ECUADOR EARTHQUAKE AND TSUNAMI OF 17 APRIL 2016

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In 1980, I published the results of my survey of the 1979 Tumaco Earthquake and Tsunami, and reviewed the 1906 event (Mw=8.8, rupture 600 km.), which generated a tsunami with destructive near and far-field impacts. My survey in 1979, extended from Buenaventura, Colombia to San Juan Island to Tumaco and along the coast of Colombia to Esmeraldas, Ecuador.

I emphasized that the Colombia/Ecuador subduction zone is a region where high seismic stress is accumulating and that rupture of two or more segments along the coast of Ecuador - as in 1906 - could generate a destructive Pacific-wide tsunami. My conclusions were based on statistical probability studies and subsequent GPS measurements of crustal deformation, clearly indicating that the region has an increased potential to generate in the near future a major or great tsunamigenic earthquake similar to 1979 or 1906.

Clustering of the aftershocks of the earthquake of 17 April 2016 (M+7.8), off Ecuador indicated that two faults were activated and that another earthquake or a major aftershock was possible along the zones of the 1942 and 1958 earthquakes. A repeat of the 31 January 1906 event with more than two fault segments rupturing for about 500 km could generate a destructive local tsunami as well a damaging Pacific tsunami.

Specifically my most recent evaluations included: a) the controlling inter-plate coupling mechanisms of the tectonic regime of the margin – including lithospheric structure deformation, sea-floor relief and the subduction or accretion of highly folded, hydrated sediments along the seismogenic zone of southern Colombia/North Ecuador; b) the seismo-dynamics and role in tsunami generation as affected by the Carnegie Ridge’s oblique subduction beneath the South American continent; and c) the seismotectonic extensional processes in the vicinity of the Gulf of Guayaquil-Tumbes Basin and how the northwestward movement of the North Andes block away from the South American continent along the Dolores Guayaquil mega-thrust and the resulting strain rotation which may cause sudden detachment, décollement and deformation, with the potential for local tsunami generation in the Gulf of Guayaquil and coastal areas along southern Ecuador.

The earthquake of 17 April 2016 and the tsunami, did not surprise me as I was expecting, since 2013, that some major event would occur in the region. However, what was perplexing was the clustering of aftershocks and their spatial distribution, as well a triggering earthquake mechanism, I had not considered previously – that being heavy rainfalls in the Andes and the coastal peninsula. The recent earthquake in Oklahoma was triggered by water injection used in fracking
SEISMICITY OF THE REGION

Both Colombia and Ecuador have high seismicity. Major and great earthquakes along the Colombia/Ecuador margin have the potential of generating destructive local and Pacific-wide tsunamis.

Several large tsunamigenic earthquakes (inter-plate events) have occurred in Ecuador's subduction zone with varied rupture mechanisms.

Subduction of the Nazca plate beneath the Ecuador-Colombia margin has produced four mega-thrust tsunamigenic earthquakes during the 20th Century.

A great earthquake with estimated moment magnitude Mw=8.8 and a rupture of about 600 km occurred on 31 January 1906 along the Colombia/Ecuador Trench in southern Colombia and northern Ecuador.

The same segment of the Colombia/Ecuador subduction zone ruptured by this event was partially reactivated by a sequence of three lesser thrust events in 1942 (Mw = 7.8), 1958 (Mw = 7.7) and 1979 (Mw = 8.2). All four quakes generated destructive tsunamis.
HISTORIC TSUNAMIGENIC EARTHQUAKES OF THE REGION

Four mega-thrust tsunamigenic earthquakes occurred in close sequence along the Colombia/Ecuador subduction margin in 1906, 1942, 1958 and 1979.

Noticeable is the high rate and obliquity of subduction, the chronological sequencing of three historical events and the extent of limited ruptures due to local asperities following the great 1906 earthquake.

The 1906 event ruptured for 600 km encompassing the ruptures of the three subsequent events along the inter-plate megathrust.
The following is a brief examination of these historical events and their impacts, for the purpose of evaluating future events along this complex subduction margin. Noticeable is the high rate and obliquity of subduction, the chronological sequencing of three historical events and the extent of limited ruptures due to local asperities following the great 1906 earthquake.

