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POTENTIAL OF TSUNAMI GENERATION ALONG THE COLOMBIA/ECUADOR SUBDUCTION MARGIN AND THE DOLORES-GUAYAQUIL MEGA-THRUST

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ABSTRACT

The Colombia/Ecuador subduction zone is a region where high seismic stress is presently accumulating. Statistical probability studies and GPS measurements of crustal deformation indicate that the region has an increased potential to generate in the near future a major or great tsunamigenic earthquake similar to the 1979 or 1906. Although most of the major earthquakes along this margin usually generate local tsunamis, the recurrence of a great mega-thrust, inter-plate earthquake, similar in magnitude and rupture to the 1906 event (M_w=8.8, rupture 600 km.), can generate a tsunami with destructive near and far-field impacts. To understand the potential for such destructive tsunami generation in this region, the present study examines and evaluates: 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 may cause sudden detachment, décollement and deformation, with the potential for local tsunami generation that may affect the Gulf of Guayaquil and other coastal areas along southern Ecuador.

Keywords: *Colombia/Ecuador Trench, subduction, tsunami, earthquake, Carnegie Ridge, Guayaquil-Tumbes Basin, Dolores Guayaquil megathrust*.

1. INTRODUCTION

Both Colombia and Ecuador have high seismicity (Fig. 1). 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 (Kanamori and McNally, 1982). Subduction of the Nazca plate beneath the Ecuador-Colombia margin has produced four mega-thrust tsunamigenic earthquakes during the 20th Century (Collot et al., 2004). 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 (*M w* = 7.7) and 1979 (*Mw* = 8.2) (Collot et al., 2004). All four quakes generated destructive tsunamis. The 1906 tsunami, because of its greater generating area, had more significant far-field effects.

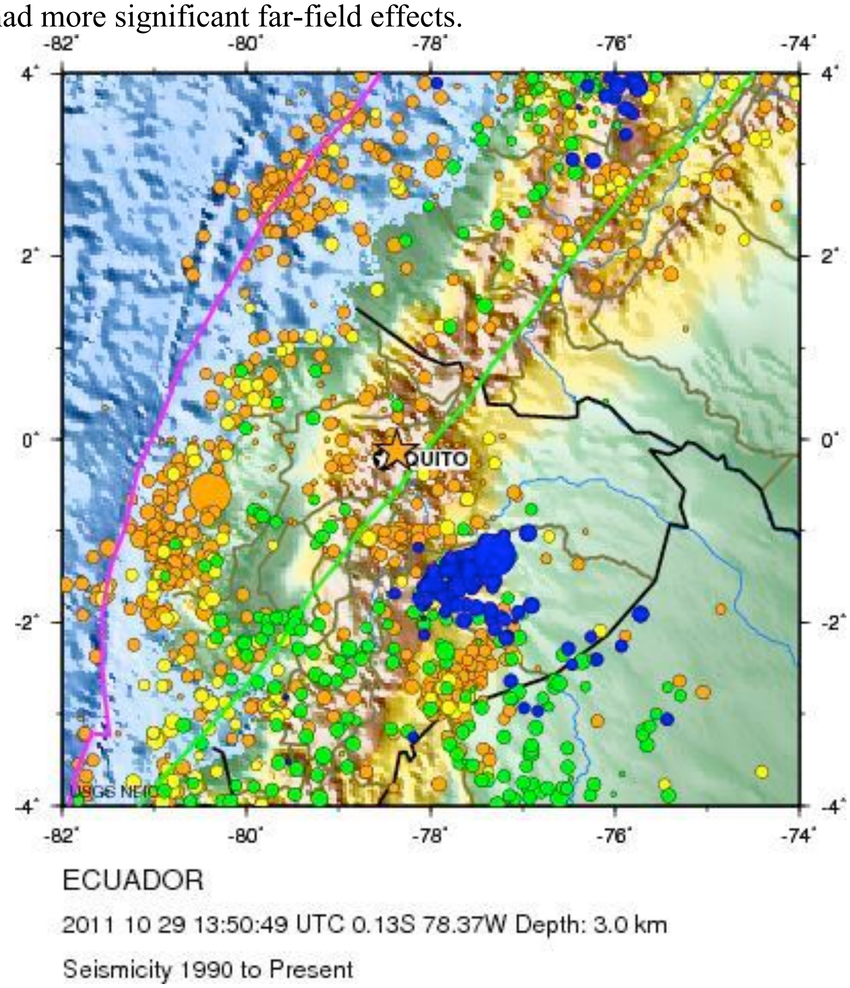

Figure 1. Seismicity of Ecuador from 1990 to present. USGS map showing the epicenter of the earthquake of 29 October 2011 near Quito, in relation to inter-plate and other intra-plate events.

The present paper provides an account of the 1906 tsunami based on a literature review and an account of the 1979 tsunamis - the latter based on an in situ survey immediately following this event (Pararas-Carayannis, 1979) and briefly discusses the 1942 and 1958 events. Subsequently, it evaluates the potential for tsunami generation along the Colombian/Ecuador margin by examining the overall controlling inter-plate coupling mechanisms of the tectonic regime along southern Colombia/North Ecuador, the seismo-dynamics and potential tsunami generation as affected by the Carnegie Ridge's oblique subduction beneath the South American continent along Central Ecuador and the seismotectonic processes in the vicinity of the Gulf of Guayaquil-Tumbes Basin that could result in an earthquake and a potentially destructive local tsunami in Southern Ecuador.

2. RECENT DESTRUCTIVE EARTHQUAKES AND TSUNAMIS

As indicated, four mega-thrust tsunamigenic earthquakes occurred in close sequence along the Colombia/Ecuador subduction margin in 1906, 1942, 1958 and 1979. More than 33 years have elapsed without another tsunamigenic earthquake in the region. Figure 2 illustrates the ruptures and focal mechanisms of these earthquakes on the inter-plate megathrust fault along the Colombia/Ecuador subduction zone.

