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INCIPIENT EVALUATION OF TEMPORAL EL NINO AND OTHER CLIMATIC ANOMALIES IN TRIGGERING EARTHQUAKES AND TSUNAMIS – Case Study: The Earthquake and Tsunami of 16th April 2016 in Ecuador.

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ABSTRACT

The present study provides an incipient, cursory evaluation of the unusually strong 2015-2016 El Niño Southern Oscillation (ENSO) and of the quasi-periodic fluctuation and anomalies of sea surface temperature (SST) across the equatorial Pacific during that period, as being the cause for the prolonged rainfall and flooding of coastal valleys near Guayaquil and Esmeraldas in Ecuador in December 2015, as well as in late January and February 2016 – which proceeded the 16 April, 2016 tsunamigenic earthquake in Ecuador. Also examined is the seasonality of recent tsunamigenic and non-tsunamigenic earthquakes in Ecuador and elsewhere in South America, in relation to strong ENSO and documented SST Anomalies - as well as to the differently proposed mechanisms that may cause them in Ecuador and elsewhere, with climatic changes induced by the global impact of volcanic explosions and by other terrestrial and extraterrestrial influences, as to impacts they may have on the geostrophic circulation and surface water temperatures of oceanic currents, which perhaps are also associated with the cycles of Atlantic Multidecadal Oscillations (AMO's) of small water temperature differences which may result in clusters of hurricanes generated near the earth's oceanic equatorial zones.

Regarding the 7.8 M_w earthquake and tsunami of 16 April 2016 in Ecuador and based on the above stated partial data, the present study postulates that the excessive volume and weight of flood-waters retained in the coastal crustal layers following the cataclysmic rains of late 2015 and early 2016, triggered an earlier rupture of the already strained offshore fault near the city of Muisne. As an additional contributing mechanism of earthquake and tsunami generation, the evaluation proposes that the extreme volume and weight of floodwaters may have also altered temporarily the crustal buoyancy characteristics of the intersecting Carnegie Ridge with the South America continent along

the central part of the country. Additionally examined and evaluated are the unusual clusters of the 16 April 2016 event(s) and the three-dimensional and temporal anomalous distribution of aftershocks - which did not follow a typical pattern as would have been expected. Similarly atypical was the distribution of observed Modified Mercalli high intensities of this earthquake over a rather large and separated geographical area that stretched more than 200 km along the Ecuadorian coastline.

Keywords: *Climatic Anomalies; El Niño Southern Oscillation (ENSO); Triggering Earthquakes; Precursor Events; Earthquake and Tsunami of 16th April 2016 in Ecuador.*

1. INTRODUCTION

The Colombia/Ecuador subduction zone is a region where high seismic stress has been accumulating and where the rupture of two or more offshore fault segments - as in 1906 (Mw=8.8, total rupture 600 km.) - could generate a tsunami with a very destructive near and far-field impacts in Ecuador, in South Colombia and in the entire Pacific Basin (Pararas-Carayannis, 1980, 2012; Beck & Ruff, 1984). Fig. 1 shows the major tectonic features along northwestern South America, parallel to the convergence direction of the Ecuador-Colombia trench where such events frequently occur.

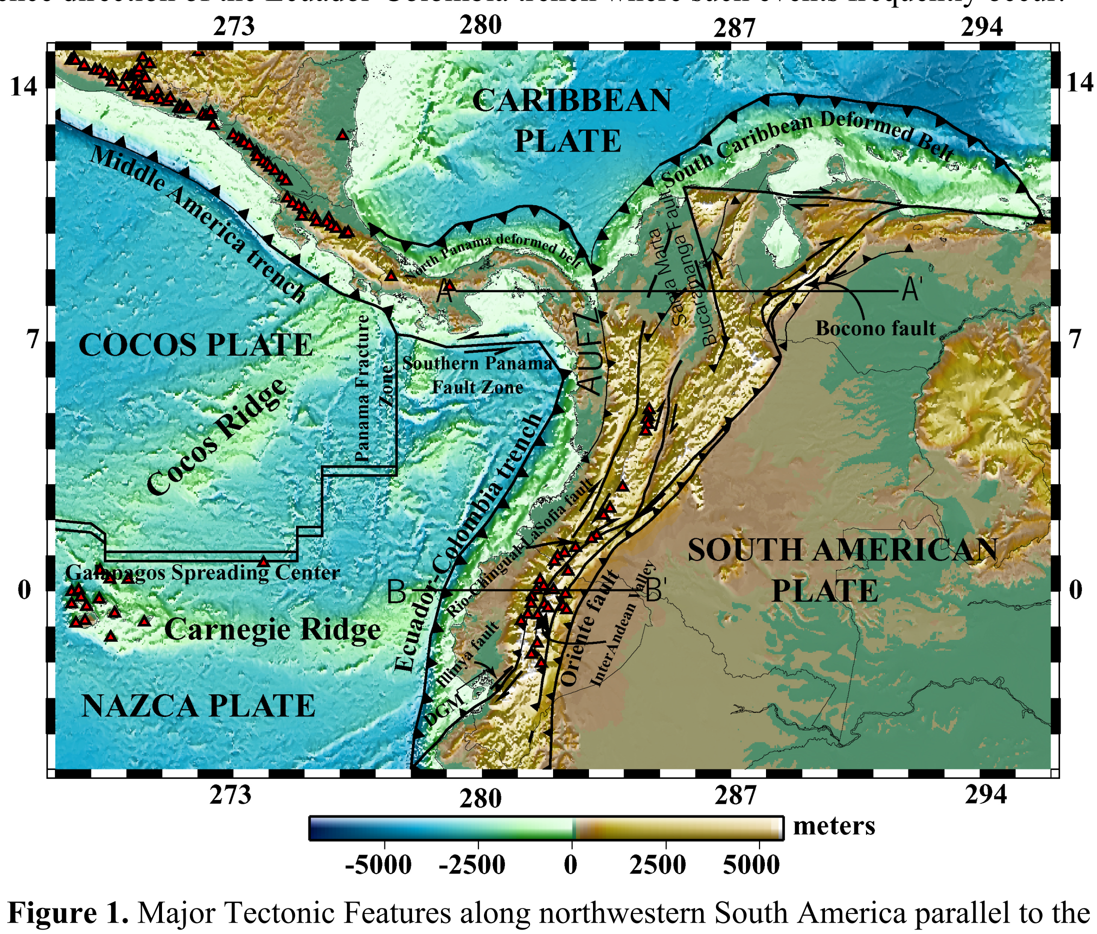

Figure 1. Major Tectonic Features along northwestern South America parallel to the convergence direction (Pararas-Carayannis 2012, after Trenkamp et al. 2002).

Statistical probability studies and subsequent GPS measurements of crustal deformation after the survey of the 1979 Tumaco earthquake and tsunami along Southern Colombia near Ecuador clearly indicated that the region still had a great deal of stress remaining and there was an increased potential for the recurrence of a great tsunamigenic earthquake similar to that of 1906. Furthermore, all three fault segments 1942, 1958 and of the 1979 events represented seismic gaps where a major earthquake was expected (Pararas-Carayannis, 1980, 2012). Fig. 2 shows the major faults that ruptured in 1942, 1958, 1979 and the continuous rupture of all three-fault segments in 1906.

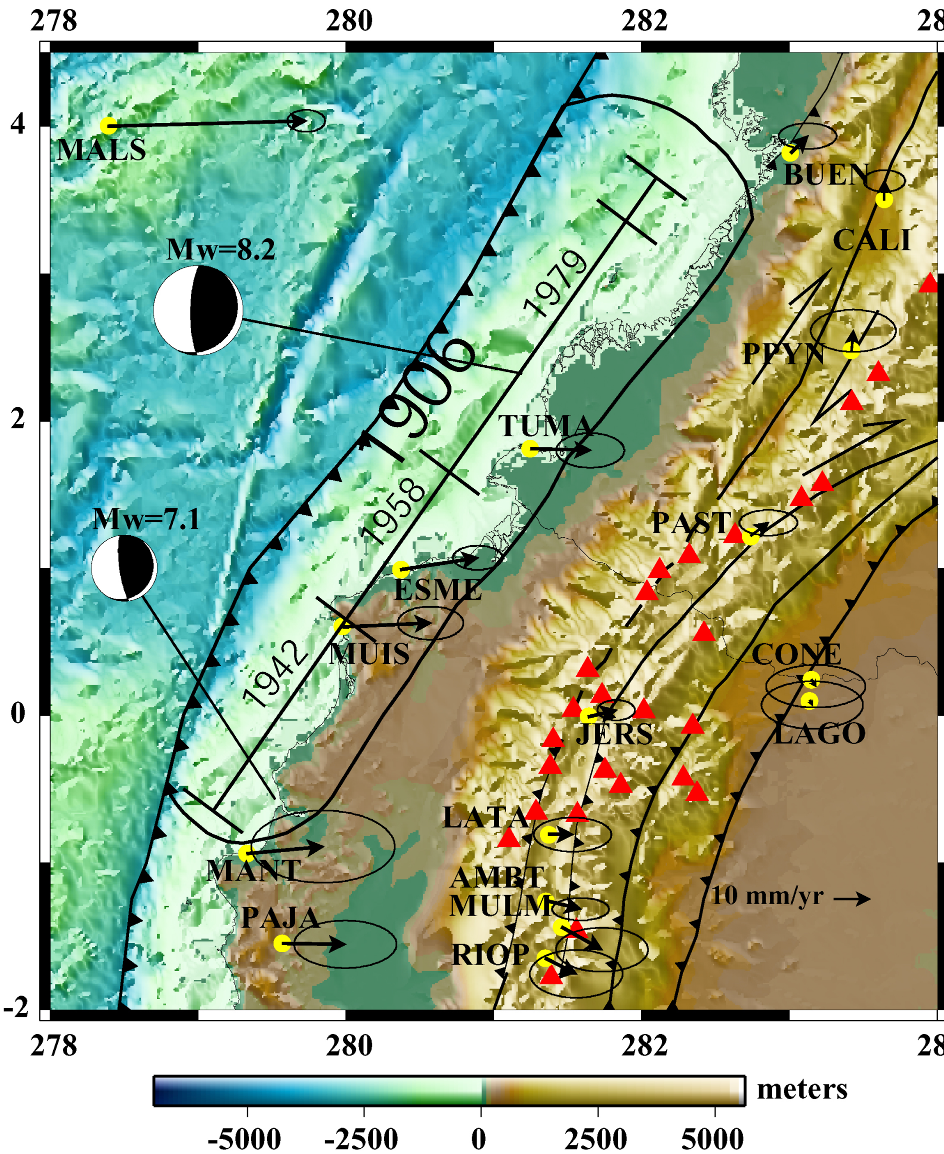

Figure 2. Ruptures of the 1906, 1942, 1958 and 1979 tsunamigenic earthquakes (Pararas-Carayannis, 2012, after Trenkamp et al. 2002)

