The M_w 7.8 2016 Pedernales, Ecuador Earthquake Aftershock Sequence: a Detailed Spatio-Temporal Analysis of the Rupture Processes, Stress Patterns and Slip Behavior

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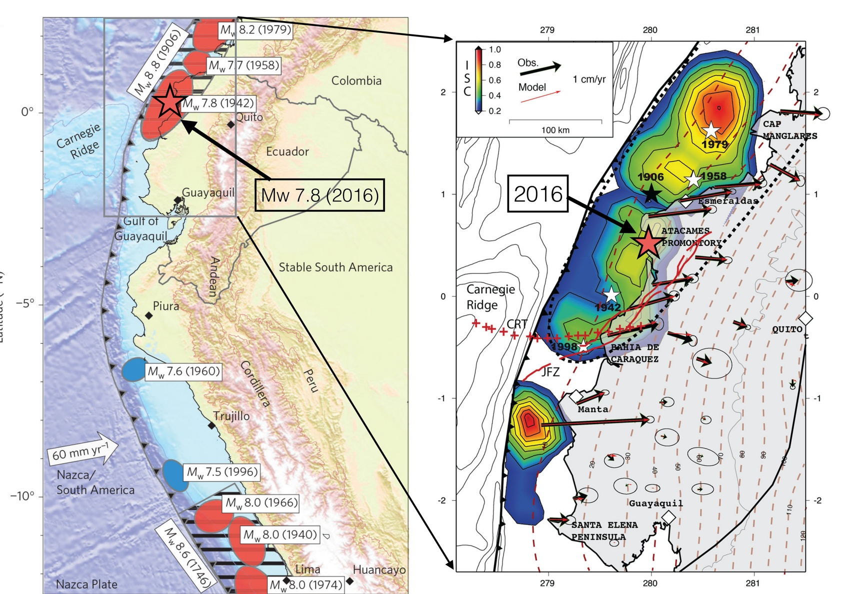
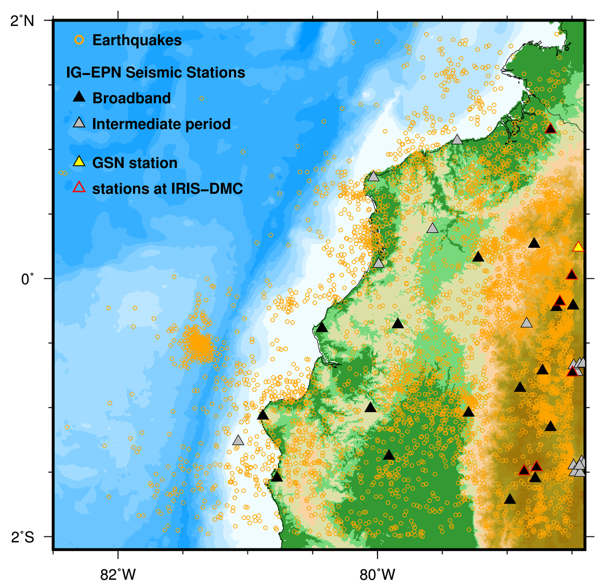
Tectonics, Background Seismicity & Aftershock Deployment

The epicentral region of the 2016 Mw 7.8 Pedernales Earthquake lies just north of the intersection of the Carnegie Ridge with the subduction zone where the orientation of the trench shifts from ~N20°E to ~N32°E. This portion of the subduction zone has ruptured on decadal time scales in Mw7.8 (1942), Mw 7.7 (1958), and Mw 8.2 (1979) earthquakes. In 1906 the plate interface offshore northern Ecuador and Colombia ruptured in a Mw 8.8 event. The rupture zone of the 2016 Pedernales earthquake falls within the rupture area of the 1906 event and overlaps with the 1942 event.



Interseismic coupling offshore northern Ecuador from GPS data. Red/yellow are locked asperities and white/blue are creeping sections of the subduction zone. The creeping section in the vicinity of the Jama Fault Zone JFZ ruptured in 1998 in a Mw 7.2 earthquake. Red +++ is projected trace of the Carnegie Ridge. Dashed contours depth to plate interface. Epicenter of Mw 7.8 2016 Pedernales earthquake superimposed.