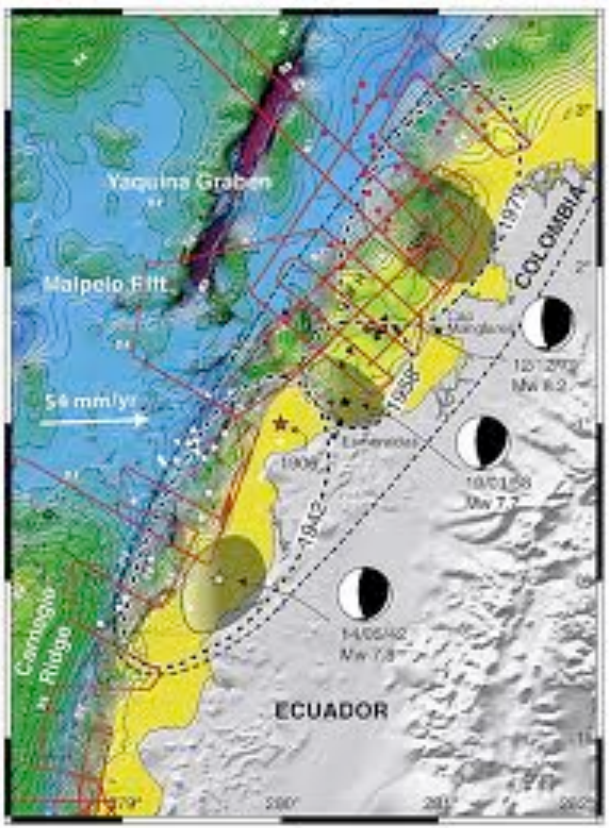

Figure 2. Tsunamigenic Earthquakes of 1906, 1942, 1958 and 1979 on inter-plate thrust faults along the Colombia/Ecuador subduction zone (after Collot et al. 2004)

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 latter event ruptured for 600 km encompassing the ruptures of the three subsequent events (Collot et al. 2004) 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.

2.1 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.

2.1.1 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).

The second populated area that was hardest hit by the quake was the town of Tumaco, only about 80 kilometers from the earthquake epicenter (Fig. 3). 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. Evidence of liquefaction was evident in many areas of the city where structures failed and particularly evident along the waterfront. Evidence of subsidence was found on either side of the bridge connecting the island where Tumaco is situated to the island where the airport is located.

Figure 3. Earthquake damage at Tumaco, Colombia (photo by G. Pararas-Carayannis**)**

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.

2.1.2 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 as shown in Figure 2. As stated, 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. Figure 4 is another illustration of the aftershocks and extent of ruptures of the tsunamigenic earthquakes 1906, 1942, 1959 and 1979.

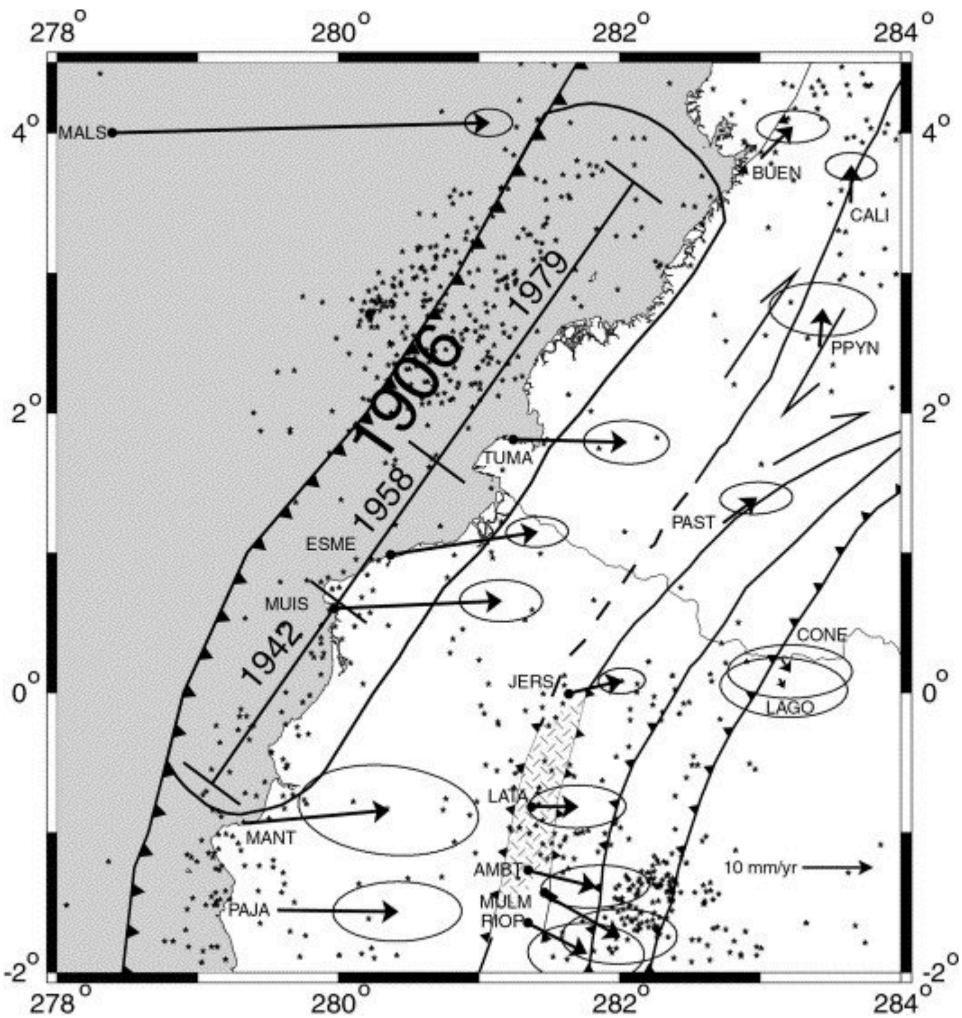

Figure 4. Ruptures of the Earthquakes 1942, 1959 and 1979 Earthquakes. Note that the 1906 earthquake rupture was over 500 km long and included those of the subsequent earthquakes (after Kanamori and McNally, 1982).

