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FIRST EVIDENCE OF PALEO-TSUNAMI DEPOSITS OF A MAJOR HISTORIC EVENT IN ECUADOR

Kervin Chunga[1] and Theofilos Toulkeridis[2]

[1]Escuela de Ciencias Geológicas y Ambientales, Facultad de Ciencias Naturales, Universidad de Guayaquil, Ecuador

[2]Universidad de las Fuerzas Armadas - ESPE, Campus Sangolquí, Sangolquí, Ecuador

ABSTRACT

The Ecuadorian shoreline is considered highly susceptible by impacts of tsunamis triggered by marine quakes or submarine landslides occurring close or nearby the subduction zone between the Nazca, Caribbean and South American plates. Since 1877 one dozen known tsunamis have been witnessed along this coast, mostly related to short-distanced seismic activities (earthquakes between Mw 6.9 to 8.8). However, no evidence of these impacts has been recorded in the sedimentary stratigraphy on the Ecuadorian platform so far. Nonetheless, in the southwestern part of the Gulf of Guayaquil, due to a biological, chemical, stratigraphic and geochronologic study of a few cored samples an anomalous horizon to the other sedimentary layers has been identified and recognized as a paleo-tsunami deposit. This layer having a thickness of up to 10 cm and up to 1100 meters away from the actual shore, demonstrates various criteria which confirm its origin such as deep sea foraminifera like *Pullenia bulloides*, run-up and backwash features, fragments of molluscs, which are absent in other sedimentary levels, matrix of weathered chlorite potentially originated by glauconite besides other. Geocronologic evidence together with the calculated sedimentation rate, implies that a the tsunami surged the coastal lowlands around Villamil Playas about 1250 ± 50 yrs ago and must have been a major event originated from the western or northwestern direction.

Keywords: Paleo-tsunami deposit, sedimentary facies, Gulf of Guayaquil

1. INTRODUCTION

Due to its active geodynamics the Ecuadorian continental platform similar to almost all other countries along the Pacific rim is a frequent target of tsunami impacts (Gusiakov, 2005; Pararas-Carayannis, G., 2012). The active continental margin and associated subduction zone between the oceanic Nazca Plate with the continental South American and Caribbean Plates, both separated by the Guayaquil-Caracas Mega Shear (Kellogg and Vega, 1995; Gutscher et al., 1999; Egbue and Kellog, 2010) give rise to tsunamis of tectonic as well submarine landslide origin.

From the known record the Ecuadorian shoreline has witnessed a dozen times impacts of tsunamis by mainly local origins in the last 200 years with various intensities one being of up to 8.8 Mw in 1906 (Rudolph and Szirtes, 1911; Kelleher, 1972), without leaving known traceable evidences. Even less is known and evidenced of previous tsunami impacts and their potential deposits along the coast. Research of such deposits is an important tool in order to characterize frequency and intensity of past phenomenon and such information may help out to forecast short and long-term probabilities of future potential impacts. Classic studies of the identification of paleo-tsunami deposits have been summarized in Dawson and Shi (2000) and examples of such studies have been published around the world (e.g. Dawson et al., 1991; Minoura et al., 1994; Benson et al., 1997; Smoot et al., 2000; Pinegina and Bourgeois, 2001; Rhodes et al., 2006; Dahanayake and Kulasena, 2008; Morales et al., 2011; Nanayama et al., 2011; Jankaew et al., 2011). In South America most of the research about some paleo-tsuami deposits has been performed in Chile and Peru (e.g. Jaffe et al., 2003; Cisternas et al., 2005; Satake and Atwater, 2007; Moernaut et al., 2007; Roux et al., 2008; Peters and Jaffe, 2010).

Unfortunately, very little research has been focused on past tsunami deposits in Ecuador and the associated Galápagos islands due to the lack of basic information such as detailed stratigraphic records, missing knowledge about the identification of such events and associated deposits as well as the lack of means of correlation of events along the coast at different localities. Additionally, the Ecuadorian coast undergoes a rapid uplift (Pedoja et al., 2006a; 2006b) and subsequent erosion erases a high amount of potential (minor) tsunami deposits. Therefore the main aim of the present study is to present to our knowledge the very first evidences of dated and correlateable paleo-tsunami deposits in Ecuador, namely in the alluvial plains of the Gulf of Guayaquil.

