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ANALYSIS OF TSUNAMI-MAGNETIC ANOMALY SIGNAL IN INDONESIAN REGIONS USING THEORETICAL APPROACH AND RECORDED MAGNETOGRAM

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ABSTRACT

The flow of conducting ocean water generates weak magnetic signals relative to the main field. These signals lead to magnetic anomaly observed as variations in the vertical component b_z of time-varying secondary field and the horizontal component b_H during past tsunamis across the Pacific and Indian oceans. In this study, the maximum amplitude of b_z was predicted using theoretical approach and the prediction was compared with magnetogram provided by INTERMAGNET and/or BCMT for tsunamigenic events and cases with no tsunami threats in Indonesian regions. The focus of this study is thus to examine whether theory used to estimate tsunami-magnetic signals is consistent in terms of accuracy with real-time field records from the two world wide magnetic institutions. For three events where tsunami occurred, including the 2004 Aceh event, it was found that frozen-flux theory provides a useful tool for best estimates of b_z with its application to b_H signals is here limited with caution. While b_z is a measure of tsunami wave height offshore, b_H is likely to be a good indicator for tsunami propagation direction. For four recent earthquakes of no tsunami potential after shocks the b_z signal provided no anomaly with convincing signs of tsunami absence were, in the same period of time, given by almost zero declination. The results for all cases considered in the present study confirm that detection of magnetic anomaly owing to tsunami passage prior to tsunami arrivals at coastal zones is possible. This is of primary importance for tsunami early warning in the country.

Keywords: *weak signals, magnetic anomaly, frozen-flux theory, magnetogram*

1. INTRODUCTION

It has been widely known that the flow of electrically conducting fluid of ocean waters across the main field during tsunami passage in the open oceans induces the secondary source of relatively weak magnetic field. This is referred to here as ocean dynamo effect (see for example, Tyler, 2005). Within this context, tsunami-induced magnetic signal is apparently observed as small magnetic perturbation with respect to the main field and possibly detected as local anomaly by satellites and ground-based observatories (Manoj et al., 2011; Wang and Liu, 2013) and deployed instrument at the ocean floor (Ichihara et al., 2013; Sugioka et al., 2014). These records have suggested that vertical and horizontal variations in the weak field can be related to tsunami height in the ocean and its corresponding wave propagation direction, respectively. Klausner et al. (2016) utilized magnetic data from field records given by International Real-time Magnetic Observatory Network (INTERMAGNET) and Geospatial Information Authority of Japan (GIS) to examine in details the effects of the 2011 Tohoku tsunami on the vertical component b_z and found that the b_z signal was strongly influenced by tsunami passage. Using tsunami simulations, Minami and Toh (2013) and Tatehata et al. (2015) examined the same event to find the main mechanisms of tsunami signals generation, including the horizontal field b_H. Numerical codes by Minami et al. (2015) and further by Minami (2017) were used for examination of electromagnetic induction signals due to tsunami passage. Prior to these studies, Zhang et al. (2014) combined observations with simulations to estimate tsunami wave height and its corresponding wave propagation direction. All of these investigations into tsunami-magnetic local anomaly signals have indicated that remote detection of the presence of a tsunami wave in the open ocean is made possible by sensitive instrument.

In this study, tsunami-magnetic signal generated after main shocks in Indonesian regions is of primary interest. Adopted the methodology discussed in Prastowo et al. (2017), we use frozen-flux approximation elaborated in great details by many (Tyler, 2005; Minami et al., 2015; Minami, 2017) to estimate the maximum amplitude of b_z and compare it with magnetogram from INTERMAGNET and/or Bureau Central de Magnetism (BCMT) for three Indonesian tsunamis, namely the 2004 Aceh, the 2018 Palu-Donggala, and the 2018 Sunda Strait events. We include here four cases for direct comparison where tsunami threats were absent after the shocks of relatively large earthquakes in Banten on 23 January 2018, Lombok on 5 August 2018, Central Sulawesi on 12 April 2019 and the northen part of Maluku on 7 July 2019. For the tree tsunamigenic events, the results were compared with respect to trans-Pacific tsunamis (the 2010 Maule, Chile and the 2011 Tohoku, Japan) to examine similarity in the prediction of b_z in terms of accuracy. As early detection of tsunami magnetic signals is essential for tsunami forecasting, this study provides an alternative method of Indonesian tsunami early warning to support disaster risk reduction efforts.

2. METHOD

Tsunami-induced magnetic anomaly is examined from the fact that temporal variation of b_z signal appears in the magnetic induction equation below as the sum of advection and diffusion terms**,**

$$\partial_t b_z = -\nabla_H \cdot (F_z \mathbf{u}_H) + \kappa \nabla^2 b_z \tag{1}$$

Equation (1) describes how the b_z component changes with time (Tyler, 2005; Ichihara et al., 2013; Sugioka et al., 2014), and is represented by the production of the secondary field by tsunami flow $\mathbf{u}_H$ and the contra-production term due to diffusion with diffusivity κ. With respect to the time-averaged main field F_z, analysis of Eq. (1) was discussed by Tyler (2005) for observations at the ocean surface. The analysis suggested that the ratio of local magnetic perturbation to the quasi-steady field b_z/F_z is proportional to the ratio of surface elevation to the ocean depth η/h times a speed ratio c/c_s in which $c_s = c + i\, c_d$ with c_d being the rate of diffusion (Tyler, 2005). As prompted by Tyler (2005) and further extended in relevant work (Ichihara et al., 2013; Sugioka et al., 2014) to bottom measurements in the presence of diffusion the proportionality takes the form,

$$b_z/F_z = c/c_s \times \eta/h \tag{2}$$

where c_d and c are respectively defined as $c_d = 2\kappa/h$ and $c = \sqrt{gh}$ with g being gravity.

Equation (2) indicates that tsunami-magnetic signal is a function of ocean depth and describes interplay between physical processes in the ocean, namely horizontal advection and vertical diffusion. Previous studies (Minami et al., 2015; Minami, 2017) went further to calculate the amplitude of b_z by defining the characteristic length-scale $L =$ 2.53 km for a local occurrence and using this value to define different regimes based on the depth ratio h/L. These regimes include diffusion dominance where $0 \leq h/L \leq 0.5$, intermediate where $0.5 \leq h/L \leq 2.0$ and advection dominance where $h/L \geq 2.0$. However, regime classification based on the fractional depth is out of the scope of this study except for tsunamis in deep ocean waters, where the dominant feature is horizontal advection.

Following the method developed by Tyler (2005) and explored by many (Ichihara et al., 2013; Sugioka et al., 2014; Minami et al., 2015; Minami, 2017, Prastowo et al., 2017) we derive a formula for the maximum value possible for b_z in a specific condition where $c/c_s \approx 1$ (advection dominates over diffusion) for Indonesian tsunamis. Equation (2) simply becomes

$$b_z/F_z = \eta/h \tag{3}$$

Equation (3) is here referred to as frozen-flux approximation and is used to the first order to estimate the vertical component of b_z. In turn, Ichihara et al. (2013) have used knowledge of b_z obtained from measurements at the ocean floor to estimate the horizontal component of b_H for the 2011 Tohoku case as follows,

$$b_H = i\, b_z \tag{4}$$

Equation (4) indicates a phase difference (lag) between the b_z and b_H signals, making them difficult to detect during the same period of time (Sugioka et al., 2014; Prastowo et al., 2017). The application of Eq. (4) is limited in the sense that Eq. (4) is not directly derived from frozen-flux theory and thereby it may break down or no longer use whereas Eq. (3) is applied to all cases with $h/L \geq 2.0$ or $c/c_s \approx 1$, as reported by Prastowo et al. (2017).

All tsunami occurrences in this study were examined in details by either calculation of b_z using frozen-flux approximation or recorded magnetogram provided by INTERMAGNET and/or BCMT. Comparison between b_z values obtained from calculation and magnetogram may provide the essence of tsunami-induced magnetic signals for tsunamigenic events as well as those of no tsunami potential threats in Indonesian territories. The data were in numerical values for the main and secondary fields and global bathymetry. Data for F_z were from http://www.ngdc.noaa.gov/IAGA/vmod/ organized by International Association of Geomagnetism and Aeronomy (IAGA) in the form of International Geomagnetic Reference Field (IGRF), 12th Generation Magnetic Model, bathymetry for the depth h at http://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/ organized by the US government through National Geophysical Data Centre (NGDC), National Oceanic and Atmospheric Administration (NOAA), and data for η taken from the 2010 Chilean and 2011 Tohoku events are accessible from http://www.ngdc.noaa.gov. In addition, magnetogram are available at http://www.intermagnet.org (INTERMAGNET) and http://www.bcmt.fr (BCMT). Note that the focus of this study is examination of the three Indonesian tsunamigenic earthquakes and the four cases with no tsunami threat generated whereas the two trans-Pacific tsunamis are here provided as reference for the former.