2.1.3 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). Figure 5 shows tsunami damage at Tumaco.

A total of four waves were observed, the first wave 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.

Figure 5. Tsunami damage at Tumaco (photo by G. Pararas-Carayannis**)**

Figure 6 is a hand trace of the tsunami as recorded by a tide gauge at the port of Esmeraldas in Ecuador, approximately 95 nautical miles to the south of the epicenter. The record confirms that the tsunami arrived at the lowest possible tide and that the first wave activity was a recession followed by approximately 3 to 4 waves. No major tsunami damage occurred in Tumaco (Colombia) or Esmeraldas (Ecuador), but had the wave occurred at high tide, it is believed that flooding and considerably more tsunami damage would have occurred at these two cities. If the wave had occurred at high tide, its elevation would have been 1-3 meters higher than the one-meter wave observed in Tumaco and could have resulted in extensive tsunami damage of that city where the maximum elevation is only 3 meters above sea level.

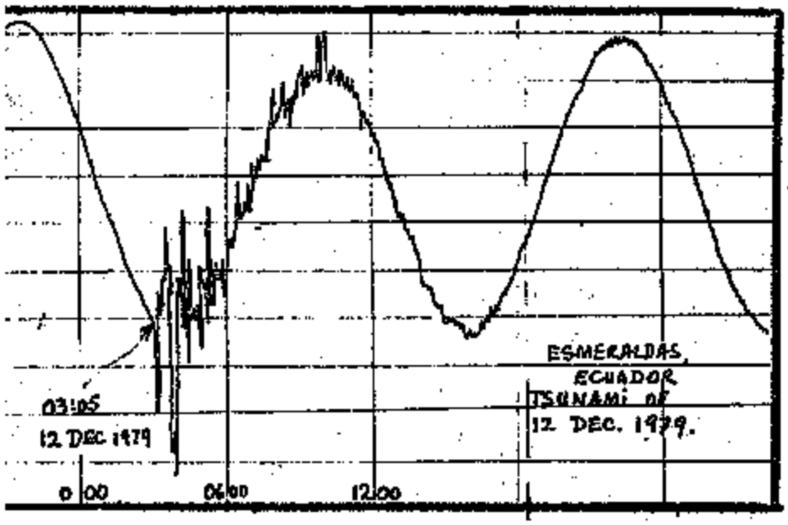

Figure 6. Hand-trace of the mareographic record of the 1979 tsunami as recorded at Esmeraldas, Ecuador. Based on this record, it appears that the travel time to that tide station was only 5-6 minutes after the quake (after Pararas-Carayannis, 1980).

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 of wave approach was obtained by observing fallen palm trees, detritus material wrapped around objects and the way buildings had moved or structurally failed (Pararas-Carayannis, 1980).

2.1.4 Far-Field Impact of the 1979 Tsunami

The tsunami was 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. However, at Johnston Island the 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.

2.2 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 (Fig. 7). Its magnitude (Richter) was originally estimated at 8.2, but subsequently revised to a Moment Magnitude M_w=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 – as reported earlier - 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.

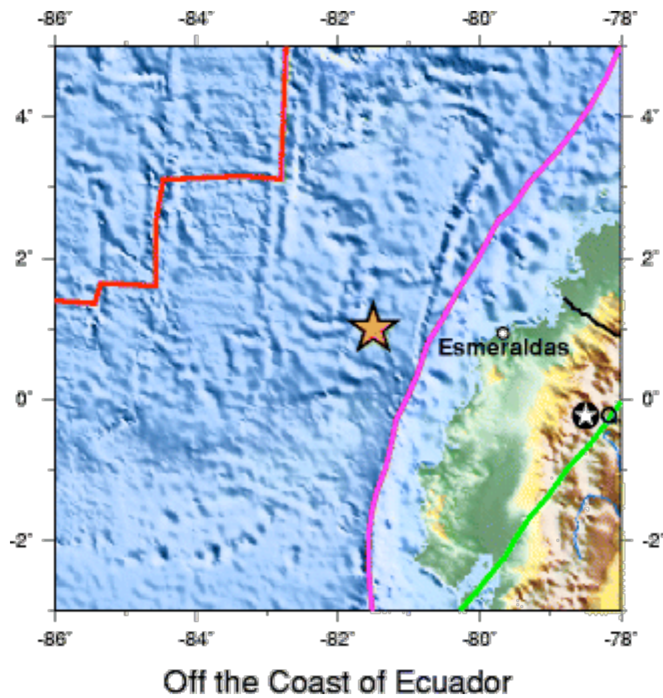

Figure 7. Epicenter of the 31 January 1906 earthquake off the coast of Ecuador near the city of Esmeraldas (modified USGS map).

2.2.1 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. It flooded the floor of the old wharf at the end of Waianuenue Street and the railroad tracks between there and Waiakea. 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; Lander and Lockridge, 1989).

3. SEISMODYNAMICS OF THE ECUADOR-COLOMBIA SUBDUCTION MARGIN

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.

Furthermore, 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 15^0 to 18^0 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) (Fig. 8). This wedge is referred to as the ‘‘North Andes block’’ and inferred from geologic and seismicity data.

