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EVALUATION OF TSUNAMI SOURCE MECHANISMS ALONG THE TONGA TRENCH AND VOLCANIC ARC – Case Study: Earthquake and Tsunami of 29 September 2009

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ABSTRACT

The present report provides an evaluation of the tectonics of the upper part of the Tonga Trench and Volcanic Arc Region. The overall tectonics of the region are dominated by the convergence of the Pacific and Australia plates. The active westward movement of the Pacific oceanic lithosphere underneath the Australian plate has formed an extensive tectonic boundary. The boundary consists of the Tonga-Kermadec Subduction Zone, marked by a great trench and its associated adjacent volcanic arc. The eastern edge of the Australia plate is a collection of smaller micro-plates that move with respect to each other, and with the Pacific plate and the interior of the Australia plate. Many earthquakes along the boundaries of these tectonic boundaries have generated relatively small tsunamis. However, on 29 September 2009 a major 8.3 Richter magnitude earthquake near the upper segment of the Tonga trench generated an unusually destructive tsunami. Large waves struck coastal villages and towns in Samoa, American Samoa and the island Kingdom of Tonga, causing extreme damage and many deaths at Pago Pago harbor, the village of Leone and elsewhere. The destruction by this particular event was unprecedented. A tsunami warning issued by the Pacific Tsunami Warning Center did not reach the affected region in time for people to evacuate. The following report documents the tectonics of subduction along the northern segment the Tonga Trench and Volcanic Arc, the source mechanism of the 2009 tsunami, and a brief history of past events. Furthermore, and in view of the tsunami generated by the 15 January 2022 eruption/explosion of the submarine volcano Hunga-Tonga-Hunga-Ha'apai near Tonga, the present report provides a preliminary evaluation of stresses along a cross-section in the middle segment of the Tonga trench from Pacific plate subduction along the spreading center of Lau Basin, for a report under preparation pertaining to tsunami generation mechanisms along the adjacent volcanic arc.

Key Words*: Tonga-Kermadec Subduction Zone*, *29 September 2009 Earthquake Tsunami*

1. INTRODUCTION

The overall tectonics of the Tonga-Kermadec subduction region are dominated by the convergence of the Pacific and Australia plates at an average rate of 86mm/year. The active westward movement of the Pacific oceanic lithosphere underneath the Australian plate has formed an extensive tectonic boundary. The 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 is a collection of smaller micro-plates that move with respect to each other and with respect to the Pacific plate and the interior of the Australia plate.

A major earthquake occurred on 29 September 29, 2009 in the Samoan Islands region (Fig. 1). A destructive tsunami struck coastal villages and towns in Samoa, American Samoa and the Tonga island Kingdom, causing extreme damage and many deaths. A tsunami warning issued by the Pacific Tsunami Warning Center, did not reach the affected region in time for people to evacuate. Severe damage and deaths occurred at Pago Pago harbor, the village of Leone and elsewhere. The following report documents this earthquake, 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 the tsunami's source mechanism.