Earthquake and tsunami of 12 December 1979

This earthquake occurred at 07:59:4.3 (UT). Its epicenter was in the ocean at 1.584° North 79.386° West. Originally the magnitude was given as M=7.9 (Richter scale) but subsequently it was revised to a moment magnitude Mw 8.2. The earthquake and the tsunami were responsible for the destruction of at least six fishing villages and the death of hundreds of people in the State of Narino in Colombia (Pararas-Carayannis, 1980).

Strong motions were felt in Bogota, Cali, Popayan, Buenaventura and other major cities and villages in Colombia and in Guayaquil, Esmeraldas, Quito and other parts of Ecuador. Tumaco and San Juan Island were the two areas that were mostly affected by both the earthquake and the tsunami. Esmeraldas, and other cities and villages of Ecuador close to the epicenter did not sustain much damage. Review of the structural geology indicates why the earthquake had far more severe effects in Colombia than in Ecuador. An offshore ridge in the vicinity of epicenter has an orientation in a northwest/southeast direction and may have acted as a barrier.

Effects of the 1979 Earthquake

The shock was felt from Bogota to the north, to Quito and Guayaquil to the South. There were three major shock waves lasting from 0759 to 0804 UT. At least 10 major aftershocks were recorded subsequently. It was the strongest since 19 January 1958 when an event of 7.8 occurred in the same general area and the second large earthquake to occur in Colombia within a month. On 23 November 1979 an earthquake of magnitude M=6.7 (Richter) had occurred further north. The quake caused most of the damage in the State of Narino in Colombia which borders Northern Ecuador. There were numerous dead and injured. Thousands of buildings were destroyed - principally in the State of Narino. Hardest hit in the State of Narino was Charco, a fishing village of 4,000 persons -- about 300 kilometers north of Ecuador. Most of the victims were women and children. Homes of at least 10,000 persons were destroyed. Electrical power and telephone lines were knocked out. The majority of casualties (at least 807) were the result of the tsunami rather than of the earthquake. Bogota and other major cities, tall buildings swayed, but damage was not significant. Preliminary reports estimated the number of persons killed in the hundreds with up to 2,000 people missing (Pararas-Carayannis, 1980).
Effects of the 1979 Earthquake and Tsunami

The second populated area hardest hit by the quake was Tumaco about 80 kilometers from the epicenter.

At least 40 persons were killed and 750 injured and approximately 10% of the houses and other buildings were destroyed. Tumaco is built on an island made up of alluvial deposits of Rio Mira and Rio Caunapi. Liquefaction was evident in many areas of the city where structures failed and particularly evident along the waterfront. Subsidence was found on either side of the bridge connecting the island where Tumaco is situated to the island where the airport is located.

The island dropped by as much as 60 centimeters. Evidence of subsidence of about 60 centimeters also was reported from the island of Rompido, offshore from Tumaco, and a good portion of that island was under water.

Subsidence of approximately 50 centimeters was reported from Cascajal Island (Pararas-Carayannis, 1980). Surprisingly there was little damage at Ecuador either from the earthquake or the tsunami.

Earthquake damage at Tumaco, Colombia (photo by G. Pararas-Carayannis)
The 12 December 1979 tsunami
The rupture of the 12 December 1979 earthquake was about 200 km along the Northeastern inter-plate segment of the Colombia-Ecuador tectonic boundary – thus the generating area of the destructive local tsunami was at least that long and about 80 km wide. This segment was the third to rupture in sequence along the megathrust and generate a tsunami, following the segments ruptured by the 1942 and 1958 earthquakes along the same fault. All three of these quakes involved three different segments – all of which had been ruptured previously by the 1906 earthquake. Apparently, localized asperities had limited the ruptures of the 1942, 1958 and 1979 earthquakes and their size of the tsunami generating areas. However, the 1906 quake had packed a lot more energy and broke all three segments in succession for a total length of 600 km, thus generating a much more destructive tsunami locally - but also one with significant far field impact.
Near-field Effects of the 12 December 1979 tsunami

Approximately 30-35 kilometers of the coast were hardest hit by the tsunami, while the length of the area hardest hit by the earthquake was approximately 225 kilometers in length, from Guapi to Tumaco.