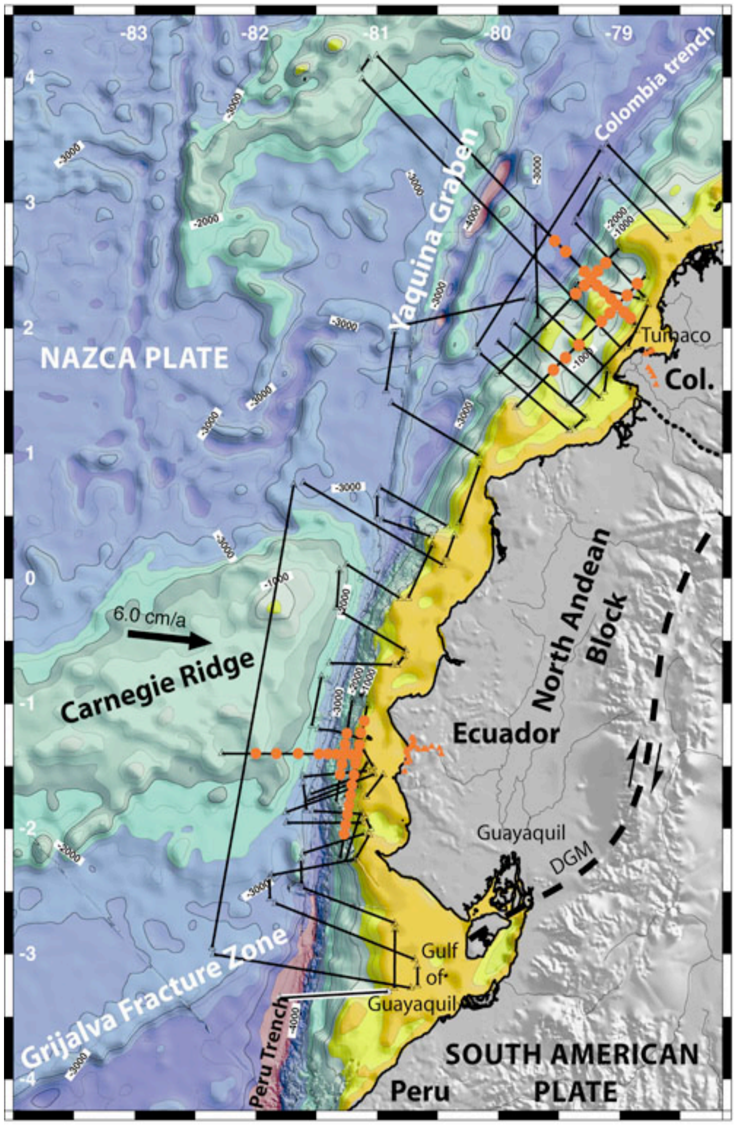

Figure 8. Yaquina Graben, Colombian Trench, Carnegie Ridge, the Grijalva Fracture Zone, the North Andean Block and the Dolores Guayaquil megathrust (DGM). Epicenters of the 1979 earthquakes on the North Andean Block coastal intra plate region (after Collot et al. 2004).

This wedge appears to move at about 10 mm/year toward 055 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 1^0 to 4°N and longitude 77^0 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.

3.1 Examination of Sequential Ruptures Associated with Recent Historical Earthquakes along the Colombia-Ecuador Coast – Implications for Future Events.

As reported, 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. Figure 9 is another illustration of the ruptures of these tsunamigenic earthquakes.

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 $6–8\times10^{20}$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 (Sennson & Beck, 1996). 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 (Mendoza & Dewey, 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.

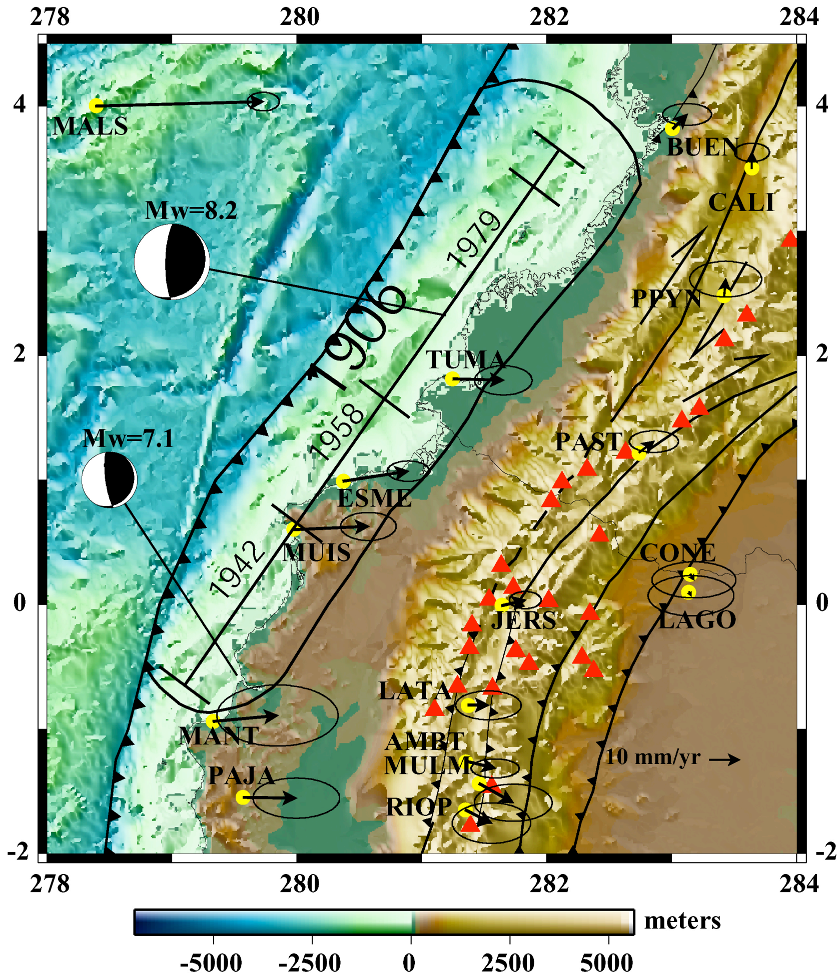

Figure 9. Ruptures of the 1906, 1942, 1958 and 1979 tsunamigenic earthquakes (after Trenkamp et al. 2002)

More specifically it was observed that 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 than the 1979 event. 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).