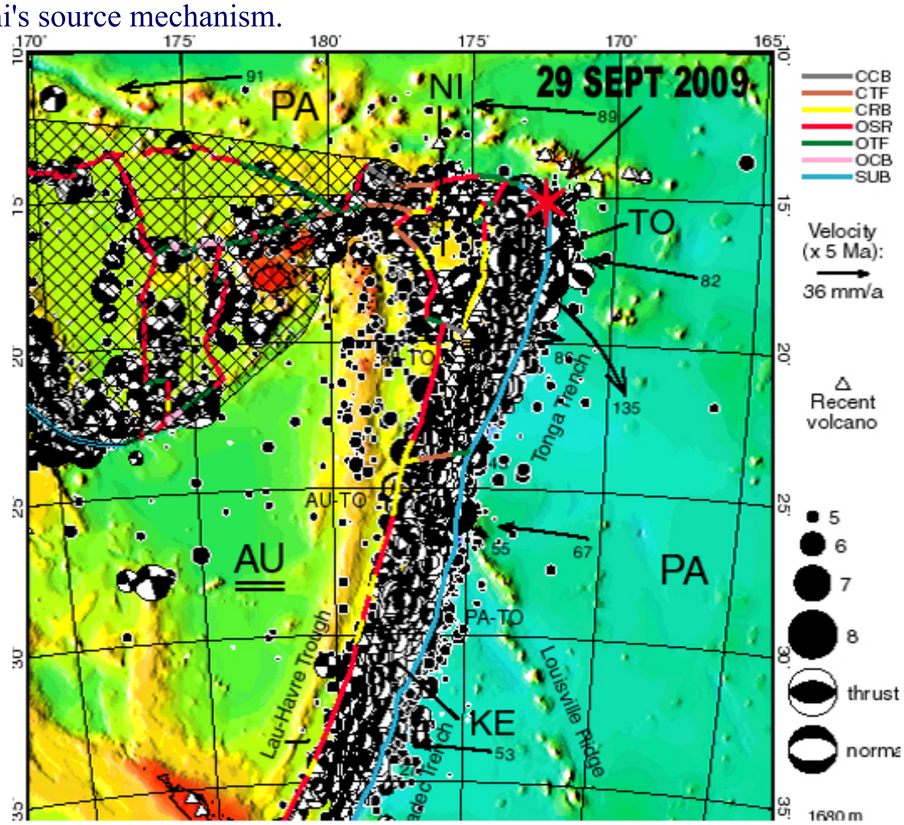

Fig. 1.The Tonga-Kermadec Trench and Arc. *Seismotectonics, Kinematics and Plate Boundaries of the Tonga subplate seismic activity along the Tonga Trench and its northern boundary near the region where the 29 September Earthquake occurred. TO-Tonga plate, PA-Pacific plate. KE-Kermadec plate, AU-Australian plate (modified graphic after Bird, P. (2003).*

2. TECTONIC SETTING OF THE TONGA-KERMADEC SUBDUCTION REGION

As shown in Fig. 1, the Kermadec-Tonga Arc is an intra-oceanic arc, 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). The Tonga-Kermadec Trench and Arc consist 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.

The earth's most active zone of mantle seismicity arises from the westward subduction of the Pacific plate beneath the Australia plate at the Tonga trench. Convergence rates across the trench 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).

The intra-oceanic convergence tectonics along the Tonga Trench and the adjacent fore-arc between 14 S and 27 S Latitude is somewhat complicated and varies from North to South. The Pacific plate subducts westward beneath the northeast corner of the Australian plate at about 15 cm 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 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.

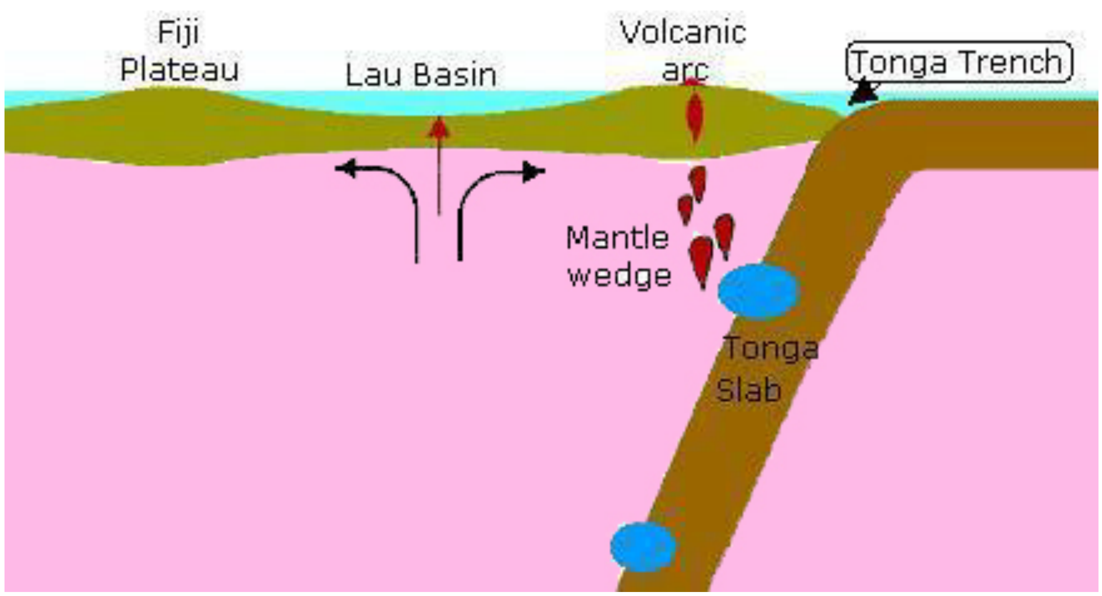

Fig. 2 Illustration of stresses along a cross-section in the middle segment of the Tonga trench from Pacific plate subduction and from the spreading center of Lau Basin (modified USGS graphic).

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 adjacent cross-sectional chart across the middle part of the Tonga Trench, illustrates the tectonic complexity of this region the steepness of the subducting plate, the a 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.