More recent evaluation of the seismicity of Ecuador and of the potential for recurrence of significant earthquakes, included a review of controlling inter-plate coupling mechanisms, changes in the tectonic regime of the margin, ongoing lithospheric structure deformations, changes in sea-floor relief and on the impact of ongoing subduction or accretion of highly folded, hydrated sediments along the South American continent (Pararas-Carayannis, 2012 a, b, c). Also evaluated were the seismo-dynamics and role in earthquake and tsunami generation, as affected by the Carnegie Ridge's oblique subduction beneath the South American continent and by its resulting buoyancy effects on both sides of the region of interjection and underthrusting that control the magnitudes and tsunami-genesis of earthquakes. Based on this analysis, it was concluded that there was still a lot of tectonic stress remaining in the region both to the north and to the south of the Carnegie Ridge intersection, but principally to the north along the faults of the 1942 and 1955 earthquakes. Also the clustering of aftershocks of the 1979 Tumaco earthquake in Southern Colombia indicated that two major faults offshore from the Esmeraldas/Muisne coastal region in Ecuador had been nucleated and, as previously stated, another major earthquake was very possible along these zones (Pararas-Carayannis, 1980, 2012). Furthermore, the recent analysis concluded that a repeat of the 31 January 1906 event with more than the two fault segments rupturing for about 500-600 km, was also possible, and that such an event could generate a tsunami with very destructive near and far field impacts (Pararas-Carayannis, 2012). What was not considered previously was whether climatic changes and heavy rainfalls in the Andes and in the coastal peninsula – related to the El Niño Southern Oscillation (ENSO) may have contributed to an early triggering of tsunamigenic earthquakes along the Colombia/Ecuador subduction zone.

Fortunately, a great earthquake such as that of the 31 January 1906 did not recur but - as predicted - on 16 April 2016 a 7.8 M_w earthquake ruptured the already strained fault offshore from Muisne in Ecuador, causing great destruction and a local destructive tsunami. This event occurred on the same fault as the one in 1942 (see Fig. 2) where a seismic gap had been identified - with no significant activity for 75 years (Pararas-Carayannis, 2012). However, the epicenter of this event occurred near the northeast end of the 200 km. fault, closer to the city of Muisne. As stated, what was unusual about this quake was that it occurred following prolonged rainfall and flooding of coastal valleys near Guayaquil and Esmeraldas in December 2015, as well as in late January and February 2016. The question was then raised on whether the prevailing anomalous seasonal climatic conditions had some influence in perhaps triggering earlier this and other earthquakes in the region. Thus, using the 16 April 2016 earthquake as a case study, the present paper examines and provides an incipient evaluation of the unusually strong 2015-2016 El Niño's Southern Oscillation (ENSO) and of the quasi-periodic fluctuation and anomalies of sea surface temperature (SST) across the equatorial Pacific, as being the cause for the prolonged rainfall and flooding, not only in Ecuador but elsewhere along the western side of South America. A prolonged drought followed by intense rainfall is very hazardous. This preliminary evaluation postulates that the excessive volume and weight of flood-waters from the prolonged rainfall and flooding of coastal valleys were retained in the coastal crustal layers, thus increasing significantly the weight of the continental coastal crust and triggering an earlier-than-expected rupture of the already-strained fault offshore from Muisne, causing the tsunamigenic earthquake of 16 April 2016. Thus, the present paper reviews and evaluates:

a) The Earthquake and Tsunami of 16th April 2016 in Ecuador, as well as the focal depths and time history of aftershock clusters and whether the quake was a single event or two events in close sequence.
b) The speed of the rupture as well as any bridging of asperities on one or more offshore/onshore zones of the 1942 and 1958 earthquakes.
c) The anomalous distribution of Modified Mercalli intensities of the 16 April 2016 earthquake.
d) A 4.8 quake which may or may not be characterized as a foreshock associated with the major event(s) of 16 in April quake(s) because of its large separation in the spatial/time distribution and the initiation point of rupture(s).
e) Satellite measurements which may be indicative of changes of crustal movements along the known tectonic boundaries.

Another study under preparation will examine in detail the seasonality of recent tsunamigenic and non-tsunamigenic earthquakes in Ecuador and elsewhere in South America, in relation to strong El Niño Southern Oscillations and documented SST Anomalies - that may be causing them. The forthcoming study will also examine selectively the possible correlation of the El Niño Southern Oscillations in Ecuador and elsewhere, with climatic changes induced by the global impact of volcanic explosions and of other terrestrial and extraterrestrial events, as to what impact they may have on the geostrophic circulation of oceanic currents in both in the North and South Pacific, as well as on similar circulation in the Atlantic Ocean - perhaps associated with the observed cycles of Atlantic Multidecadal Oscillations (AMO's) of small surface water temperatures, which may also result in nucleating periodic clusters of sequential hurricanes.

1. TSUNAMIGENIC AND NO-TSUNAMIGENIC EARTHQUAKE PRECURSORY PHENOMENA

There is not a single geophysical instrument that can measure any direct parameter of an earthquake and give a warning in advance. It is only secondary precursor parameters that are being monitored - which are primarily byproducts of the subsurface tectonic stress. Magnetic field changes, strain, tilt, subsidence, and bulging of the earth's surface, are being studied as primary precursors. For example, "dilatancy" (granular volume change due to shear deformation (Reynolds, 1886; Pararas-Carayannis, 2000)) occurs when the rocks on a fault are stressed and the ground "dilates" or swells. Symmetric tilting of the ground can be expected in a uniform pattern away from the potential earthquake epicenter. Asymmetric tilting of the ground around the earthquake source area can occur also from no uniform stresses on the rocks, which eventually will result in strike-slip type of faulting when the earthquake finally occurs (Pararas-Carayannis, 2000). Micro fracturing prior to an earthquake is responsible for some of the precursor events, which are thought to result from the preliminary stages of failure of the subsurface rocks preceding a major earthquake. A few of the precursory phenomena may be indicative of imminent rock failure, while others may be longer-term manifestations of such failure.

There are many other precursor phenomena observed prior to an earthquake. Several of the short-term, physical and geochemical precursors of earthquakes that can be measured with instruments, include: a) Increase in the rate of a seismic creep and the slow movement along the fault; b) Unusual straining and gradual tilting of the ground near the fault zone; c) Drop or rise in the water level within wells; d) Increase of hydrogen gas in the soil; e) Release of radioactive radon gas from wells; f) Decrease in the number of micro quakes and foreshocks; g) Lessening of electrical resistance in the rocks; h) Flashes and other lights in the sky; i) Appearance of a ring-like pattern of micro quakes surrounding the epicenter of a future quake, called "Mogi's donut", and many other physical and chemical manifestations (Pararas-Carayannis, 2000).

As stated, most of the precursor phenomena are believed to be caused by imminent or longer-term manifestations of subsurface rock failure before a major earthquake occurs. When crustal blocks are stressed along a fault - by tectonic plate interaction - the rocks begin to break and crack at some depth below the fault area, thus losing their strength. This initial stage of rock failure is a mechanical process. Part of this mechanical energy is stored in the fault-rock as potential energy, while the rest becomes either thermal, chemical, or electrical energy. In turn, these forms of energy may result in all sorts of accompanying, chemical/physical effects and manifestations - precursory phenomena that may be measurable and indicative of an impending earthquake (Pararas-Carayannis, 2000). The initial stage of rock failure may also change the pressure/temperature phase relationship or release of gases. Methane hydrate may generate methane, which may catch fire on the surface of the earth before or during an earthquake. Such extensive fires occurred during the 1945 Makran earthquake in the North Arabian Sea (Pararas-Carayannis, 2006). Underground water may fill in the cracks of the failing rocks and change their electrical resistance. Such chemical and physical changes may continue as failing rocks contract and crack further by the constant, tectonically-induced strain. Rise in the temperature of the water often results from such crust alterations (Pararas-Carayannis, 2000).

1a. Terrestrial and Extraterrestrial Factors of Climate Change, Global Warming and Precursory Phenomena Affecting Major Oceanic Currents' Circulation and Temperature Anomalies

The sun is the primary source of energy that affects climate. During long periods of geologic time, the Earth's climate has been an unstable dynamic system that has undergone short and long term cycles of change - heating up or cooling down - with corresponding rises and falls in sea level. Important natural drivers of climatic change include both astronomical and terrestrial factors. Since climate change on Earth is a dynamic process affected by such factors, the impact of the Greenhouse Effect has also varied during long periods of geologic time. The effect of global warming on weather patterns is frequently blamed for an apparent increase in weather-related disasters. Continuing global warming can be expected to contribute significantly to future disasters (Pararas-Carayannis, 2003, 2004 a, b, c). Also, it is very possible that climatic disasters can collaterally influence local tectonic conditions of crustal isostacy and buoyancy near stressed fault zones, and thus influence the triggering of earthquakes. The present study presents a cursory review of such phenomena, focusing primarily on recent quakes in Ecuador, Colombia and Peru.

1b. Triggering of SSTA and ENSO Anomalies

For triggering mechanisms of precursory phenomena associated with earthquakes (tsunamigenic or not) we must also consider not only the chemical/physical effects and manifestations of crustal failures along seismically active regions, but also larger scale phenomena that may have an impact. Specifically, we must also examine the possible correlation of the El Niño Southern Oscillations in Ecuador and elsewhere, with other climatic changes induced by the global impact of volcanic explosions or by other terrestrial or extraterrestrial events. For example, we know that some of these phenomena, such as solar storms, changes of incoming solar radiation, holes in the ozone layer, migrating hot spots in the earth's mantle and many other seemingly unrelated causes, may have an effect on the ocean temperatures and on the geostrophic circulation of oceanic currents in both the North and South Pacific, as well as on similar geostrophic circulation of ocean currents in the Atlantic and other of the world's oceans and seas. These are also associated with the observed Atlantic Multidecadal Oscillations (AMO's) (Schlesinger, 1994) - small changes of surface water temperatures (SST) in the Northern Atlantic influenced by both natural and anthropogenic factors - which also result in climate cycles and the nucleation of periodic clusters of severe historical hurricanes (Pararas-Carayannis, 1975).