Similarly, recent results from Global Positioning System (GPS) measurements show deformation along the coast of Ecuador and Colombia that can be linked to the rupture zone of the 1979 earthquake in 1979 (White et al., 2003; Trenkamp et al., 2002). The observed wide plate boundary deformation in Ecuador - as determined by the GPS measurements - has been explained by 50% apparent locking on the subduction interface. Although there have not been any historic large earthquakes (Mw >7) south of the 1906 earthquake rupture zone, 50% apparent elastic locking is necessary to model the deformation that has been observed there (White et al., 2003).

In Colombia, only 30% apparent elastic locking is occurring along the subduction interface in the 1979 earthquake rupture zone (Mw 8.2), and no elastic locking is necessary to explain the crustal deformation observed at two other GPS sites (White et al., 2003). There is no evidence from seismicity or plate geometry that plate coupling on the subduction zone is reduced in Colombia. However, simple visco-elastic models suggest that the apparent reduction in elastic locking can be explained entirely by the response of a viscous upper mantle to the 1979 earthquake. These results suggest that elastic strain accumulation is occurring evenly throughout this region, but post-seismic relaxation masks the true total strain rate (White et al., 2003). In other words, the total strain accumulating in the region since 1979 is difficult to estimate and indeed may be reaching a critical stage. The earthquake strain accumulation along the Ecuador/Colombia Trench has been estimated to be in the order of -26 ± 4 mm/yr due to shortening since 1991 at the coastal sites at Muisne and Esmeraldas, Ecuador, hypothesized to reflect three modes of deformation roughly parallel to the convergence direction (Trenkamp et al., 2002).

The asperities, shorter ruptures and offsets of the 1942, 1958 and 1979 earthquakes can also be supported by results of multichannel seismic reflection and bathymetric data acquired during the SISTEUR cruise (Collot et al., 2004)). This data shows evidence that the margin wedge is segmented by transverse crustal faults that potentially correlate with the limits of the earthquake co-seismic slip zones. Subduction of the buoyant Carnegie Ridge – as it will be discussed further – apparently controls some of the seismo-dynamic processes south of the margin where the 1906, 1942, 1958 and 1979 tsunamigenic earthquakes occurred.

3.3 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 magmatims 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. Wideangle 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.

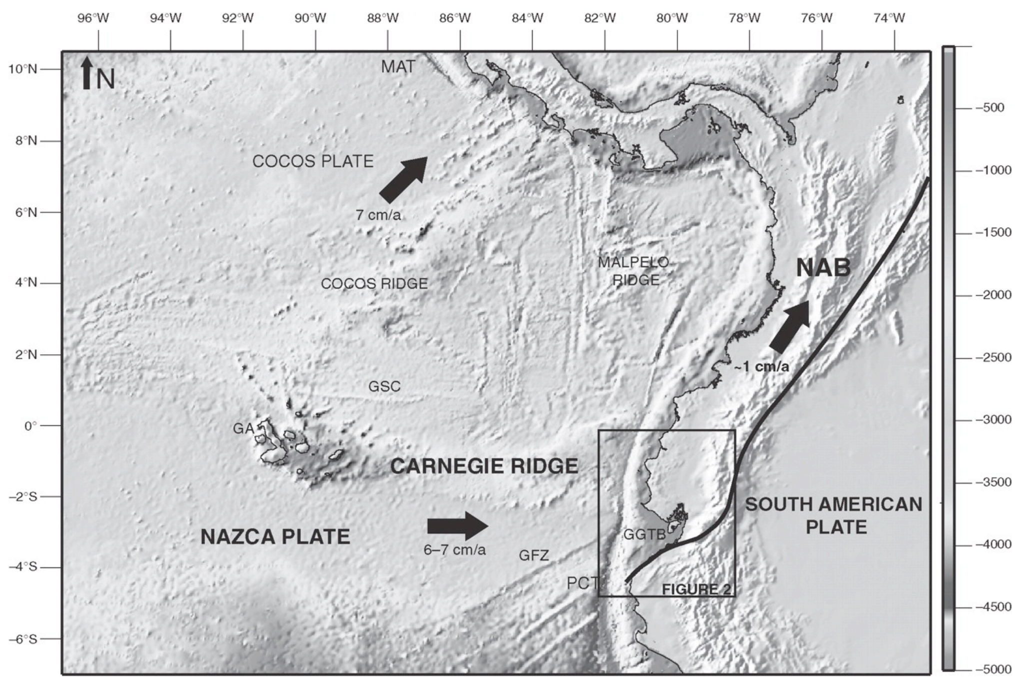

Figure 10. Subduction of the Carnegie Ridge beneath Ecuador. Convergence rates of the Cocos and Nazca plates and rate of movement of the North Andean Block along the Dolores Guayaquil megathrust (DGM) (after: Collot et al., 2004; Witt and Bourgois, 2009)

3.3.1 Influence of the Carnegie Ridge subduction.

The buoyancy of the subducting Carnegie Ridge appears to have an influence on the lithosphere of the Nazca Plate which, in its northern part, has a gentle angle of subduction and a non-uniform geometrical configuration. Where the subduction of the Carnegie Ridge takes place along central Ecuador, the trench is shallow and the coastal region is being uplifted (Fig. 11). Also, the ridge appears to partially lock the plate interface and to limit the incidence of tsunamigenic earthquakes along central Ecuador south of 1^0 latitude. The mode of faulting and seismicity of this region may be related to the subduction of the Carnegie Ridge (Gutscher et. al., 2005). The buoyancy of the Ridge is inferred to partially lock the plate interface along central Ecuador. For example, co-seismic slip during the 1942 and 1906 earthquakes terminated against the subducted northern flank of the Carnegie ridge. Similarly, at about 2^0 North latitude, the Manglares fault which cuts transversally through the margin wedge, correlates with the limit between the 1958 and 1979 tsunamigenic earthquake rupture zones (Collot et al., 2004).