2. GEOLOGICAL SETTING AND SAMPLE LOCATION

The Gulf of Guayaquil in the south-central oceanic side of Ecuador is part of the Guayaquil-Tumbes Basin and it is situated in a triple-junction between the Nazca, Caribbean and South American plates (Ego et al., 1996). Structurally it is representing a pull-apart basin, which is controlled by detachments extending downward across the brittle crust and the mentioned plate coupling of the triple-junction (Witt and Bourgois, 2010). The opening of the basin was initiated in Middle Miocene times, while due to the tectonic activities flower structures and diapirism as well as a significant accumulation of Pliocene sediments took place since (Dumont et al., 2005).

Approximately 60-80 km southwest and south of the city of Guayaquil are situated the alluvial plains of General Villamil Playas, Posorja, Puerto Balao y Tenguel all based near or at inner rims of the center of the Gulf of Guayaquil, where paleo-seismic analyses were performed together with a series of cored samples of unconsolidated sediments (Fig. 1a). These samples allowed the identification of diverse sedimentary events of the estuary and beach. In total six core samples of 1.6 to 2.0 meters length were taken of which two correspond to the intertidal area, while all others are related with the back-shore area and the alluvial plain (Fig. 1b). The cored sample of Posorja has been taken in the stoa of the ebb tide, while those of Puerto Balao and Tenguel in the stoa of the tide. The textural composition and grain size of the obtained sediments has been sandy, sandy to muddy, fine-grained sand including silt and clay mineral sizes. Three samples were taken at General Villamil Playas where some thin layers of organic material have been observed. While samples of Posorja, Puerto Balao and Tenguel did not evidence any traces of paleo-tsunami deposits, only the three samples (Villamil 1, 2 , 3) of General Villamil Playas will be described in detail.

