The 2016 Mw 7.8 Pedernales Earthquake, Ecuador: RAPID Response Deployment

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Abstract

The April 2016, Pedernales Earthquake ruptured a 100 km by 40 km segment of the subduction zone along the coast of Ecuador in an M_w 7.8 megathrust event east of the intersection of the Carnegie Ridge with the trench. This portion of the subduction zone has ruptured on decadal time scales in similar size and larger earthquakes, and exhibits a range of slip behaviors, variations in segmentation, and degree of plate coupling along strike. Immediately after the earthquake, an international rapid response effort coordinated by the Instituto Geofísico at the Escuela Politécnica Nacional in Quito deployed 55 seismometers and 10 OBS above the rupture zone and adjacent areas to record aftershocks. In this article we describe the details of the US portion of the rapid response and present an earthquake catalog from May 2016-May 2017 produced using data recorded by these stations. Aftershocks focus in distinct clusters within and around the rupture area and match spatial patterns observed in long term seismicity. For the first two and a half months, aftershocks exhibit a relatively sharp cutoff to the north of the mainshock rupture. In early July an earthquake swarm occurred ~100 km to the northeast of the mainshock in the epicentral region of a M_w 7.8 earthquake in 1958. In December, an increase in seismicity occurred ~70 km to the northeast of the mainshock in the epicentral region of the 1906 earthquake. Data from the Pedernales earthquake and aftershock sequence recorded by permanent seismic and geodetic networks in Ecuador and the dense aftershock deployment provide an opportunity to examine the persistence of asperities for large to great earthquakes over multiple seismic cycles, the role of asperities and slow slip in subduction zone

megathrust rupture, and the relationship between locked and creeping parts of the subduction interface.

Introduction

Subduction zone megathrust faults generate the largest earthquakes and devastating tsunami. A spectrum of slip behaviors including earthquakes, non-volcanic tremor, slow slip events (SSE), low-frequency earthquakes (LFE) and very low-frequency earthquakes (VLFE) is observed in many subduction zones contributing to the seismic cycle that ultimately culminates in large subduction zone earthquakes (Bilek & Lay, 2018; Brown et al., 2009, 2013; Dragert et al., 2001; Ide, 2012; Lowry et al., 2001; Obara et al., 2002; Peng & Gomberg, 2010; Peterson & Christensen, 2009; Rogers & Dragert, 2003; Saffer & Wallace, 2015; Schwartz & Rokosky, 2007; Shelly et al., 2007; Wallace & Eberhart-Phillips, 2013). Lateral variations in structure or mechanical properties in the subduction zone, roughness on the down going plate, seamounts, seafloor offsets, ridges, and sediments, segment the subduction zone and can act as asperities or as barriers inhibiting rupture (Bangs et al., 2006; Husen & Kissling, 2002; Kodaira, 2000; Wang & Bilek, 2011, 2014). Features within the overriding plate, batholiths, forearc basins, and faults can also influence rupture behavior (Hicks et al., 2014), and there are regions in the downgoing slab as well as earthquakes in the overriding plate that may be triggered by megathrust events (Sherrod & Gomberg, 2014). Linking physical processes to the spectrum of deformation and understanding the interactions between the range of slip behaviors and their contributions to the seismic cycle can lead to improved hazard assessment and mitigation strategies (Brodsky & Lay, 2014; Kanamori, 2014).