3. RESULTS AND DISCUSSIONS

3.1. Cases of Tsunamigenic Earthquakes

Tsunami on the boxing day, 26 December 2004, widely popular as the 2004 Indian Ocean tsunami was initiated by a large earthquake of M_w 9.1 and epicentered at a source point of 3.4^{o}N and 95.7^{o}E in the subduction zone between Eurasian and Indo-Australian Plates. When the wave was generated at tsunami origin time (OT) at 01:18 UTC, nothing was reported owing to the absence of tsunami early warning system in the Indonesian territories, including regions along the west coast of Sumatra Island, which is vulnerable to tsunami hazard. Concerning with the lack of monitoring instrument at the time when tsunami propagated towards and eventually hit Aceh coastlines, estimate of tsunami-magnetic signals are therefore provided by magnetogram from INTERMAGNET and/or BCMT in Fig. 1 below.

The presence of tsunami generation was detected as recorded magnetogram at station PHU (Vietnam), positioned at 21.3ºN and 105.95ºE.

Figure 1 shows increased vertical component of secondary field during tsunami passage between 1:15–1:22 UTC. For comparison, we also provide field records from BCMT in Fig. 2. As illustrated, the observed vertical component of tsunami-magnetic signal confirms that the maximum amplitude of $b_z \approx 2.0$ nT peaked within time interval of 1:13–1:25 UTC, in good agreement with that observed by INTERMAGNET. This is supported by previous work of Tyler (2005) and Prastowo et al. (2017) who claimed the same value of b_z for this case. A relatively small difference in the b_z values reported here by the two institutions is considered unimportant.

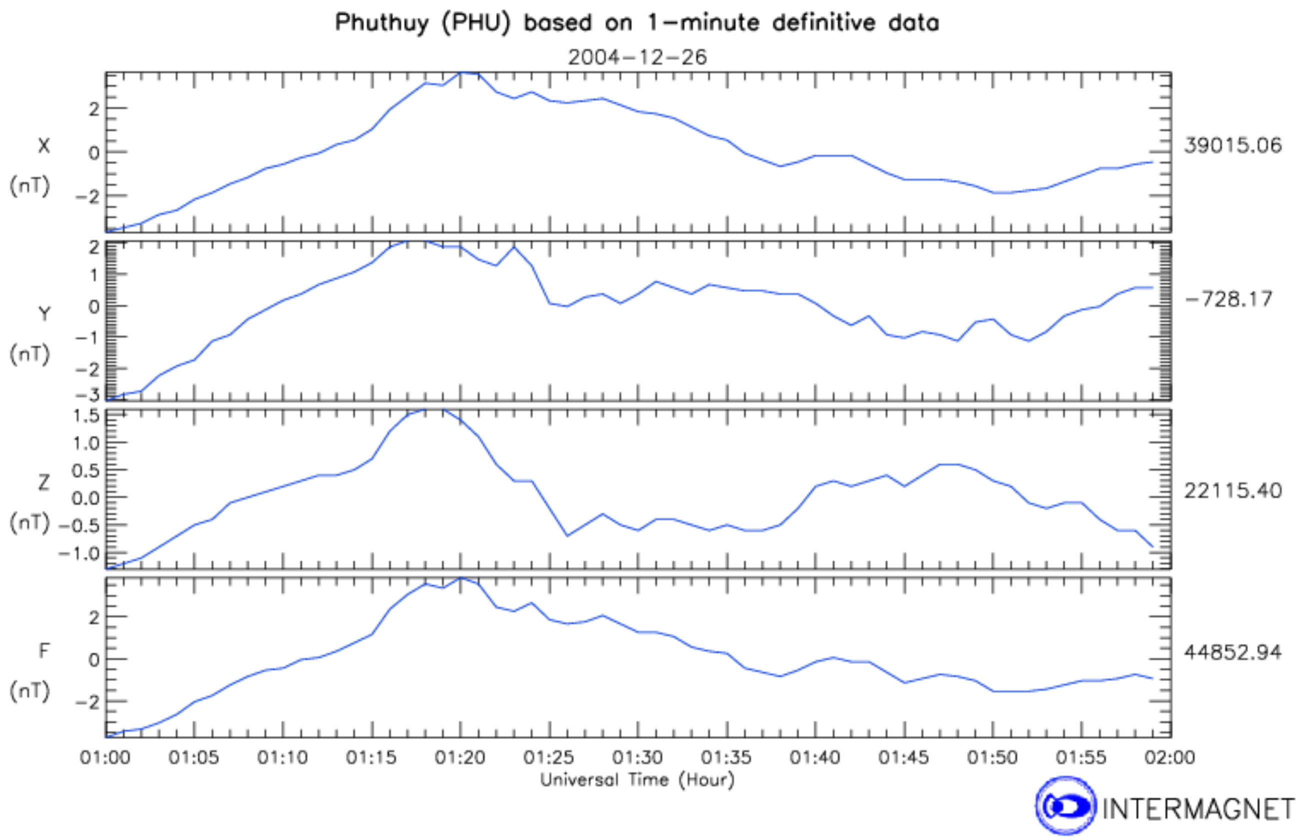

Figure 1. Magnetogram from INTERMAGNET for the 2004 Aceh event recorded at station PHU about 2300 km away from the epicenter, showing the observed vertical component of $b_z \approx 1.8$ nT.

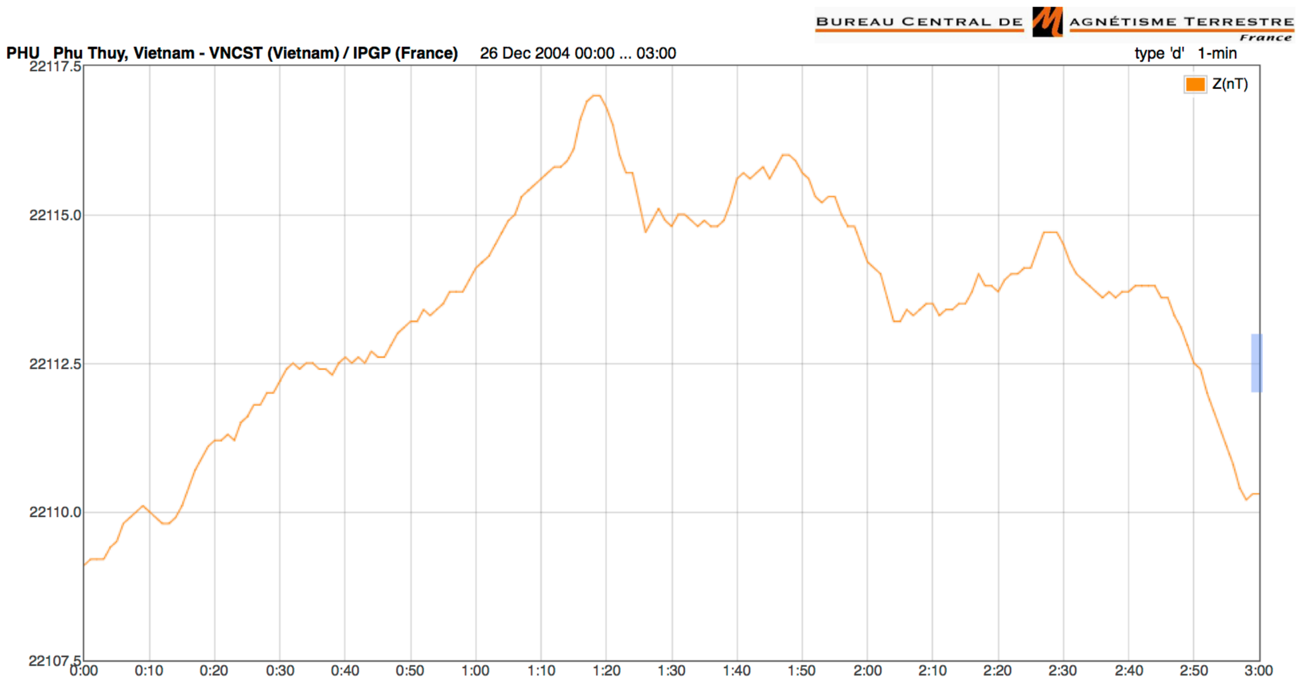

Figure 2. Magnetogram from BCMT for the 2004 Aceh event recorded at station PHU about 2300 km away from the epicenter, showing the observed vertical component of $b_z \approx 2.0$ nT.

Possible seismic sources of tsunami generation have recently been a crucial issue. The quest for magnetogram is that whether it remains consistent providing accurate information about the presence of a tsunami wave in the oceans when the tsunami is generated by sources other than tectonic ones along subduction zones. For past Indonesian tsunamis during the last three centuries, records indicated that a large number of occurrences were initiated by tectonic movement at inter plates from western to eastern provinces (Hamzah et al., 2000). However, the results of recent work by National Center for Indonesian Earthquakes in 2017 (unpublished work) have suggested that fault plane dynamics is also considered as a potential source for major earthquakes and hence possible tsunamis in the country. This enables us to test accuracy and consistency of magnetogram using recent occurrences generated by seismic activities at Palukoro-faulting zone on 28 September 2018 and by volcanic activities of Anak Krakatau in Sunda Strait on 22 December 2018, predicted by Giachetti et al. (2012).

