ISSN 8755-6839

SCIENCE OF **TSUNAMI HAZARDS**

Journal of Tsunami Society International

Volume 39 **Number 1** **2020**

TSUNAMI GENERATION FROM MAJOR EARTHQUAKES ON THE OUTER-RISE OF OCEANIC LITHOSPHERE SUBDUCTION ZONES - Case Study: Earthquake and Tsunami of 29 September 2009 in the Samoan Islands Region.

George Pararas-Carayannis
Tsunami Society International

ABSTRACT

The present study examines the crustal deformational characteristics caused by earthquakes occurring primarily on the outer-rise of the oceanic lithosphere in zones of tectonic plate collision and subduction. Additionally it examines the possible reasons why more significant and catastrophic tsunamis are generated in such regions. The analysis is based primarily on observations of the extreme tsunami in the Samoan Islands region, which was generated by the large magnitude earthquake of 29 September 2009, which had its epicenter and tsunami generating area on the front end of the outer-rise of the seismically active northern end of the Tonga Trench and Arc. This is a region where there is greater obliquity of collision, substantial crustal deformation of the ocean floor, and a sharp change in direction of the zone of subduction towards the West. Also, this zone is characterized by extraordinary seismic activity of the oceanic slab, which subducts into the earth's mantle at the highest-known rate in the world. The 2009 outer-rise earthquake generated a tsunami which struck coastal villages and towns in Samoa, American Samoa and the Tonga Island Kingdom, causing extreme damage and many deaths. The present report documents the effects of the earthquake, the tsunami's source mechanism, past events in the region, and the tectonics of subduction along the northern segment of the Tonga trench. Additionally, the report provides a preliminary evaluation of tsunamis generated from other earthquakes on the outer-rise of other zones of subduction and deformation, but mainly on the upper north end of the Tonga-Kermadec trench and arc.

Keywords: *Oceanic lithospheric subduction; Tonga Trench and Arc; Tonga-KermadecTrench; Earthquake, Outer-rise crustal faulting and deformation; Tsunamis in the Samoa Region.*

1. INTRODUCTION

A major earthquake occurred on the 29 September 2009 in the Samoan Islands region with estimated moment magnitude (Mw) ranging from 8.0 – 8.3, a maximum Mercalli intensity of VI , and epicenter near the seismically active northern end of the Tonga Trench and Arc - a region where there is greater obliquity of tectonic collision and a sharp change in direction towards the West (Fig. 1). The earthquake was unusual in that it occurred on the outer-rise of the subducting oceanic plate, which is a region of stresses induced by the bending of the plate as it enters the trench. The region is also considered to be the earth's most active zone of mantle seismicity. According to reports from Apia in Samoa, the duration of shaking lasted for at least two minutes, which seems to be very long even for an earthquake of such high magnitude-unless there were a series of rapidly sequential indistinguishable sub-events that extended the perception of duration of ground motions.

The destructive tsunami that was generated, struck coastal villages and towns in Samoa, American Samoa and the Tonga Island Kingdom causing extreme damage and many deaths. Severe damage and deaths occurred at Pago Pago harbor, the village of Leone and elsewhere. A tsunami warning issued by the Pacific Tsunami Warning Center, did not reach the affected region in time for people to evacuate. The first part of this report documents the earthquake, provides a preliminary evaluation of the tsunami's wave heights and source mechanism, and a summary of past events in the region. The analysis in subsequent sections, examines the dynamics of subduction and the crustal deformational characteristics of earthquakes and faulting, occurring primarily on the outer-rise of the oceanic lithosphere in zones of tectonic plate collision, as well as the reasons why more significant and catastrophic tsunamis are generated in such regions.

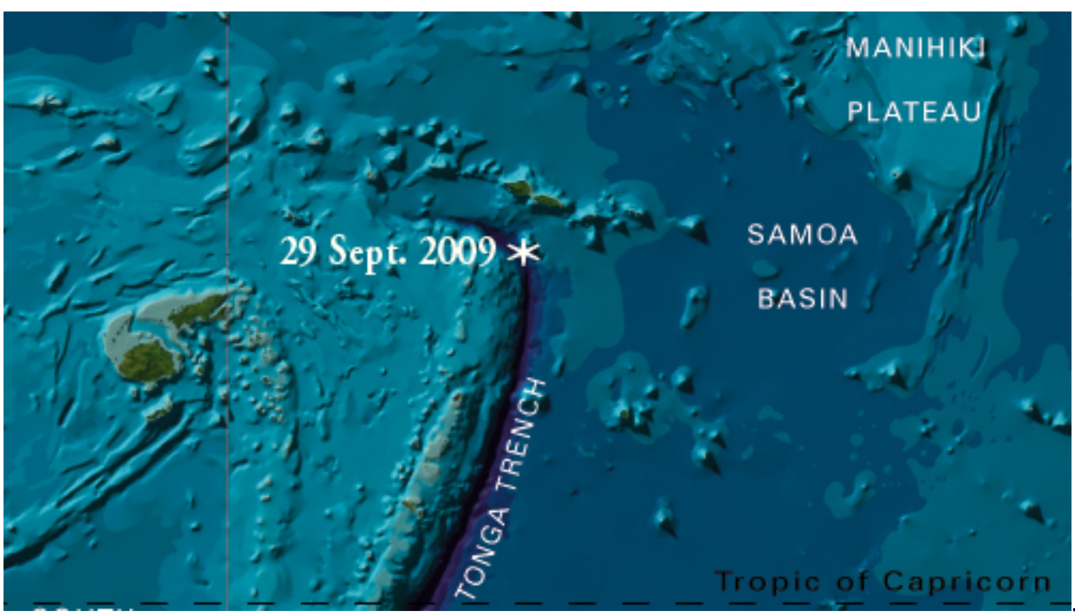

Fig 1. Epicenter of the 29 Sept. 2009 Earthquake at the northern end of the Tonga Trench.

2. THE EARTHQUAKE OF 29 SEPTEMBER 2009

Origin Time - 29 September 2009 at 17:48:10 UTC; 06:48:10 AM (local time).
Magnitude - The US Geological Service estimated the magnitude at 8.0. The Pacific Tsunami Warning Center put the quake's magnitude at 8.3.
Epicenter - 15.509 S, 172.034 W
Focal Depth - 18 km (11.2 miles) (USGS)

Fig. 2. Schematic of centroid moment tensor solution of the 29 September 2009 earthquake (USGS)

Distances from Epicenter (USGS) - 120 miles (190 kilometers) from American Samoa; and 125 miles (200 kilometers) from Samoa, with to 193 km (120 miles) S (189 degrees) from APIA, Samoa 199 km (124 miles) SW (226 degrees) from PAGO PAGO, American Samoa; 406 km (252 miles) NNE (31 degrees) from Neiafu, Tonga,185 km (115 miles) ENE of Hihifo, Tonga 710 km (440 miles) NNE of NUKU'ALOFA, Tonga 2700 km (1,680 miles) NNE of Auckland, New Zealand.