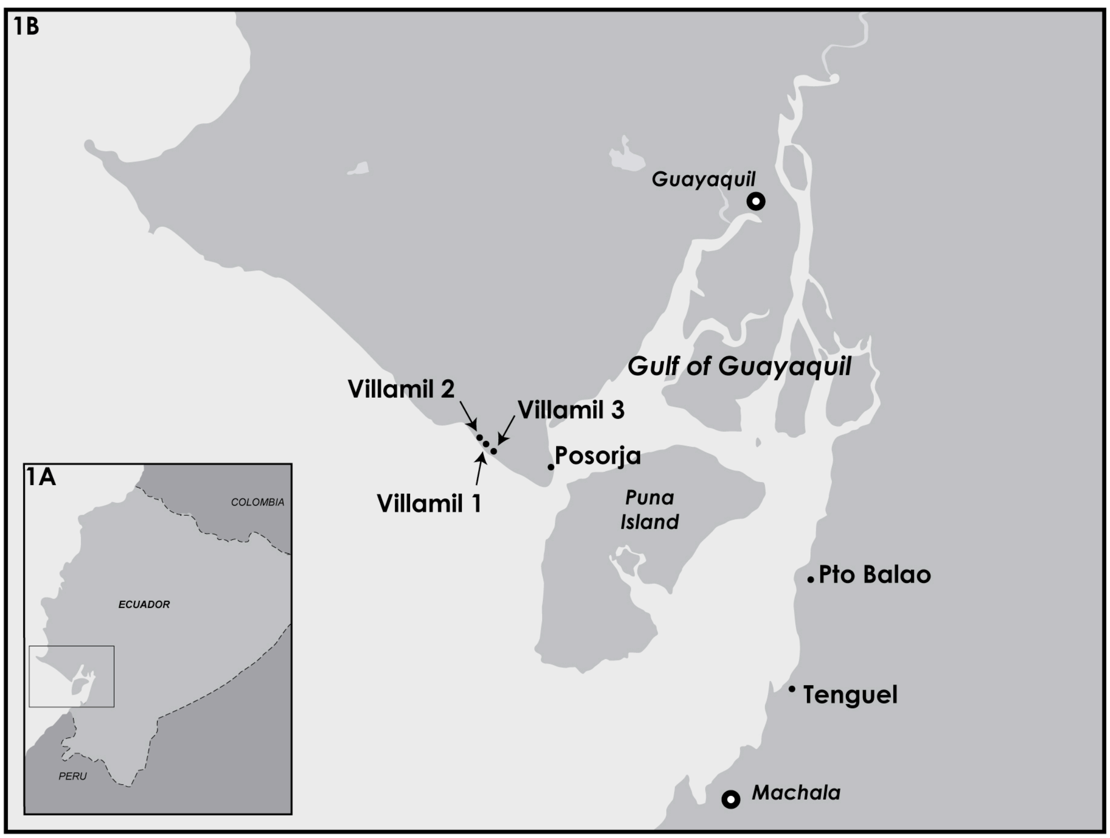

Fig. 1a: Location of sample area within Ecuador. Fig. 1b: Sample localities Villamil 1, 2, 3, Posorja, Puerto Balao, Tenguel within the Gulf of Guayaquil.

3. RESULTS

a) Stratigraphy and sedimentary environments

Sample Villamil 1

The very first sample, being in the center of the other two samples, is the farthest of all samples in respect to the distance of the shore with some 1128 meters. On this cored sample three different sedimentary environments have been identified, namely from top to bottom being coastal river, transitional and subtidal estuary (Fig. 2). The first and hereby upper (youngest) environment being the coastal river appears in the cored sample in the interval of 2 until 127 cm. It is interpreted as a deposit interfered with effects of low, moderate and high energy. Rhythmic sequential deposition of fine to medium-grained silt is overlying a lensatic stratification of moderate to high energy composed of very fine-grained sand in silty sediment with discontinued layers of sand. Successively, cross-stratifications with inclined, bidirectional deposits and silty clasts indicate a high-energy tide deposition with the predominance of sandy silt and continued layering of very fine-grained sand of low energy. The lithological change of sandy silt sediment towards silty sand is interpreted as a progressive gradual interference of the tide with common fragments of carbon (lignite).