3. HISTORIC EARTHQUAKES AND TSUNAMIS IN THE TONGA-KERMADEC SUBDUCTION ZONE REGION

Extensive fracturing along the Tonga Trench, form natural asperities that often limits an earthquake's rupture length. Shorter ruptures and greater focal depths also 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 southern portion of the Tonga Trench and fore-arc, 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 visually observable 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 around 30 quakes of magnitude 7.0 or more have occurred along the Tonga plate boundary since 1900 (http://earthquake.usgs.gov/regional/neic). The most significant and largest of these in the northern segment was the magnitude 8.5 earthquake of June 26, 1917. It was an outer-rise earthquake on the northern end of the Tonga *Trench*, with epicenter at 15.500 S, 173.000 W. It generated a very destructive tsunami that had an observed local, maximum height of 12 meters (Pararas-Carayannis & Dong, 2980). Also the tsunami reached Japan and had at maximum recorded height at Kushimoto.

Another significant 7.5 magnitude earthquake occurred on April 14, 1957. Its epicenter was at 15.403 S, 173.129 W. (Pararas-Carayannis & Dong, 1980). A shallow 7.5 magnitude earthquake in the same region occurred on 1 September 1981, with epicenter 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 was a magnitude 7.2, deep (69km) event that 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 March 9, 1994. This earthquake had a moment magnitude Mw= 7.6 and depth of 564 km - too deep to generate any tsunami. At least 50 strong but very deep aftershocks followed the main event.

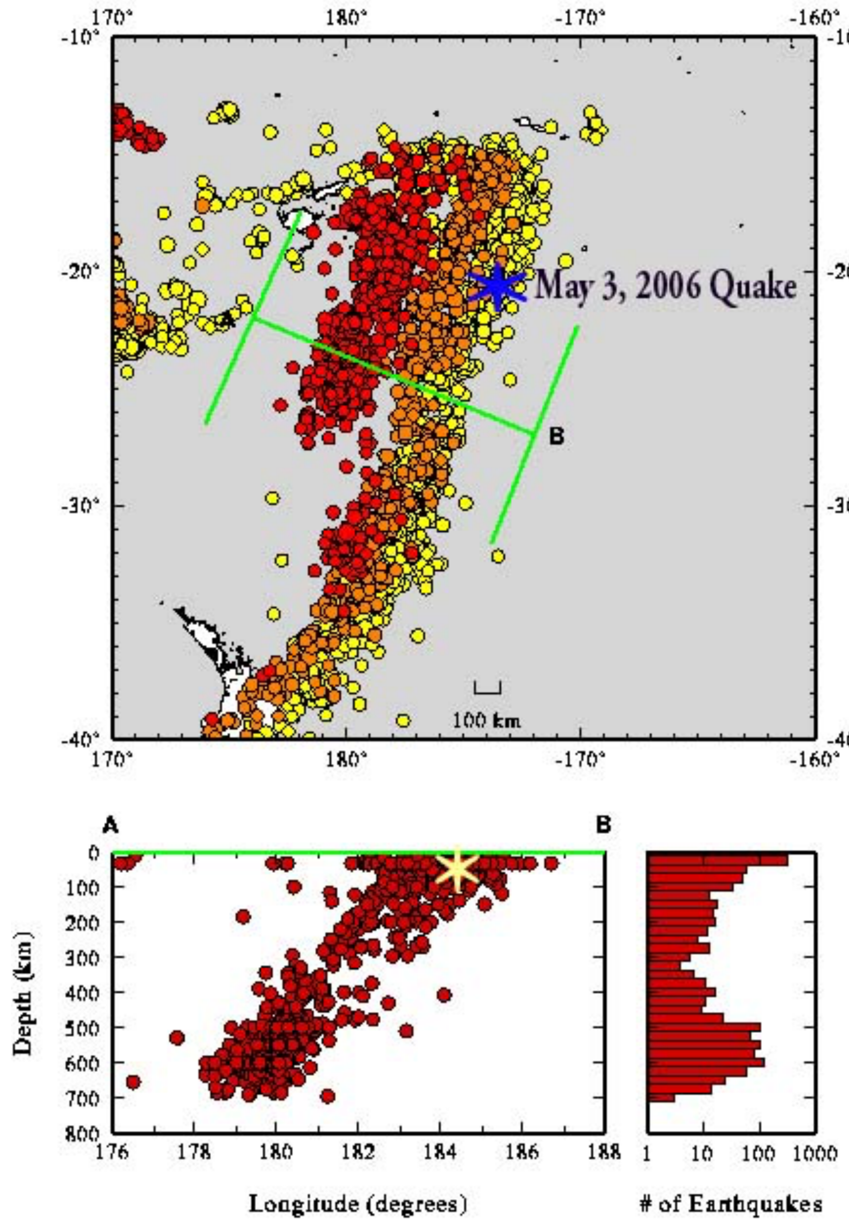

Fig. 3 Cross-section along the upper Kermadec-Tonga Arc, the epicenter of the 3 May 2006 earthquake, and variation in the number of earthquakes with focal depths (modified graphic from www.seismo.berkeley.edu)