The 28 September 2018 Palu-Donggala event was sourced from shallow foreshocks of seismic energy release starting at 10:03 UTC with magnitude of M_w 7.5 and epicentered on land at 0.18°S and 119.84°E in the northern part of Palu, Central Sulawesi. Subsequently, these shocks were followed by tsunami generation and propagating tsunami waves, approaching shorelines and sweeping out of all infra structures near the bay. Tsunami alert was issued at the beginning but ironically was called off before consecutive waves arrived at the shorelines. Many believe that a strike-slip Palu-Koro fault induced submarine landslides, in turn generated a deadly tsunami. Figure 3 shows magnetic anomaly recorded by station GUA in the western Pacific during limited arrival times but distinguishable from fields in normal conditions before and after the event. The b_z signal peaked at approximately 1.3 nT, again consistent with $b_z \leq 2.0$ nT (Tyler, 2005; Prastowo et al., 2017) for equatorial tsunamis.

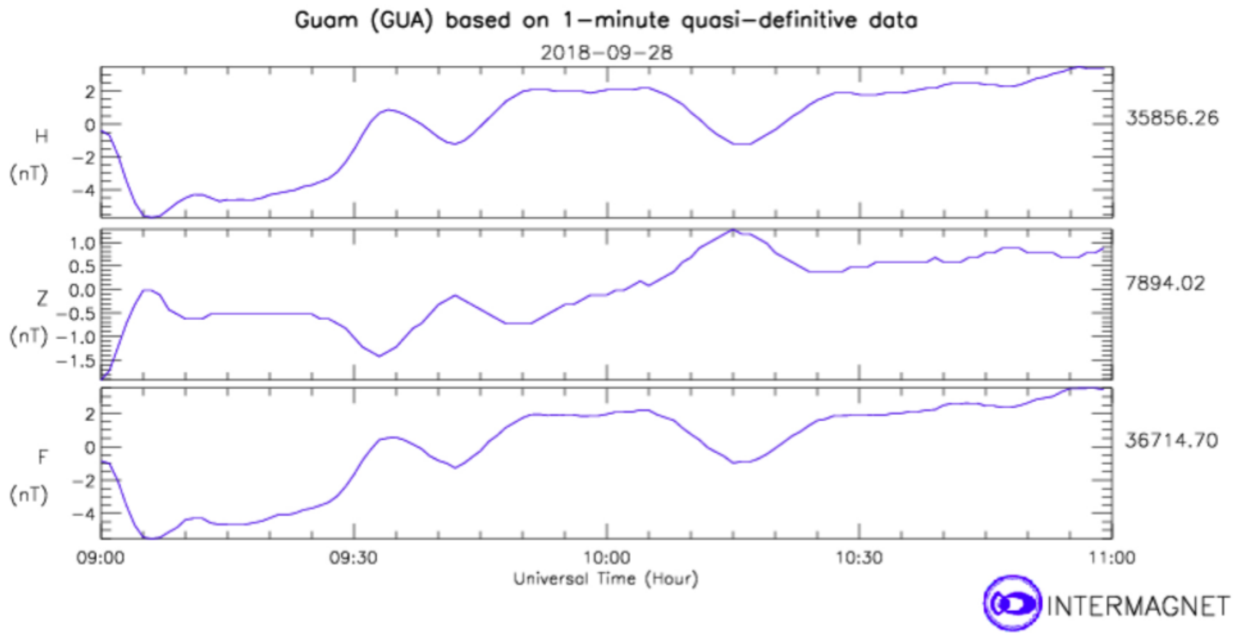

Figure 3. Magnetogram from INTERMAGNET for the 2018 Palu-Donggala tsunami showing the *H* and *Z* signals with *F* is the total field observed at GUA about 3200 km away from the epicenter.

Volcanic tsunami in Sunda Strait on 22 December 2018 was unique in that it was generated by collapses of a partial body of Anak Krakatau following its eruption a day before in a manner similar to the one predicted by Giachetti et al. (2012). Tsunami generation was arguably detected by CKI at 14:03 UTC when continual tremors were recorded by sensors before the wave struck nearby coastal Banten regions in western Java. Tsunami alerts were not issued because of the lack of monitoring instrument for detection of volcano-triggered tsunamis. Instead, a wave of high amplitude advancing towards shorelines was reported as propagation of high tides during a full moon period on the day.

Figure 4 shows a clear anomaly recorded by equipment at CKI in the southwest direction away from the epicenter. The vertical signal was that of $b_z < 0.5$ nT, smaller than the b_z value observed in the Palu-Donggala case depicted in Fig. 3 but remaining consistent with $b_z \leq 2.0$ nT for equatorial tsunamis (Tyler, 2005; Prastowo et al., 2017). The relatively large difference in magnitude between the b_z signals for the 2018 Palu-Donggala and the 2018 Sunda Strait events is predicted to be due to differences in the mechanical energy available for tsunami generation but discussion on this is beyond of this work. For a further discussion on the privilege of magnetogram in terms of tsunami warning, we pay attention to the shape difference in the vertical signals between the 2018 Palu-Donggala and the 2018 Sunda Strait events. In the former case a single soliton was observed, contrary to the latter where periodic signals were detected. We take different source mechanisms responsible for each event and different locations where tsunamis occurred into account for the different waveforms.

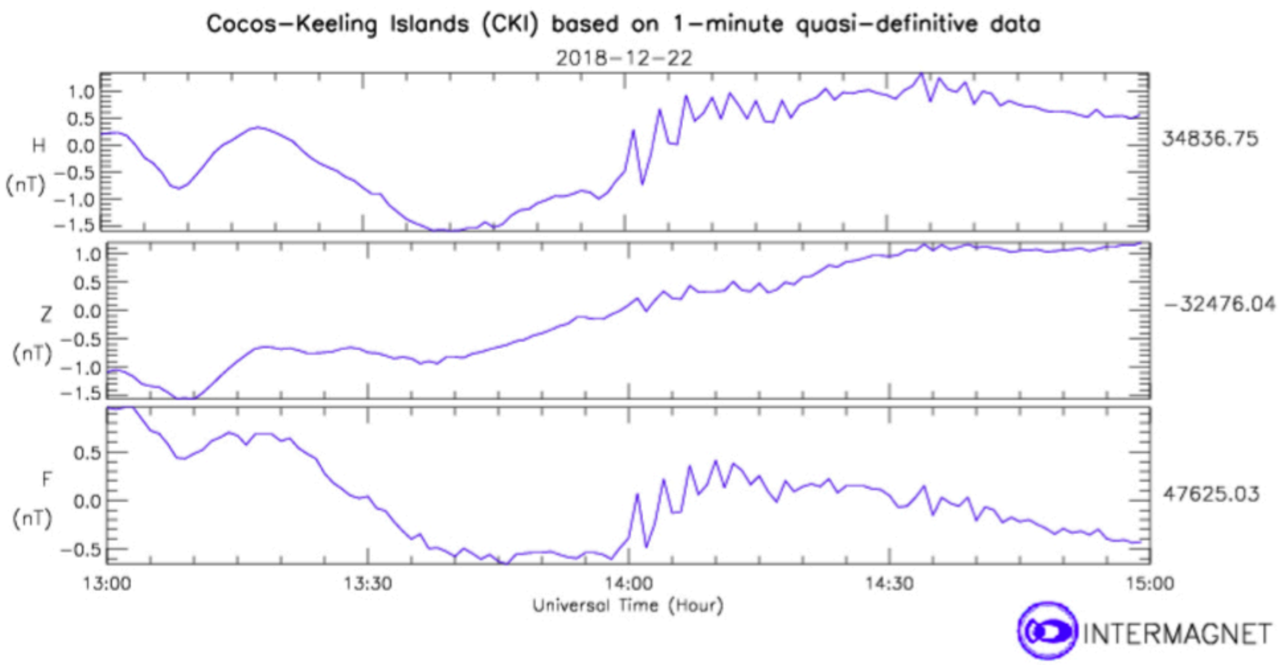

Figure 4. Magnetogram from INTERMAGNET for the 2018 Sunda Strait event, showing the *H* and *Z* signals with *F* is the total field observed at CKI about 1100 km away from the epicenter.

Different values of b_z reported from the above cases are likely caused by different positions of magnetic stations and types of instrument and their corresponding sensitivity used in data collection and measurement techniques (Toh et al., 2011). This suggests that, as addressed by Prastowo (2019), the relatively weak signals require sensitive magnetic sensors to examine past tsunamis and hence better predict future tsunamis. However, the use of routine monitoring of magnetic signals in the form of magnetogram for detection of tsunami generation may help us to be aware of tsunami arrivals as the signal is independent of whether it is generated by tsunami of tectonic origin in the deep oceans or relatively shallow waters, or even by volcanic tsunami. Hence, within this context it may be useful to see if magnetogram records provide clues for a set of recent earthquakes with no tsunami potential generated after shocks.