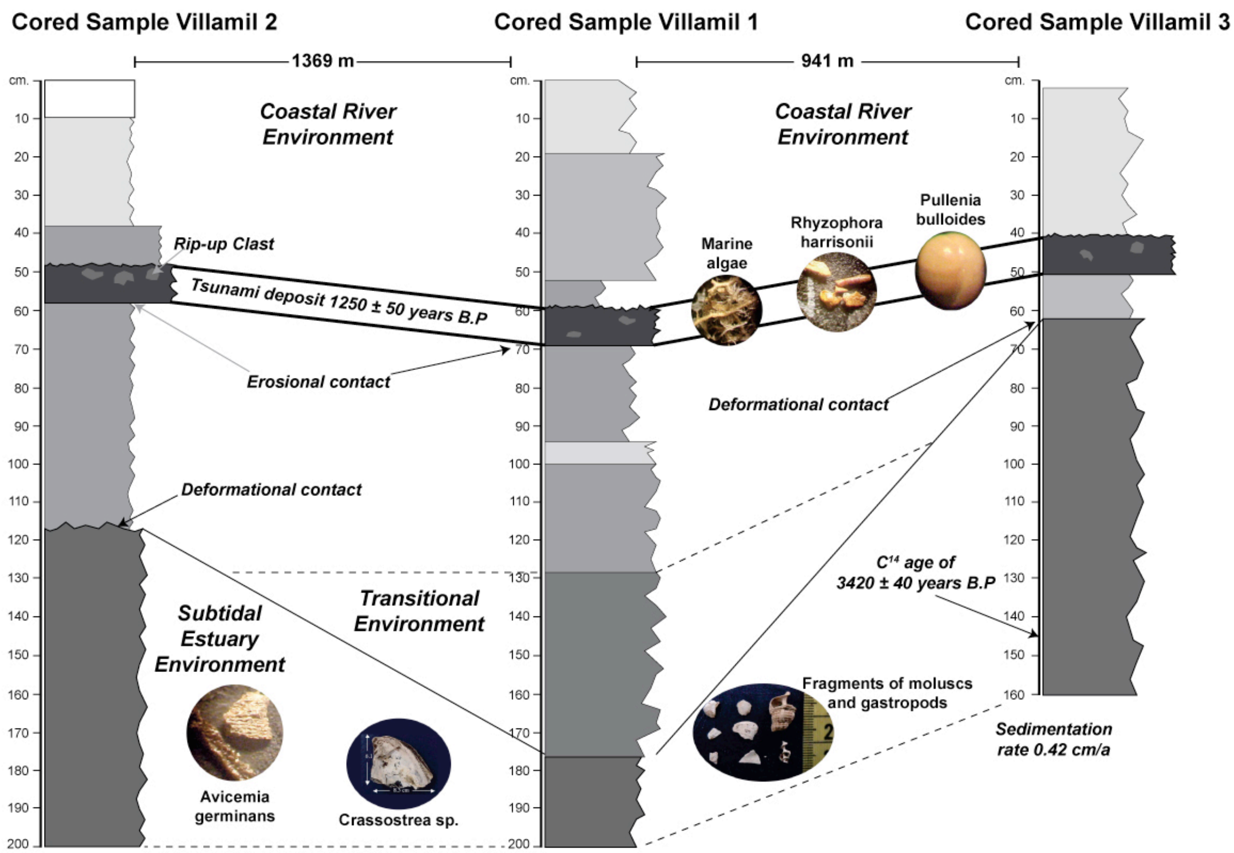

Fig. 2: Stratigraphic profiles of sampled cores Villamil 1, 2 and 3.

An anomalous sedimentary event has been identified in the interval of 59 until 67 cm. There appears a brownish, reddish and gray-green colored, sandy silt with chaotic sedimentation (Fig. 3). It is interpreted as a tsunamogenic event of a preserved tsunami deposit with some fragmented rests of mangrove wood named Rhyzophora harrisonii. The encountered wood is in oxidation state most probably due its composition of ionic iron, which appears to have interacted with the oceans high salinity transported from the continental shelf by a tsunami wave. Elongated clasts of clay and fine-grained sand inside sandy silt sediment are demonstrating a low energy deposition just below the tsunami deposit.

The second sedimentary environment reaching the interval of 127 until 177 cm is a transitional environment (Fig. 2). It is interpreted as a progressively decreasing sequential deposition of silty sand with a gradational contact at the interval of 166 cm, which indicates an increase of clay and the gradual decrease of sand with some common carbonaceous fragments. The determination of this environment is based on present lithological characteristics and accessories of components being part of the studied sediment like lignites.

A deformational contact of wavy contours due to the density of the sediments is the stratigraphic limit between the transitional and subtidal estuary environments at about 177 cm until 206 cm of the cored sample (Fig. 2). There silty sand is the dominating sediment. This last environment of the drilled core has been interpreted as subtidal estuary due to the high amount of rests of mangrove plants named *Avicemia germinans*, which can be found actually on the coastal areas of the estuary of the Gulf of Guayaquil. The sorts of molluscs encountered in this environment correspond to the species *Turritelas* y *Crassostrea sp*. The estimated age based on C^{14} dating realized at this site and the stratigraphic correlation of this third and oldest sedimentary unit is of approximate 3420 ± 40 years before present (Fig. 2).

Sample Villamil 2

This cored sample, which is located at the southwestern side of El Botadero, some 788 m away from the shore, exhibits only two sedimentary environments being the coastal river and the sub-tidal estuary (Fig. 2). The upper environment has been identified in the interval of 9 until 103 cm and interpreted as gradually interfered deposition with effects of low, moderate and high energy. The sequential rhythmic deposition of fine to medium grained silt up to coarse-grained sizes with reddish colored clasts of clay of low energy, allows to correlate this section with the one of sample Villamil 1.

The interval between 48 and 58 cm evidences a tsunami deposit, which is characterized stratigraphically with the presence of rip-up clasts of silt in very fine-grained sand. The rip-up clasts correspond to the incoming run-up wave, while the silty sediments are deposits caused by the backwash wave, stressing out that both deposits belong to the same tsunamigenic event (Fig. 2, Fig3). The lower limit is an eroded contact. In this anomalous sedimentary unit have been found also rests of marine algae and fragments of mollusks, which are absent entirely in all other sedimentary units of the coastal river environment. Further evidence allowing the identification of this anomalous unit has been the presence of wood fragments in oxidation state of *Rhyzophora harrisonii* also known as red mangrove.