Aftershocks - A 5.6-magnitude aftershock occurred 20 minutes later. The main quake was followed by 14 aftershocks of magnitude 5.0 or higher.

Felt Motions - Fairly strong ground motions were felt throughout the islands of Samoa, American Samoa and northern Tonga. There were reports from Apia that the shaking lasted for at least two minutes. Such duration seems long even for an earthquake of high magnitude. Given the magnitude of 8 (USGS) or 8.3 (Pacific Tsunami Warning Center), the shallow focal depth and the length of rupture, the duration of ground motions could not have been greater than 50 to 60 seconds, with perhaps possible brief interruptions, unless there were sequential sub-events that extended the ground motions.

Death Toll and Damages - As of November 29, 2009, the reported death toll was about 160 but it may have been higher. Most of the deaths occurred in Samoa, in American Samoa and some in Niuatoputapu, in Tonga. Damaged telephone lines made it difficult to assess the casualties and the destruction from both earthquake and tsunami.

American Samoa - The tsunami waves flattened coastal villages and killed many people. At the National Park Service facilities many people were reported missing. Cars and people were swept out to sea. A large boat washed ashore and deposited at the edge of the coastal highway (Fig. 3).

Samoa - More than 110 people were reported dead. The beach village of Sau Sau Beach Fale was leveled. There was extensive destruction of buildings in Apia and damage to plantations outside of the city. Many of the residents reported cracks to their homes. Several landslides occurred in the Solosolo region of the main Samoan Island of Upolu. About 3,000 people were rendered homeless.

Fig. 3. A large boat washed ashore and deposited at the edge of the coastal highway.

2 a. Estimated Rupture Length and Crustal Displacements of the 29 September 2009 Earthquake.

The distribution of aftershocks, the quake's magnitude and focal mechanism analysis of the earthquake suggest that the rupture was as much as 175 kms long on one or more normal faults on the outer-rise of the subducting Pacific plate. Maximum displacements of as much as 7 meters were reported but available centroid moment tensor solutions (USGS) indicated an average of 3.6 meter vertical change.

3. THE TSUNAMI OF SEPTEMBER 29, 2009 IN THE SAMOAN ISLANDS REGION

The tsunami generated by the earthquake of 29 September 2009 was destructive along the coasts of Samoa, American Samoa and Tonga. It resulted in many deaths and left thousands of people homeless. Widespread damage was reported to the infrastructure at Pago Pago, American Samoa, in many parts of Samoa and on Niuatoputapu, Tonga.

American Samoa - The first tsunami wave arrived at Pago Pago in American Samoa, (approximately 250 km from earthquake epicenter) at 18:08 UTC, about 20 minutes after the earthquake. A five-foot tsunami wave swept into Pago Pago and surged inland about 100 meters before receding, leaving some cars and debris stuck in mud. Electricity outages were reported and telephone lines were jammed. In Fagatogo, the tsunami inundation extended to the town's meeting field and covered portions of the main highway. Also, there were numerous rock slides in the area.

The following peak-to-through wave heights were recorded: 3.14 m at Pago Pago (American Samoa); 1.40 m at Apia (Samoa); 0.47 m at Rarotonga and 8 cm at Penrhyn (Cook Islands); 14 cm at Nukualofa (Tonga) and 11 cm at Papeete (French Polynesia). However, wave heights on the open coasts were much higher. Only a 16-centimeter wave was recorded by the tide gauge in Honolulu, Hawaii. However, boaters at the Ala Wai Yacht harbor in Waikiki, observed a much greater sea level fluctuation.

Samoa - The southern coasts of Savai and Upolu Islands were hardest hit by the waves. Yet, in spite of extensive damage to villages on the two main islands of Upolu and Savaii, the people in the stricken area wanted to rebuild on the same sites.

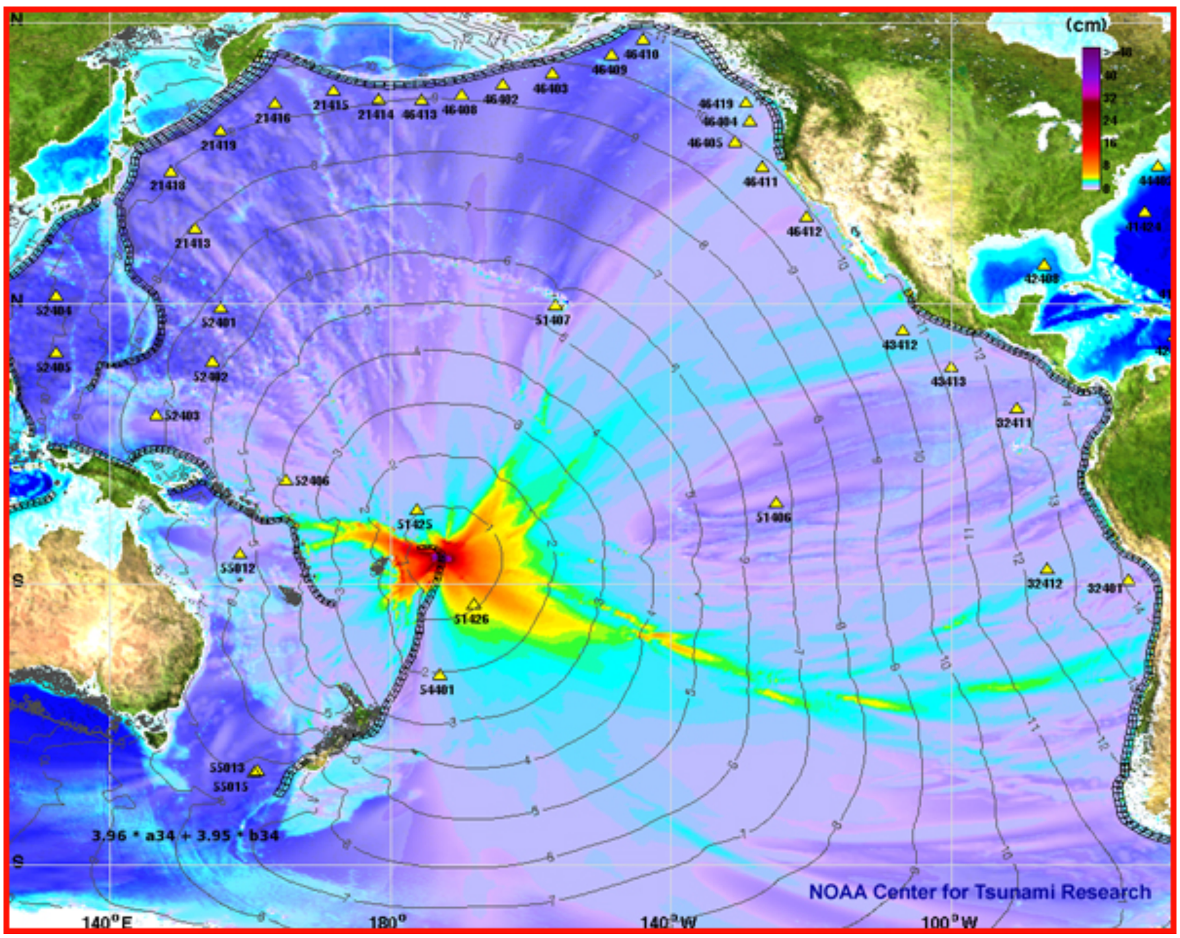

Fig. 4. The 29 September 2009 tsunami travel time chart. Location of DART buoys (Source: NOAA Center for Tsunami Research).