3.2. Cases with no Tsunami Potential

As previously stated, for comparison with tsunamigenic events we here provide four cases where tsunamis were absent although the suspected occurrences were relatively large in size. These cases involve earthquakes, which occurred in Banten on 23 January 2018 (Fig. 5), in Lombok on 5 August 2018 (Fig. 6), in Central Sulawesi on 12 April 2019 (Fig. 7) and in North Maluku on 7 July 2019 (Fig. 8). It is clear from each figure representing each event that based on magnetogram from INTERMAGNET the b_z and in particular the declination D signals for all cases of varying magnitude M_w 6.1-7.0 examined show similarity in forms in some points. Both the vertical component and declination give no clues of tsunami-induced magnetic anomaly signals. As final reports provided by both Indonesian Agency for Meteorology, Climate and Geophysics (BMKG) and National Oceanic and Atmospheric Administration (NOAA) have confirmed no tsunami generated, we then may come to a simple conclusion that magnetogram is reliable to detect the presence of a propagating tsunami wave several minutes after shocks. This result also suggests that earthquake parameters, such as origin time, magnitude and epicenter are all not good measures of whether tsunami is generated (Madlazim and Prastowo, 2016).

From all events with and with no tsunami threats in the eastern and western Indonesian regions, where mechanical sources triggering events were not only tectonic release along a subduction zone but also along an active fault as well as a volcanic energy, we could argue that for practical purposes tsunami-magnetic signals introduced by tsunami passage are possible to detect and possibly becoming good indicators for the initiation of tsunami generation hence the presence of tsunami in the ocean.

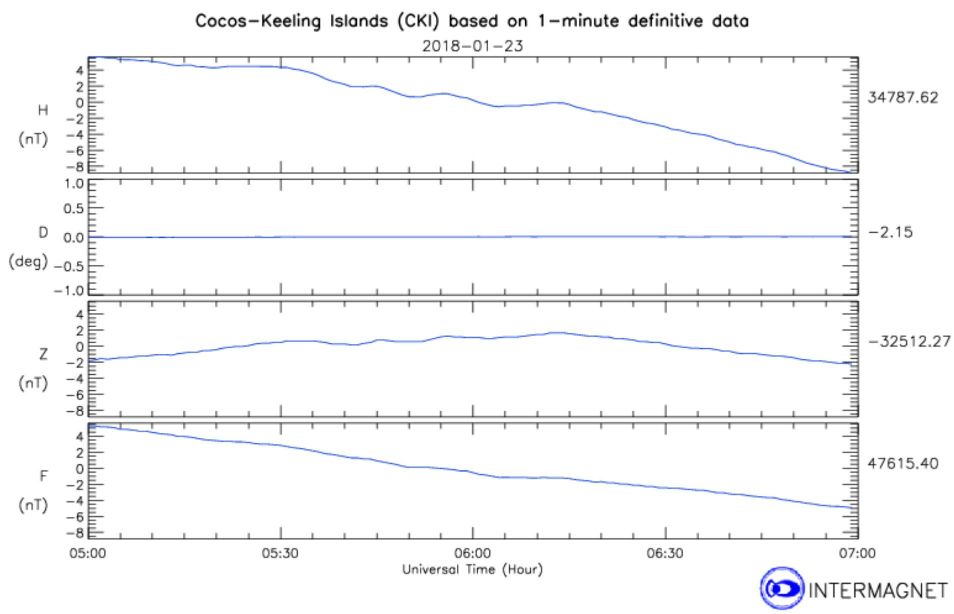

Figure 5. Magnetogram from INTERMAGNET for local earthquake with magnitude of M_w 6.1 in Banten on 23 January 2018 recorded at 6:34 UTC by CKI, where declination D is seen flat, confirming no tsunami generation.

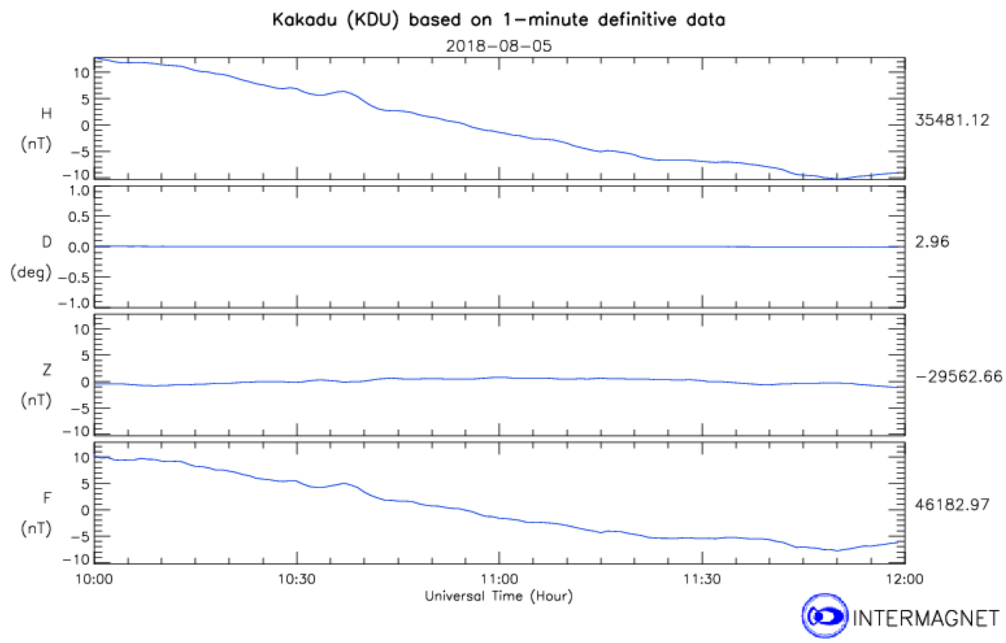

Figure 6. Magnetogram from INTERMAGNET for local earthquake with magnitude of M_w 7.0 in Lombok on 5 August 2018 recorded at 11:46 UTC by KDU, where declination D is seen flat, confirming no tsunami generation.

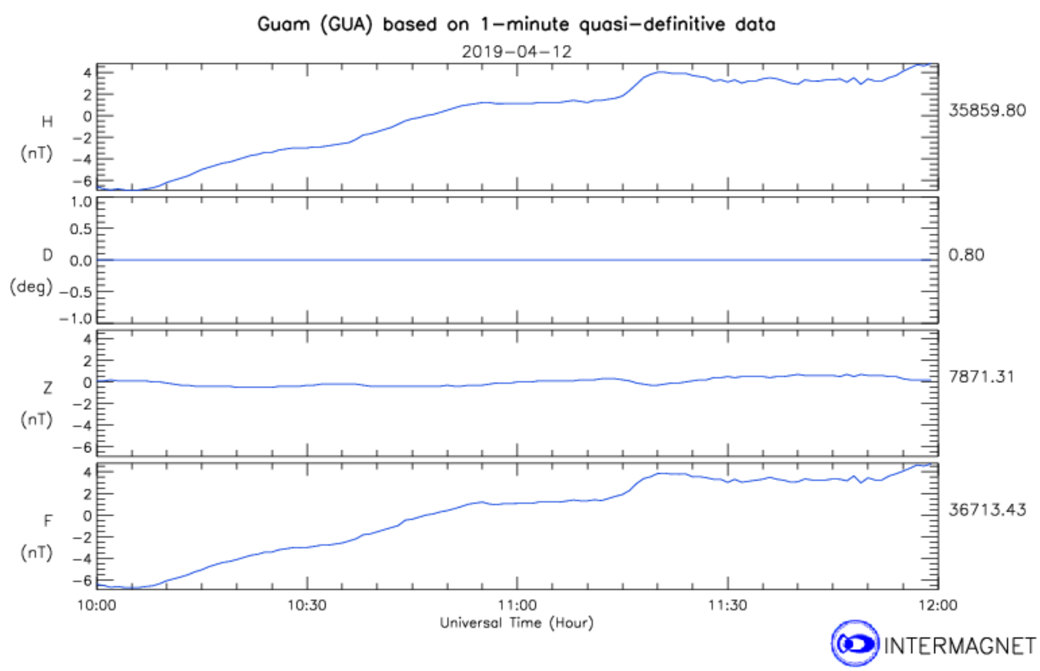

Figure 7. Magnetogram from INTERMAGNET for local earthquake with magnitude of M_w 6.8 in Central Sulawesi on 12 April 2019 recorded at 11:40 UTC by GUA, where declination D is flat, confirming no tsunami generation.