On May 3, 2006, a magnitude 7.9 earthquake with focal depth of 55 km (34.2 miles) struck 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 (see Fig. 3 above). 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. The earthquake generated a small tsunami (Pararas-Carayannis, 2006).

Figure 3 shown above illustrates the horizontal and vertical distribution of earthquake epicenters on the surface, and of hypocenters 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 event, 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 earthquake have been plotted on these diagrams.

3.1 The 29 September 2009 Earthquake and Tsunami on the Northern End of the Tonga Subduction Zone.

According to the U.S. Geological Service (USGS), at 17:48:10 UTC (06:48:10 AM local time) on 29 September 2009, a magnitude M 8.0 earthquake with focal depth of 18 km (11.2 miles) and epicenter at 15.509 South and 172.034 West (Fig. 4), occurred in the northern region of the Tonga Trench. The Pacific Tsunami Warning Center put the quake's magnitude at 8.3, and issued a tsunami warning.

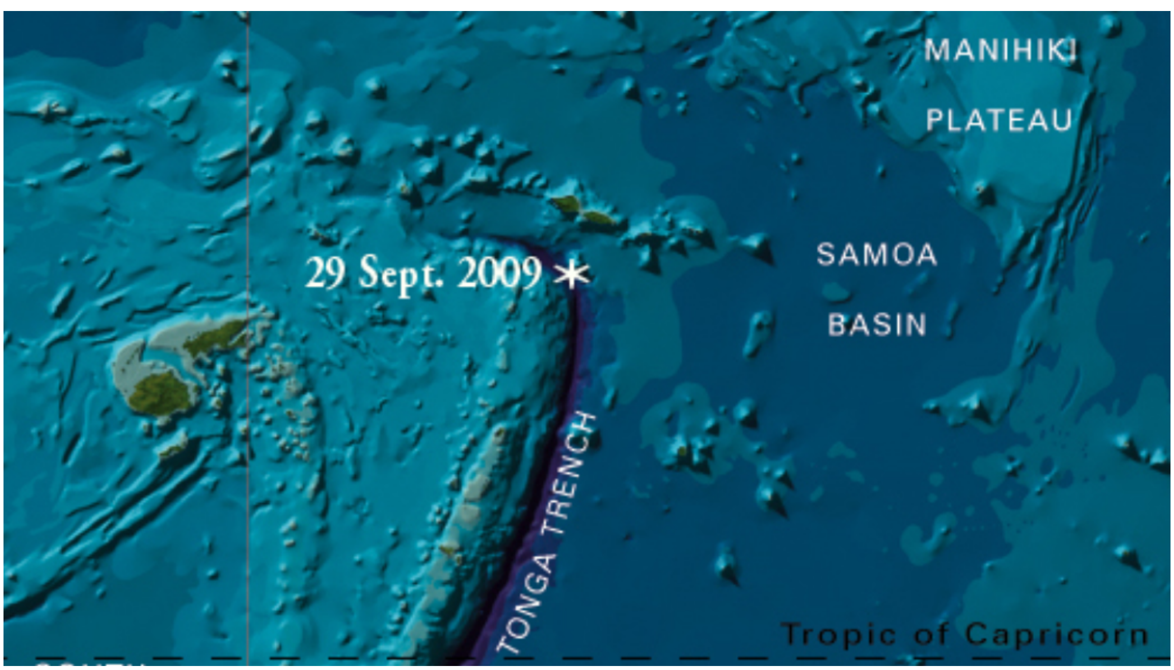

Fig. 4. Epicenter of the 29 September 2009 Earthquake on the Northern End of the Tonga Trench.

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 a normal fault rupture at the outer rise of the trench, as shown in Figure 4 above.

According to the USGS the distance of the epicenter of this earthquake was 120 miles (190 km) from American Samoa, 125 miles (200 kms) from Western Samoa, 406 km (252 miles) NNE from Neiafu, Tonga, 185 kms (115 miles) ENE of Hihifo, Tonga, 710 kms (440 miles) NNE of NUKU'ALOFA, Tonga, and 2700 kms (1680 miles) NNE of Auckland, New Zealand.