Fishing villages that were destroyed were Curval, Timiti, San Juan, Mulatos and Iscuande. Most of the damage and deaths in these villages were the result of the tsunami (Pararas-Carayannis, 1980).

A total of four waves were observed, the first arriving approximately 10 minutes after the main quake. The water recessed first to about 3 meters below the level of the sea. The third wave was largest.

San Juan Island was approximately 5 meters above the level of the tide, which fortunately was at its lowest at that time. The tsunami wiped out many villages. Most of the houses at Charco and Iscuande were destroyed. Hardest hit was the fishing village of San Juan, where the waves completely overran the island destroying just about everything in their path. Numerous deaths were reported from this area.

Tsunami damage at Tumaco (photo by G. Pararas-Carayannis)
Near-field Effects of the 12 December 1979 tsunami in Tumaco and Esmeraldas, Ecuador

Hand trace of the tsunami as recorded by tide gauge at the port of Esmeraldas, Ecuador. Record confirms tsunami arrival at lowest possible tide. First wave activity was a recession followed by approximately 3 to 4 waves. If the wave occurred at high tide, its elevation would have been 1-3 meters higher than the one-meter wave observed in Tumaco – which has maximum elevation of only 3 meters above sea level.

At San Juan Island, where maximum waves were observed, the direction of approach of the waves was from the southwest, rather than from the west. The direction was obtained by observing fallen palm trees, detritus material wrapped around objects and the way buildings moved or structurally failed (Pararas-Carayannis, 1980).

Far-Field Impact of 1979 Tsunami

Tsunami observed or recorded in many places of the Pacific including the Hawaiian Islands. A deep gauge off the coast near Tokyo, Japan did not record any wave activity. At Johnston Island recorded wave was only 8 cm. It took a little over 12 hours to reach the Hawaiian Islands.

At Hilo and at Kahului, the maximum observed wave (trough to crest) was approximately 40 centimeters. At Nawiliwili the wave was only 10 cm.
The 31 January 1906 Earthquake and Tsunami

A great earthquake occurred at 15:36 UTC on 31 January 1906, off the coast of Ecuador and Colombia. Its epicenter was near the port town of Esmeraldas in Ecuador.

Its magnitude (Richter) was originally estimated at 8.2, but subsequently revised to a Moment Magnitude Mw=8.8.

A destructive tsunami was generated which destroyed 49 houses and killed at least 500 people on the coast of Colombia and perhaps as many as 1500 people.

The quake’s rupture was estimated at 500–600 km long and - encompassing the rupture segments of earthquakes which occurred subsequently in 1942, 1958 and 1979.

The width of each affected block was estimated at about 80-90 km. The lack of overlap between the three subsequent events suggested the presence of minor barriers (asperities) to rupture propagation along the plate boundary. Although these three events ruptured the same area of the plate boundary overall, they released only a small fraction of the energy of the 1906 earthquake.

The ground motions of the 1906 quake were felt along the coast of Central America, as far north as San Francisco and as far west as Japan. The quake was recorded at San Diego and San Francisco in California.
Near and Far-field Effects of the 1906 Tsunami

Near Field Impact - The maximum recorded run-up height was 5 m in Tumaco, Colombia. The greatest damage from the tsunami occurred on the coast between Rio Verde, Ecuador and Micay, Colombia. Estimates of the number of deaths caused by the tsunami vary between 500 and 1,500.

Far-field impact – The tsunami was observed in Costa Rica, Panama, Mexico, California and Japan. However, there were no reports of tsunami damage from Central America or Mexico. At Acapulco, the recorded maximum tsunami height was .25 meters.

In the Hawaiian Islands the first tsunami wave arrived in Hilo, Hawaii, about 12.5 hours after the earthquake.

The wave oscillations ranged up to 3.6 m (1.8 m. run-up height) and had average periods of 30 minutes. The channels of the Wailuku and Wailoa Rivers alternately dried up, then were flooded.

In Kahului, Maui, three waves were observed with an average period of about 20 minutes. The second wave was larger and the third even larger. Sea level rose about 0.30 m above the mean sea level mark. According to other sources, the water surface rose to the level of the old steamship pier and the road running along the coast.

