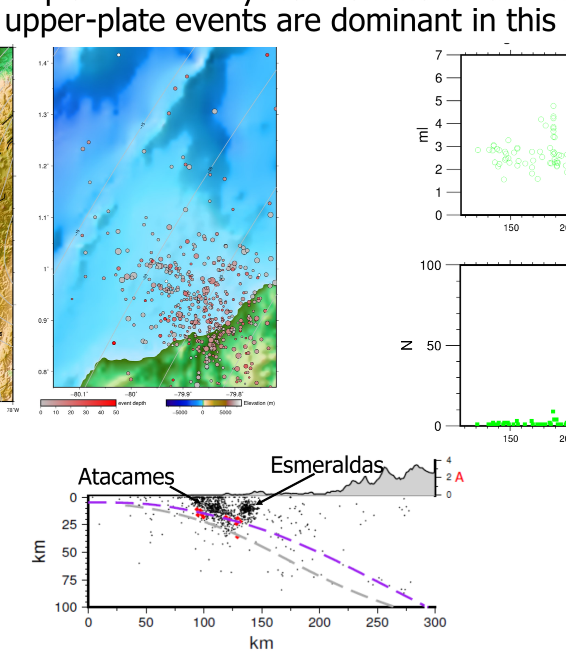
- Transient in GPS occurs near onset of swarm
- Abrupt breaks in trend of east component consistent with timing of large-magnitude events in east Punta Galera and Atacames areas

6. Atacames

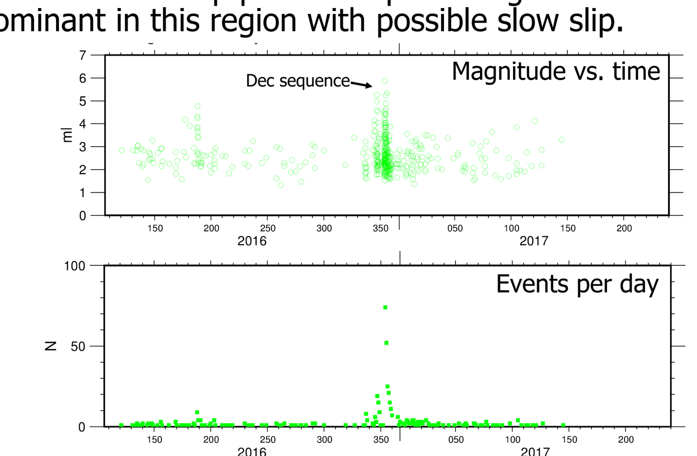
Seismicity in the Atacames area occurred mainly in December 2016 in a mixture of local mainshock-aftershock sequences with some swarm behavior. Cross-correlation analysis showed relatively few events with similar waveforms. While larger-magnitude events occur on the plate interface, shallow upper-plate seismicity was common. Fast-slip processes producing both interface and shallow upper-plate events are dominant in this region with possible slow slip.



Map showing location of Atacames area
- ml 6 events—yellow stars
- Historic rupture areas—brown dashed ellipses
- Slab depth contours from Slab 2.0—gray



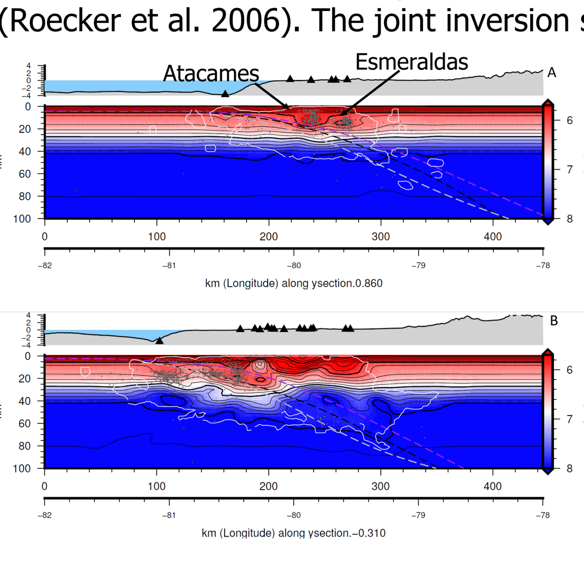
Cross-section from trench to arc through Atacames and Esmeraldas areas
- Calibrated relocated events (red) mainly interface events
- Interface and shallow upper plate activity
- Slab interface models: Font et al. 2013—purple, Slab 2.0—gray



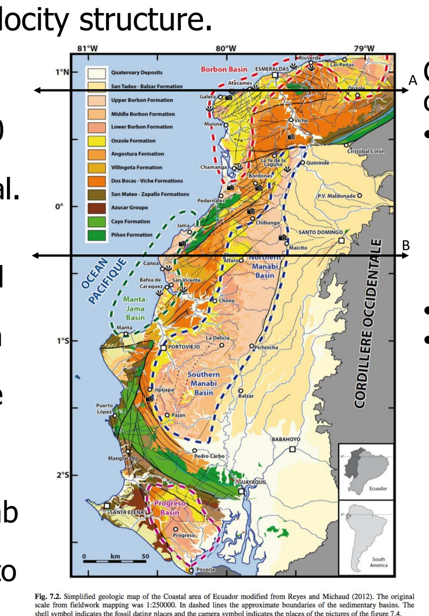
- Note the ml > 5 events in December 2016 within events of varying magnitudes followed by decay in magnitudes
- Note main activity days are clustered in December 2016

7. Preliminary Tomography

Preliminary 3D seismic tomography inversion was preformed using finite difference tomography (Roecker et al. 2006). The joint inversion solves for event location and velocity structure.