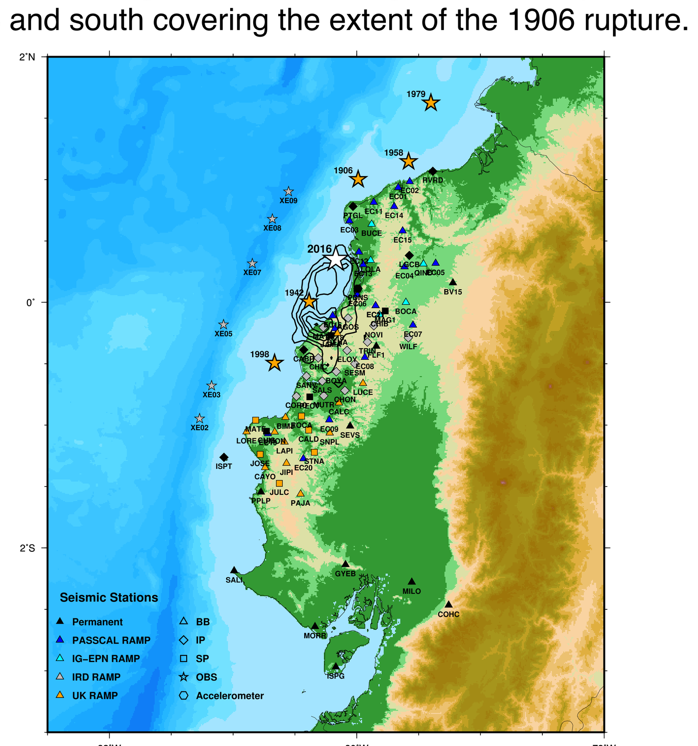
Background Seismicity



Pre-mainshock background seismicity, IGEPN permanent network catalog, May 2011 through April 16 2016 up until the mainshock. Offshore and forearc seismicity characterized by spatial clustering.