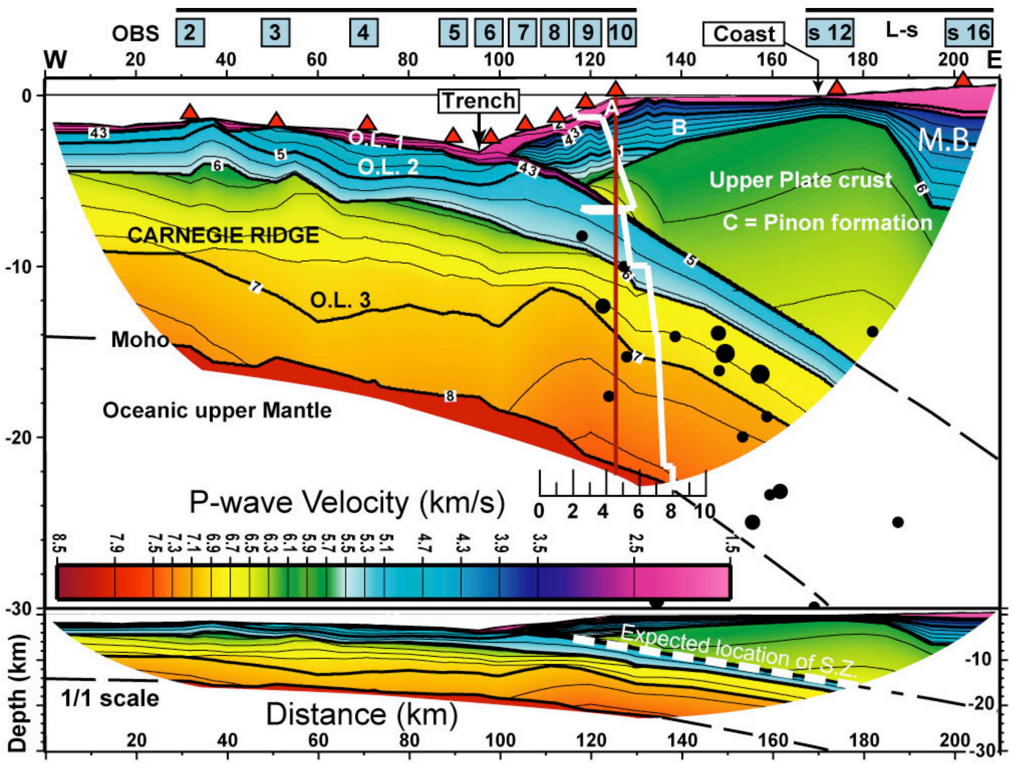

Figure 11. Subduction of the Carnegie Ridge under the continental crust along central Ecuador (from Graindorge et al. 2004 in Collot et al. 2004).

According to a recent study (Collot et al., 2004), the transversal cutting along the Colombia/Ecuador mega-thrust fault zone seems to be associated with high-stress concentration on the plate interface. Accordingly, an outer basement high, which bounded the margin seaward of the 1958 earthquake rupture zone, may also act as a deformable structure that limits seaward propagation of co-seismic slip along the mega-thrust splay fault. The cause of the 1958 tsunami is attributed to possible co-seismic uplift of the basement high. Furthermore, even weak transverse faulting reduces coupling between adjacent margin segments, together with a splay fault and an asperity along the plate interface - which presumably controlled the seismogenic rupture of the 1958 earthquake.

3.4 Seismo-dynamics of the Gulf of Guayaquil-Tumbes Basin – Potential for tsunami generation

Apparently, the collision of the Carnegie Ridge with central Ecuador has altered also the tectonic stress distribution along the southern convergent margin, resulting in the creation of numerous faults with NW-SE and NE-SW orientations. Between latitudes 2^0 and 4°S, the ocean bottom in front of the Ecuador Trench is a fractured and complex seismogenic zone, estimated to be about 230 kms in width. This region is cut by several oceanic fracture zones which have a NE-trending orientation (Fig. 12). Best known are the Grijalva, Alvarado, and Sarmiento fractures. It has been suggested that since this region is subducted under the South American continent, it may behave as a separate microplate independent of the adjacent major tectonic plates (Pennington, 1981; Hall and Wood, 1985).