3a. Dart Recording of the Tsunami

As shown in Figure 4, in a little over one hour, the tsunami was recorded at DART® buoys 51425 and 51426. DART 51425 is located 370 Nautical Miles NW of Apia at(Lat: 9.49 degrees S. Long: 176.25 degrees W). DART 51426 is located at 400 Nautical Miles SE of Tonga (Lat: 22.99 degrees S. Lon: 168.10 degrees W). Based on tsunami source inferred from DART® data, forecast results were created in real time using the MOST model (Method of Splitting Tsunami) approximation. Subsequent numerical modeling based on additional centroid data, generated somewhat different results.

3b. Recent and Historic Earthquakes in the Tonga-Kermadec Region

There have been around 30 quakes of magnitude 7.0 or more along the Tonga plate boundary since 1900 (http://earthquake.usgs.gov/regional/neic). The most significant of these in the northern segment was the magnitude 8.5 earthquake of June 26, 1917. It was also an outer-rise earthquake with epicenter at 115.500 S, 173.000 W It generated a very destructive tsunami.

Another significant 7.5 magnitude earthquake occurred on 14 April 1957. Its epicenter was at S15.403 S, 173.129 W (Pararas-Carayannis & Dong, 1980). A shallow 7.5 magnitude earthquake in the same region occurred on 1 September 1981 at 15.112 S, 173.019 W

Also, there have been several significant earthquakes along the eastern subduction zone of the Tonga Trench and Arc. The largest to strike the Tonga region in recent times was a magnitude 7.2, deep (69 km) event which occurred on 22 June 1977 (UTC). Its epicenter was considerably further south at 22.91 S., 175.74 W, approximately 190 km to the southwest of the islands of Tongatapu and Eua. The earthquake caused extensive damage to houses, public utilities, churches and many buildings, as well as to the Vuna Wharf in Nuku'alofa. There was no report that any tsunami was generated and none would have been expected given the depth of the hypocenter.

Another very deep focus earthquake occurred on 9 March 1994. This earthquake had a moment magnitude Mw= 7.6 and depth of 564 km — also too deep to generate any tsunami. At least 50 strong but very deep aftershocks followed the main event.

On 3 May 2006, a magnitude 7.9 earthquake with focal depth of 55 km (34.2 miles) struck with epicenter at 20.130 S, 174.164 W - about 160 km NE of Nuku'alofa (capital of Tonga), 165 km (100 miles) south of Neiafu, Tonga 465 km (290 miles) south of Hihifo, Tonga and 2145 km (1330 miles) NNE of Auckland, New Zealand. This was the strongest felt earthquake in recent years. According to a report from Neiafu, 180 miles north of Nuku'alofa, the quake's strong motions lasted for about 90 seconds. This earthquake generated a small tsunami (Pararas-Carayannis, 2006).

4. SUBDUCTION ALONG THE NORTHERN END OF THE TONGA TRENCH

The westward movement of the Pacific oceanic plate and its unusually rapid subduction beneath the Australian plate at the Tonga Trench, is the reason for extensive seismic activity in this region. The convergence rate across the trench vary but, at the northward segment it reaches to a maximum of 240 mm per year (Bevis et al., 2002). Thus, many researchers consider this region as being the earth's most active zone of mantle seismicity. As shown in Figure 5, the 29 September 2009, occurred near the seismically active northern end of the Tonga Trench and Arc where there is greater obliquity of collision and a sharp change in direction towards the West. As stated, this earthquake was particularly unusual in the sense that it did not occur on the inter-plate thrust fault within the subducting Pacific plate but further out on the outer-rise region.

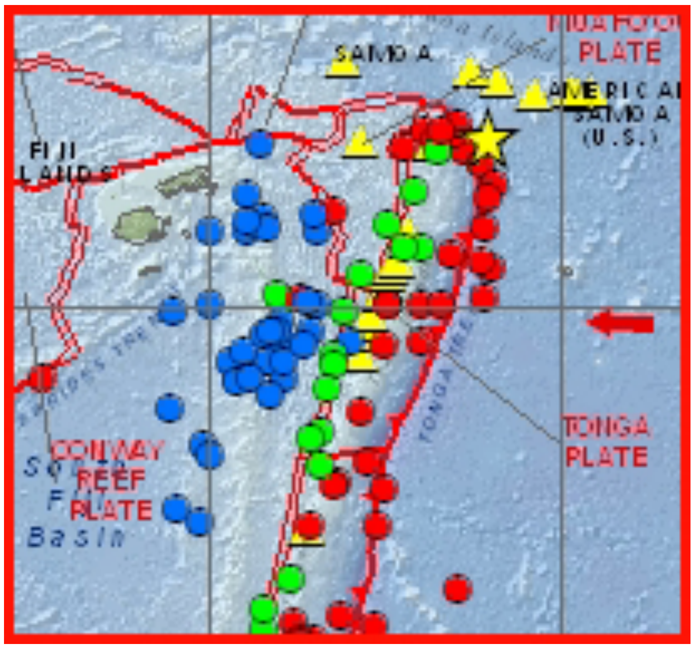

Figure 5. Epicenter of the 29 September 2009 tsunamigenic earthquake on the outer-rise of the northern end of the Tonga Trench and Arc.

The dynamics of subduction have been studied extensively. The outer-rise is a geomorphological feature on the subducting oceanic plate which usually parallels the inter-plate thrust fault of the subduction zone. It is formed further out on the front of the oceanic plate by extreme crustal stresses that force tensional flexing and bending of the subducting plate from inter-plate earthquakes, which energize existing, near failure, normal faults. The significant stresses that cause this bending range from extensional at the top to compressional at its base (Naliboff et.al., 2013).

The 29 September 2009 earthquake was an outer-rise event. As shown in Figure 5, there have been a number of similar outer-rise earthquakes along the northern section of the Tonga Trench. However, most had north-south orientation of displacements and of tsunami areas of generation, the waves that were generated did not affect as much the inhabited islands of the Samoan region.

Outer-rise earthquakes are known to generate destructive tsunamis in this region of the Tonga trench and elsewhere. For example, the earthquake of 1917 - which occurred somewhat west of the 29 September 2009 event was also an outer-rise event (Pararas-Carayannis, 1980). It had similar characteristics and generated an equally destructive tsunami.

Also, the 8.4 magnitude, Sanriku earthquake of 2 March 1933, occurred on the outer-rise of the subducting plate and generated a devastating tsunami in Japan that resulted in more than 3,000 deaths and considerable damage as far away as the island of Hawaii. Similarly, the 19 August 1977 Lesser Sunda Islands (Nusa Tenggara Islands - Sumba, Sumbawa) earthquake was also an outer-rise event which generated a large tsunami that resulted in 189 deaths and was destructive along the coasts of Sumba, Sumbawa, Lombok and Bali. The effects of crustal displacements of the 1977 earthquake were not confined to the tectonic boundary region but extended to the subducted plate itself, resulting in extensive faulting, uplift or subsidence, on offshore islands (Pararas-Carayannis, 1977).