In Honolulu, Hawaii, the tide gauge began registering water level oscillations at 3:30 UTC on 1 February -about 12 hours after the earthquake. The first wave appeared to be positive. At 4:15 UTC there was an extremely great ebb of the sea. The highest of the waves was the fourth reaching 0.25 m. The period of the tsunami waves ranged from 20-30 minutes. Three separate trains of oscillations were registered. (Pararas-Carayannis, 1980).
Seismic investigations of lithospheric structures associated with subduction megathrusts are critical to understanding the mechanics of the inter-plate seismogenic zone, where very destructive, tsunamigenic earthquakes occur.

Several factors have been proposed as controlling inter-plate coupling and tectonic regime of the Ecuador-Colombia margin, including sea-floor relief and the subduction or accretion of high-fluid content sediments which, when suddenly displaced, can enhance the height of tsunamis.

The length of earthquake ruptures and the dimensions of tsunamigenic sources are affected by buoyancy forces of bounding and migrating oceanic ridges and fractures, subducting obliquely with the South American continent. For example, in central and southern Peru, from about 15° to 18° South, the Mendana Fracture Zone (MFZ) to the North and the Nazca Ridge to the South, have created a narrow zone of considerable geologic and seismic complexity - characterized by shallow earthquakes that can generate destructive tsunamis of varied intensities.

The obliquity of convergent tectonic plate collision in this region, as well associated buoyancy, may be the reason for the shorter rupture lengths of major earthquakes and the generation of only local destructive tsunamis (Pararas-Carayannis, 2012). The seismotectonics of the Ecuador-Colombia boundary margin are analogous in that they are affected also by the buoyancy forces of the obliquely subducting Carnegie Ridge under central Ecuador. These forces have created fault heterogeneities that affect tsunami source dimensions and mechanisms of generation to the north and to the south of Carnegie Ridge’s region of subduction.

Before discussing the localized earthquake mechanisms that generate tsunamis along the megathrust north of the Carnegie Ridge – the region which parallels the Ecuador-Colombia trench – we must first review how the larger tectonic kinematics affect the North-Western region of the South American continent.

The overall seismo-dynamics along the coasts of Ecuador and Colombia are affected by the active seismicity and kinematics of the northernmost segment of the Andes - which is divided into a Western Cordillera and an Eastern Cordillera (including the Merida Andes). This wedge is referred to as the “North Andes block” and inferred from geologic and seismicity data.
SEISMODYNAMICS OF THE ECUADOR-COLOMBIA SUBDUCTION MARGIN

Yaquina Graben, Colombian Trench, Carnegie Ridge, the Grijalva Fracture Zone, the North Andean Block and the Dolores Guayaquil megathrust (DGM)

Epicenters of the 1979 earthquakes on the North Andean Block coastal intra plate region (). This wedge appears to move at about 10 mm/year with respect to South America (SA), or at about 17–19 mm/year northwestward with respect to Caribbean tectonic plate (CA). The boundary between the North Andes plate (ND) and the South America plate (SA) is the Dolores Guayaquil mega-thrust (DGM), which is apparently reactivated in an oblique dextral-normal sense.

DGM transverses the Gulf of Guayaquil and has created a pull-apart basin and resulting strain rotation which may cause sudden crustal detachment, deformation and décollement, with the potential for local tsunami generation that may affect the Gulf of Guayaquil and other coastal areas along southern Ecuador.

To understand the tsunami generation mechanisms along the Colombia/Ecuador subduction margin north of the Carnegie Ridge, we must first review the seismo-dynamics of the region from latitude 1° to 4°N and longitude 77° to 80°W, where the highest seismicity has been observed in recent years, as well as the impact of oblique subduction of larger tectonic features.

As indicated, several large tsunamigenic earthquakes (all inter-plate events) occurred in 1906, 1942, 1958 and 1979 along the Ecuador/Colombia subduction zone, north of the subducting Carnegie Ridge.
Examination of Sequential Ruptures Associated with Recent Historical Earthquakes along the Colombia-Ecuador Coast – Implications for Future Events.

Subsequent earthquakes to the 1906 event along the same zone, on 14 May 1942, 19 January 1958 and 12 December 1979, ruptured consecutive segments, apparently limited in length by asperities cutting across the mega-thrust fault that parallels the Colombia/Ecuador trench.