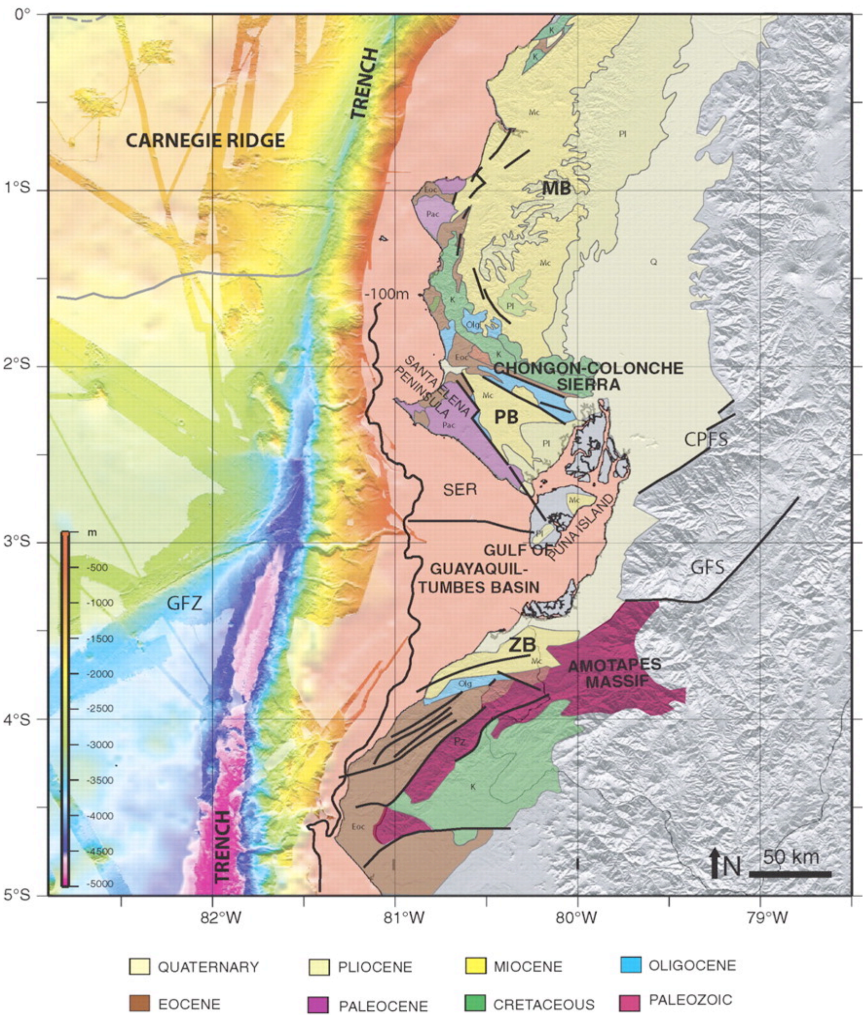

Figure 12. Faults on the southern region of the Guayaquil-Tumbes basin. Plate coupling along the subduction décollement, which controls the inward segmentation of deformation. Potential source of local tsunamis (map: Witt and Bourgois, 2009).

Such well-known fault systems with NE-SW orientation include those transversing the Gulf of Guayaquil, such as La Pallatanga and the Alausi-Guamote Valley faults, among others. Several destructive earthquakes which occurred in Ecuador – the Riobamba in 1797 and the Alausi in 1961, among others - have been correlated with these NE-SW trending faults. Major lineaments and faults with such NW-SE orientations have been also identified (Hall & Wood, 1985) as delimiting regions of tectonic segmentation, the most important being the Esmeraldas-Pastaza and the Rio Mira-Salado lineaments. Two tectonic regimes - which show different styles and ages - controlled the evolution of the southern Ecuador and northern Peru continental margin and shelf and thus the potential for the generation of tsunamigenic earthquakes. The N-S extensional regime along the shelf area is related to North Andean block drift, whereas the E-W extensional regime along the continental margin results from apparent tectonic erosion at depth.

Also, trench-parallel extensional strain resulting from the northward drift of the North Andean block – as described earlier - has controlled the tectonic evolution of the Gulf of Guayaquil-Tumbes Basin for the past ~1.8–1.6 Ma (Witt & Bourgois, 2009). Multichannel seismic and well data document that E-W to ENE, low-angle detachment normal faults, the Posorja and Jambelí detachment systems to the north and the Tumbes detachment system to the south, accommodated the main subsidence step along the shelf area during late Pliocene-Quaternary times (1.8–1.6 Ma to present) (Witt & Bourgois, 2009).

Strain rotation takes place along a major N-S–trending transfer system formed by the Inner Domito fault and the Inner Banco Peru fault, which bound the detachment systems to the west. The strike-slip component along this transfer system, roughly located at the continental margin-shelf break, evolved in response to slip along the detachment systems bounding the basin to the north and to the south.

Finally, according to recent studies (Witt & Bourgois, 2009), the Tumbes detachment system is the master fault which controlled the evolution of the basin and may represent the shallower manifestation of a reactivated subduction megathrust. This megathrust connects landward with the continental structures assumed to be part of the eastern frontier of the North Andean block. For the past ~2 Ma, the total lengthening calculated along a complete N-S transect of the Gulf of Guayaquil-Tumbes Basin ranges between 13.5 and 20 km (Witt & Bourgois, 2009). Such extend of lengthening can be justified with the documented drift of the North Andean block. However, the same studies (Witt & Bourgois, 2009) have also shown that the Gulf of Guayaquil-Tumbes Basin is not a typical pull-apart basin, but rather a certain type of basin controlled by detachments extending downward across the crust and plate coupling along the subduction décollement surface – which control the segmentation of deformation inward. Local tsunamis can be generated from such pull-apart, shallow, décollement processes in the Gulf of Guayaquil-Tumbes Basin.

3.5 Potential Tsunamis along the Colombia/Ecuador Subduction Margin

Global Positioning System (GPS) data from southern Central America and northwestern South America collected during 1991, 1994, 1996, and 1998 in Ecuador, Colombia and elsewhere (Trenkamp et al, 2002; White et al. 2003), indicate wide plate boundary deformation and escape tectonics occurring along an approximately 1400 km length of the North Andes, locking of the subducting Nazca plate (Fig. 13). Rapid subduction of the Nazca plate and of the Carnegie aseismic ridge (67 ± 6 mm/yr) at the Ecuador trench relative to the stable South America continent, are oblique to the Colombia-Ecuador margin - thus resulting in shortening perpendicular to the North Andean margin and in lateral "escape" (6 ± 2 mm/yr) to the northeast. The GPS data from northwestern South Ecuador and Colombia indicates a wide plate boundary deformation and strain accumulation along the Ecuador-Colombia fore-arc.