As stated, the earthquake of 29 September 2009 occurred near the earth's most active zone of mantle seismicity - which arises from the westward subduction of the Pacific plate beneath the Tonga trench and the Australia plate. Convergence rates across the Tonga-Kermadec Trench and Arc, increase northward to a maximum of 240 mm per year. The extraordinary seismic activity of the subducting slab is probably related to this unusually rapid subduction (Bevis et al., 2002).

5. TECTONIC SETTING OF THE TONGA-KERMADEC SUBDUCTION REGION

The overall tectonics of the Tonga-Kermadec region from about 15 degrees south to 38 degrees longitude are dominated by the convergence of the Pacific and Australia plates at an average rate of 86mm/year. However, and as previously mentioned, a maximum of 240 mm per year occurs at the North end of the Tonga segment of the trench where the 29 September 2009 earthquake occurred. The active westward movement of the Pacific oceanic lithosphere underneath the Australian plate has formed an extensive tectonic boundary. This boundary consists of the Tonga-Kermadec Subduction Zone - marked by a great trench and its associated adjacent volcanic arc. The eastern edge of the broad Australia plate on the other side of the volcanic arc, is a collection of smaller microplates that move with respect to each other, and with respect to the Pacific plate and the interior of the Australia plate.

The entire Kermadec-Tonga Arc is an intra-oceanic arc (Fig. 6). It is one of the longest on earth, extending for almost 2500 km from New Zealand to Samoa. It is bounded on both sides by oceanic crust. The arc includes at least 100 volcanoes, most of them submarine (Baker, 2004). As shown in Figure 6, the Tonga-Kermadec Trench and Arc consists of two major segments. The Tonga (TO) segment is the northernmost half based of the presence of the Louisville Aseismic Ridge located on the subducting Pacific plate, and the Kermadec segment (KE) in the southern half.

As stated, this is the earth's most active zone of mantle seismicity.

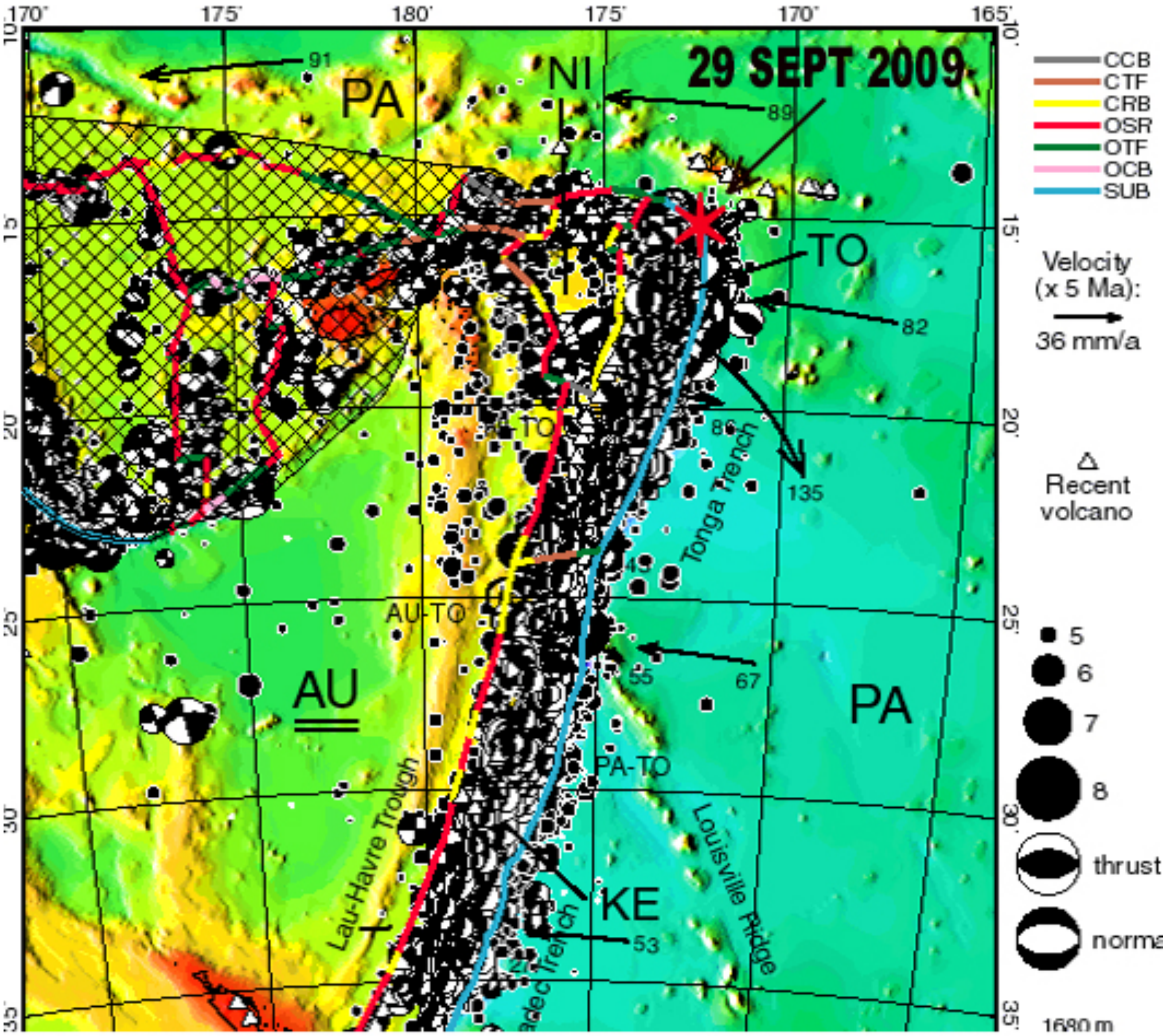

Figure 6. *The Tonga-Kermadec Trench and Arc. Seismotectonics, Kinematics and Plate Boundaries of the Tonga subplate seismic activity along the Tonga Trench and its northern boundary near the region where the 29 September Earthquake occurred. TO-Tonga plate, PA-Pacific plate. KE-Kermadec plate, AU-Australian plate (modified graphic after Bird, P. (2003) Figure 11).*

Figure 7 below, is a schematic illustration depicting the intra-oceanic convergence tectonics along the Tonga Trench and the adjacent fore-arc between 14 to 27 degrees South latitude.