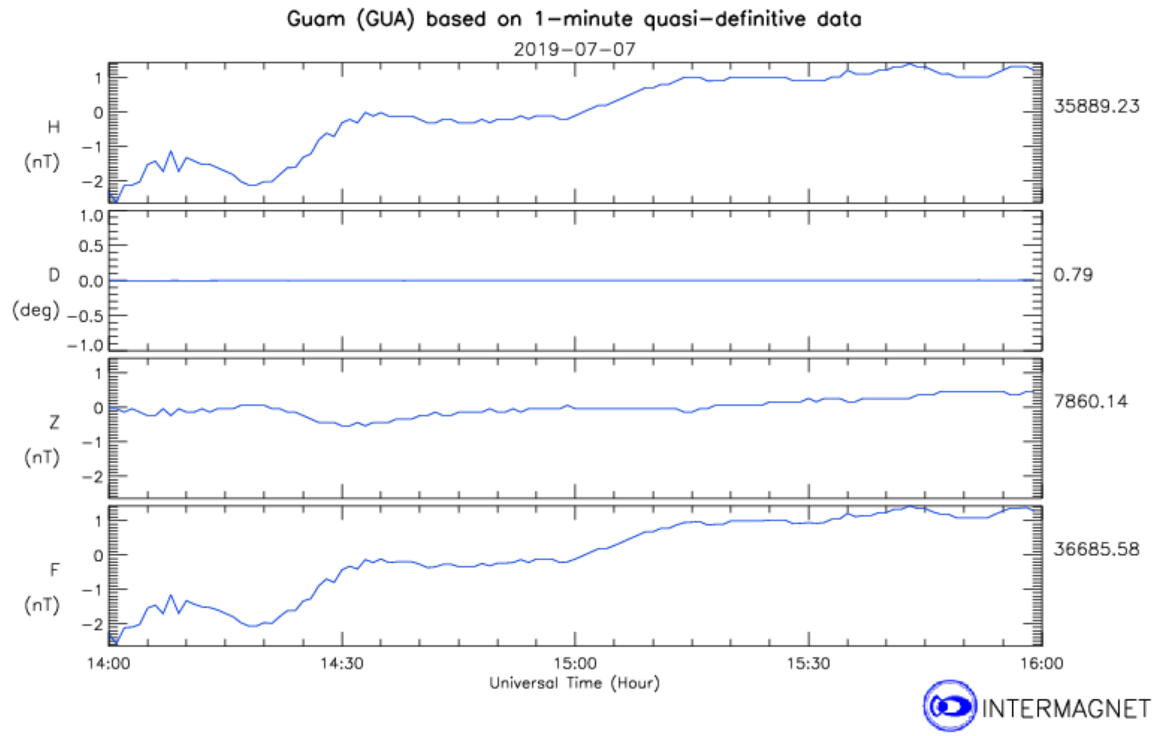

Figure 8. Magnetogram from INTERMAGNET for local earthquake with magnitude of M_w 7.0 in North Maluku on 7 July 2019 recorded at 15:08 UTC by GUA, where declination D is flat, confirming no tsunami generation.

3.3. Trans-Pacific Tsunamis

Two large tsunamis across the Pacific (the 2010 Chilean with M_w 8.8 and the 2011 Tohoku with M_w 8.9 cases) are here discussed as reference for b_z and b_H signals detection during tsunami passage. As previously addressed, best estimates of b_z and b_H were performed using theoretical approach and recorded magnetogram from INTERMAGNET and/or BCMT. Figure 9 provides magnetogram from INTERMAGNET, describing sea surface perturbations following large earthquakes causing tsunami propagated away from Chilean west coast on 27 February 2010. The vertical signal of b_z = 0.48 nT was observed at IPM to be periodic, during the time 11:55–12:55 UTC. The tsunami-magnetic signals recorded include the horizontal component b_H printed as H in Fig. 9.

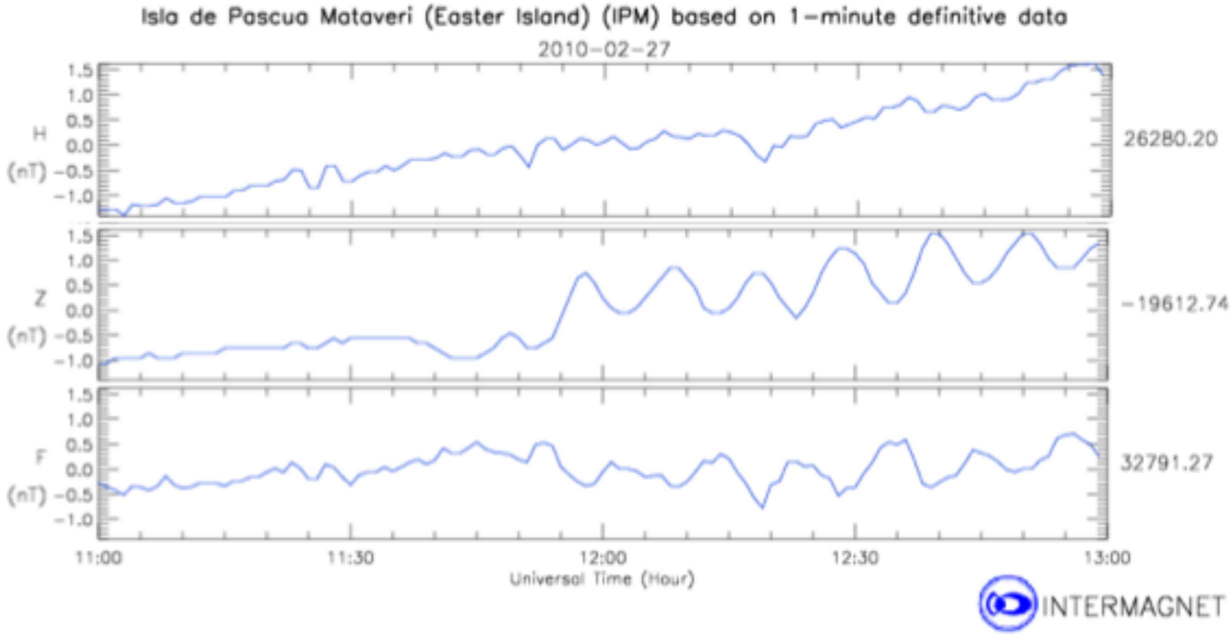

Figure 9. Magnetogram from INTERMAGNET for the 2010 Chilean tsunami, showing the H and Z signals with F is the total field observed at IPM about 3500 km away from the epicenter after approximately 5 hours-travelling across the Pacific.

The amplitude of b_z shown in Fig. 9 is approximately the same as $b_z \approx 0.5$ nT for the maximum vertical variation in the signal reported by both Sugioka et al. (2014) and Manoj et al. (2011). The b_z estimated from magnetogram is comparable with that calculated from frozen-flux theory in Eq. (3). However, the amplitude of b_H is difficult to determine from magnetogram of H-component in Fig. 9. Instead, we will estimate b_H using $H^2 = X^2 + Y^2$ where X and Y are both perpendicular components, estimated from magnetogram provided by BCMT shown in Fig. 10. This gives -0.355 nT and 0.30 nT for X and Y, respectively, corresponding to the horizontal signal of b_H = 0.465 nT, suggesting that prediction by Eq. (4) is remarkably satisfied. Thus, the X and Y signals complete vector properties of a tsunami wave, enabling us to infer the direction of tsunami propagation towards N49^{o}W, consistent with that claimed by Sugioka et al. (2014).