On April 16, 2016 the M_w 7.8 Pedernales earthquake ruptured an approximately 100 km long by 40 km wide section of the subduction zone offshore Ecuador (Figure 1) (USGS NEIC, 2016; Nocquet et al., 2017; Ye et al., 2016). The epicentral region of the mainshock lies east of the intersection of the Carnegie Ridge with the subduction zone along a section of the margin where the orientation of the trench shifts from ~N20°E to ~N32°E. In 1906 an M_w 8.8 earthquake ruptured a 500 km section of the subduction zone from the Carnegie Ridge to Colombia (Kanamori & McNally, 1982; Kelleher, 1972; Mayorga & Sánchez, 2016; Yi et al., 2016) (Figure 1). Smaller patches of the segment that ruptured in 1906 slipped from south to north in a series of major earthquakes: M_w7.8 (1942), M_w 7.7 (1958), and M_w 8.2 (1979) (Kanamori and McNally, 1982; Mendoza and Dewey, 1984; Swenson and Beck, 1996). The 2016 Pedernales earthquake ruptured the same portion of the subduction zone that slipped in 1942 (Ye et al., 2016; Nocquet et al., 2017). The death toll from this earthquake reached over 650. Close to 30,000 people were reported injured. Over 85,000 people received humanitarian assistance in the recovery and reconstruction phase (International Federation of Red Cross and Red Crescent Societies, 2016). The coastal cities of Manta, Portoviejo and Pedernales sustained significant damage (Franco et al., 2017; Goretti et al., 2017; Lanning et al., 2016; Palacios et al., 2018). Economic loss and the cost of recovery and reconstruction was estimated at $3.3

billion, ~3% of Ecuadorian GDP (National Planning and Development Secretariat, Ecuador).

The 2016 Pedernales earthquake was preceded by a M_w 4.8 foreshock by 11 minutes. The mainshock rupture propagated from north to south parallel to the subduction interface (USGS NEIC, 2016; Ye et al., 2016, Nocquet et al., 2017). Coseismic slip ranged from 1-6 meters and occurred in two distinct patches (Nocquet et al., 2017) at depths between 15 and 30 km (Figure 1). The rupture corresponds to a zone of high interseismic coupling as measured by GPS attributed to asperities in the down going plate (Chlieh et al., 2014; Nocquet et al., 2014). Immediately after the mainshock rupture aseismic afterslip was observed and evolved over a 25 day period (Rolandone et al., 2018). Two distinct patches of afterslip, each approximately 50 x 50 km, extended updip northwest and southwest of the mainshock rupture toward the trench. Cumulative afterslip and equivalent magnitude for the northern patch was up to 0.7 m and $M_w = 7.1$; for the southern patch up to 1.0 m and $M_w = 7.0$ (Rolandone et al., 2018). The earthquake also triggered a slow-slip event ~100 km south of the rupture with slip up to 0.8 m and equivalent moment magnitude of $M_w = 6.7\text{-}6.8$ (Rolandone et al., 2018). These same three regions have experienced slow slip earthquakes, earthquake swarms, and repeating earthquakes in the past (Holtkamp et al., 2011; Segovia et al., 2018; Vaca et al., 2018; Vallee et al., 2013). Within this initial 25 day period, an additional deep patch of aseismic afterslip was observed downdip to the southeast of the mainshock rupture at 60 km depth (Rolandone et al., 2018).

In the wake of the earthquake an international rapid response effort coordinated by the Instituto Geofísico at the Escuela Politécnica Nacional (IG-EPN) in Quito deployed accelerometers, seismometers, OBS, and GPS receivers to record aftershocks and measure post-seismic deformation (Font et al., 2016). In this article we focus on the US seismic portion of the rapid response effort using IRIS PASSCAL instruments (Meltzer and Beck, 2016). These data are openly available from the IRIS Data Management Center (DMC). We provide an overview of the data acquired, station locations, site conditions, data quality and availability. We also discuss earthquake locations determined from these data over the 12-month temporary deployment and make available the earthquake catalog produced by automatic processing tools using the BRTT Antelope software (http://www.brtt.com, last accessed May 2017). Finally, we use this and past experience to make recommendations to enhance rapid response deployments to better capture the unique observations that are only possible in the wake of large to great earthquakes.

The Pedernales Aftershock Deployment

Within three days of the 2016 April 16 Pedernales earthquake a team from IG-EPN went to the epicentral region and deployed 5 broadband and 5 dual short period – strong motion sensors. Between May 9 and May 22 teams from the US (Lehigh University and University of Arizona), France (Université Côte d'Azur IRD, Géoazur and CEREMA), and the UK (University of Liverpool) deployed a mix of short and intermediate period, and broadband sensors (Figure 1). Short period 3-component OBS were deployed by IRD at the end of May. The stations in the temporary aftershock deployment augment data recorded by the National Seismic Network (RENSIG) (Alvarado et al., 2018).