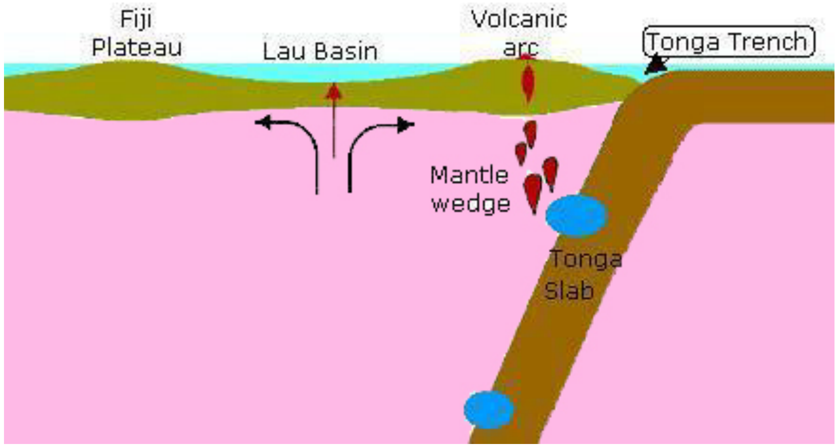

Figure 7. Illustrations of stresses along a cross-section in the middle segment of the Tonga trench from Pacific plate subduction and from the spreading center of Lau Basin (modified USGS graphic). Intra-oceanic convergence tectonics along the Tonga Trench and the adjacent forarc between 14 South and 27 South Latitude.

Figure 8 is another schematic illustration depicting the intra-oceanic convergence tectonics in general, and the probable deformations of sedimentary layers on the accretionary prism in the front of the overriding volcanic arc - similar to those near the Tonga-Kermadec Trench and Arc - and on the outer-rise of the subducting plate.

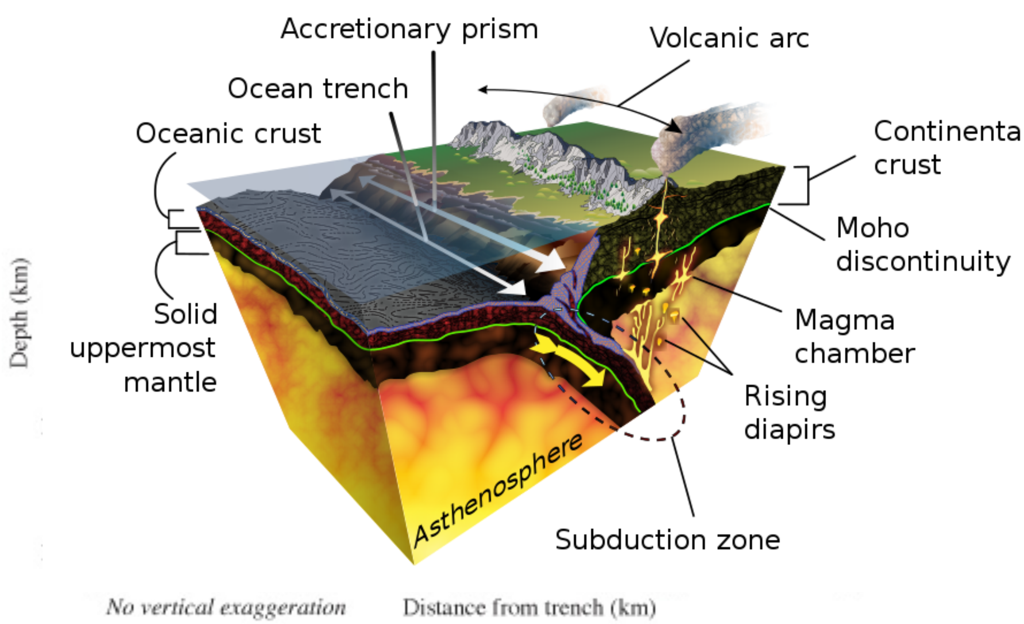

Figure 8. Schematic illustration depicting the intra-oceanic convergence tectonics in general (modified Wikipedia graphic).

Figure 8 illustrates the tectonic interactions of the oceanic lithosphere with the volcanic arcs along zones of subduction, which contribute to enhancement of tsunami generation on the outer rise of the oceanic lithosphere, and to sedimentary layer collapses on the accretionary prism of the overriding volcanic arc.

To summarize, the intra-oceanic convergence tectonics along the Tonga Trench and the adjacent fore-arc between 14 S and 27 S Latitude - mentioned previously - are somewhat complicated and vary from North to South. The Pacific plate subducts westward beneath the northeast corner of the Australian plate at about 240 mm per year - which is quite high. Also the submarine morphology of the Tonga Trench indicates changes from relatively normal convergence in the north, to oblique convergence in the south. Anomalies are greater around 26 degrees South Latitude which marks the boundary of the Tonga and Kermadec fore-arcs. Furthermore, along the entire length of the Trench axis, there are numerous transform faults at right angles which indicate that earthquakes in the region may be limited in rupture length.

What is also significant in the central region is the high number of deeper earthquakes, along a rather steep subduction boundary on the east side. The cross-sectional chart across the middle part of the Tonga Trench (Fig. 7), illustrates the tectonic complexity of this region, the steepness of the subducting plate, the lateral heterogeneity of structural features, and the stresses from both the spreading center of Lau Basin on one side of the Arc and the stresses from the subducting slab of the Pacific plate. The subduction along this central segment has created very deep bathymetry along the trench and an extensively deformed volcanic arc on the other side.

As stated, the 29 September 2009 earthquake occurred on the northern segment of the Tonga Subduction Zone where large earthquakes occur frequently. The tectonics in this northern region where the subduction zone changes direction are different than those of the central segment. The rates of crustal movements are different and, as expected, subduction becomes more oblique and shallower, thus resulting in more destructive and potentially tsunamigenic earthquakes. Fault mechanism solutions indicate that the earthquake of 29 September 2009, occurred along normal fault ruptures at the outer-rise of the subjecting oceanic plate, as shown in previous figures 5 and 6.

The following section reviews the structural deformation changes that may have triggered by the 2009 earthquake on the outer-rise of the subducting plate, which contributed in enhancing tsunami generation. Sediment movement and collapsed sedimentary layers on the accretionary prism near the Tonga trench probably contributed as well to the higher waves of the tsunami.

6. EARTHQUAKE-INDUCED STRUCTURAL DEFORMATION OF THE OUTER-RISE OF THE SUBDUCTING OCEANIC LITHOSPHERE - CONTRIBUTION TO ENHANCED TSUNAMI GENERATION.

As stated, stresses of tectonic plate convergence of the oceanic lithosphere with a continental plate or a volcanic arc, result in the buckling of the crust and in structural deformations that are particularly more significant along the front of the outer-rise region of the subducting oceanic plate. In this outer rise region there is development of many normal faults and influence on near-trench décollement propagation. Also, faulting on the accretionary prism of the overriding plate pushes sediments towards the trench in a horst and graben structure that allows sediment that reaches the trench to be deposited and carried downward. This faulting also breaks up seamounts as they approach the trench. The sudden creation of horsts and grabens by an earthquake contribute to disturbances of the water column, thus also contributing to the enhancement of tsunami generation.