In relation to strong ENSO and documented SST Anomalies in the Pacific - as well as to the differently proposed mechanisms that may cause them along the coasts of Ecuador and elsewhere, we may also need to examine climatic changes induced by the global impact of volcanic explosions, in causing nuclear winters or small changes in oceanic surface water temperatures which interact with atmospheric air masses - conditions which may be also responsible for the observed periodic clusters of storm systems generated near the earth's oceanic equatorial zones.

1c. The Strong 2015-2016 El Niño-Southern Oscillation (ENSO) in South America

As earlier mentioned, a reversal in atmospheric circulation known as the Southern Oscillation (ENSO) is a periodic phenomenon which may be caused by a variety of influences on the geostrophic flow of major equatorial ocean currents in the Pacific (See Fig. 3). When an El Niño occurs, the entire equatorial and atmospheric circulation pattern reverses. Currents and winds reverse and bring warm water and air from the western Pacific to the Galapagos and the coastal regions of South America. In the Southern hemisphere of the Pacific, the Peru or Humbolt Current carries an enormous volume of cold water northward from the Antarctic region, thus keeping the western coast of South America temperate and dry. As it passes northern Peru, the Humbolt current continues in a counterclockwise direction and joins the Equatorial Current which flows westward across the Pacific, thus causing upwelling of cooler water near Peru, Ecuador and the Galapagos region. However, small changes in the temperature of surface waters near the equator result in strong El Niño-Southern Oscillations (ENSO's) and have a significant climatic effect on South America and possibly on the overall earth's weather.

A similar oceanic flow of currents occurs in the northerns hemisphere of the Pacific where the Kuroshio current turns in a clockwise direction into the North Pacific current then joins the California current, which warms and moderates California's climate. Both the Humbolt and the California currents are parts of such large gyres - known as geostrophic currents - as they relate to the earth's rotation, the Coriolis force and the varying spherical angular velocities of the earth at different latitudes. The circulation of ocean currents is also affected by strong winds and the resulting Ekman Spiral flow of surface waters forces up cooler, nutrient rich water to the surface (Pararas-Carayannis, 1991). Similar current systems operate in the Atlantic, the Indian Oceans - although the currents in the Indian Ocean are complicated by the seasonal monsoons.

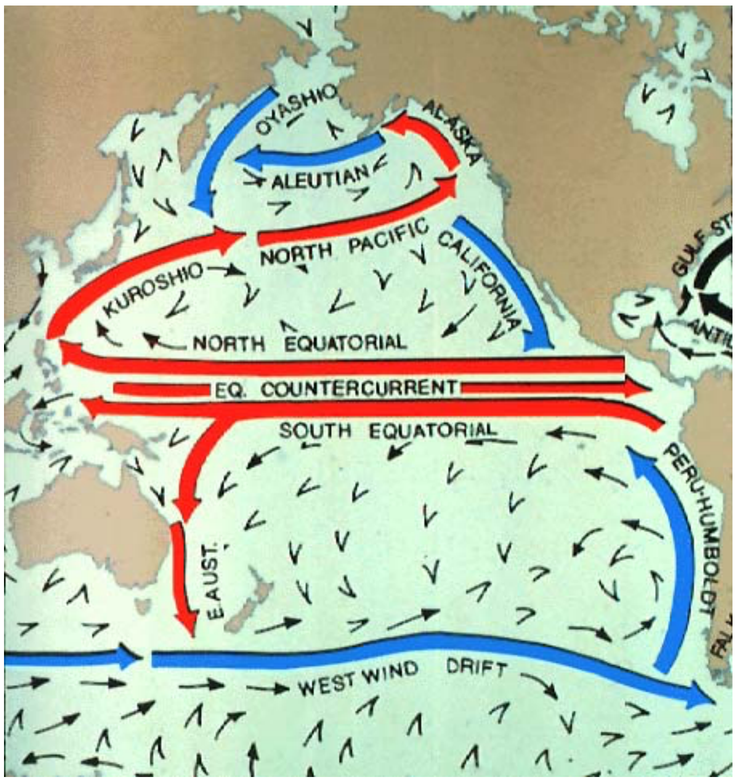

Fig. 3. Geostrophic currents in the North and South Pacific.

In brief, the temperatures of surface oceanic water masses near the equator in the Pacific generally fluctuate between a warmer than normal state along the central and eastern equatorial Pacific (El Niño) and the second state which is cooler than normal on the central and eastern equatorial Pacific (characterized as La Niña). Fig. 4 shows the monthly sea surface temperature in the Niño 3.4 region of the tropical Pacific compared to the long-term average for all moderate-to-strong El Niño years since 1950, and how the 2015/16 (black line) compared.

1d. Severe El Niño events since 1950

As shown in Fig. 4 below, a particularly severe El Niño occurred in 1982-1983. Another severe El Niño occurred in 1997-1998 and it was one of the strongest events of the 20th century. Indonesia and Australia suffered drought and wildfires while western North and South America suffered from floods and heavy snows. In the Galapagos there were heavy rains between March and June of 1997, and again in the wet season of 1998. Sea and air temperatures were 4 to 5° C above normal. The event had an adverse impact on marine life, since upwelling and hence ocean nutrient levels, were significantly reduced.

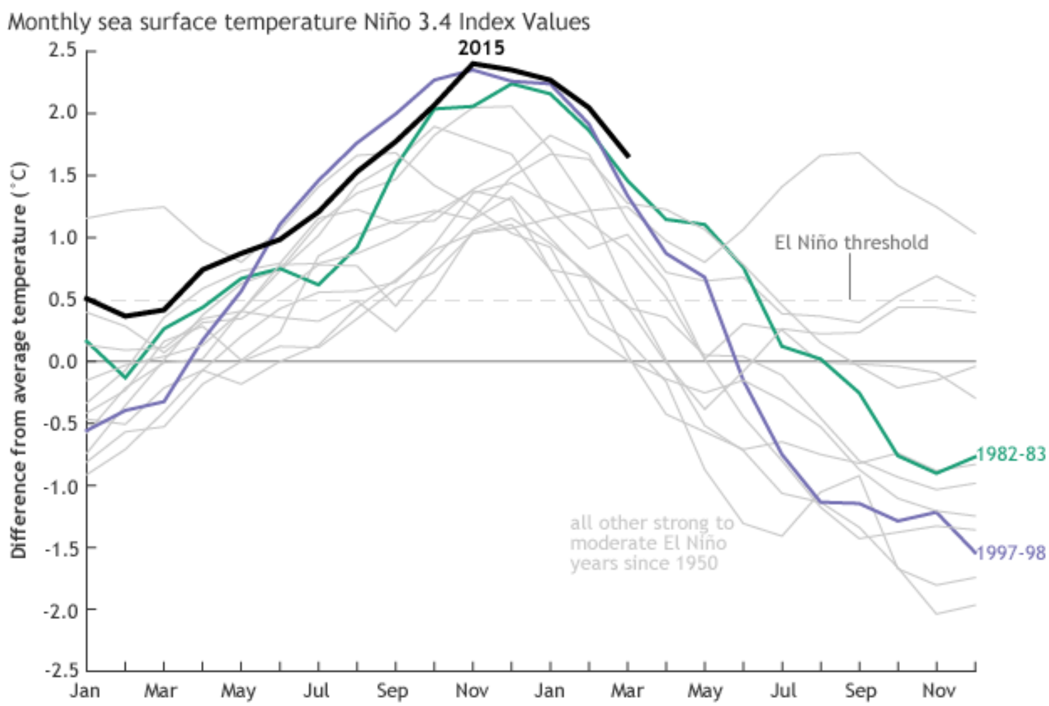

Fig. 4. Monthly sea surface temperature in the Niño 3.4 region of the tropical Pacific compared to the long-term average for all moderate-to-strong El Niño years since 1950, showing how 2015/16 (black line) compares to other strong previous events. (Climate.gov graph based on ERSSTv4 temperature)

1e. SST Anomalies in January 2016

In January 2016, the strong El Niño Southern Oscillation phenomenon appeared to be weakening, indicating a trend towards neutral conditions for the May – June 2016 period. However, a sea surface temperature anomaly was observed and associated with the 2015-2016 El Niño in the Pacific. Fig. 5 shows the SST Anomalies on 6 January 2016. Extreme SST anomalies (up to 3 degrees C.) were recorded in the central Pacific, with values higher than the records for the El Niño 1982-1983 and the 1997-1998 seasons.

However, in March of 2016, the U.S. National Oceanic and Atmospheric Administration (NOAA) issued a report on the El Niño's Southern Oscillation (ENSO), based on the sea surface temperature (SST) anomalies across the equatorial Pacific – noting a decrease since January. Nevertheless, NOAA indicated that during the decreasing phase of ENSO, significant prolonged rainfall and flood events could still occur – as indeed it happened in Ecuador as well as in Peru, Bolivia and elsewhere. As indicated, the overall conclusion was that the strong 2015-2016 El Niño Southern Oscillation phenomenon was weakening and the NOAA models indicated a transition to neutral conditions for the May – June 2016 period. More specifically, the NOAA model (Fig. 6) shows the Average SST anomalies for the period 21 February to 19 March 2016 prior to the 16 April 2016 Ecuador Earthquake.

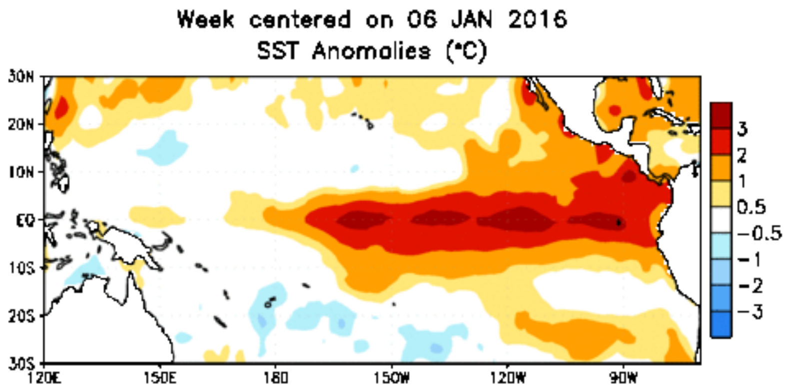

Fig. 5. 6 January 2016 SST Anomalies (NOAA graphic).