In total, 55 temporary stations were deployed on land over a 300 km x 90 km region (Figure 1). OBS deployed offshore near the trench extend lateral coverage to ~160 km and provide critical observations west of the mainshock and aftershock sequence. Station coverage adjacent to the 2016 rupture, extends north to Esmeraldas in the vicinity of the 1958 rupture, and south to Manta where slow slip events and earthquake swarms are common. The temporary deployment encompasses the aftershock zone of the previous 1942 (M_w=7.9) earthquake and the epicenter and part of the estimated rupture area of the 1906 M_w 8.8 earthquake in Ecuador (Figure 1).

On land, 35 broadband sensors, a mix of STS-2 (n=9), CMG-3 (n=10), and Trillium Compact sensors (n=16) were deployed over the entire 300 x 90 km area covered by the temporary network (Figure 1). Fourteen intermediate period (CMG-40T) sensors were deployed in the central portion of the network adjacent to and south of the southern end of the rupture spanning a portion of the margin where lateral variation in plate coupling is observed (high to low, north to south; Chlieh et al., 2014). Six short period (Lennartz LE 3D Lite) sensors were deployed in the southern portion of the network adjacent to where slow slip events and earthquake swarms are observed. Station spacing within the network varied from 10-20 km. The distribution of sensors in part reflects coordination between the teams to limit the geographic area covered by each deployment team to speed up installation of the network (EC: north, US: north, FR: central, and UK: south). The 19 broadband stations from IRIS PASSCAL were installed May 11 through May 16 2016 predominantly in the northern part of the network with a few stations deployed in the central and southern part of the network to infill broadband coverage (Figures 1 and 2).

The majority of the stations in the temporary deployment remained in the field for 12 months. The OBS recorded data for five and a half months and were removed in mid November 2016. The 19 IRIS PASSCAL stations were demobilized in early May 2017 along with most of the on land temporary stations. Twelve of the stations deployed by IRD remained in the field into August 2017.

All stations were deployed at low elevation sites in the forearc (Figure 1). For the most part, the IRIS PASSCAL stations are far from bedrock with sensors placed in soil varying from sandy, to organic rich, to almost solid clay (Table S1 in the electronic supplement to this article). The one exception is EC19 where weathered ophiolite outcrops at the surface. By necessity, approximately a third of the stations are along the coast. Much of Esmeraldas and Manabí provinces are lightly populated, rural and agricultural with small to moderate size towns and resort areas interspersed. The majority of the stations are in rural settings (Figure S1 in the electronic supplement to this article). For security, stations were located on the property of host families, generally (though not always) within proximity of houses (Table S1 in the electronic supplement to this article). The IRIS PASSCAL stations were recorded by Reftek RT130 data loggers at 100 samples per second. Each station was powered by a 12v 100 amp hour deep cycle battery and a 65-watt solar panel. Sensor vaults were simple and easy to install quickly. Sensors were placed on granite tiles, covered with an inverted plastic barrel, and buried approximately 0.5 to 1.0 meter below the surface (Figure S2 in the electronic supplement to this article).

Data Quality and Availability

Data from the 19 IRIS PASSCAL stations were archived at the IRIS DMC and openly available after service runs in September (2016) and March (2017) and after demobilization in May (2017). The average percent data recovery for the deployment was 92.4% with individual stations ranging from 50% to 100% (Table S1 and Figure S3 in the electronic supplement to this article). The only known sensor issue at the time of the initial deployment was at EC20 where the east component was bad.

Over the course of the 12 month deployment 4 additional sensors (EC01, EC04, EC06, EC17/21) developed issues (Table S1 in the electronic supplement to this article), two stations (EC11 and EC12) developed issues with the Reftek data loggers issues, and one station EC07 had data logger and sensor cable issues. Over the course of the deployment, 8 of 19 stations (42%) had issues severe enough to impact data acquisition. The failure rate is in part due to environmental factors, high humidity in an equatorial environment (condensation) and significant rainfall during the rainy season, December through March (flooding of some vaults and station boxes), but it also reflects an aging broadband pool.