A 5.6-magnitude aftershock occurred 20 minutes later, followed by 14 aftershocks of magnitude 5.0 or higher. 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.

3.1.1 ***Rupture Length and Crustal Displacements*** - The distribution of aftershocks, the quake's magnitude and the focal mechanism analysis suggest that ruptures ranged by as much as 175 kms, along 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 3.6meter vertical change.

3.1.2 Death Toll and Damages – On November 29, 2009, the reported death toll was about 160 but it may have been higher. Most of the deaths occurred in Western Samoa, in American Samoa and some in Niuatoputapu, in Tonga. Damaged telephone lines made it difficult to communicate and assess the casualties and the destruction from both earthquake and tsunami. 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 Opolu of Western Samoa. About 3,000 people were rendered homeless.

3.2 The 29 September 2009 Tsunami

Based on the high magnitude of the earthquake, the Pacific Tsunami Warning Center issued a tsunami warning for numerous islands in the Pacific, including the Samoas, (both Western Samoa and American Samoa), the Cook Islands, Tonga, Fiji, New Zealand, French Polynesia and Palmyra Island. A tsunami watch was issued for Hawaii, Vanuatu, the Marshall Islands, Solomon Island, Johnston Island, New Caledonia, Papua New Guinea, Wake Island, Midway Island and Pitcairn. In New Zealand, a tsunami alert was issued by national Civil Defense, and the nation's national emergency center was activated.

3.2.1 Tsunami Effects - In American Samoa, the 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 was deposited ashore at the edge of the coastal highway (Fig. 5). More than 110 people were reported dead. The beach village of Sau Sau Beach Fale was leveled.

Fig. 5 Boat deposited ashore at the edge of the coastal highway

3.2 SOURCE MECHANISM OF THE EARTHQUAKE OF 29 SEPTEMBER 2009 ON THE NORTHERN END OF THE TONGA SUBDUCTION ZONE

As previously stated, the 29 September 2009 earthquake 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. 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 – as discussed further in the following section.

3.2.1 The Outer Rise Earthquake of 29 September 2009 – This earthquake was an outer-rise event. The outer-rise is a geomorphologic feature on the subducting tectonic plate, which usually parallels the inter-plate, thrust fault of the subduction zone. It is formed further out by crustal stresses that force tensional flexing of the subducting plate, or by flexing due to transference of stresses from inter-plate earthquakes to the outer rise, which energize the existing, near failure, normal faults. Such outer-rise earthquakes are caused by extreme stresses that result in bending within the subducting oceanic plate itself before it enters the subduction zone. Fig. 6 shows both the epicenter of the 29 September 2009 earthquake and a schematic of the centroid moment tensor solution (USGS).

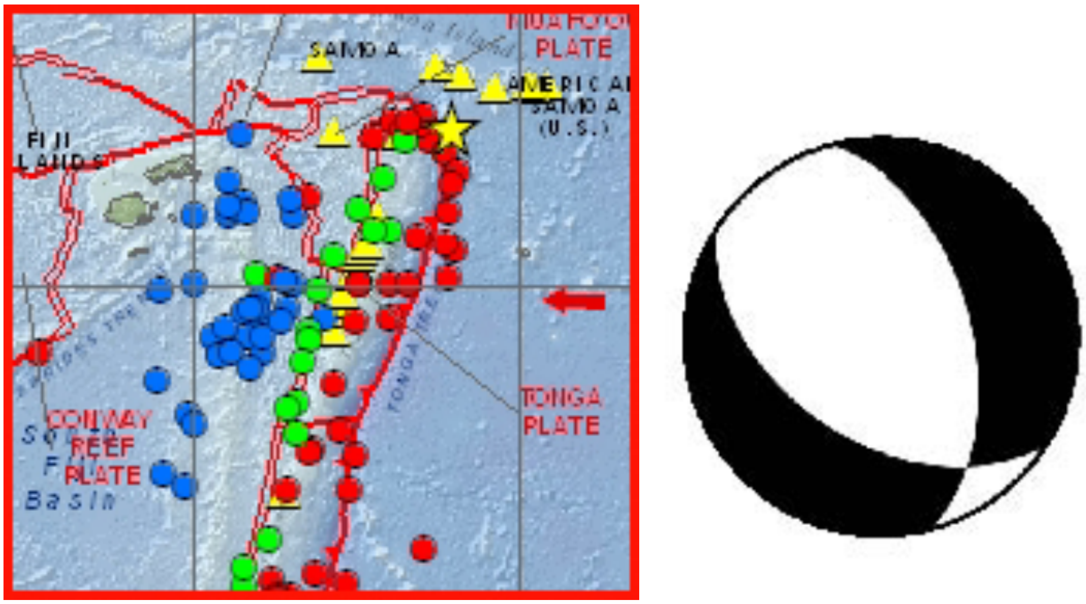

Fig. 6 Epicenter of the September 29 earthquake - Schematic of centroid moment tensor solution (USGS)

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 September 29, 2009 event - was also an outer-rise event (Pararas-Carayannis, 1980). It had similar characteristics and generated an equally destructive tsunami.