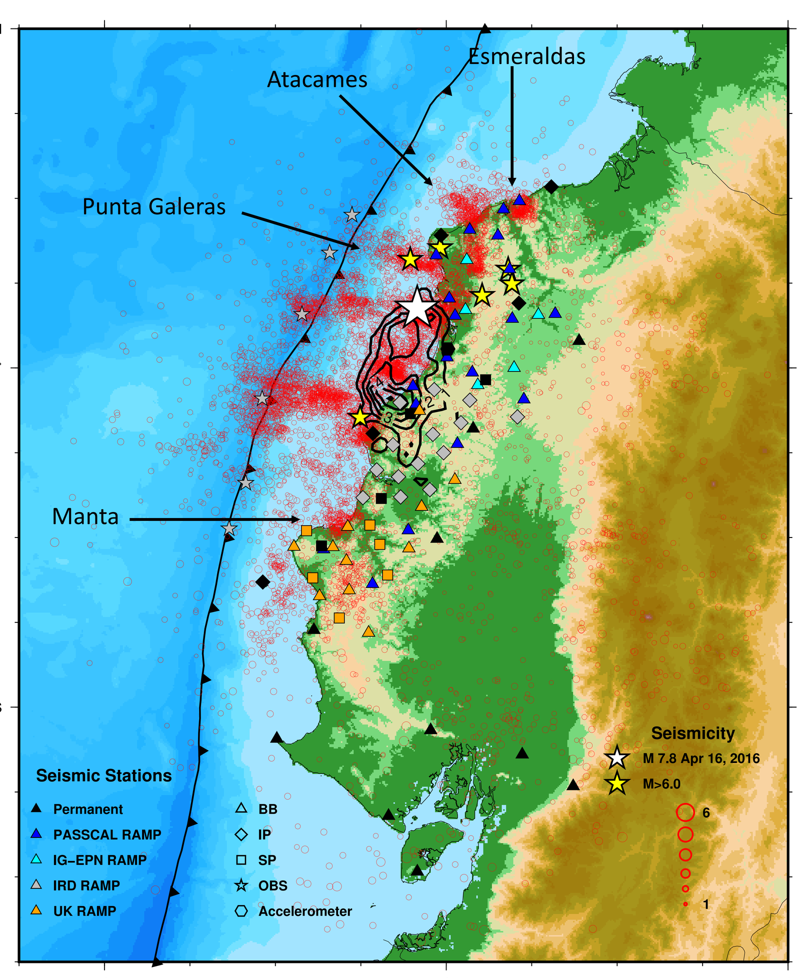
Aftershock Deployment

An international rapid response effort deployed a dense array (66 stations) of broadband, intermediate, and short period seismometers and OBS to record aftershocks for a year. The aftershock deployment densified stations from the National Network and covered the 2016 rupture zone, extending north to the segment that ruptured in 1958 and south covering the extent of the 1906 rupture.



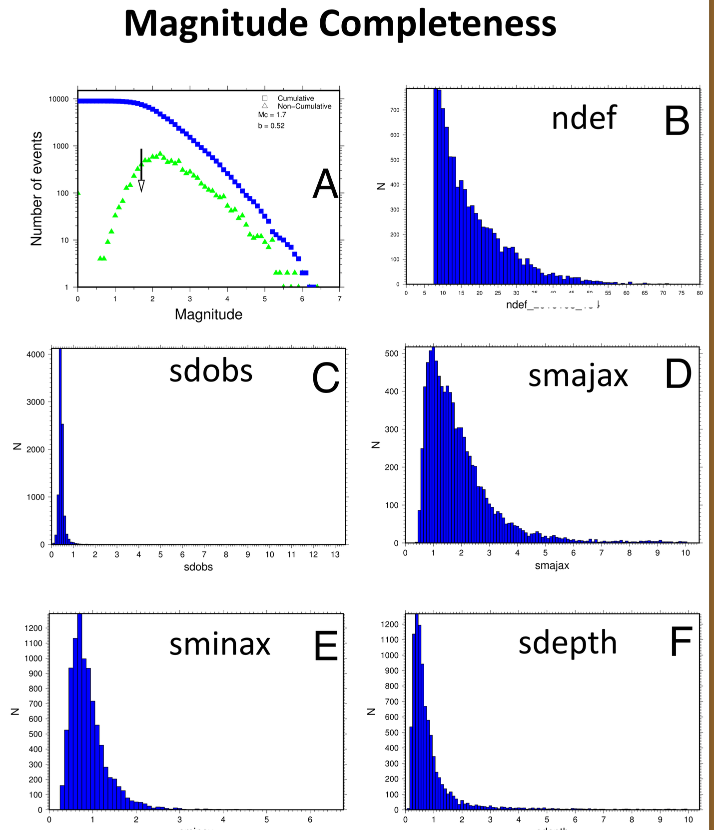
Station coverage. The 2016 Pedernales earthquake ruptured to the south with two main slip patches (Nocquet et al.,2017). Mainshock (white star), rupture, and slip contours (1 m interval, 6 m max) from Nocquet, et al., 2017. Historic ruptures, orange stars.

Aftershocks' Evolution in Space and Time



- Preliminary aftershock locations (9,056 events, minimum of 8 phases, errors <10km) through August 2017 from rapid response deployment and coastal permanent stations (82 stations total).
- Events located using automatic STA/LTA detection and IASP91 velocity model.
- Mainshock (white star), M≥6 aftershocks (yellow stars) and slip (1m contours) from Nocquet et al., 2017.
- Two distinct streaks of aftershocks extending to the trench outline the north and south ends of the rupture.
- A cluster of aftershocks is observed in the region of smaller slip between the two slip patches.
- Aftershocks M ≥4.0 are concentrated outside rupture area (map below)
- To the south, in the Manta region, a cluster of seismicity occurs across an area of low coupling.
- Northward migration of seismicity started ~2months after the mainshock (see seismicity by latitude plot below) in the northernmost Esmeraldas region.
- Intense burst of seismicity occurred to the north (Atacames) in December 2016 resulting in structural damage.
- Note general similarity of spatial distribution of aftershocks and background seismicity (panel above).
- Rate of seismicity approaches background within ~12 months.