Representative frequency dependent noise levels for stations in the temporary deployment are included in Figure S3 in the electronic supplement to this article. For the most part stations have intermediate noise levels in three period bands: 0.1-1 second, 1-10 seconds, and 10-100 seconds on the vertical component. Noise levels at long periods are higher on the horizontal components. Higher noise levels between 1 and 10 Hz reflect high earthquake activity associated with the aftershock sequence. There are no consistent differences in noise characteristics between coastal vs. inland sites, soil vs. bedrock sites, or between stations located tens vs. hundreds of meters from local houses or buildings.

All data from the US portion of the Pedernales earthquake aftershock deployment are archived and openly available at the IRIS DMC, network code 8G (2016-2017) (http://www.iris.edu/dms/nodes/dmc/). Data from France and the UK will be available through Réseau Sismologique & Géodésique Français (RESIF) summer 2019..

Automatic Earthquake Catalog

Earthquake locations were determined for events recorded by the PASSCAL stations through automatic processing using tools from the BRTT Antelope software (http://www.brtt.com, last accessed May 2017). Automatic detections were picked using short term average (STA) versus long term average (LTA) ratios on vertical and horizontal components for P and S waves respectively (P waves: 1-10 Hz, STA/LTA>4.0; S waves: 1-5 Hz, STA/LTA>4.0). Detections are associated into potential earthquake arrivals using a precomputed travel time grid built with the iasp91 velocity model. Hypocenter locations are determined via an iterative least squares inversion of travel time residuals (Pavlis et al., 2004). Traditional Richter (local) magnitude (M_l) is calculated automatically for events with a minimum of three stations with a signal to noise ratio greater than 3.

The automatic catalog contains 3246 events (Figure 2). The magnitude of completeness, Mc = 2.3, is estimated using the maximum curvature method (Wiemer and Wyss, 2000; Wiemer and Katsumata, 1999). Using Mc = 2.3 and the maximum likelihood method for calculating b-values (Aki, 1965) and magnitude binning width of 0.1, results in b=0.88. Manual inspection of the automatic catalog indicates that events with at least eight phases and locations errors less than 10 km (using 68% confidence ellipses) are reliably earthquakes. Earthquakes were detected and associated with less than 8 phases, but the number of false detections or spurious signals is higher. Location errors and comparisons between the full catalog and events with at least 8 phases are provided in Figures S4 and S5 in the electronic supplement to this article. These formal uncertainties do not reflect any bias introduced by using a 1D global velocity model in a region with 3D velocity heterogeneity. The full catalog ,including magnitudes and uncertainties, is included in QuakeML format in the electronic supplement to this article.

Initial Observations

Aftershocks of the Pedernales earthquake show a clear pattern of clustering within, around, and to the north and south of the rupture (Figure 2). From south to north earthquake clusters are observed under the coastline north of Manta (A Figure 2), updip and extending to the trench at the southern end of the rupture (B Figure 2), within the rupture zone between the two patches of higher slip (C Figure 2), updip at the trench and down dip of the mainshock extending beneath the coast at the northern end of the rupture (D Figure 2), offshore Punta Galera 20 km north of the end of the rupture and on land east of the offshore Galera cluster (E Figure 2), ~70 km northeast of the mainshock in the vicinity of Atacames (F Figure 2), and ~100 km northeast of the mainshock at Esmeraldas (G Figure 2). The eastern down dip limit of seismicity is quite sharp (Figure 2). The up dip limit is more diffuse but this could change, as data from the OBS are included.

The cumulative number of events, number of events per day, and event magnitude per day indicate a high rate of seismicity that gradually decays with time (Figure 3 and animation in the electronic supplement to this article). Superimposed on this gradual decay are small bursts of activity, spatially focused higher rates of seismicity, lasting from several days up to a week. Higher magnitude events ($5 \leq M \leq 7$) are interspersed throughout the post-seismic sequence up to 9 months after the mainshock. By the end of January 2017 both the magnitude and frequency of events decay to background levels through the end of the temporary deployment. Two significant upticks in seismicity correlate with an earthquake swarm in July 2016 at Esmeraldas and a series of moderate earthquakes (M_l 4-5) in December 2016 at Atacames. For the most part, both moderate to large and small magnitude events occur within the clusters (Figure 2). Notable exceptions are the cluster of events within the rupture zone between the two patches of larger slip (C Figure 2), and a cluster of events between the mainshock and the series of magnitude 6 earthquakes to the east (east end of D, Figure 2). These two areas contain only smaller magnitude events (Figure 2).