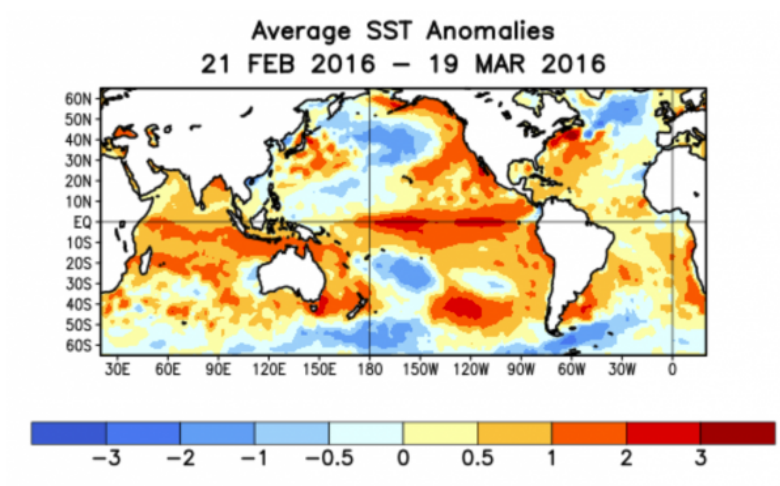

Fig. 6. Average SST Anomalies 21 February to 19 March 2016 prior to the 16 April 2016 Ecuador Earthquake (NOAA graphic).

1f. Heavy Rainfall in January 2016 in Ecuador and in South America

Indeed, and as predicted, significant prolonged rainfall and flood events resulted in Ecuador and elsewhere in South America (Fig. 7). Extensive flooding and landslides after torrential rainfall in late January 2016 occurred in Guayaquil (Fig 9) and elsewhere in Ecuador, Peru and even in Bolivia, Brazil and Argentina. Heavy rains between 19 and 20 January 2016 in Ecuador caused severe flooding in the provinces of Manabi and Guayas. The cities of Chone and Portoviejo were some of the worst affected in Manabí. In Guayaquil, there was extensive flood damage to houses and roads. In the Muisne Province, the Esmeraldas rain station recorded 244.5 mm of rainfall in 24 hours, while in Muisne (50 km to the west) the rain station recorded 88.5 mm (Source: INAMHI).

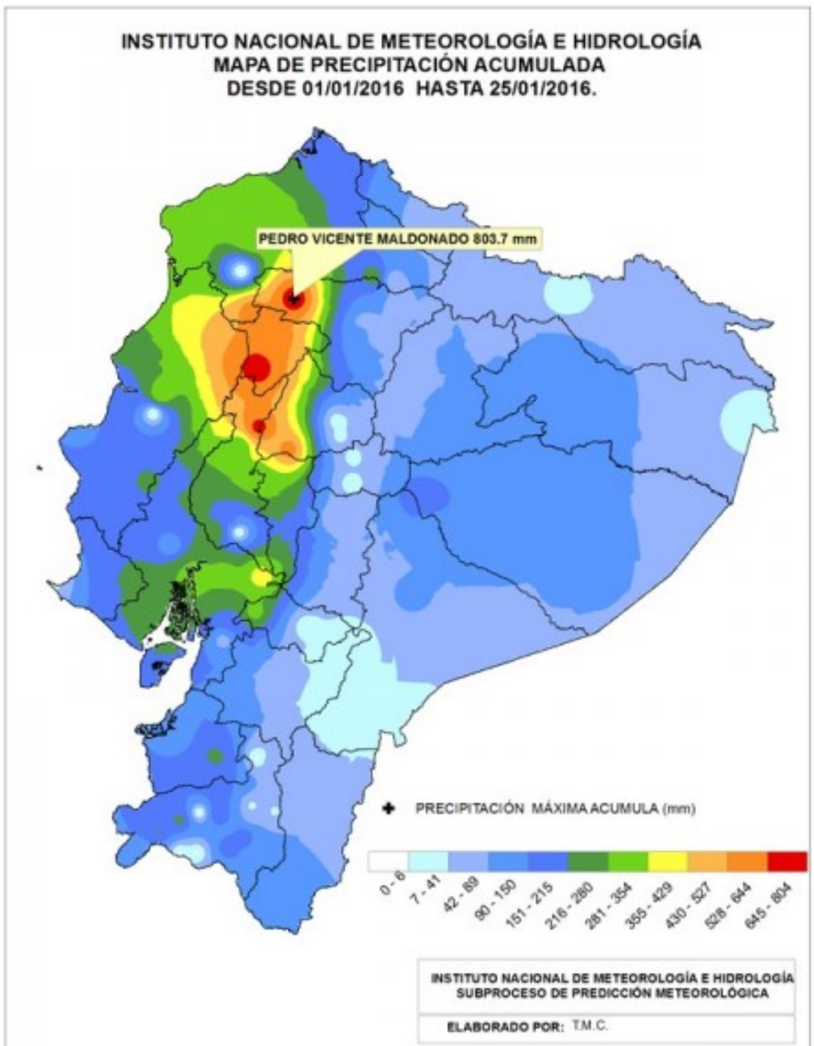

Fig. 7. Rainfall for January 2016 in Ecuador. (Image: INAMHI)

As shown in Figure 8, the rainfall was heavy at 22:00 on 24 January 2016, intensified at around 23:00 and lasted through the night, causing severe flooding by 24:00 early on 25 January and many landslides. The heavy flooding caused a state of emergency for the region and particularly for the city of Esmeraldas (Fig. 9)(Secretaría de Gestión de Riesgo – SGR).

Fig. 8. Rainfall, Esmeraldas, Ecuador, 22:00 on 24 January 2016 (Japanese Aerospace Agency)

Fig. 9. Floods in Esmeraldas. (Photo: Municipio Esmeraldas)

1g. El Niño-Southern Oscillations (ENSO's) impact on the frequency of earthquakes.

Whether El Niño-Southern Oscillations (ENSO's) have an impact on the frequency of earthquakes in South America remains to be investigated. As shown in Fig. 10 below, the strong 2015-2016 ENSO was accompanied by a large number of earthquakes of intensities with Richter magnitudes of 5.0 or greater since 1/1/2016 in Ecuador, Colombia and Peru.

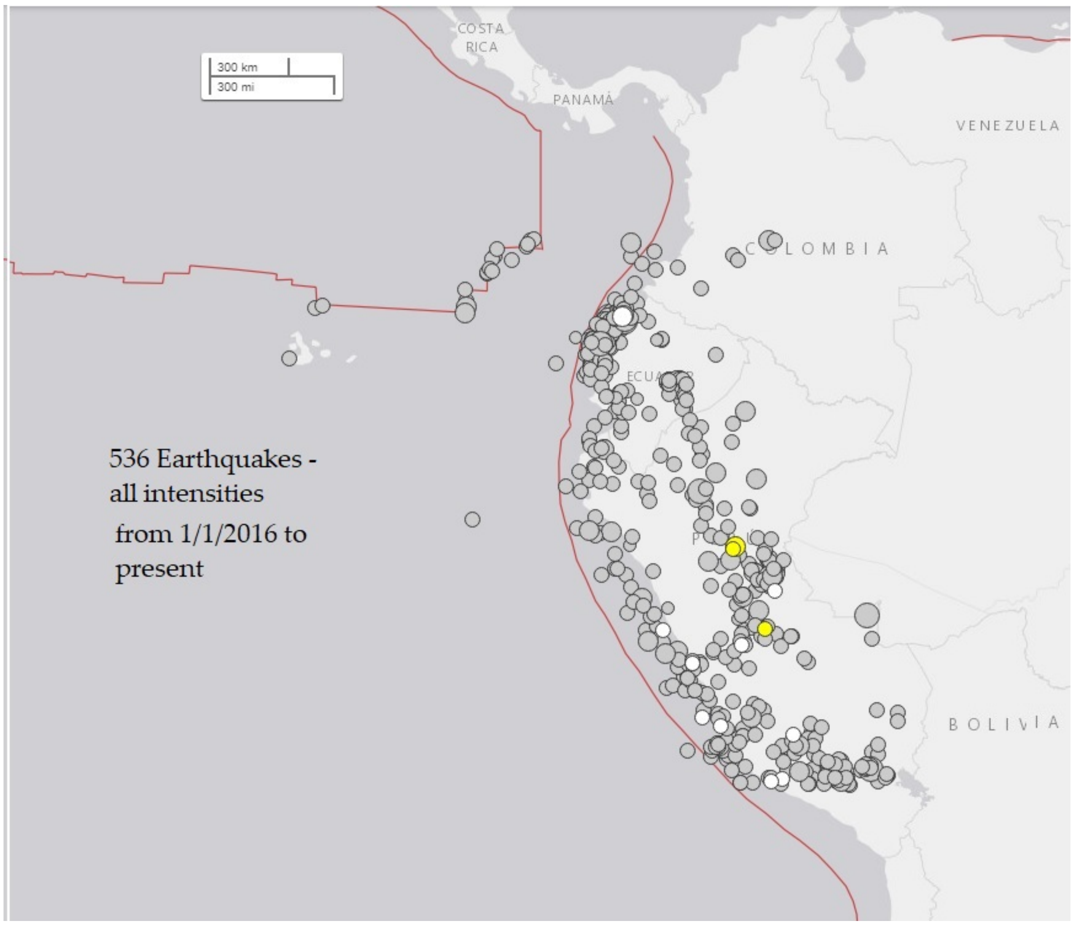

Fig. 10. Earthquakes with Richter magnitudes of 5.0 or greater since 1/1/2016 in Ecuador, Colombia and Peru.