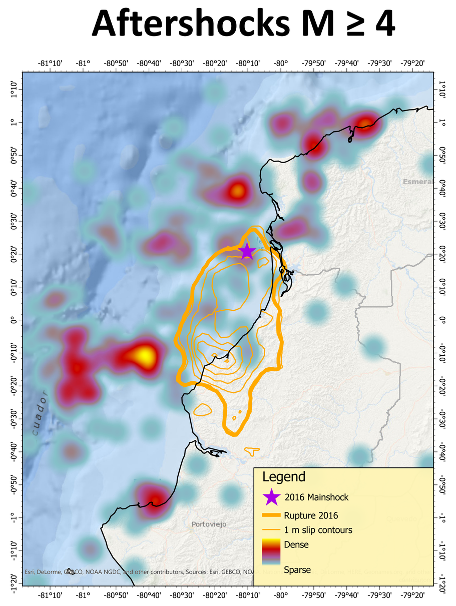
Automatic Location Errors & Magnitude Completeness



A. magnitude vs. frequency and cumulative number of events. B. Histogram of number of phases used to locate the events. C. Histogram of standard error of observation. D. Histogram of length (km) of error ellipse semi-major axis. E. Histogram of length (km) of error ellipse semi-major axis. F. Histogram of depth error (km).

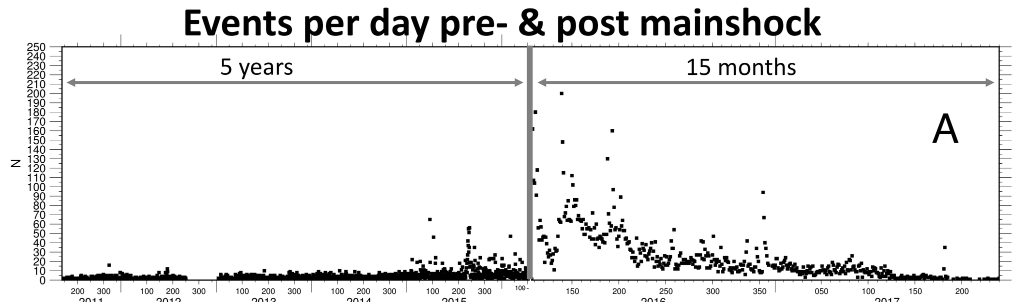
- Magnitude of completeness for the aftershock sequence is Ml1.7.
- Most events located using 8 to 40 phases.
- Locations have standard errors of observations ≤ 0.6
- Error ellipse semi-major and semi-minor axis are smaller than 6 and 2.6 km in length, with a few outliers.
- Depth errors tend to be less than 3 km.

Aftershocks M ≥ 4

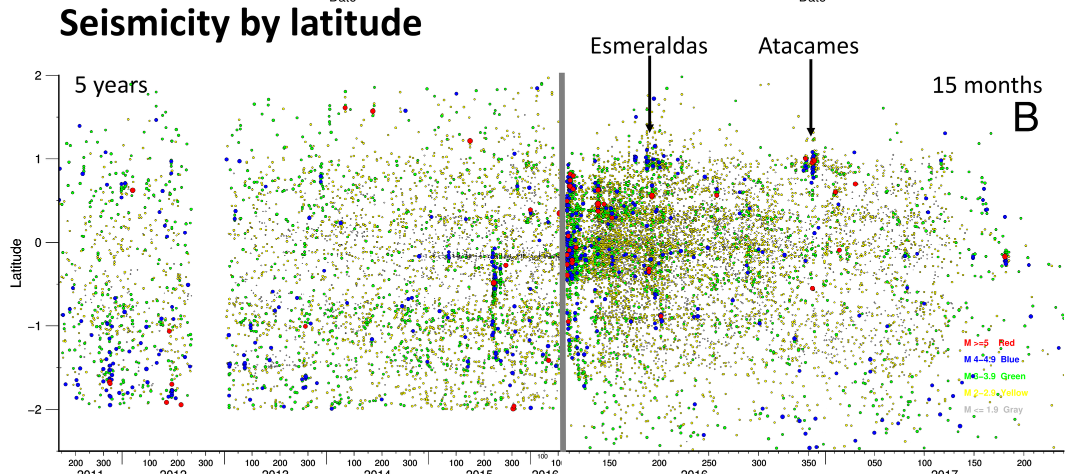


Aftershock density, M ≥ 4. Larger events focused updip from the southern end of the rupture toward the Carnegie Ridge, north of the rupture by Punta Galeras, and north toward the area of the 1958 rupture.