For the first two and a half months after the mainshock, earthquakes are generally restricted to Punta Galera and south (Figure 2 and animation in the electronic supplement to this article). On June 18th, a month after the mainshock, two large aftershocks, M_w 6.8 and M_w 6.9 (USGS NEIC, 2017), occurred within 8 hours of each other, beneath the coast at the northern end of the rupture in an area where interseismic plate coupling is high (Nocquet et al., 2017; Rolandone et al, 2018). In July an earthquake swarm occurred in the upper plate ~100 km northeast of the rupture beneath the town of Esmeraldas (Hoskins et al., 2018). The swarm occurred close to the southern edge of the 1958 M_w 7.7 earthquake (Figures 1 and 2). The swarm contains events with local magnitudes up to 5 within the sequence, but is not preceded by a large magnitude event. During the July swarm at Esmeraldas, two large earthquakes (M_w5.9 and M_w6.3, NEIC, 2017) occurred in the earthquake cluster beneath the coast at the northern end of the rupture (Figure 2). In contrast, the uptick in seismicity in December at Atacames begins with a M_w 5.2 event and contains multiple events of similar magnitude (M_w 5.4, M_w 4.8, M_w 4.8; USGS NEIC, 2017) over the next 7-9 days. Ground shaking associated with the June 18 events and the Esmeraldas and Atacames sequences caused additional damage to buildings weakened in the main shock.

The general pattern of earthquake clustering from Punta Galera south was established within the first week of the mainshock (IG-EPN catalog; Rolandone et al., 2018). This clustering is also observed in the long-term catalog (from south to north the Manta, Jama, and Galera clusters; Font et al., 2013; Segovia et al., 2018; Vaca et al., 2018). These clusters outline regions of aseismic slip that evolved over a 25 day period after the mainshock (Rolandone et al., 2018), ending just as the temporary deployment was being installed. These regions continued to be the site of focused seismic activity for months and contain the majority of the magnitude 4 and larger events (Figure 2). The Galera cluster lies between the northern end of the patch of aseismic slip and a region of high interseismic plate coupling associated with Punta Galera. The Jama cluster is associated with a region of high interseismic coupling (Collot et al., 2017; Nocquet et al., 2017; Rolandone et al., 2018).

North and northeast of the rupture, toward the epicentral regions of the 1906 and 1958 great earthquakes, the earthquake clusters with epicenters on land trending north toward Atacames align with the eastern boundary of Miocene Borbon Basin (Reyes and Michaud, 2012) and a break in topography associated with uplifted Miocene sediments. A series of crustal faults (e.g. Galera fault, Mache lineament, and others) are mapped in this area and farther east toward Esmeraldas (Eguez et al., 2003). The relationship between observed seismicity and crustal faults is being explored using high precision earthquake relocation methods.

Earthquake catalogs combining data from the complete rapid response deployment (EC, US, FR, and UK temporary stations) and permanent network stations have been completed (Soto-Cordero et al, 2017 and in prep; Agurto et al, 2017 and in review). These catalogs support the observations presented here, but reveal additional detail on the temporal and spatial evolution of the sequence of events following the Pedernales earthquake especially in the central and southern portions of the temporary deployment. The number of events detected using stations from the complete temporary array increased three fold and the magnitude of completeness improved by 0.5 to M_c 1.8. Preliminary joint inversion for earthquake location and 3D velocity structure shifts event locations within individual earthquake clusters but does not shift the spatial distribution of the clusters themselves.

Lessons Learned.