The 8.4 magnitude, Sanriku earthquake of 2 March 1933 occurred also 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, and Lombok 4.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 more extensive faulting, uplift and subsidence, offshore and on offshore islands (Pararas-Carayannis, 1977).

4. THE TSUNAMI OF 29 SEPTEMBER 2009 IN THE SAMOAN ISLANDS REGION

The tsunami generated by the earthquake of September 29, 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 (Western) and on Niuatoputapu, in the Kingdom of Tonga. Fig. 7 below is the tsunami travel time chart of this event, showing also the location of DART buoys that recorded it (Source: NOAA Center for Tsunami Research).

4.1 The 29 September 2009 Tsunami in American Samoa, Western Samoa and Tonga

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.

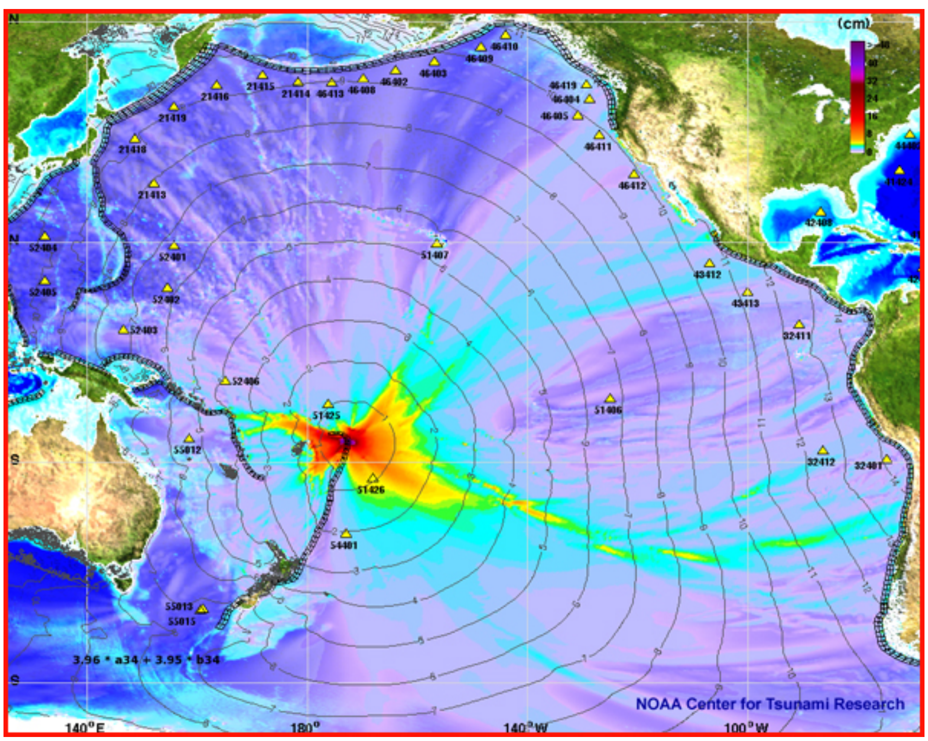

Fig. 7 The 29 September 2009 tsunami travel time chart. Location of DART buoys (Source: NOAA Center for Tsunami Research).

The following peak-to-through wave heights were recorded: 3.14m at Pago Pago (American Samoa); 1.40m at Apia (Samoa); 0.47m 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.

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

4.2 Dart Recordings of the 29 September 2009 Tsunami

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 (Lat: 9.49 degrees S Lon: 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.

4.3 Evaluation of the Earthquake and Tsunami Source Mechanisms

As previously indicated, and as shown in Figures 1 and 4, 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 down-warping and tearing of the Pacific plate as it enters the northern Tonga subduction zone, as well as shoaling of the subducted slab and 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 down-warped 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 crustal bending and have formed an 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.

This 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

September 29, 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. 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 modeling results give a fairly good picture of the tsunami's flux energy and directions of maximum propagation.