Events per day pre- & post mainshock



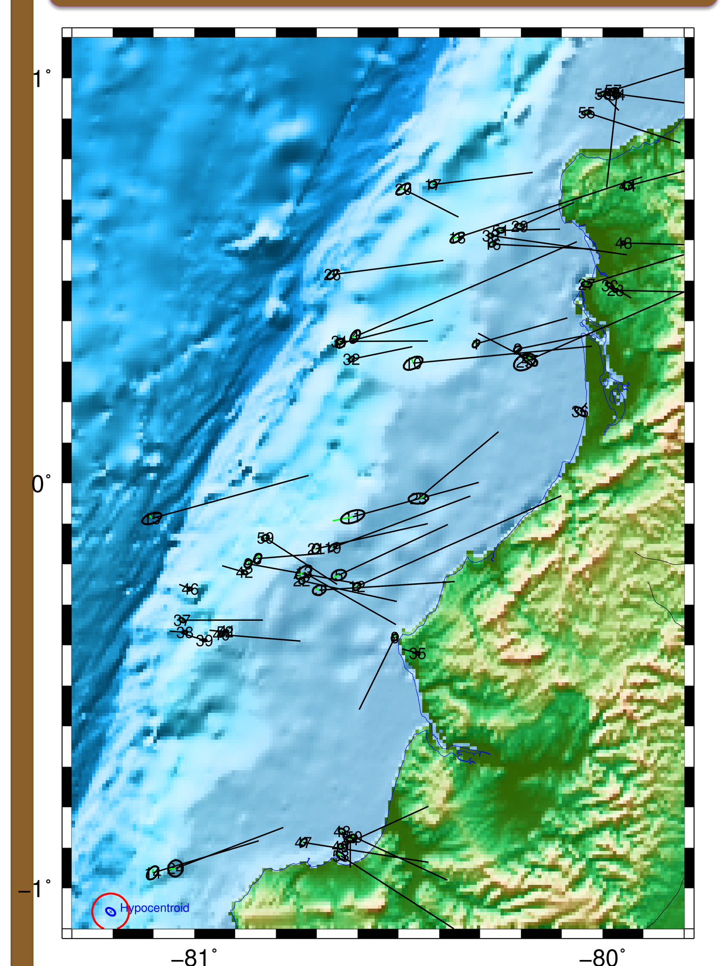
Seismicity by latitude



A. Comparison of events/day pre and post mainshock. Note difference in time period: 5 years pre-event (left), 15 months post-event (right).

B. Comparison of seismicity by latitude pre and post mainshock. Note streaks in seismicity by latitude corresponding to clusters in map view and migration of seismicity north with time.

Calibrated Relocations



Map showing relocated events. Location errors are considerable smaller than 5km (scale: bottom left red circle) for most events. Error ellipse is placed at the final location while the vector connects to the initial location.