It remains to be examined whether some of the large historical earthquakes (Fig. 10) along the west coast of South America (Colombia, Ecuador and Peru) since 1906, with the exception of a Richter 8.0 event in 1970 - occurred during periods of strong El Niño-Southern Oscillations (ENSO's)

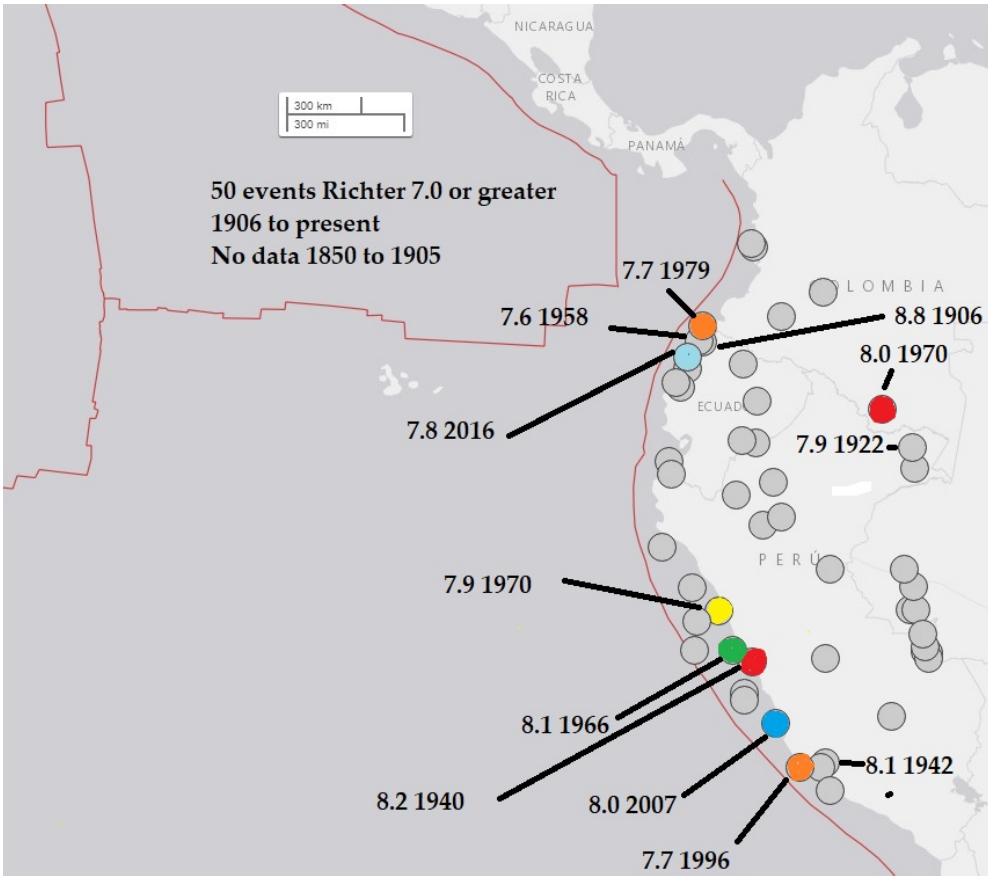

Fig. 11. Epicenters and Magnitudes of Fifty Richter 7.0 or greater, historic earthquakes most along the west coast of South America (Colombia, Ecuador and Peru) since 1906 – with the exception of a Richter 8.0 event event in 1970. No data exists for the period of 1850 to 1905.

2. ECUADOR EARTHQUAKE AND TSUNAMI OF 16 APRIL 2016

The floods, landslides and the destruction in Ecuador were followed by a major tsunamigenic earthquake on 17 April 2016 (local date). According to Ecuadorian government reports, more than 650 people were killed and there was widespread destruction. The town of Portoviejo, close to the epicenter, was devastated. The quake generated a locally damaging tsunami. Fig. 12 shows the epicenter of this tsunamigenic earthquake, as well as the epicenters, dates and magnitudes of significant historic earthquakes since 1906 in the region (as in Fig. 2)(Swenson & Beck, 1996). Fig. 13 shows the epicenter of the 2016 earthquake (blue circle) in relation to other recent significant historical earthquakes in Ecuador and Colombia.

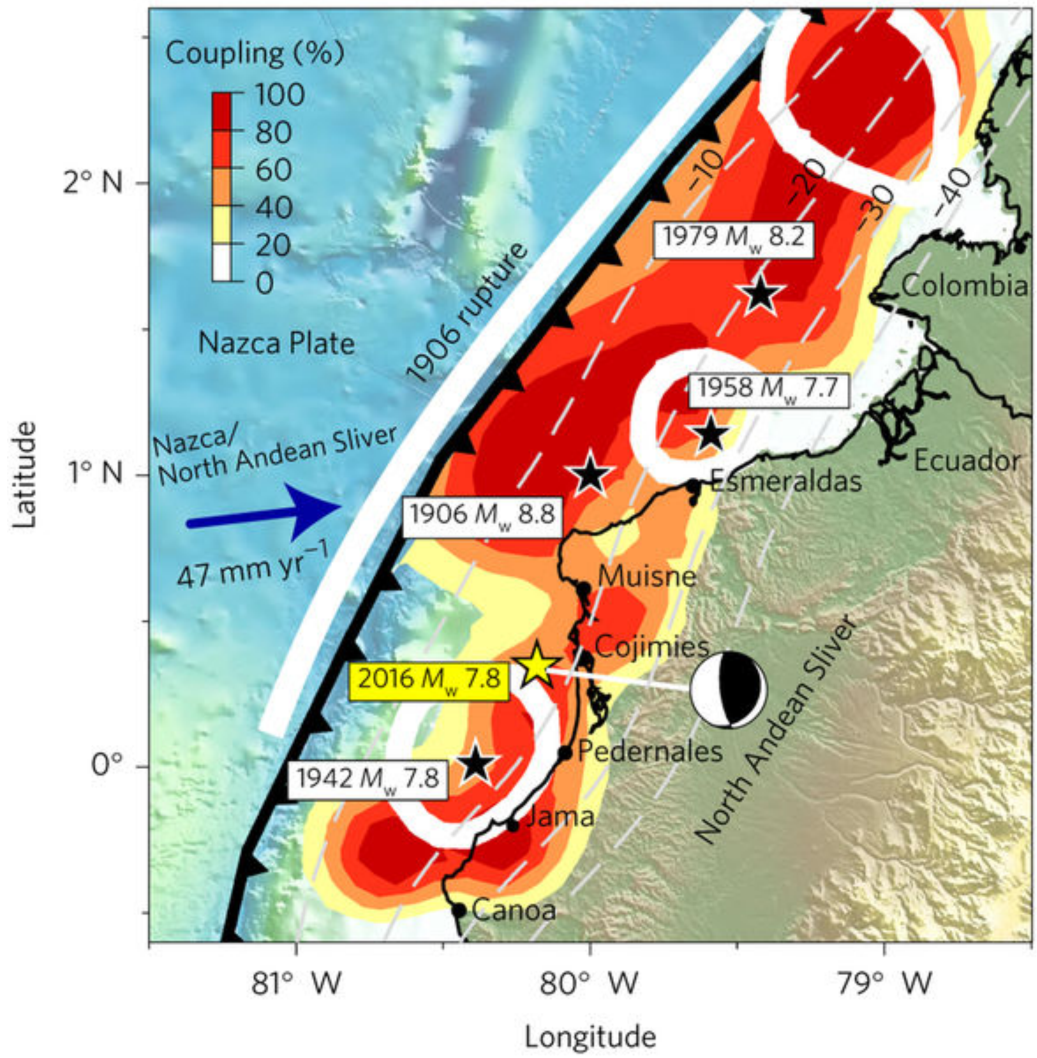

Fig. 12. Epicenter and mechanism of the 17 April 2016 earthquake and of other major historical tsunamigenic earthquakes in Northern Ecuador and Southern Colombia since the great 1906 earthquake (Internet graphic after Gabriel Lotto, 2016).

As established and reported, the 7.8 M_w magnitude earthquake of 17 April 2016 in Ecuador (local date) (2016-04-16T23:58:36.980Z) had its epicenter at 0.3819 N. and –79.9218 W., about 29 km SSE of the city of Muisne in the Esmeraldas Province, but somewhat NE of the epicenter of the 1942 quake which also had a magnitude (M_w7.8 revised) and apparently involved the same offshore fault. The focal depth of the quake was estimated at 20.59 km (about 12 miles). The 2016 quake had many similarities with the 1942 event.

Based on recent evaluations of Ecuador's seismicity, this earthquake was not a surprise. Since 2013 a major event was expected to occur in the region, given the fact that the Ecuador–Colombia plate boundary is being obliquely underthrust by the Nazca plate at the rate of ~ 4.6 cm/yr, with the upper plate being a fragment of the South American plate known as the North Andean Sliver (Nocquet et al., 2014; Chlieh et al., 2014). The Nazca tectonic plate moves slightly eastwards at a varying rate which ranges from 80 mm/yr in the south to about 65 mm/yr in the north (Pararas-Carayannis, 2012). Although of large magnitude, the 2016 earthquake was not as large as it could have been if its rupture extended beyond the existing 1942 fault asperity and included all or part of the rupture of the 1958 quake (M_w 7.7), or that of the catastrophic 1906 quake (M_w 8.8). Furthermore the 2016 quake may not have been a single event as reported. As postulated in this evaluation - its impact may have been somewhat ameliorated by the 2015 – 2016 El Niño climatic conditions that preceeded it. However, what was also perplexing about this event was the clustering of its aftershocks and their spatial distribution, as well as the possible contributing triggering mechanism, following the strong 2015-16 El Nino period - associated specifically with heavy rainfalls in the Andes and extensive flooding of Ecuador's coastal peninsula.

An extensive and detailed survey of the earthquake was conducted by scientists in Ecuador and their report is included in this issue of the journal (Chunga et. al. 2016; Toulkeridis et. al., 2017 a, b). The report reviews the literature on the country's geodynamic setting and seismogenic origin, the volcanism of the region, the geologic setting of the earthquake's epicentral area and a statistical evaluation and geophysical clustering of the main earthquake and of the aftershocks. Thus - and to avoid redundancy - the present section of this study mainly avoids reporting on details of the social and economic impact this earthquake had in Ecuador and concnctrates only on non-reported anomalies and further analytical evaluation of this event.

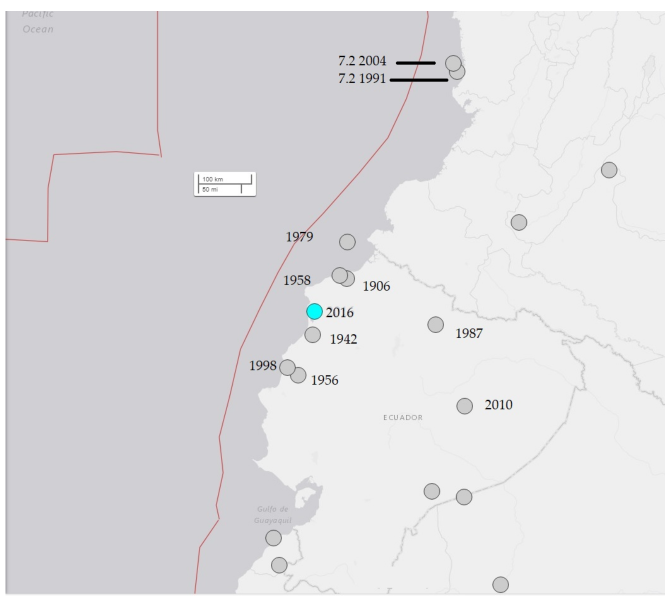

Fig. 13. Epicenter of the 2016 earthquake (blue circle) in relation to Recent Significant Historical Earthquakes in Ecuador and Colombia.