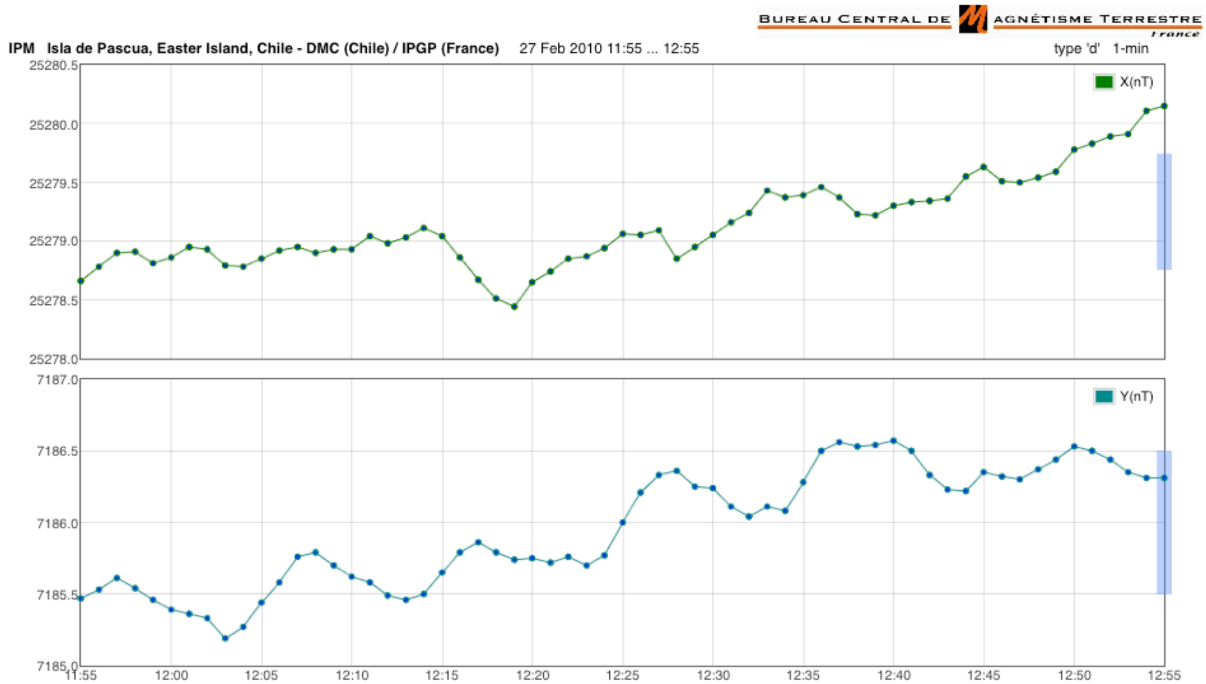

Figure 10. Magnetogram from BCMT for the 2010 Chilean tsunami, showing the *X* and *Y* signals observed at IPM about 3500 km away from the epicenter.

For 11 March 2011 Tohoku event, starting from 6:45 to 7:45 UTC recorded at KAK station with vertical magnetic signals recovered at a value of $b_z \approx 15.8$ nT, as seen in Fig. 11, in good agreement with $b_z \approx 15.6$ nT predicted for the same occurrence and station using frozen-flux theory. Further, Ichihara et al. (2013) measured a mid-value of vertical variations in the signal to be $b_z \approx 15.5$ nT, slightly different from that predicted by Eq. (3) using frozen-flux theory. In addition, we could also infer that $b_H \approx 12$ nT. A rather large difference in the values of b_H between the value estimated from magnetogram data in Fig. 11 and that predicted by Eq. (4) is here unexpected. Considering this, b_z is more reliable for use of tsunami detection than b_H, suggesting that b_z is likely to be a good indicator for tsunami wave generation and thereby the presence of a tsunami wave in the open ocean.

It should be noted here that estimates of b_z and b_H using frozen-flux approximation as written in both Eqs. (3) and (4) are limited in that the two equations assume oceanic diffusion does not exist. When the diffusion takes place, we may then use Eq. (2) to predict the two signals better. However, magnetogram seems unaltered in providing a good indicator for the presence of tsunami in the ocean. What is important to note that prediction of b_z can be performed using only simple parameters, such as the ocean depth, the intensity of the main field and tsunami wave amplitude measured offshore. From all recent Indonesian tsunamis and cases of earthquakes with no tsunami generation considered in this study and given that tsunami-magnetic signals are in common relatively weak in magnitude compared with the background Earth's field, we may design and carry out research on development of sensitive magnetic sensors for future work. In building a more reliable tsunami early warning system, and to some degree to complete an existing method of Indonesian tsunami early warning system based on only seismic observations (see Wang et al., 2019), future research requires an integrated approach, combining theoretical analysis, field measurement and numerical simulation for a developed method of tsunami-generated magnetic anomaly signal monitoring.

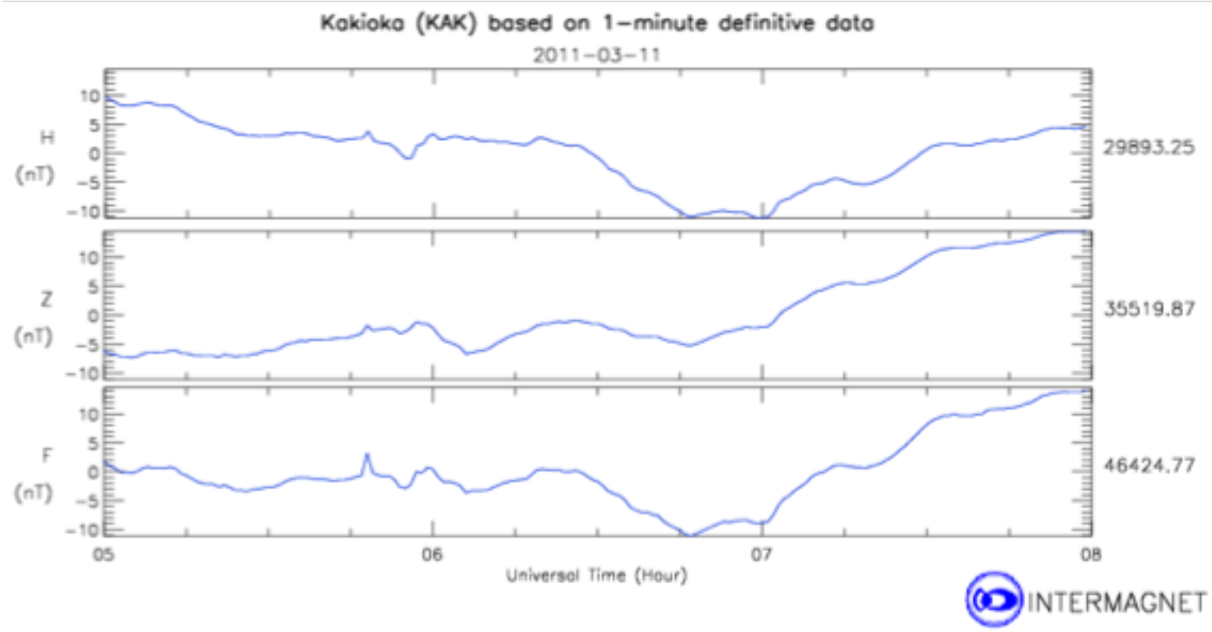

Figure 11. Magnetogram from INTERMAGNET for the 2011 Tohoku tsunami, showing the *H* and *Z* signals with *F* is the total field observed at KAK about 320 km away from the epicenter.

To better suit this problem, knowledge of tsunami dynamics propagating over a large distance in the ocean may also be completed with a study of tsunami amplitude variations hence tsunami energy with increasing travel time and travel distance as previously discussed by Rabinovich et al. (2013) and Prastowo and Cholifah (2019), as well as accurate prediction of tsunami arrival times that leads to accounted travel time delays for different stations, as reported by Prastowo et al. (2018), from near-to far-field tsunami observations. In this regard, data feasibility extracted from electromagnetic signals owing to tsunami passage is of fundamental interest for remotely identifying tsunami generation and propagation hence tsunami development in its early stages.

4. CONCLUSIONS

Geophysical disturbances due to either submarine landslides or earthquakes with the hypocentre is located below the sea surface or the ground near the sea surface may generate a tsunami that leads to local magnetic anomalies, measured as the vertical b_z and horizontal b_H signals. In the pesent study, the amplitudes of the two signals are determined using frozen-flux approximation and magnetogram from INTERMAGNET and/or BCMT for Indonesian events with and with no tsunami potential threat generated. For the 2004 Aceh, the 2018 Palu-Donggala and the 2018 Sunda Strait tsunamis, b_z values predicted from theory, $b_z \leq 2{,}0$ nT, are consistent with magnetogram provided by the two institutions while b_H signals vary with locations where the wave is generated owing to local topographical effects. For cases of no tsunami potential threat, including major earthquakes in Banten on 23 January 2018, Lombok on 5 August 2018, Central Sulawesi on 12 April 2019 and North Maluku on 7 July 2019 both the b_z and in particular the declination D signals indicate no magnetic anomaly recorded and thereby the absence of a tsunami wave after the shocks. However, frozen-flux approximation remains useful for the best estimate of b_z detecting tsunami generation far away from coastlines that is supported by real-time magnetogram obtained from INTERMAGNET and/or BCMT. In some sense, magnetogram is more reliable than any other instrument to detect adequately accurate tsunami passage in the oceans. This is vital for the development and future use of Indonesian tsunami early warning in the context of hazard mitigation study.

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BUILDING A TSUNAMI DISASTER RESILIENT COASTAL COMMUNITY IN SRI LANKA

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ABSTRACT

Natural disasters are inevitable, but strategic planning could alleviate or ameliorate their adverse impacts. The frequency of natural disasters in Sri Lanka has risen over the past few decades, thus the number of disaster-affected communities, casualties, and victims have clambered simultaneously. It is has been observed that in Sri Lanka, strategic dealing has not strengthen enough the needed modification of community-level planning for evacuation, for emergency preparedness systems, or for the needed advance considerations that must be evaluated and taken by the appropriate Civil Defense authorities. Thus, the main focus of the present research is to review the vulnerable coastal communities that were affected by the 26 December 2004 tsunami, and to determine which may still be at risk from future disasters. The research objective is based on three main questions: a) How resilient are today Sri Lankan coastal communities? b) Why is resilience critical to these coastal communities? c) What is needed to build coastal hazard resilient communities? The research proposes that solutions could be possible with a specific identification study on how to bridge the gap between the current national-level proposals and the practical applications at the community-level. This study could be further helpful in enhancing viable relationships among local governments and coastal communities in evacuation planning for future tsunami disasters.