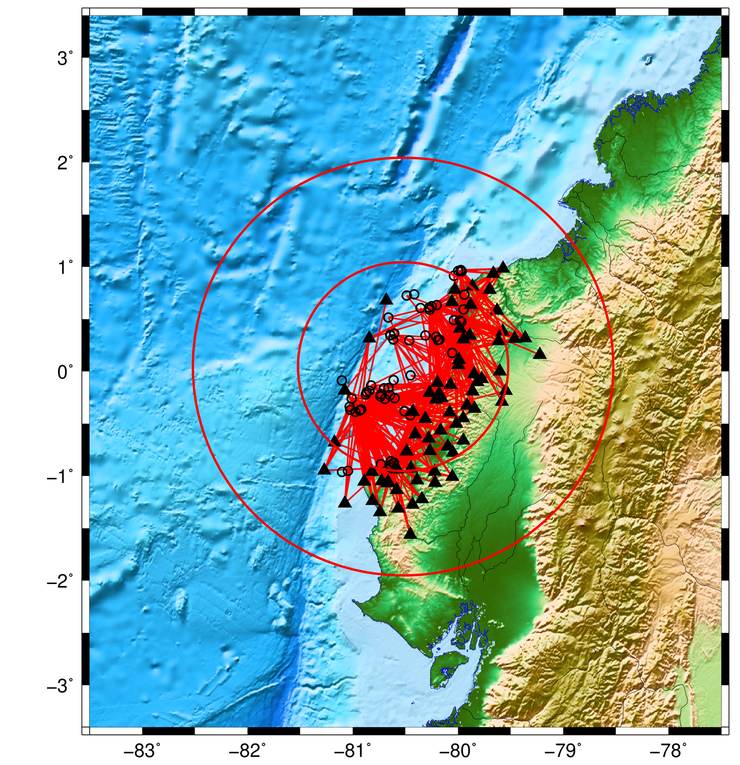
Multiple-Event Relocation Method

Calibrated relocations calculated using a multiple-event relocation procedure: Hypocentroidal Decomposition method (Jordan and Sverdrup, 1981)

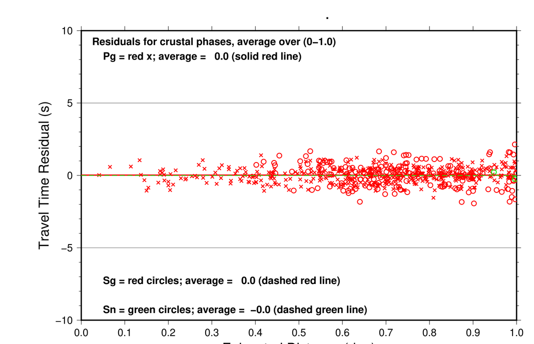
- Relocation problem is separated in two sections:
  1. calculation of the absolute location of the hypocentroid of the event cluster and
  2. relative location of the individual events within the cluster.
- Location uncertainties calculated for each event within the cluster.
- Iterative process estimates station-phase empirical reading errors to identify outlier readings. These are flagged so that they will not be used in subsequent relocations.

Approach

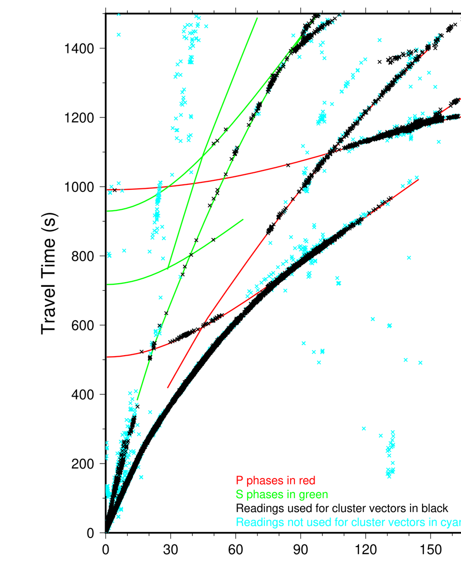
- Using events M ≥ 4.1 with focal depths < 50km
- Integrating regional and teleseismic phase arrival data from International Seismological Centre locations with near source and regional phases recorded by Ecuador permanent network and deployment stations.
- Gave priority to events with OBS data which improve azimuthal coverage to the west
- Using locations with an azimuthal gap <240°
- Most hypocentral depths were obtained by manually fitting the arrival times at near-source stations.



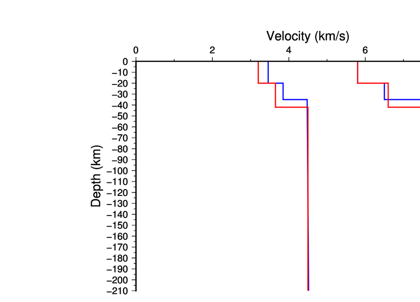
Connectivity of relocated events and near source stations (within 1° epicentral distance). Connectivity with inland stations is quite good. Connectivity is stronger with southern OBS stations than those to the north. These phase-station arrivals were used for the direct calibration of the hypocentroid.