2a. Crustal Mechanism

The mechanism and location of the 2016 earthquake was consistent with a subduction type of seismic events that occur along the Colombia/Ecuador Trench but also with the coastal structure of the continental margin of southern Ecuador and northwest Peru (Shepperd, G.L. and Moberly, R., 1981). According to the post-disaster survey of the earthquake, the crustal displacements involved an area which was approximately 160 km long and 60 km wide (Toulkeridis et. al., 2017 c). The main quake was followed for weeks by numerous aftershocks – some of which appeared to have an anomalous spatial distribution.

2b. Rupture of the 16 April 2016 Earthquake in Ecuador.

The M_w 7.8 earthquake of 16 April 2016 ruptured along the zone where the Nazca plate interfaces with the South America. As illustrated in Fig. 12 and as previously stated, it occurred along the same fault where a similar M_w 7.8 earthquake occurred in 1942, a region where a seimic gap had been identified. It was along a part of the segmented zone which the great tsunamigenic earthquake of 1906 had ruptured in much greater length. This is a tectonic interface belt, north of the Carnegie Ridge intersection with the South America continent - a zone characterized by variable rupture modes, heavy sedimentation and tranversed by transform faults, which have formed mechanical barriers (asperities), thus preventing a continuous rupture similar to that caused by the great 1906 earthquake (Ruff & Kanamori, 1980; Kanamori & McNally, 1982; Beck & Ruff, 1984; Pararas-Carayannis 1980, 2012; Ye et. al., 2016). This heavy sedimentation along this zone is attributed to the heavy erosion caused by heavy rainfalls on the western slope of the Andes. Large amounts of sediments of heterogeneous density structure are deposited on Ecuador's coastal plains and subsequently find their way to the offshore areas and to the trench's fore-arc zone. The heterogeneous density structure of the decoupled Ecuador fore-arc could explain the propagation of the rupture zone of the April 2016 Ecuador earthquake. In particular, this rupture zone developed through a relatively low-density zone of the fore-arc sliver. Seismic and tsunami observations indicated a rupture of about 120 km length, north of the 1998 earthquake's rupture (Ye, et. al., 2016) and overlapping with that of the 1942 earthquake.

Something similar occurred with the 2 September 1992 tsunamigenic earthquake in Nicaragua near the Middle America Trench along the intra-oceanic convergent margins of the Cocos and Caribbean plates - a zone of active, oblique, shallow subduction. Also, Nazca Ridge's oblique subduction and migration along central and southern Peru had a similar effect on generating the tsunami of 23 June 2001 (Pararas-Carayannis, 2001 b). The quantity and thickness of subducted sediments along certain sections of such margins alter the seismic focal mechanisms and the geometry and velocity of ruptures. Certain large earthquakes, along such zones, can be expected to be "slow" - that is to have lower rupture velocities and to generate seismic waves of longer periods. The greater tsunamigenic potential of such earthquakes - along such zones of oblique shallow subduction - is not only the result of greater energy release but of the contribution of subducted sediments to the geometry of ocean floor deformation and volumes of displacements (Pararas-Carayannis, G. 1992; 2014).

2c. Unusual Clustering of Aftershoks

'The 2016 earthquake was also unusual in that it involved separate clusters of aftershocks from April to July 2016, with peculiar distribution over a great areal distance and widely separated in time, which indicated that this was not just the Mw 7.8 event with some aftershocks. (see Fig. 14 below). The unusual clustering was also discussed in the report by Toulkeridis et al. (2017).

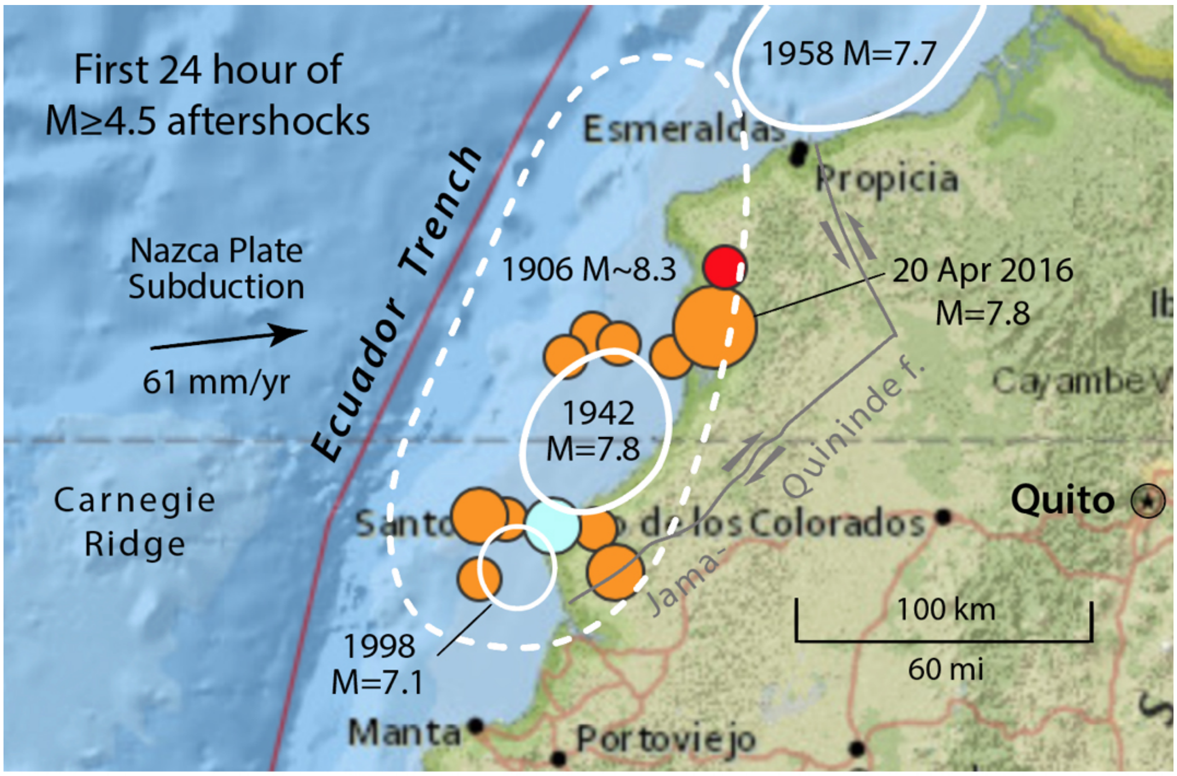

Fig. 14. Epicenters of Historic Earthquakes and Unusual Clustering of Major Aftershocks of the 1906 and 1942 earthquakes.

Figure 15 is a time series chart of major 25 aftershocks with Richter magnitudes 5.0 or greater to 8/1/2017 (marked as present in the figure) which followed the 16 April, 2016, quake (focal depth 20.6km) 27 km SSE of Muisne Ecuador (note the two separate clusters). Figure 16 shows three additional aftershoks until 28 November 2017. What was unusual about the three afterhocks of Richter 5s magnitudes is that they occurred close in time and space near the largest and most economically important city of Ecuador, particularly since the only other Richter 5 or greater in that time was a 5.2 magnitude far inland aftershock on October 7, 2017 represented by the gray dot in Figure 16. Actually, this October 5.2 event was part of a cluster of four including a 4.9 magnitude event which occurred on 9 October 2017.

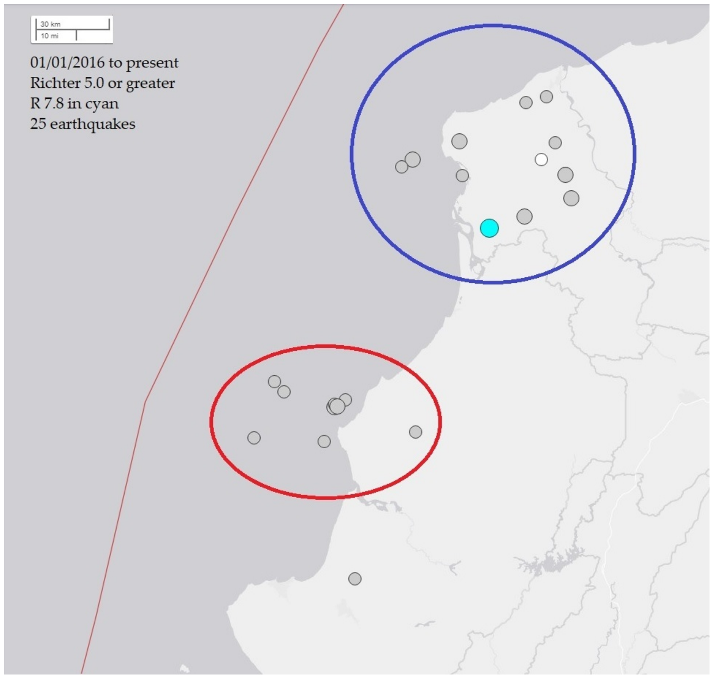

Fig. 15. Twenty-five major aftershocks of Richter magnitudes 5.0 or greater to 8/1/2017 (marked as "present") following the 16 April, 2016 quake (note the two separate clusters)(Source: USGS).

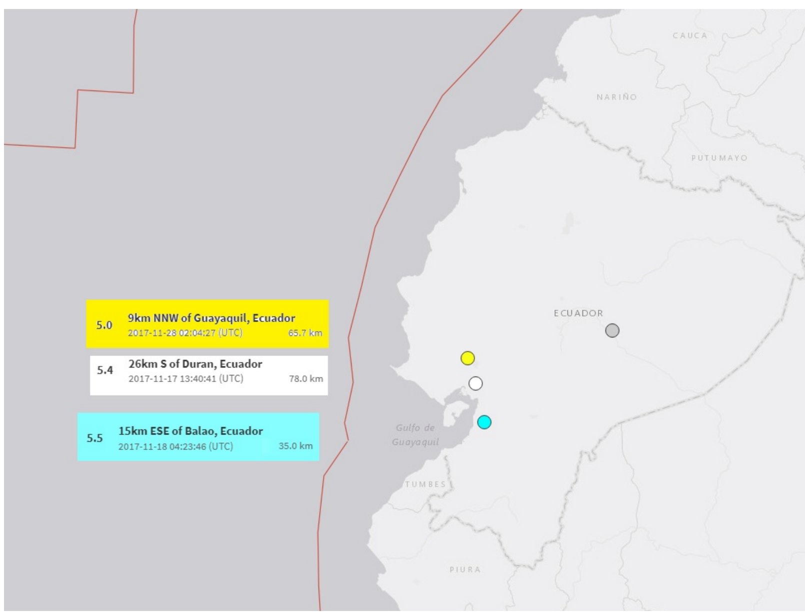

Figure 16. Three additional aftershocks until 28 November 2017.