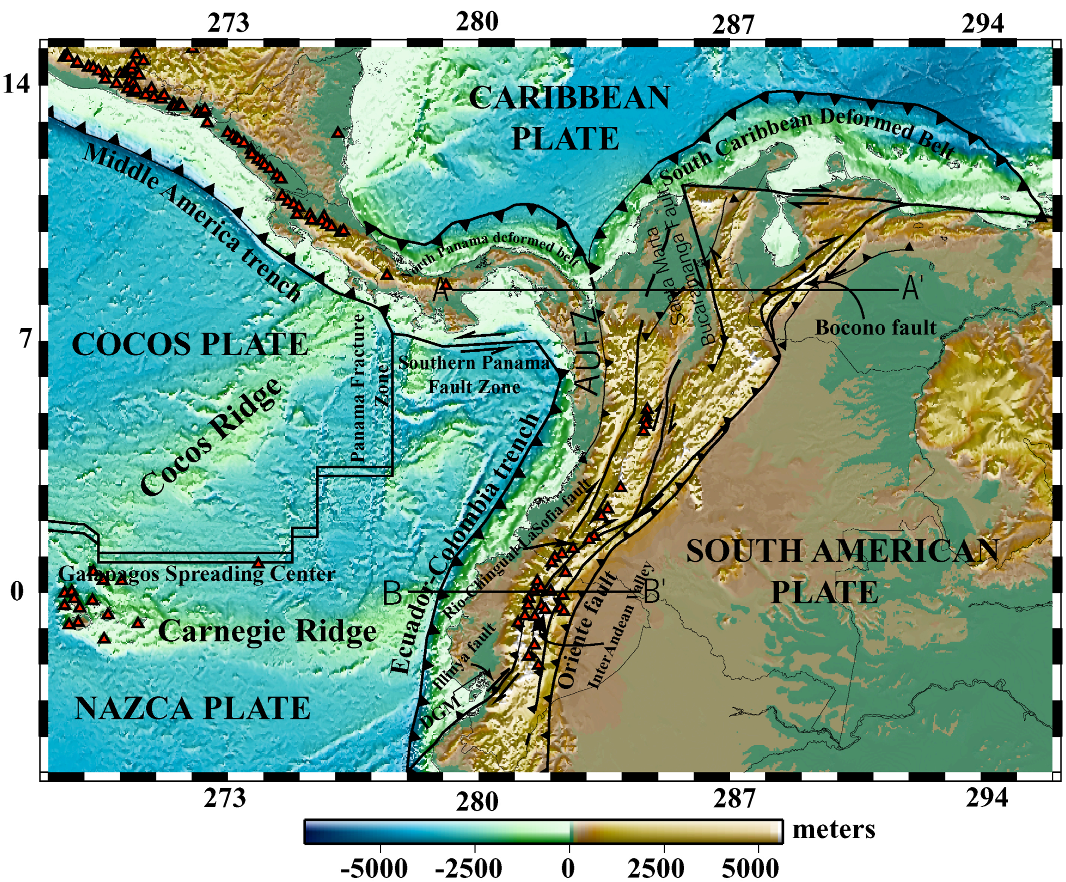

Figure 13. Major Tectonic Features along northwestern South America parallel to the convergence direction (after Trenkamp et al. 2002).

The same data indicates that elastic modeling of observed horizontal displacements in the Ecuador forearc is consistent with partial locking (50%) in the subduction zone and partial transfer of motion to the overriding South American plate. The deformation is assumed to reflect elastic recoverable strain accumulation associated with past seismicity of the area and active faulting associated with permanent shortening of 6 mm/a. (Trenkamp et al. 2002). Thus, substantial strain increase along the Ecuador-Colombia mega-thrust region since the 1979 earthquake will result in a major or great tsunamigenic earthquake – perhaps in the near future. A major earthquake cold rupture a short segment similar to the 1942, 1958 and 1979 events, or a great earthquake will have a longer rupture and larger tsunami generation area, as that of 1906. It is also possible that the next earthquake along the Colombia-Ecuador margin will rupture a segment of the mega-thrust to the north of where the 1979 rupture terminated.

In summary, although the historical record is short and poorly documented for this tectonic regime of the Colombia-Ecuador margin, studies of earthquake potential using conditional probability estimates, had indicated a 66 percent probability for a major earthquake (M_s = 7.7) to take place along the subduction zone in the recurrence period of 1989-1999. However, no such earthquake occurred during this period, thus indicating that the probability of a major or great earthquake in this margin region has greatly increased. Furthermore, because the sequence of the three earthquakes that ended in 1979 did not release as much energy as the 1906 event, it has been suggested that an earthquake of similar magnitude to that of 1906 was likely in the near future.

Further evaluation of the amount of slip associated with the three subsequent events (1942, 1958 and 1979), suggests that they have released most of the accumulated displacement across the plate boundary since 1906. However, this is not consistent with the recent GPS data which indicates a wide plate boundary deformation and strain accumulation along the Ecuador-Colombia fore-arc. Thirty-three years have elapsed since 1979 without a major earthquake, thus there must be substantial strain accumulation in this region. Based on the 1948, 1952 and 1979 earthquakes, it can be concluded that a local destructive tsunami is likely to be generated in the near future from an earthquake with shorter length of rupture, while a local and Pacific-wide tsunami is likely to be generated if a greater earthquake strikes that has a rupture of 400 or more kms - as that of 1906. Also, south of the Carnegie subduction zone, there is potential for tsunamigenic earthquakes of lesser magnitude on faults of the southern region of the Guayaquil-Tumbes basin. Plate coupling along the subduction décollement, which controls the inward segmentation of deformation – as discussed earlier - could result in earthquakes and local tsunamis that would impact Southern Ecuador and the Gulf of Guayaquil.

3.5 Potential Impact of Future Tsunamis on Coastal Communities in Colombia and Ecuador

Given the observed strain accumulation along the Colombia/Ecuador subduction margin, there is high probability that a large tsunamigenic earthquake is going to occur in the same vicinity as that of 1906 and that it may have a similar long rupture and large tsunami generating area. A major tsunamigenic earthquake is also very possible along the Colombia/Ecuador mega-thrust. The tsunami that will be generated may be as great as that of 1906 and will be destructive – particularly if it occurs near high tide. Tumaco and coastal villages in southern Colombia and northern Ecuador are extremely vulnerable. For example, Tumaco is located on a coastal island sand bar with maximum elevation of 3 meters above sea level. If the tsunami is 5 meters high as in 1906 and occurs at high tide, the entire city will be completely inundated. Since the population density has greatly increased along coastal areas of Ecuador and Colombia, the death toll will be great. For example, the population of Tumaco in 1979 was about 80,000 people. Presently the population has increased to120,000.

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