4.4 Dimensions of the Tsunami Source of the 29 September 2009 Event

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 can be estimated:

$A= \pi , r1 . r2 = 3.14 \times 150 \times 60 = 28, 260 \text{ km2}$

4.5 Modeling Studies

Based on centroid solutions for source characteristics, preliminary modeling studies were carried out by several 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 TUNAMI 2 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 modeling 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. Figures 8 and 9 illustrate the two different tsunami source regions that were used for these calculations which, as expected, generated somewhat different results.

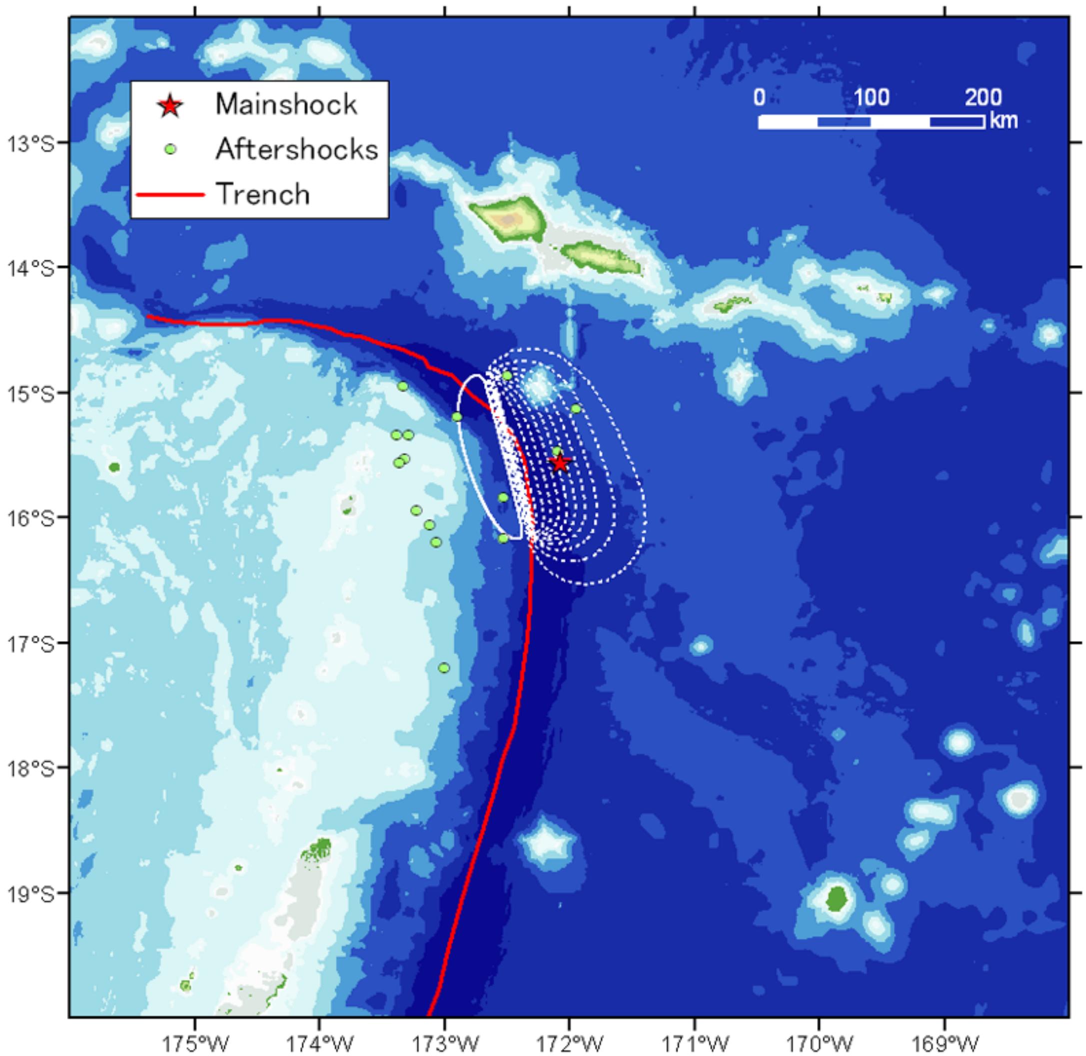

Fig. 8 Case 1. Tohoku University, (USGS data), Mo = 1.2 x 10**21 Nm
Fault Length / Width: 150 km / 75 km
Source Mechanism (Strike, Dip, Slip) = (345, 52, -61) Reference: USGS
Dislocation: 3.6 m.
http://www.tsunami.civil.tohoku.ac.jp/hokusai3/J/events/samoa_090930/source_case1.png

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.