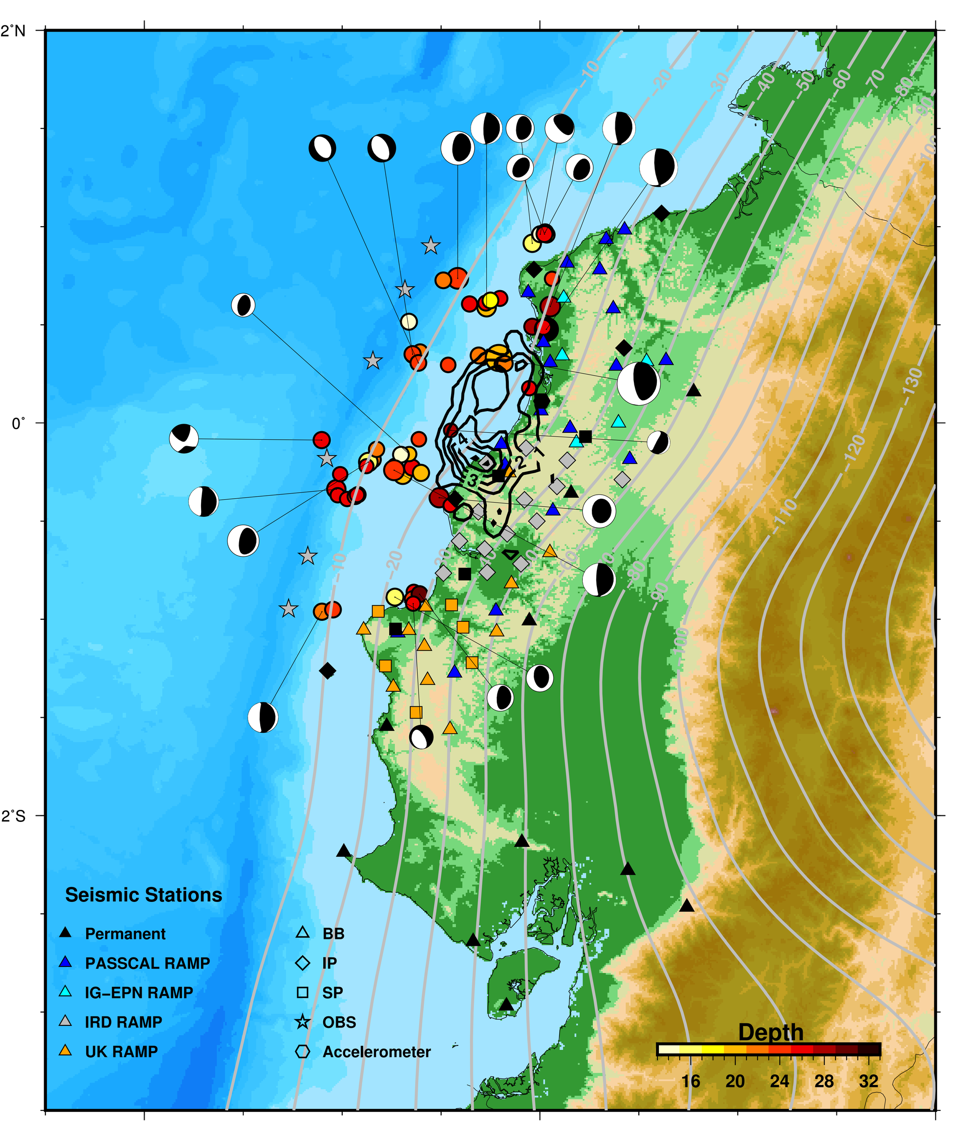
Travel time residuals for near source phases used. Pg residuals are less than 1 second. S residuals show more scatter but they are less than 2 seconds.



Travel time-distance plot for phases used in the calibrated relocation process of the Ecuador cluster. There is a good fit between phase readings and travel time curves.



Ak135 was used as our starting velocity model (blue). The model was modified iteratively to manually fit the phase arrival readings to the predicted travel time curves at near source distances. The most recent model (red) has slightly lower velocities with a Vp/Vs of 1.80-1.81 at crustal depths.