Such structural deformation occurred on the outer rise of the Pacific oceanic plate along the Japan Trench, and possibly contributed to subsequent aftershocks - even outside the tsunami generating region when the Tohoku-Oki earthquake of March 11, 2011 struck off the island of Tohoku in Japan (Pararas-Carayannis, 2014; Boston et. al., 2014), as well as along other tectonic plate convergence zones. Slumping of near normal faults on the outer rise, as well as bookshelf failure of normal faults in sedimentary layers of the accretionary prism on the other side of the trench, contribute to the tsunami generation enhancement as postulated by the evaluation of the 2011 Japan tsunami (Pararas-Carayannis, 2014), and as subsequently determined by multichannel seismic reflection analysis and multiple bathymetric surveys (Boston et. al., 2014).

Similarly, the 29 September 2009 earthquake near the Tonga-Kermadec Trench and Arc as illustrated in Figures 5, 6, 7, 8, and 9, caused buckling and crustal deformations of thick sedimentary layers on the accretionary prism in the front of the overriding volcanic arc, but mainly on the outer-rise of the subducting plate. Combined these crustal deformations enhanced the height of the destructive tsunami waves that struck the islands in the region.

6a. Numerical Modeling of the Tsunami Generating Source Area

Furthermore, the orientation of the tsunami generating area of the 29 September 2009 earthquake - as illustrated by numerical modeling at Tohoku University - of two postulated scenarios of the tsunami generating areas (Figures 10 and 11) indicate how its orientation and directivity contributed to the propagation of the higher waves that resulted in the destructiveness of coastal villages and towns in Samoa, American Samoa and the Tonga Island Kingdom.

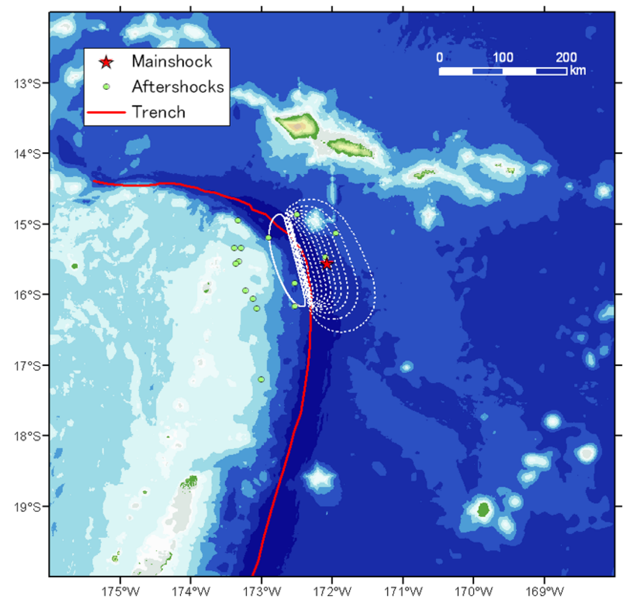

*Figure 10. Case 1. Tohoku University, (USGS data), Mo = 1.2 x 10**21 Nm; Fault Length / Width : 150 km / 75 km; Source Mechanism (Strike, Dip, Slip) = (345, 52, -61) Reference:USGS Dislocation: 3.6 m. http://www.tsunami.civil.tohoku.ac.jp/hokusai3/J/events/samoa_090930/source_case1.png*

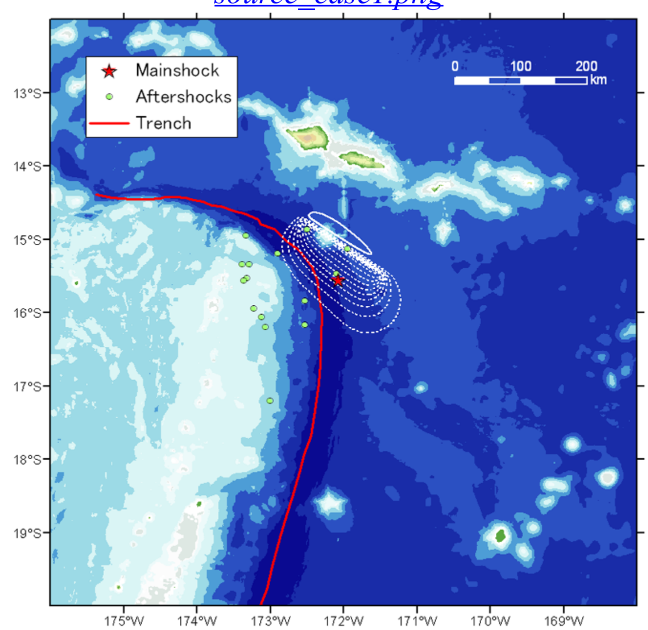

*Figure 11. Case 2 Tohoku University, (USGS DATA, Mo = 1.2 x 10**21 Nm Fault Length / Width : 150 km / 75 km; Source Mechanism (Strike, Dip, Slip) = (124, 46, -120) Reference :USGS Dislocation : 3.6 m http://www.tsunami.civil.tohoku.ac.jp/hokusai3/J/events/samoa_090930/source_case2.png*

The diagrams shown in Figure 12 illustrate the horizontal and vertical distribution of earthquake epicenters on the surface and hypo-centers along a cross-section that was taken on the Tonga segment of the trench by a recent study. The cross-section is somewhat south of the May 3, 2006 earthquake, but the diagrams show the high incidence of deeper focus earthquakes in the region and the steepness of the downward bending Pacific oceanic plate beneath the Australian plate. The epicenter and hypocenter of the May 3, 2006 have been plotted on these diagrams.