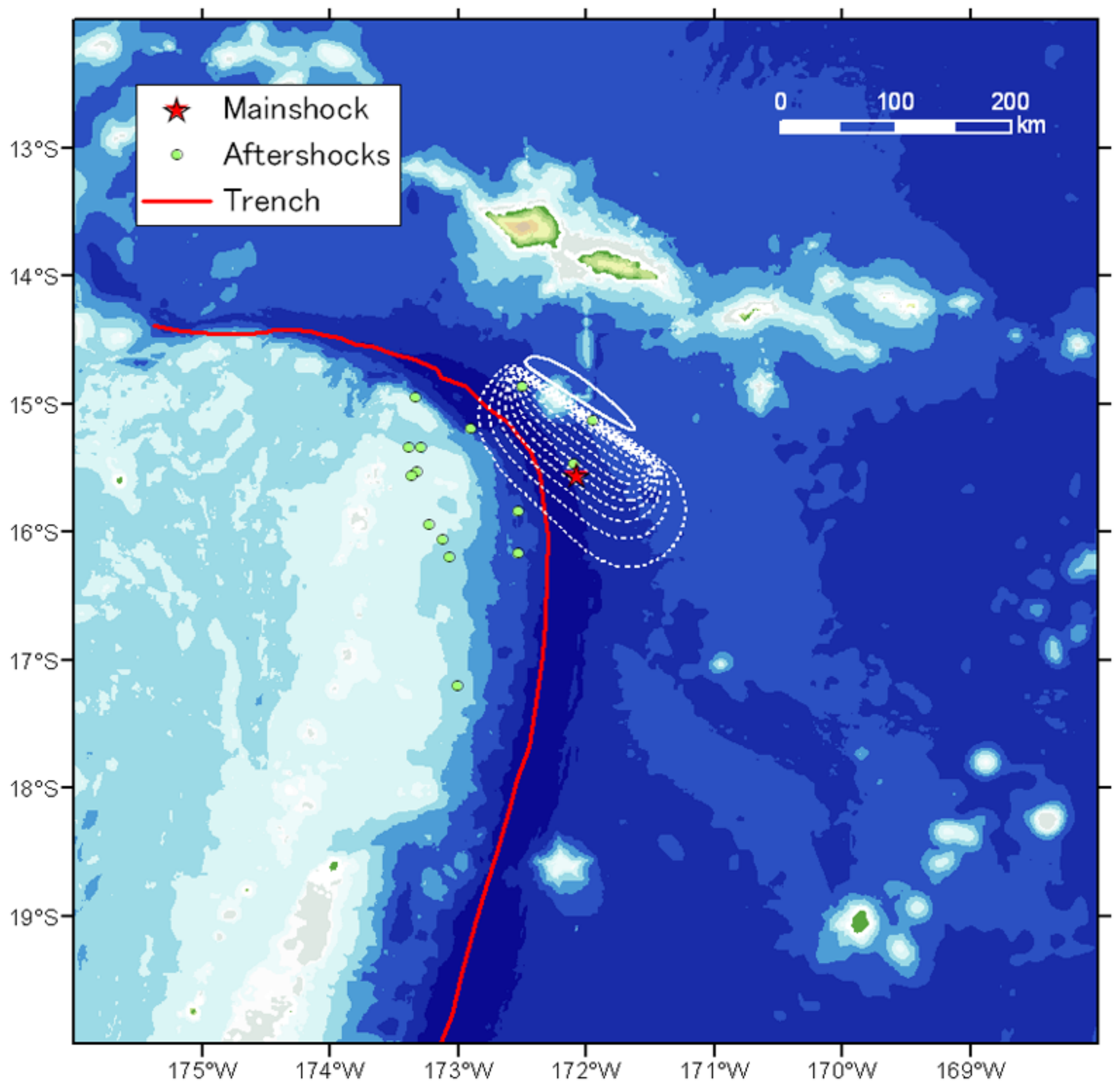

Fig. 9 Case 2 Tohoku University, (USGS DATA, Mo = 1.2 x 10**21 Nm
Fault Length / Width: 150 km / 75 km
Source Mechanism (Strike, Dip, Slip) = (124, 46, -120) Reference: USGS
Dislocation: 3.6 m

CONCLUSIONS

It must be obvious from the discussion above that there is still a great deal of uncertainty regarding the actual ocean floor displacements and the source mechanism of the outer-rise tsunami generated by the earthquake of 29 September 2009. A subsequent analysis will provide estimates of energy that went into tsunami generation and will attempt to reconcile results obtained by numerical modeling with the recording of the tsunami at DART buoy 51326.

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