The second sedimentary environment is localized between 103 and 200 cm of the cored sample and is interpreted as a gradually progressive deposition with very asymmetrical fine-grained sizes. This sediment includes carbonaceous fragments and rests of plants. It is composed of sandy silts with horizontal discontinued layers of very fine-grained sand of moderate energy with four different individual gradational contacts (at 142 cm, 180 cm, 184 cm and 198 cm), which indicate a weak tidal energy deposition. The woody rests of the mangroves correspond to those previously described in the first sample.

Sample Villamil 3

This sample is located northwest of Arenal and represents the closest site in respect to the shore with a distance of 580 m (Fig. 2). The identified sedimentary environments are the same as in sample Villamil 2. Coastal river section appears between 2 and 62 cm and interpreted as gradually interfered deposition with effects moderate and high energy. The rhythmic sequential deposition of sometimes coarse but mainly medium to fine-grained silt includes the presence of irregular shaped gypsum minerals indicating low energy transport of the sediments in suspension, correlating to the interpretation of the previous two samples. Below this sequence appear clasts and continued and interrupted layers of clay in silty sediment interfering with sandy silt sediments. The latter is overlying a layer of 7 cm in thickness composed dominantly of fragments of gypsum minerals being between 0.25 and up to 2 mm in diameter, being transported in a coarse-grained silt matrix.

An anomalous sedimentary event has been preserved in this sample in the interval of 51.5 until 55 cm of the core (Fig. 2, Fig. 3). This event is interpreted as a chaotic tide deposition of high energy, which can be correlated to the tsunami deposits identified in the previous two sampled cores. Rests of mangrove wood of the species *Rhyzophora harrisonii* in oxidation state as well as fragments of mollusks are also present in this anomalous unit.

Nonetheless, in this sample occurs the most convincing evidence of the tsunami deposit due to the presence of the benthonic foraminifer *Pullenia bulloides* (Fig. 4), as species of which habitat corresponds to abyssal depths of 3000 meters below the sea level (Gross, 2001; Sabbatini et al., 2004).

This microorganism does not appear in the platform of the Gulf of Guayaquil at all (Boltovskoy and Muñiz, 1975), allowing the conclusion that this species has been transported by refraction due to a tsunami wave and deposited subsequently in the interior part of the continent. This observation together with the sedimentary formation described excludes a potential consideration that this sedimentary deposition might by a result or generated by tempestites (Duke, 1990; Seilacher and Aigner, 1991; Madsen et al., 1993; Myrow and Southard, 1996; Myrow, 2005).