Cross-sections along lines of latitude shown on map to right
- Resolvable area with at least 10 ray crossings—white contour
- Slab interface models: Font et al. 2013—purple, Slab 2.0—gray, Slab 1.0—black
- Font et al. 2013 interface based on 3D a-priori model, which fits with event locations in northern areas
- Locations from inversions agree that Atacames and Esmeraldas area seismicity is interface to shallow upper-plate
- Line through −0.3° suggests Slab 2.0 fits event locations better and shows lower plate activity to the west near the trench

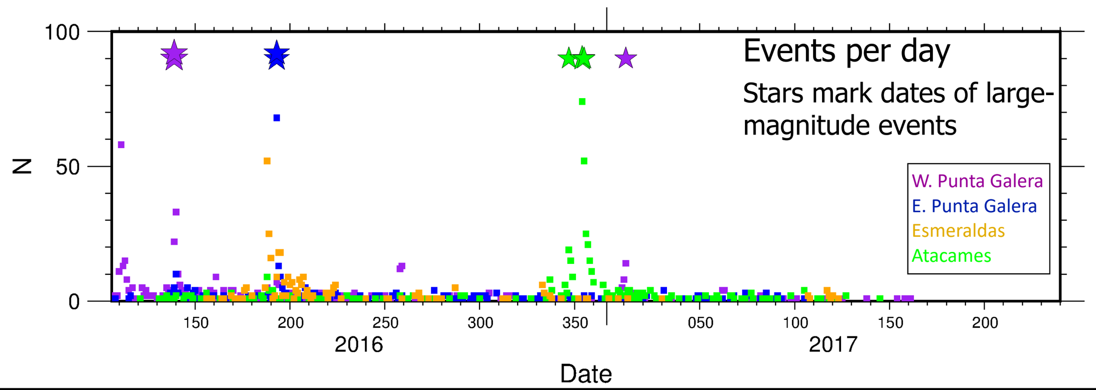


Reyes 2013

Geologic map of coastal Ecuador
- Borbon, Manta-Jama, and Northern Manabi sedimentary basins highlighted in dashed ellipses
- Major faults—black
- Cross sections through tomography extend beyond map

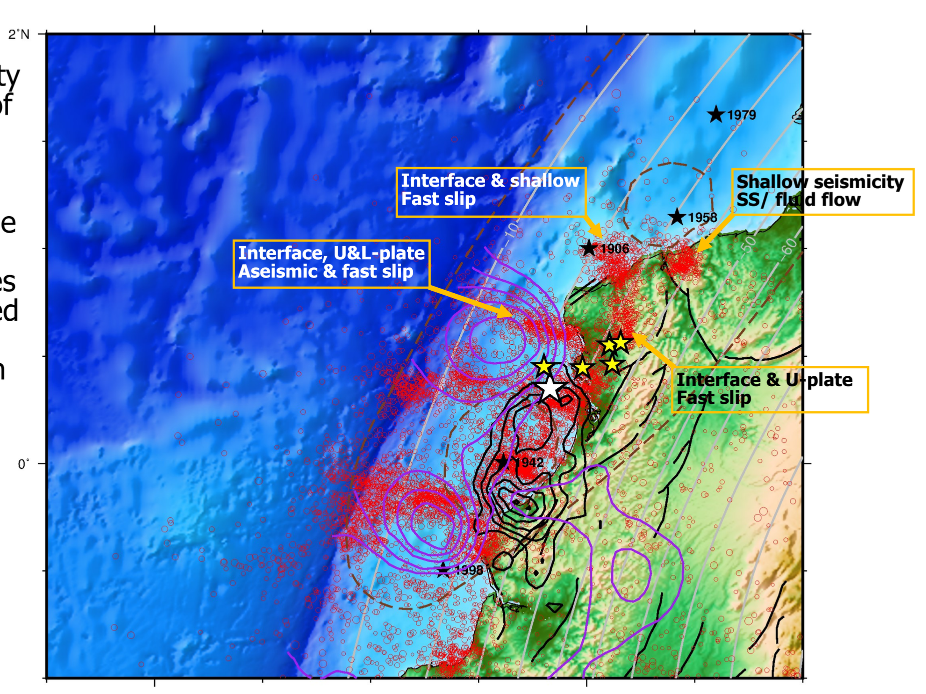
8. Conclusions

- Clustering in aftershock locations mirror patterns in long-term seismicity over multiple seismic cycles
- Locations of event clusters are controlled by subducting topography and crustal structure
- North of the Pedernales rupture, there is evidence for fast, slow, and aseismic slip
- Near Atacames and Esmeraldas, shallow upper plate seismicity occurred
- Punta Galera seismicity influenced by both fast slip and aseismic afterslip
- Atacames area seismicity influenced by fast-slip processes
- Esmeraldas seismicity influenced by slow slip and/or fluid flow



- Number of events per day in each area discussed in sections 4-6 shown in different color
- Stars marking dates of large-magnitude events colored corresponding to areas where they caused increased seismicity

Summary map of seismicity and slip processes north of the rupture
- ml ≥ 6 events—yellow stars
- Aseismic afterslip—purple contours
- Seismicity and slip modes seen in each area marked on map
- Historic ruptures—brown dashed lines



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- Thanks to the PASSCAL facility of the Incorporated Research Institutions for Seismology (IRIS) for supporting instrumentation used in the US portion of the aftershock deployment.
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