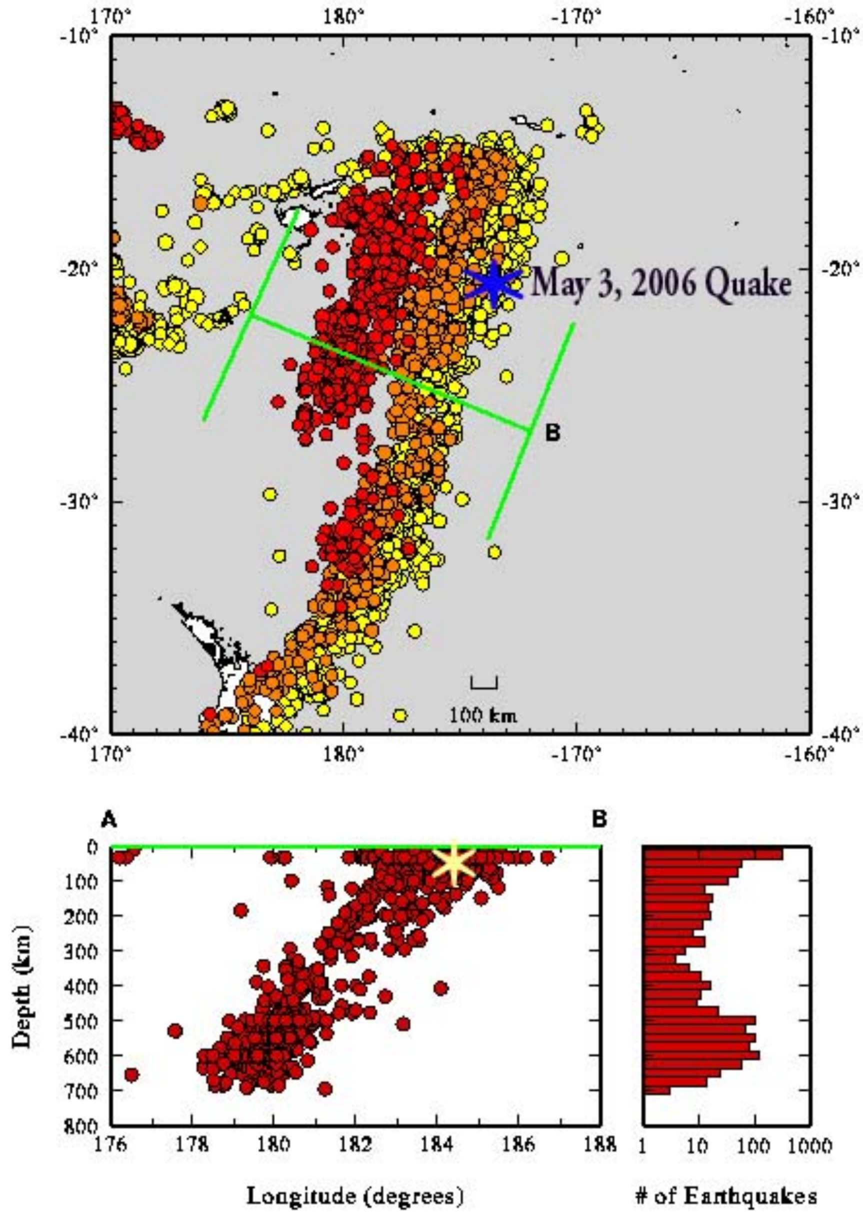

Figure 12. Cross-section along the southern Kermadec-Tonga Arc (modified graphic from www.seismo.berkeley.edu).

7. HISTORIC TSUNAMIS IN THE REGION

Extensive fracturing along the Tonga Trench, form natural asperities may constrain an earthquake's rupture length. Shorter ruptures and greater focal depths limit the likelihood that tsunamis generated in this region will have a Pacific-wide impact. Most of the tsunamis generated in the past were local events. Yet, in spite of the obliquity of the northern portion of the Tonga Trench and Forearc, a large magnitude earthquake could rupture two or more segments and produce a larger tsunami - although very infrequently. Most of the large magnitude earthquakes along the eastern boundary of the Tonga subduction zone, occur at greater focal depths and - as already stated - none of the historical earthquakes in this region are known to have generated a significant Pacific-wide tsunami. The only exceptions may be the November 17, 1865 and the April 30, 1919 Tongan earthquakes which generated tsunamis that were observable visually at great distance. However, this is not the case along the northern segment where subduction changes direction and obliquity. Destructive local tsunamis can be generated. Pacific-wide tsunamis are also possible from this region, although they do not pose a significant, far field threat.

Review of historic records indicates that the earthquake of June 26, 1917, with an estimated Ms magnitude of 8.4, was the largest ever in this area. This was also an outer-rise event on the northern end of the Tonga Trench. It generated a tsunami that had an observed local, maximum height of 12 meters (Pararas-Carayannis & Dong, 1980). This tsunami reached Japan where the maximum recorded height at Kushimoto was 1 meter.

7a. Evaluation of the Earthquake and Tsunami Source Mechanisms of the 29 September 2009 and of Future Events.

As previously stated, at the northernmost segment of the Tonga subduction zone near the area where the September 29, 2009 earthquake occurred, the direction of convergence and subduction change in a westward direction. Earthquake distribution and source-mechanism determinations for 57 events along a narrow belt of high seismicity indicate a progressive downwarping and tearing of the Pacific plate as it enters the northern Tonga subduction zone. It is also indicative of the shoaling of the subducted slab and of dip-slip faulting along near-vertical planes oriented 285 degrees - coinciding with the observed direction of plate convergence. In fact, specific analysis of 21 events with focal depths of aftershocks ranging from 18-57 km, and of the 7 April 1995 (Ms =8) event and aftershocks, suggests that the Pacific plate is downwarped prior to the initiation of tearing - a process which may extend through the entire thickness of the oceanic lithosphere (Millen and Hamburger, 1998).

It has also been suggested that the northern Tonga ridge is the boundary of a rigid microplate (Bevis et al., 2002). The suggestion appears to hold true. Such microplate rigidity appears to be responsible for stresses that have resulted in the crustal bending and have formed the previously-mentioned extensive outer-rise on the Pacific plate before it enters the subduction zone at a rather steep angle. Oblique convergence may be also responsible for some rotation of the Tonga microplate.

As previously indicated, this section of the outer rise is apparently traversed by several large, normal faults at different phases of potential failure. Significant tsunamigenic earthquakes may be triggered on this outer-rise region by the overall stresses of convergence as well as from stress transference from inter-plate thrust earthquakes occurring closer to the subduction boundary. Apparently, the 29 September 2009 earthquake resulted from such a large-scale failure of not one, but of several E-W trending normal faults on the outer-rise that parallel the trench. Failure of large normal faults on the outer rise can be very effective tsunami generators as they result usually in larger scale, crustal, vertical displacements and more extensive slip than earthquakes that occur closer to the convergence boundary. Also, the relatively shallow focal depths of such earthquakes on the outer rise, contribute to greater tsunamigenic efficiency. This is evident from both the 1917 (12 meter tsunami) and the 2009 earthquakes in this northern region of the Tonga microplate, as well as in other regions in Japan, Indonesia and elsewhere (Pararas-Carayannis, 1977, 1980, 1994).

Also, at the outer-rise there may be transform faults at oblique angles to the overall tectonic trend and these may be asperities that may have limited the September 29, 2009 earthquake's rupture length and altered its source characteristics - thus resulting in differences in the centroid moment tensor solutions. The centroid solutions suggest two possible source geometries that differ mainly in orientation (Hong Kie Thio and Paul Somerville, 2009). However, it is possible that none of the centroid solutions depict all the source characteristics, particularly if there was rotation or a slight extrusion of crustal material along a transform fault at the southeastern end of the designated source. Such source mechanism could account for the abnormal tsunami wave recorded at the DART gauge to the south.

Therefore, any discrepancies in the results of numerical tsunami modeling studies can only be explained, if we assume that the centroid solutions of source parameters may not reflect accurately the characteristics of an outer-rise event that involved a rather complex generating mechanism - which may have included rotation, several ruptures and crustal offsets. However, in spite of possible anomalies that cannot be properly justified, the overall modelling results give a fairly good picture of the tsunami's flux energy and directions of maximum propagation as illustrated by Figures 10 and 11.

7b. Dimensions of the Source Area of the Tsunami of 29 September 2009 on the Outer-Rise of the Subducting Oceanic Lithosphere at the Northern End of the Tonga-Kermadec Trench.

Based on centroid solutions the dimensions of the tsunami generating area can be approximated by an ellipsoid with major and minor axes. Thus, the total tsunami generating area for this event was estimated to be 28.260 sq. km.