Keywords; *Tsunami Disaster Resilient Coastal Community, Resilience Gap, Community-level Risk Assessment, Community Participation in Mitigation, Evacuation*

1. INTRODUCTION

Natural disaster resilience is the capacity of a community to adapt and influence the change caused by a particular natural disaster. Sri Lanka was a not considered as a natural disaster-prone country until a few decades ago. But the situation by now has changed drastically. Furthermore, coastal communities around the world are experiencing presently an unprecedented rate of change due to population growth in the coastal areas, humanly induced vulnerability, and global climate change. The effects of this change are placing communities at increasing risks from coastal hazards such as tsunamis, severe storms, and shoreline erosion. [2]

The frequency of natural disasters in Sri Lanka, which are considered as coastline hazards include tsunamis, storms, coastal beach erosion, and inland hazards such as landslides, floods, and a variety of other collateral catastrophes, which have been increasing over the past few decades. As a result, disaster-affected vulnerable communities and resulting casualties are rising annually. It is obvious that tsunamis constitute the highest risk disaster for Sri Lanka's coastal communities - as determined by the impact of the 26 December 2004 event. The records of this particular event revealed clearly which coastal communities have a high possibility to become vulnerable again. High population density and massive sudden threat levels of tsunamis, could be considered as the main reasons for increasing the coastline hazard risk.

The present study considers risk evaluation, early warning efficiency, evacuation and emergency responses as important elements in improving the existing low resilience level of coastal communities. Furthermore, the study identifies the low resilience level of coastal communities through hearings and onsite observations conducted based on the above elements (Early Warning and Evacuation and Emergency Response) on the research fields. The current resilience level of the coastal communities has been recognized as being at the 40% level, which indicates that there is a 60% gap in order to achieve the ideal condition. This has been determined by a quantitative data analysis research which was done at Panadura coastal DS (District Secretarial) division [6] Fig. 2. The research was conducted under the framework proposed by UNSAID 2007 and it combines eight significant resilient elements: Governance, Society and Economy, Coastal Resources Management, Land-use, Structural Design, Risk Knowledge, Warning and Evacuation, as well as Emergency Response and Disaster Recovery. Fig. 1.

The present research identifies that most of the risk assessments and evacuation programs such as the PDNA (Post Disaster Need Assessments) action programs and the NDMP (National Disaster Management Plan) are being focused on the more frequent hazards such as floods and landslides. Hence, in our research we propose that due to the non-predictability massive level, there should be no less priority for sudden coastline hazards like tsunamis.

The first step in establishing resilience should be the identification and determination of actions that need to be taken to reduce the risk of the hazard. Therefore, building on lessons learned and experienced gained, is important. Hence the Sri Lankan coastline is most in need of building resilience. How to enhance resilience through a top-down system has become the most challenging task at present for all types of hazards in the country. The present study identifies the well established and organized national level emergency response and evacuation guidance programs which have been conducted nationwide, mainly by the DMC (Disaster Management Centre) - the top-level disaster mitigation authority of the country - but with rather low level of participation at the community-level. Consequently, there should be a proper assessment of risk by each local community, so that the understanding of the risk can be impacted positively in address properly each community's resilience.

Fig.1. Elements of coastal community resilience. (Source: USAID/ASIA Report 2007)

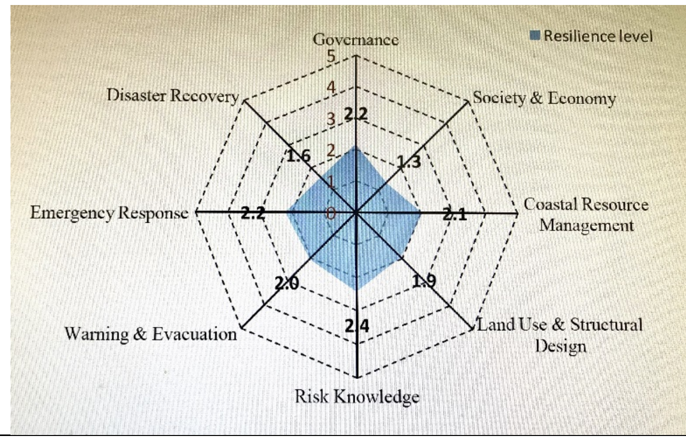


Fig. 2. Resilience Level Coastline Sri Lanka
(Source: Coastal Community Resilience level of Tsunami prone area, procedural Engineering 212(2018) p.686)

1.1. Past Disaster Experiences on the Sri Lanka Coastlines

The 2004 Great Sumatra tsunami claimed the lives of 35,000 people in Sri Lanka and displaced one in twenty. The disaster highlighted the critical importance of developing an effective National Early Warning System (NEWS: SL). [5]. The tsunami generated by the 9.2 magnitude 2004 Indonesian earthquake, affected two-thirds of the entire coastline Sri Lanka. The disaster destroyed 80,000 houses and partially damaged another 40,000. The total economic loss in housing, infrastructure, tourism, and fisheries sectors was estimated at more than US $900 million. [7]. Since it was the first major disaster that impacted the entire coastline of the country, the damage was high, primarily due to the lack of safety building codes, of adequate land use planning and of evacuation procedures for coastline communities. In the post-disaster period, major reconstruction projects were implemented with financial support of the Sri Lanka government and of many national and international donor organizations to help obtain full recovery.

Two types of permanent housing programs were dedicated in repairing and rebuilding the damaged houses. They were known as reconstruction programs established on the coastline, and resettlement programs, established inland on lands away from the original coastal sites. Unfortunately, the most essential part of post-tsunami reconstruction and safety concerns on the coastline, were neglected during the reconstruction process. In the beginning, a 200m buffer-zone regulation (Set-back Zone) was proposed by the coastal conservation department, but later it was revised several times and was reduced to a minimum of 35m which could be difficult to count as a safety precaution. Hence there is a great necessity for revisions and of more efficient emergency evacuation planning for coastal communities.

2. RESEARCH QUESTIONS

1. How resilient are Sri Lankan coastal communities today to natural disasters?
2. Why natural disaster resilience is critical to Sri Lanka's coastal communities?
3. What is needed to build a resilient community for tsunami and other coastal hazards?

3. RESEARCH HYPOTHESIS

The main objective of the study is to emphasize to top-level decision makers the importance of community-level risk assessment at each coastal community. Additional objective is to provide support to the Sri Lankan coastal communities to know the possible tsunami risk at the community-level (in an easily understandable manner), so that it will be helpful to increase the disaster awareness and active community participation in current disaster mitigation and evacuation activities. Finally, another objective of the study is to promote active community participation, such as community-level hazard map development, and other related information needed for disaster mitigation for preparedness activities and evacuation from risk areas, and for enhancing future disaster resilience and address DRR (Disaster Risk Reduction) aspects strategically.

4. METHODOLOGY

Onsite observations were completed in Mirissa south 1 and 2, GN divisions (*Grama Niladari* division/Village) in Matara DS division (District Secretarial division) in the southern coastline of Sri Lanka, from 30/01/2019-01/02/2019. Data was gathered through multiple collection methods, literature surveys, community hearings, simple questionnaire surveys, informal interviews of government officers of authorities such as the Disaster Management Centre, at the Colombo head office, project officers of the disaster management division in Matara District Secretaries office, the village officers in Mirissa GN divisions, as well as from municipal drawings, field visits, and informal interviews with people of different communities.

5. EXPLANATION OF REREARCH QUESTIONS

5.1. How resilient are Sri Lankan coastal communities today to natural disasters?

Presently, Sri Lanka is receiving considerable attention at the international level as a natural disaster-prone country and substantial assistances to upgrade the resilience level of its citizens for natural disasters.

Most of the recent recovery plans have focused on those disasters which occur frequently, such as floods and landslides. The Post Disaster Recovery Plan (PDRP) for floods and landslides of May 2017 was developed as a collaborative effort of the Government of Sri Lanka with United Nations agencies, the World Bank, the European Union, and other organizations. In response to catastrophic floods and landslides that affected the entire country in May 2016 and May 2017, a Post Disaster Assessment (PDNA) study was conducted which assessed both the effects and the recovery needs, across affected sectors and districts. PDNA directed the development of the National Disaster Management Plan, including the Comprehensive Action Program for five years for the 2018-2023 period, and the Sri Lanka Comprehensive Disaster Management Program (SLCDMP). This plan further explains it would take into account recommendations for medium- and long-term recovery needs, outlining in PDNA and global targets outlined in the Sendai Framework for Disaster Risk Reduction and sustainable development goals. The Department of National Planning initiated the Post Disaster Recovery Plan (PDRP) and the Recovery Framework in September 2017 with the assistance of the World Bank and UNDP.