As indicated in Figure 17 below, the leftmost (earliest) event marked by a green arrow was pretty far apart in time so it is difficult to say that it was a precursor event without conducting a new fault analysis. Then with essentially no warning, a 6.2 (red arrow) event occurred and subsequent aftershocks started declining in a classical pattern. Then a surprising 6.0 occurred which looks like a separate cluster – with its aftershocks also declining in the expected way. The three events to the right of the orange arrow might be a separate cluster. Then all is quiet for a while giving the impression that all stress on the fault has diminished, when all of a sudden a magnitude 7.0 (purple arrow) occurs that is just way out of pattern. The subsequent sequence of the aftershocks (black arrows) are also out of expected normal pattern.

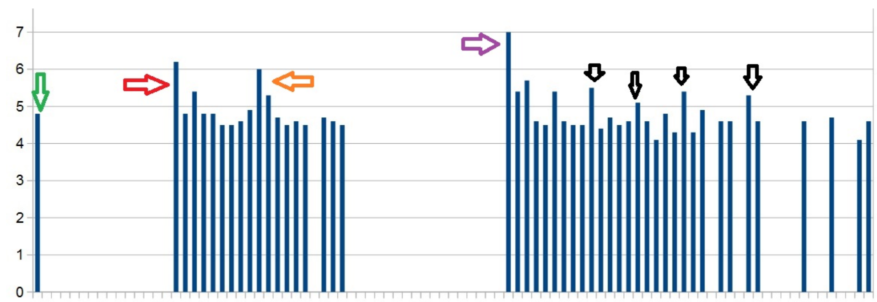

Fig. 17. Clustering of major aftershocks of the Ecuador Earthquake from April 16-23.

Figure 18 shows quake clusters from April 16-23, 2016, clusters on May 18 and clusters from July 8-11, 2016. As shown, two large events occurred on May 18, 2016. The clusters depend a bit on the size of the region involved as well the intensity of the earthquakes. For a large region with all earthquakes you would get the six clusters. A statistical argument can be made for breaking the blue cluster into 2 pieces and for breaking the orange cluster into three pieces as shown. Overall, the aftershock sequence and the subsequent clusters appear to have nucleated around the area of maximum slips in the rupture zone, and that suggests that asperities can be persistent features which can be determined by the spatial variations of the mechanical properties of the subduction megathrust zone. This observation implies that the heterogeneous density structure of the fore-arc can be determined from gravity data - whch could be used to forecast zones of future potential damage.

Fig. 18. Unusual occurrence of two more quakes on May 18 and more significant aftershocks from July 8-11, 2016.

2d. Distribution of Earthquake Intensities

Post-disaster evaluation indicated a large areal distribution of ground effects and intensities of the 2016 earthquake (Chunga et. al. 2016). Fig. 19 below shows the extensive and unusual distribution of the earthquake's high intesities and destruction.

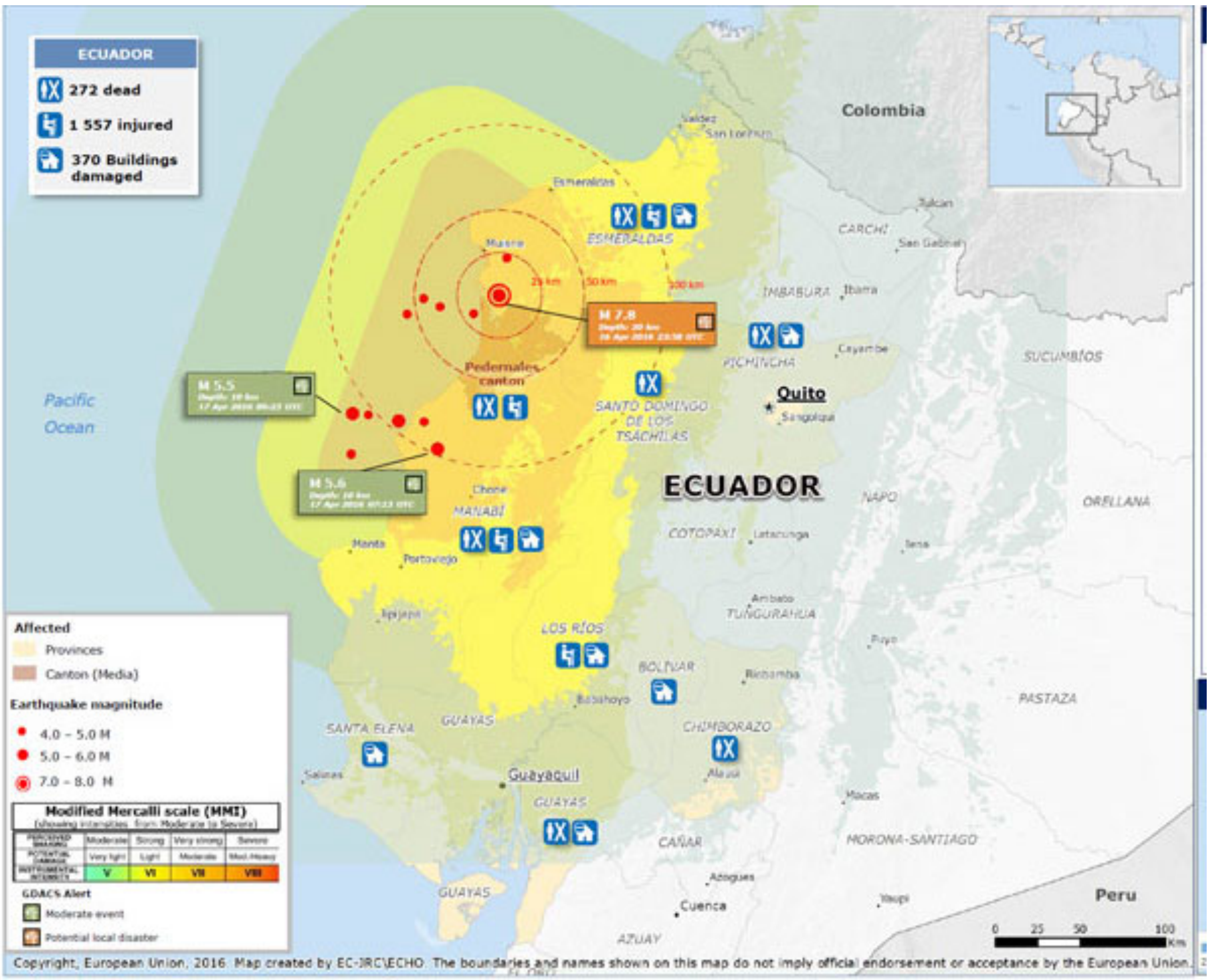

Figure 19. Unusual distribution of the earthquake's high Modified Mercalli intesities and destruction.

2e. The Tsunami

Based on data from the INOCAR-DATA buoy, INOCAR issued a Tsunami Warning for coastal areas of Ecuador and the Galapagos Islands. The warning lasted for four hours. According to eyewitnesses, there were significant changes in the level of the sea but not an extreme runup – because the tsunami ocurred at low tide. A much higher runup and damage would have occurred if the quake had occurred at high tide. As shown in Fig. 20 below, the INOCAR tide gauge at the Port of Esmeraldas begun recording a recession of sea water level at 19:00 and within a short period of about three minutes the arrival of the tsunami crest with subsequent fluctuations of about ~50 cm/min (Toulkeridis et al., 2017). Note that the crest of the first wave of the tsunami arrived 6 minutes after the quake. The tsunami resulted in lasting currents within the port of Esmeraldas which were strong enough to displace some small boats and buoys from their anchorage sites.

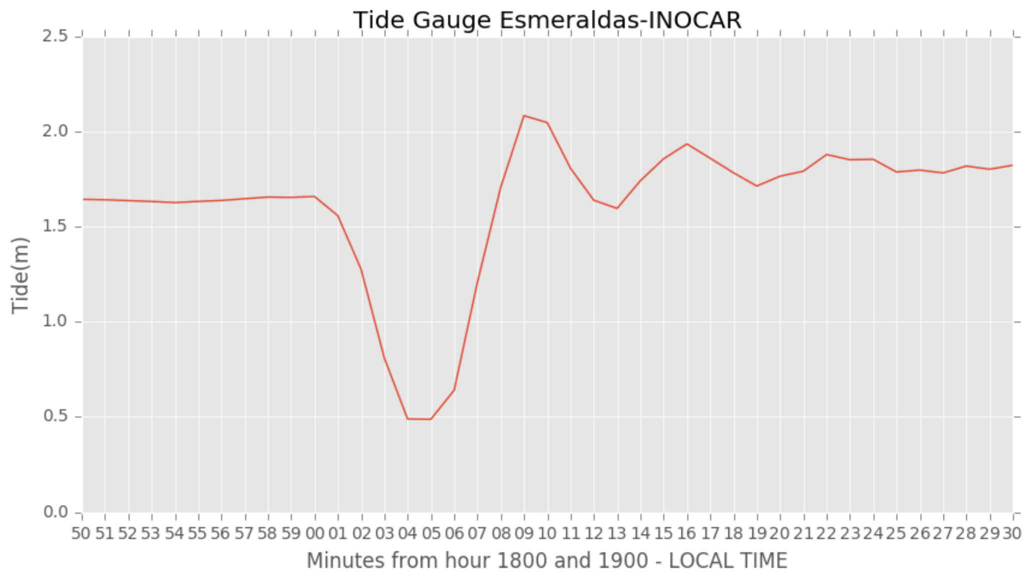

Fig. 20. Mareogram of the Tsunami Recorded at the Port of Esmeraldas tide station. (Toulkeridis et al., 2017; Source: INOCAR)

3. SEASONALITY OF HISTORICAL EARTHQUAKES ALONG THE ECUADOR TRENCH AND THE WEST COAST OF SOUTH AMERICA.

As previously mentioned, Ecuador is very vulnerable to earthquakes. Although infrequent, large earthquakes as that of 1906 can occur from time to time along the subduction zone of Colombia/Ecuador and generate destructive Pacific-wide tsunamis. The historic record shows that large earthquakes in the region are often preceded by increasing activity of smaller events. The morphology of the offshore region is further complicated by the extensive sedimentation which takes place as a result of erosion of the Andes mountain ranges and the numerous rivers flowing into the sea. A very thick sedimentatry column enters the subduction zone, so part of the trench associated with the present accretionary front in the offshore region of Ecuador has been buried and does not have much of a morphological relief as other subduction-caused trenches around the world oceans.