7c. Modelling Studies of the 29 September 2009 Tsunami

Based on centroid solutions for source characteristics, preliminary modelling studies were carried out by several other researchers using three different numerical codes: the SWAN-JRC code, the HyFlux2 code which solves the equations with a different numerical method which is particularly relevant for inundation calculations; and the TUNAMI2 code, of Prof. Imamura (Annunziato et al., 2009).

These calculations were compared with the results obtained by the NOAA forecast MOST model (Method of Splitting Tsunami).

Subsequent numerical modeling studies of tsunami heights were carried out by other researchers (Thio & Somerville, Oct. 2009; Tohoku University, Oct. 2009) using the centroid and seismic moment information from Dr. Jascha Polet (Cal Poly, Pomona)(Magnitude 9, 15.321 South, 172.103 East;Strike -30.2, dip 50, slip -82) and from USGS, respectively.

Based on available centroid moment tensor solutions (USGS) that give different dimensions and orientations of tsunami sources, scientists at the Disaster Control Center of Tohoku University in Japan, used the Leap-frog Finite Difference Method (the TUNAMI-CODE they have developed) for their modelling study. The Leap-frog Finite Difference Method makes use of the non-linear shallow water equations, with a spatial grid size of 30 seconds and GEBCO bathymetry. The previous Figure 10 and the following Figure 11, illustrate the two different tsunami source regions that were used for their calculations which, as expected , generated somewhat different results.

Both cases involved a different interpretation of source characteristics, orientation and displacements which indicates uncertainties involving the tectonic interactions in this northern segment of the Tonga Trench and Arc. The USGS centroid moment tensor solutions are best double couple estimates based on data from 134 stations.

8. CONCLUSIONS

Larger magnitude earthquakes with shallow focal depth occurring on the outer-rise of the oceanic lithosphere in zones of tectonic plate subduction with high rates of collision, are triggered by stresses induced by the bending of the plate as it enters the adjacent trench region. Such outer-rise earthquakes appear to be associated with a variety of crustal deformational characteristics of the ocean floor, thus generating more destructive tsunamis than earthquakes which occur on the overriding tectonic plates or on volcanic arcs. The 29 September 2009 earthquake in the Samoan Islands region was such a shallow outer-rise event on the front end of the seismically active northern end of the Tonga Trench and Arc - a zone of extraordinary seismic activity of the oceanic slab, which subducts into the earth's mantle at the highest-known rate in the world. The tsunami that was generated had azimuthal orientation on the outer-ridge which favored propagation of its more destructive waves towards the islands of Samoa, of American Samoa and of the Tonga Island Kingdom. This is a region of the Tonga Trench and Arc where there is greater obliquity of collision, crustal deformation, and a sharp change in direction of the zone of subduction towards the west.

Although there is still a great deal of uncertainty regarding the actual ocean floor displacements and the source mechanism of tsunamis generated on the outer-rise of the oceanic lithosphere in zones of tectonic plate subduction, the present study postulates that the bending of the oceanic lithosphere involves bookshelf failures, ruptures of normal faults, thrust faults, and collapses of other structural features, mainly on the front end region of the oceanic lithosphere, as supported by numerical modelling results. In reference to the 29 September 2009 event, a subsequent analysis may be required to determine estimates of energy that went into tsunami generation and to attempt to reconcile results obtained by numerical modeling with the recording of the tsunami at DART buoy 51326.

A subsequent analysis may examine the geologic evidence of other regions of tectonic collisions and oceanic subduction with high rate of convergence of as much as 20 to 30 millimeters/year, similar to that which occurs at the Eastern Segment of the Northern Caribbean Margin - where large tsunamis were generated in prehistoric times (before 1400 AD) along the northern margin of Puerto Rico.

REFERENCES

Annunziato A., Franchello G., E. Ulutas E., and De Groeve T,, 2009. The 29 SEPTEMBER 2009 SAMOA TSUNAMI. Joint Research Centre, European Commission report.

Baker, Edward T., 2004. Exploring for Hydrothermal Systems Along a Submarine Volcanic Arc. NOAA Vents Program. Web report.

Bevis M., Taylor F.W., Schutz B.E., Recy J., Isaks B.L.. Helu S., Singh R., Kendrick E., Stowell J., Taylor B., & Calmantli S., 2002, Geodetic observations of very rapid convergence and back-arc extension at the Tonga arc. Nature 374, 249 - 251 (16 March 2002)

Bird, P. (2003) Figure 11. An updated digital model of plate boundaries, Geochemistry Geophysics Geosystems, 4(3), 1027, doi:10.1029/2001GC000252.

Boston B., Moore G.F., & Nakamura, Y,m 2014. Outer-rise normal fault development and influence on near-trench décollement propagation along the Japan Trench, off Tohoku. December 2014, 66:135

Disaster Control Research Center, 2009. Modeling the Tsunami of 30 September 2009 in Samoa islands. Preliminary Report, Tohoku University.

Millen, D. W. and Hamburger, M. W., 1998. Seismological evidence for tearing of the Pacific plate at the northern termination of the Tonga subduction zone, Geology; July 1998; v. 26; no. 7; p. 659-662.

Naliboff J.B., Billen M.I., Gerya T., and Saunders, J., 2013. Dynamics of outer-rise faulting in oceanic-continental subduction systems. Geochemistry, Geophysics, Geosystems, Vol. 14, Issue 7, May 2013 https://doi.org/10.1002/ggge.20155

Pararas-Carayannis, G., 1977, Indonesian Earthquake and Tsunami of August 19, 1977, Intern. Tsunami Information Center Report, Abstracted article in Tsunami Newsletter, Vol. X, No. 3, September, 1977.

Pararas-Carayannis, G. & B. Dong, 1980. Catalog of Tsunamis in the Samoan Islands. International Tsuanmi Information Center Report. June 1980, pp. 75.http://www.drgeorgepc.com/TsunamiSamoaIslandsCatalog.pdf

Pararas-Carayannis, G. 1994. THE EARTHQUAKE AND TSUNAMI OF AUGUST 19, 1977 IN INDONESIA. http:/www.drgeorgepc.com/Tsunami1977Indonesia.html

Pararas-Carayannis, G., 2006. EARTHQUAKE AND TSUNAMI OF MAY 3, 2006 IN TONGA http://www.drgeorgepc.com/Tsunami2006Tonga.html

Pararas-Carayannis G., 2014. The Great Tohoku-Oki Earthquake and Tsunami of March 11, 2011, in Japan. Pure Appl. Geophys. 171, 3257-3278, Springer, DOI 10.1007/s00024-013-0677-7

Hong Kie Thio and Paul Somerville, URS, October 2, 2009 (updated Oct 7).September 29, 2009 Mw 8.0 Samoa Earthquake – Preliminary Tsunami Wave Height Modeling Results

Wright D. J., Bloomer S H., MacLeod C. J., Taylor B., and A. M. Goodliffe, 2000. Bathymetry of the Tonga Trench and Forearc: A Map Series. *Marine Geophysical Researches,* 21(5): 489-512, 2000.