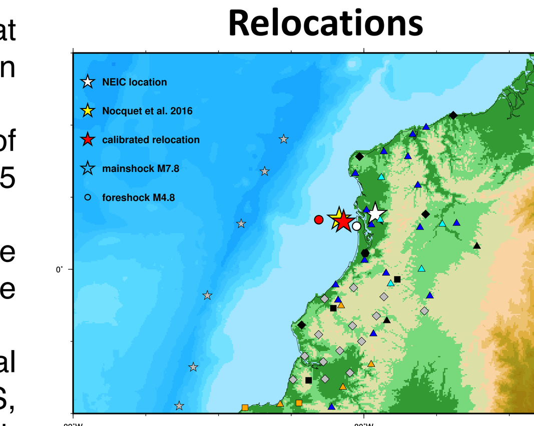


Relocated events, color-coded by depth, with respect to the Nocquet et al., 2016 rupture model and subduction interface depth contours (gray; 10 km interval; Slab 1.0). Harvard CMT and NEIC RMT solutions for 22 of the relocated aftershocks. Earthquake symbols and moment tensors scaled by magnitude.

Main Observations

- 59 M ≥ 4.1 events were relocated
- Similar to M ≥4 aftershocks automatic locations, relocated events concentrate outside the mainshock's rupture area.
- Events tend to concentrate into tight groups
- Event depths within some groups vary from 14 to 32 km suggesting that seismicity occurred in the upper plate, interface and downgoing plate in those localities.
- MT solutions for 22 of the relocated aftershocks indicate predominance of thrust events. This is consistent with observed rupture styles of all M ≥4.5 aftershocks (relocated or not).
- Two, closely located, extensional earthquakes occurred offshore in June 2016, and one strike-slip event occurred close to the intersection of the Carnegie Ridge and the trench.
- The mainshock's calibrated location coincides closely to the epicentral location obtained by Nocquet et al., 2016 through the inversion of GPS, accelerograms, InSAR, and body waves at global scale. The mainshock depth was constrained to 20 km which is comparable with the CMT and NEIC depths of 22 and 20.6 km respectively.
- Aftershock automatic catalog includes 326 events Ml≥4 and will provide substantial detail on faulting.
- Connectivity to stations to the north, particularly OBS stations, is weaker than to the south. We lost connectivity to the northernmost OBS (XE09), which could provide stronger control to the northwest of the aftershock sequence. Upcoming work involves adding more M>4 events, particularly located to the north, and recorded during the OBS deployment period.

Mainshock & Foreshock Relocations



The multiple-event relocation method allowed for the calibrated location of both the M7.8 mainshock and a M4.8 foreshock that occurred 11 minutes earlier. The mainshock calibrated location coincides closely to Nocquet et al., 2016 epicentral location. Similar to the mainshock, the foreshock relocation moved ~25km to the west.

Conclusions

- Aftershock activity is heavily clustered with 2 bands of seismicity delimiting the northern and southern ends of the 2016 rupture.
- Aftershocks show a strong temporal component with seismicity migrating to the northern Esmeraldas region ~2 months after the mainshock. The Esmeraldas cluster exhibits swarm behavior (more details in Hoskins, et al. poster in this session). Seismic activity intensified 6 months later in the Atacames region. The Atacames and Esmeraldas seismicity occurs in the southern part of the 1958 rupture.
- Aftershocks M ≥4.0 concentrate outside the 2016 rupture area. A cluster of smaller magnitude events (M<4) occur in the region of smaller slip between the two slip patches in Nocquet et al., 2016 rupture model.
- Calibrated relocations for M ≥ 4.1 events tend to concentrate into tight groups surrounding the 2016 rupture area. Event depths (14 to 32 km) within some groups suggest upper plate, interface and lower plate activity in those localities.
- CMT and RMT indicate predominance of thrust events. However, 2 extensional earthquakes occurred offshore and one strike-slip event occurred close to the intersection of the Carnegie Ridge and the trench.

We are working on a final automatic aftershock catalog (using a multiband filter detection algorithm, Lomax et al., 2012). The automatic locations and phases will be made openly available. Calibrated relocations will also be made available.

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