The epicenter of the 1942 Ecuador earthquake was in close proximity to the northern flank of the Carnegie Ridge. This quake’s moment release occurred in one simple pulse near the epicenter in 22 seconds.

The relocated aftershocks distributed over an area parallel to the trench that was approximately 200 km long and 90 km wide. The majority of the aftershocks occurred north of the epicenter. The seismic moment as determined from the P waves was $6-8 \times 10^{20}$ N·m, corresponding to a moment magnitude of 7.8–7.9.

The reported location of the maximum intensities (IX) for this event was south of the main epicenter. The 1958 earthquake occurred immediately north of the 1942 event and was also tsunamigenic and destructive in both southern Colombia and Ecuador.

The nature of fault heterogeneities that controlled the northward propagation of plate-boundary rupture from the source region of the earthquake of 1942 to the source region of the 1958 earthquake and eventually to the source region of the earthquake of 1979, were examined with the method of Joint Hypocenter Determination & Dew (Mendoza ey, 1984). This examination determined that the relocated hypocenters lie on the same plane to within the approximately 20-km uncertainty of the focal depths. Also, the main shocks apparently nucleated at nearly the same distance from the Ecuador-Colombia trench. Based on such observations, it was suggested that the heterogeneities between the 1942 and 1958 ruptures and between the 1958 and 1979 ruptures do not correspond to a major distortion of the down-going crustal slab but rather to either minor distortions of the slab or to regions of high friction or low available strain energy on a continuous fault surface.
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The heterogeneity between the 1958 and 1979 rupture zones seemed to have been a high-strength barrier (asperity) with dimensions much smaller than the dimensions of either of the rupture zones. Both the 1942 and 1958 earthquakes had source dimensions no larger than the 1979 main shock, but had stronger aftershock sequences.

Based on this observation it has been suggested that the stoppage of the earthquake rupture in 1979 left the plate-boundary segment that had ruptured in 1906 in a state of lower stress than it had been following the 1942 and 1958 earthquakes.

Long-term seismicity in the decades preceding the 1979 earthquake occurred mostly outside or on the boundaries of the rupture area defined by the distribution of 1979 aftershocks.

The intense aftershock activity that followed the 1958 main shock within tens of kilometers of the eventual 1979 hypocenter was attributed to a long-term precursory seismic swarm for the 1979 earthquake (Mendoza & Dewey, 1984).
Seismo-dynamics of the Carnegie Ridge

In between the two major tectonic regimes of Ecuador’s tectonic margin -specifically between latitude 1°N and 2°S -the Carnegie Ridge collides against the South American continent in an E-W direction and subducts under central Ecuador at a relative plate velocity of 5 cm/yr (Pilger, 1983).

The formation of the Carnegie Ridge and other aseismic ridges started at about 20 Ma when the Galapagos volcanoes were generated by a mantle plume hotspot, formed following the break-up of the Farallon Plate and the formation of the separate Cocos and Nazca Plates (Fig. 10).

At about 19.5 Ma, the Galapagos spreading center moved so that most of the hotspot magmatism affected the Nazca Plate, forming the combined Carnegie and Malpelo Ridges. At about 14.5 Ma the spreading center jumped south, such that most of the magmatism affected the Cocos Plate and caused the Malpelo Ridge to rift away from the Carnegie Ridge (Salares et al., 2005). The Galapagos Rise moved north again at about 5 Ma, leaving the hotspot activity within the Nazca Plate – the current situation.

It has been estimated that the subduction of the Carnegie Ridge under the South America plate started about 2 or 3 million years ago (Lonsdale 1978), while Pennington (1981) estimated an even earlier beginning.

The seismicity of Ecuador and South Colombia -and therefore tsunami generation -are influenced by the Carnegie Ridge subduction under central Ecuador.

In summary, the Carnegie Ridge extends eastward over 1,000 km from the Galapagos Islands to the Colombia-Ecuador trench and continues beneath northern Ecuador for about 700 km. It consists of thickened oceanic crust. Wide angle seismic reflection and refraction data acquired over the central and eastern part of the ridge give crustal thicknesses of 13 km and 19 km respectively for crust that has estimated ages of about 11 Ma and 20 Ma.
Seismo-dynamics of the Carnegie Ridge
Rainstorms in Esmeraldas, Ecuador  21 February to 19 March 2016
THANK YOU