While the seismic rapid response deployment after the Pedernales earthquake was relatively smooth and efficient, improvements in instrumentation and protocols established in advance of destructive events are needed to facilitate rapid deployments and field studies after large subduction zone earthquakes. Rapid response deployments have the potential to uniquely capture a range of subduction zone processes complementing the observations from permanent networks to shed new light on rupture of megathrust earthquakes and transient processes associated with these events. Real-time data from rapid response deployments can be used to monitor the post seismic evolution of aftershock sequences and triggered seismicity to improve aftershock forecasting and seismic hazard assessment immediately after large magnitude events. Systemic changes are needed in rapid response deployments in to order maximize what we can learn about earthquake rupture and post-seismic response, and to reduce risk in the wake of large magnitude earthquakes.

After a large earthquake, time is of the essence to capture the immediate post-seismic response. The first stations from the international rapid response effort were installed three weeks after the main shock. This reflects the time required to marshal resources (financial, technical, and human), ship instruments, arrange customs clearance, acquire materials and supplies, and arrange transportation to the field. This time needs to be shortened to no more than 48 to 72 hours. Advance planning and regional instrument pools can ensure that protocols are in place and resources accessible to speed the time between event and response. Appropriate robust instrumentation is needed, that can be deployed easily and quickly, and operate reliably in a range of environments and site conditions. Integrated systems are needed that take advantage of new options for power supply, allow for multiple collocated sensors to record the full spectrum of ground motions (strong to weak), include options for real time communications, and directly capture and log metadata. Rapid response efforts need to adopt a system approach from instrument deployment to data capture and integration, time series analysis, and data products including robust earthquake locations, magnitudes, and source characterization. Coordination, collaboration, and near-real time open data should be the standard for all rapid response efforts.

Data & Resources

All data from the US portion of the Pedernales earthquake aftershock deployment can be obtained from the IRIS Data Management Center, http://www.iris.edu/dms/nodes/dmc/ network code 8G (2016-2017) doi: 10.7914/SN/8G_2016. The full automatic catalog is included in the electronic supplement to this article in QuakeML format. Maps and figures were made using the Generic Mapping Tools version 5.2.1 http://gmt.soest.hawaii.edu (Wessel et al., 2013).

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Figure 1. Station map Pedernales earthquake international seismic rapid response. Inset South America, Ecuador outlined by red box. 2016 Pedernales earthquake mainshock location (white star) and coseismic slip contours from Nocquet et al. (2017), coseismic slip contour 1m, maximum slip 6 m. Coastal stations from the permanent national network in black, other colors in key designate temporary stations. RAMP: Rapid Array Mobilization Procedure. IG-EPN: Instituto Geofísico at the Escuela Politécnica Nacional, IRD: Institut de Recherche pour le Développement, BB: broadband sensors, IP: intermediate period sensors, SP: short-period sensors, OBS: ocean bottom seismometer. Historic earthquakes, epicenters yellow stars, estimated rupture areas red dashed ellipses after Swanson and Beck (1996), Beck and Ruff (1984), and Bilek (2010).

Figure 2. Earthquake epicenters and temporal sequence of events from automatic catalog produced from IRIS PASSCAL stations, May 2016-May 2017, minimum of eight phases and errors less than 10 km, n=2499 events. IRIS PASSCAL stations blue triangles. Mainshock location and coseismic slip contours from Nocquet et al. (2017), coseismic slip contour 1m, maximum slip 6 m. Slab contours every 10 km depth from Slab2 (Hayes et al., 2018). Temporal sequence of events plotted by latitude (vertical axis=latitude, horizontal axis = Julian Day), circles scaled and color coded by magnitude: yellow $M_l \geq 6$, orange $6 > M_{l\ l} \geq 5$, brown $5 > M_{l\ l} \geq 4$, red $M_l < 4$. Earthquake clusters designated by letters discussed in the text. See Figure 1 for topography and bathymetry scaling.

Figure 3. (a) Cumulative number of events, (b) number of events per day, and (c) event magnitude per day from automatic catalog produced from IRIS PASSCAL stations, May 2016-May 2017 minimum of eight phases and errors less than 10 km, n=2499 events. Horizontal axis is Julian Day.. Partial data gap around jd250 due to disk storage problems. Uptick in seismicity associated with Esmeraldas and Atacames swarms labeled in (b).