There is little historical data on earthquakes for Ecuador and the rest of the west coast of South America on which to base a correlation of the seasonality of the El Nino phenomenon and possible mechanism(s) that may be contributing to their triggering. A search for historical earthquakes for a catalogs of tsunamis for South America by the Internarional Tsunami Information Center (Pararas-Carayannis, 1975) included all available literature and historical letters and data of the Archives of Seville in Spain, the records of the British Museum in London and of the Bishop Museum in Hawaii.

The historic record for Ecuador was found to be incomplete but some cursory documentation for South America earthquakes was found in a publication by the French mathematician Fernard Montessus De Ballore, for events beginning in 1441 after the Pizzaro brothers conquered Peru. In continuing the search for older historical earthquakes in Ecuador, nothing much was found for events prior to 1906. Many more quake events – some of which may have been significant - were also missing for the period from 1905 to 1940 for the coasts of northern Peru, Ecuador and Southern Colombia. Figure 21 provides epicenters of 298 earthquakes of Richter 6.0 or greater that ocurred in the northwestern region of South America (between 1850 and 1906). Most of these events occurred along the West Coast of Colombia, Ecuador and Peru and some of the coastal quakes generated small local tsunamis, but no details are available.

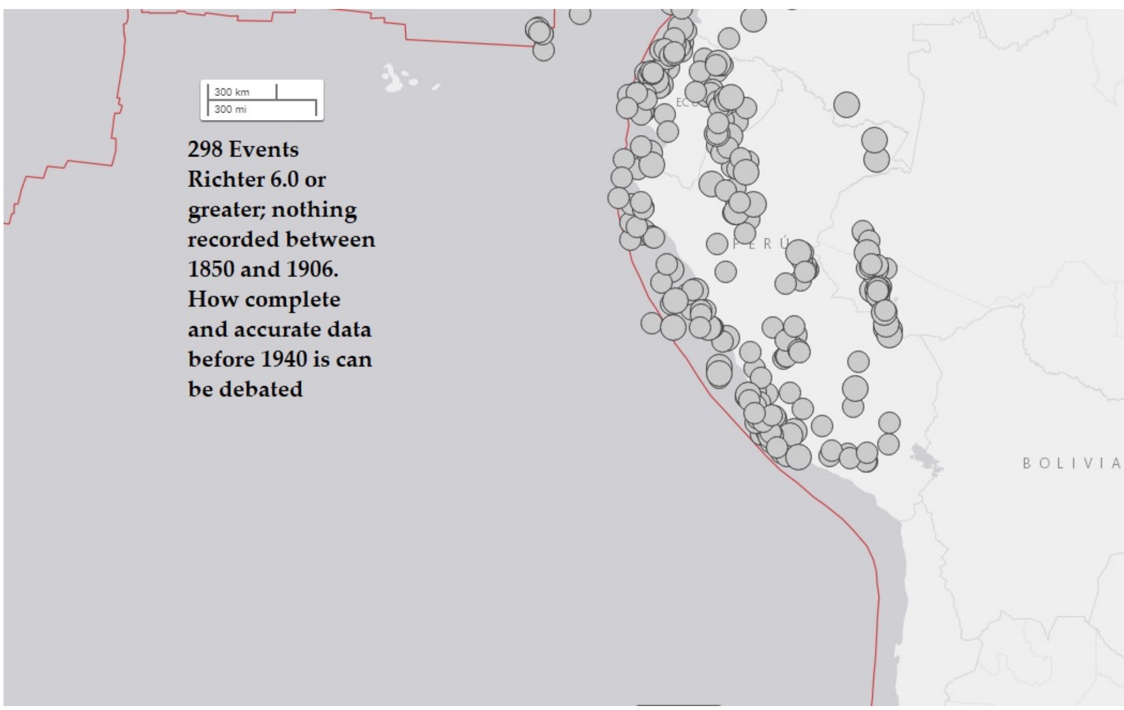

Fig. 21 Epicenters of 298 Historical Earthquakes with Magnitudes 6.0 or greater in the northwestern region of South America (between 1850 and 1906).

Figure 22 shows 187 earthquakes of Richter 6 and above as well as some details for the Richter 7's in the region since 1906. Given the small size of the region and the short times between powerful events, it is concludethat a lot of stress was imposed by the eastward moving Nazca Plate (See also Fig.12).

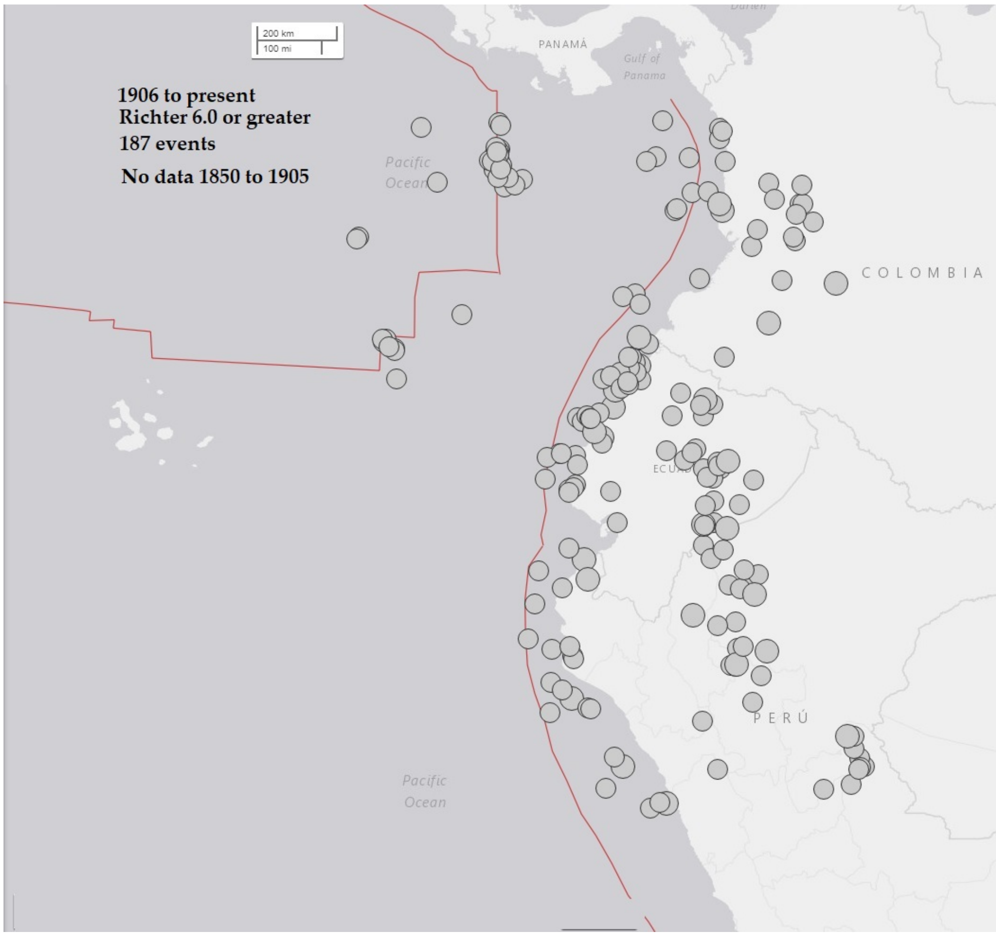

Fig. 22 Recent Historical Earthquakes along the Colombia, Ecuador and Peru (since 1906) with Magnitudes 6.0 or greater.

The seasonality of historical earthquakes along the Ecuador/Colombia and Peru subduction zones and their possible correlation to recent known periods of strong El Niño-Southern Oscillations (ENSO's) remains to be examined in order to determine if indeed there is a contributing factor to the triggering such events - at least along coastal margin regions with high thickness of subducted and greatly hydrated sediments.

3. VOLCANIC IMPACTS ON CLIMATE CHANGES AND IN TRIGGERING EARTHQUAKES

Convergent, compressional and collisional tectonic activity is responsible for zones of subduction, the formation of island arcs and the evolution of particular volcanic centers on the overlying plates. The inter-plate tectonic interaction and deformation along such marginal boundaries result in moderate seismic and volcanic events that not only can generate tsunamis by a number of different mechanisms but also result in significant climatic changes - based on the geochemical consistency and viscocity of the material in their magmatic chambers which control the intensities and explosivity of eruptions. Such active geo-dynamic processes have created volcanoes characterized by both effusive and explosive activity for both continental and oceanic volcanoes (Pararas-Carayannis, 2006).

Eruption mechanisms of volcanoes are complex and often anomalous. Earthquakes precede collapses of lava domes often prior to major eruptions, which may vary in intensity from Strombolian to Plinian. Locally catastrophic, short-period tsunami-like waves can be generated directly by lateral, direct or channelized volcanic blast episodes, or in combination with collateral air pressure perturbations, nuess ardentes, pyroclastic flows, lahars, or cascading debris avalanches. All these occurrences – depending on their severity – affect climatic conditions both locally and globally. Submarine volcanic eruptions can also alter the temperature of the overlying waters and create climatic changes as well as changes in the circulation of geostrophic ocean currents. Studies of intensive volcanic eruptions and their impact on climate changes have been made for numerous volcanoes in Hawaii, Alaska, Kuril Islands, Indonsesia, Japan, the Cascade Range, South America, Reunion Island, the Lesser Antilles, the Canaries, the Mediterranean Sea, the Northern Arabian Sea and other regions of the world (Pararas-Carayannis, 2001a; 2002; 2003; 2004 b, c, d; 2006).

Specically, the volcanoes of Ecuador are the result of subduction of the Pacific tectonic plate under the continental plate of South America. Four rows of volcanoes can be identified in Ecuador compared to a single line in Colombia to the north. The volcanoes of the Galapagos Islands have been thoroughly described in a book by Toulkeridis (2011).

One of the largest eruptions in the world in the past 1000 years was that of the Quilotoa Volcano in 1280 A.D. (80 km SSW from Quito). This eruption came after 14,000 years of dormancy. It was a Plinian eruption which discharged ~11 cubic km of magma during four eruptive phases. Although not adequately documented, this eruption must have had a global impact on climate change and severe reduction of incoming solar radiation. Such large explosive eruptions of this volcano in Ecuador occur every 10,000-14,000 years.

Also, the Cotopaxi stratovolcano's eruptions (60 km. South of Quito) of 1744, 1768, 1877, 1880 and 2015, the eruptions of volcanoes in the Galapagos, the 1600 Huaynaputina volcano's explosion in Southern Peru (Volcanic Explosivity Index [VEI] 6), and of the cataclysmic 1991 eruption of Mount Pinatubo volcano in the Phillipines must have a significant impact on climate. Also, the thermal impact of undersea volcanoes such Kick-Them-Jenny, will be examined in a subsequent study.

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