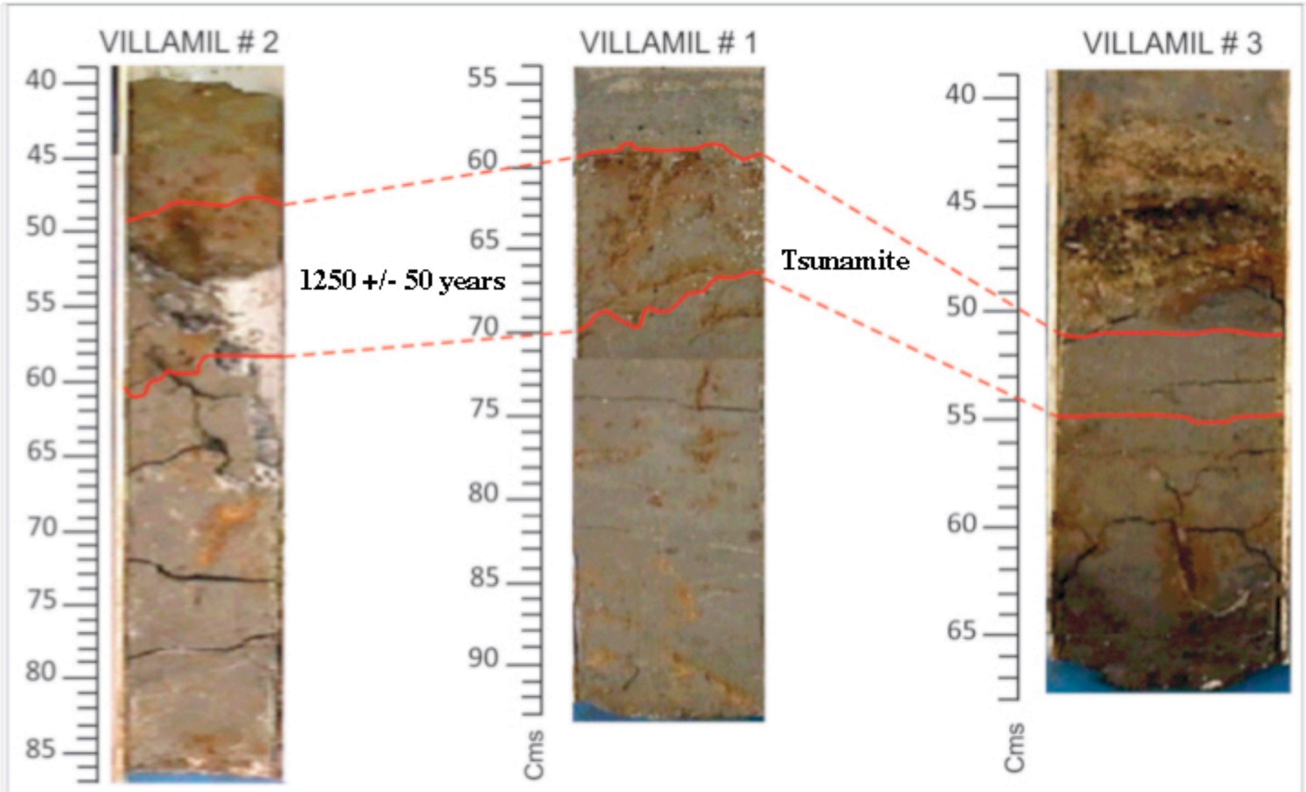

Fig. 3: Detailed indication of the tsunamigenic deposit within the stratigraphic profiles of cored samples Villamil 1, 2 and 3.

The second sedimentary environment being the sub-tidal estuary has been identified between 63 until 160 cm of the cored sample. This unit is composed of sandy silt, plant rests of *Avicennia germinans*, also commonly known as black mangrove and fragments of mollusks of the species *Crassostrea.*

This sedimentary environment is separated of the coastal river environment by well-defined deformational contacts of off-shots, which have been formed by density differences of the sediments. Four gradual contacts were identified at the interval of 98, 101, 120 and 122 cm of the sample Villamil 3 (Fig. 2, Fig. 3).

Fig. 4: Micro photo of foraminifera *Pullenia bulloides*.

b) Spectrometry

Four samples of different intervals have been taken for further chemical analysis with an ion microprobe and X-ray difractometer. All samples have been taken from one cored sample (Villamil 1) and correspond to levels shortly above (58 cm), within (60 and 66 cm) and shortly below (67 cm) the tsunami deposit in to determine their chemical composition.

The youngest sample at 58 cm includes salt crystals of 30 mm in size and quartz crystals of 70-100 mm in size inside a sandy silt sediment, which contains also rests of plants (values high in carbon and oxygen). Besides other minor minerals and their corresponding chemical composition, a high amount of iron reflects the oxidation state and brownish color of the sample.

The samples taken of the interval at 60 and 66 cm inside the tsunami deposit correspond to a sandy silt containing predominantly quartz minerals of 30-50 mm in size and a matrix composed of oxidized chlorite, potentially due to weathering of glauconite, having a concentration of up to 4% iron reflecting the composition of iron-bearing clay minerals, suggesting mixed deposition of marine and continental environments. A relatively high amount of iron of up to 48.5 wt % (together with some 17.01 wt % of carbon and 9.55 wt % of oxygen) has been detected in rests of contaminated mangrove rests of *Rhyzophora harrisonii.*

Below the tsunami deposit at 67 cm of the interval the presence of abundant quartz and salt minerals (50-100 mm in size) is notorious in this sandy silt sediment. Higher amounts of calcium and magnesium correspond to an evaporate environment, without any further importance.

c) Sedimentary rate of the area of Villamil and timing of the tsunami event

Based on the C^{14} dating of a wood sample at the interval of 145 cm of sample Villamil 3 determining an age of 3420 ± 40 years B.P., an approximate age for the tsunami deposit can be calculated by interpolation of the thickness of the profile of the cored sample with a constant sedimentation rate of 0.42 mm per year for the alluvial plains of Playas Villamil. Thus, the tsunami event appears to have occurred between 1300 - 1200 years B.P. The low sedimentation rate also explains the absence of mollusks in all cored samples corresponding the coastal river environment, as the mollusks of calcareous composition are exposed to a sub-aerial biota where they can be weathered and destroyed easily (Aguayo-Camargo, 1978). Obviously, the conservation of the foraminifera *Pullenia bulloides* encountered in the tsunami deposit is due to the rapid burial in a sub-oxic environment in sediments derived by tsunami waves (Fig. 4).

Inhabitants of this site affirmed, that the ocean has not advanced up to the alluvial plains in the last 70 years, except in periods of high precipitations and rain falls such as the "El Niño" phenomenon in 1982, in which the estuary got overflown sedimentation a mixture of sandy and silty material. The spit sites and the sequential changes of the deep sedimentary environments indicate that the study area corresponds to a regressive beach type with slow sedimentary deposition rates.

4. SUMMARY AND CONCLUSIONS

Extreme geological events are represented as recorded anomalies throughout stratigraphic history from the Precambrian until recent times usually appearing with a marked, distinctive horizon

(Lowe et al. 1989; Pope et al., 1996; MacLeod et al., 1997; Lowe et al., 2003; Morgan et al., 2006; Sawai, 2008; Rashi et al, 2011). One of these unusual extreme events has been identified and recognized in the cored sedimentary samples at General Villamil Playas. Taking into consideration, that no tsunami deposit has been identified from the last dozen tsunami impacts at the Ecuadorian shoreline of the last two centuries, potentially due to the relatively low sedimentation rate, leads to the assumption that only a major event some 1250 years ago could have deposited the anomalous unit marked as paleo-tsunami deposit found in the samples Villamil 1, 2 and 3. The low sedimentation rate explains also the absence of rests of mollusks in the sub-oxic environment of the upper parts of the cored samples, as the mollusks are easily destroyed and or weathered in this sub-aerial area.

Further biological, chemical, stratigraphic and sedimentary analyses provided essential criteria in the identification of an anomalous layer near the actual shoreline of the Gulf of Guayaquil. These criteria allowed completing a missing part of the paleo-historic record of this area and so enabling to reconstruct the paleo-environmental evolution of the studied region.

Three different sedimentary facies with variable energy effects have been identified with mainly silty sands or sandy silts as dominant sediments. Inside one of these facies an unusual horizon of a chaotic layer different to its upper and lower record has been recognized as a paleo-tsunami deposit.

This anomalous layer with a thickness between 3.5 and up to 10 cm at around half a meter of depth of the up to two meters long cored samples has been identified in all three samples of the General Villamil Playas area. The criteria which allowed the identification of the paleo-tsunami deposit with an age of around 1250 ± 50 years B.P. based on the calculated low sedimentation rate are various, including: a) depositional features such as "run-up" and "backwash"; b) structures of *Rhyzophora harrisonii* in oxidation state implying high salinity water present from deep sea areas; c) the presence of the foraminifera *Pullenia bulloides* of which natural habitat is located in the deep sea; d) fragments of mollusks, which are absent in other sedimentary levels; e) types of "rip-up" clasts; f) matrix of weathered chlorite, possibly due to degradation of glauconite; g) gradational and erosive stratigraphic contacts.

This is the very first time that such a deposit has been identified with the criteria listed above in the coast of Ecuador. As no such deposit has been identified in the two samples of the southern part of the Gulf of Guayaquil (Puerto Balao and Tenguel) we may suggest that the tsunami came from the western or northwestern side of the shoreline impacting the area of General Villamil Playas and could not be recorded in the other sites due to the presence of a natural barrier represented by the island of Puna.

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