Additionally, recognized by the National Disaster Management Plan was the need for advanced disaster mitigation and emergency evacuation system for the coastline communities. Thus the national plan that was subsequently established, included disaster awareness and preparedness, training, mitigation research and development, emergency operations, early warning system procedures and evacuation of the public from risk areas. Based on interviews with top-level officials of the safety planning hierarchy, it was determined that the national plan is now well organized and properly executes the assigned tasks throughout the country. However, based on further observations, it was also recognized that when a natural disaster occurs, the resilience for recovery at the community-level remains a critical issue. This could be identified as lack of knowledge in preparing to deal with actual disaster situations in those communities. At present, how to fulfill the gap between the local community level and the national authority level, has become a greater challenge in achieving natural disaster resilient communities.

The high coastal population density also increases the risk level. Since over 50% of the total population live in maritime districts and of this 42.7 % live in the coastal region, the coastal region has to play a greater role in meeting the major challenges of the nation. The tsunami impact on coastal regions also reflected in the fishing and the tourism sub-sectors. Future development planning in the coastal region is needed because it has significant implications for the national economy according to the National GDP through the Coastal GDP. Coastal GDP in 2004 was reduced clearly by the Year 2005. [1]

Figure 2 reveals the coastal community resilience level by the year 2018 and it is clear that the coastal community of Sri Lanka further needs to enhance their resilience to a tsunami in all dimensions of the resilience framework of USAID 2007. [6] Therefore, the elements of Early Warning and Evacuation and Emergency Response play a great role.

5.2. Why the Natural Disaster Resilience is Critical to Sri Lankan Coastal Communities?

A major issue that still remains is on how to bridge the gap between the current national level safety and evacuation proposals and practical applications at the community level. Hence, emphasizing the importance of obtaining advance knowledge on the possible risk from future earthquakes and tsunamis for the top-level decision-makers is still an issue not properly achieved. Achieving such understanding would be helpful to continually conduct risk assessments and evacuations programs in a more positive and effective manner at the local coastline community level. Presently there is insufficient understanding of the possible risk of coastal communities to the potential impact of future earthquake and tsunami disasters. Increase in the awareness of future tsunami risks and of the needed evacuation, has become a challenge. The actual risks for each coastal community need to be assessed and evaluated separately.

The majority of the post-disaster reconstruction projects on the southern coastline had been established without proper safety measures or adequate evacuation procedures. This means that the beneficiaries don't feel safe in the buildings which they received by donor parties, which still have to assessed for safety precautions from the basic level.

The Sri Lankan navy forces are responsible presently for conducting safety activities and maintaining the safety level of communities along the coastline. For this reason they conduct an annual evacuation drills for the coastline communities with the support of the GN division and DS division officers. Additional reason for the drills is to be combine strategic and community friendly manner/practices with community leaders in order to improve communications between local community members and authorized decision making officials.

5.3. What is Needed to Build an Effective Coastal Hazard (Tsunami) Resilient Community?

In order to make the existing National Early Warning System and community-level strategies more effective, steps must be taken to issue in a timely manner the evacuation warning to the threatened coastal communities. This needs to be done through simple community-friendly methods and directives about the potential threat and thus enhance the safety of each vulnerable community. To accomplish this objective the following steps are suggested:

- Proper and shared community-level risk assessment among community members, which will include recognition of hazards areas and safety zones, which are supported by simple and accurate hazard maps.
- With the participation of community members, the development of functional and detailed networks of escape routes and safety zones for evacuation.
- Emphasis on the necessity of future land-use changes and identification of the safe habitable areas, by using the hazard maps.
- Consideration for safe evacuation that can enhance the safety standards of coastal communities in an emergency situation for protection from tsunamis and other risks associated with coastal hazards. For example, the use of local high-rise buildings, such as hotels, for quick vertical evacuation.

6. CURRENT DISASTER MITIGATION SYSTEM AND PUBLIC WARNING PROGRAMS FOR TSUNAMI HAZARDS

A public warning system has the responsibility to properly identify a hazard, to assess its potential risk to vulnerable communities, and to issue a warning in a timely fashion so that measures of protection can be taken and evacuation to designated safe areas. The accurate identification of the vulnerability of a population at risk, and finally the communication of information about the threat in sufficient time and clarity, is needed so that action can be taken to avert the negative consequences, constitute an effective system of public warning. The warning allows people to act to respond and to prevent hazards from becoming disasters. Effective public warning saves lives, reduces economic loss, reduces trauma and disruption in society, and instills confidence and a sense of security in the public. It is an important component of the foundation of a sound economy. Effective warning is just one of the critical parts of a comprehensive risk management system that includes mitigation, preparedness, response, and recovery. A warning is a crucial component of the overall risk management system that did not exist when the 2004 Indian Ocean tsunami struck. [5]

6.1. National Level

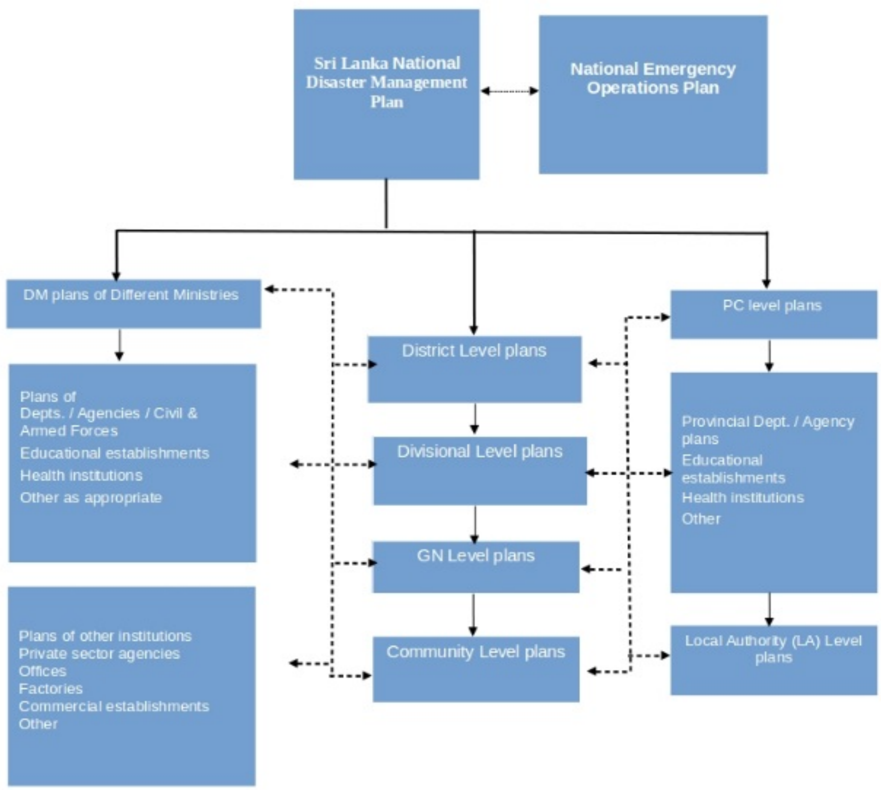


Fig. 3. Conformity of disaster management plans at all levels and in all sectors.
(Source: http://www.dmc.gov.lk)

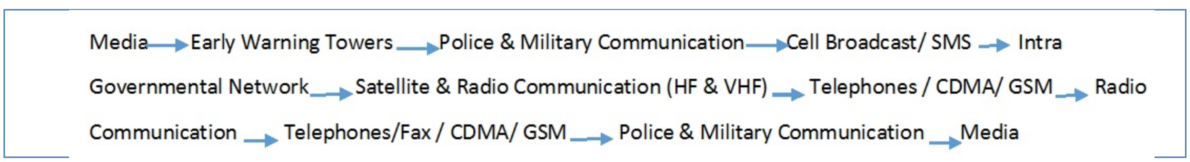
As shown in the organizational diagram (Fig. 3),the Disaster Management Centre controls disaster relevant activities. It is the leading agency for disaster management in Sri Lanka. It is mandated with the responsibility of implementing and coordinating national and sub-national level programs for reducing the risk of disasters with the participation of all relevant stakeholders.

The main activities of DMC are Research and Development, Mitigation, Planning Preparedness, Dissemination of Early Warning for the vulnerable population, Emergency Response, Coordination of Relief, and Post Disaster Activities in collaboration with other key agencies.

To facilitate the coordination and implement all DMC activities, Disaster Management Committees were established at District, Divisional, GN/village, across the country. Also, District Disaster Management Coordination Units (DDMCU) were established in all districts to carry out Disaster Risk Reduction (DRR) activities at the sub-national level. [5]

6.2. Communication Systems for Early Warning Disseminations

The present system of communication from the national level to district/divisional/local authority/GN division levels or other specifically identified locations is mainly through the Police and military communication systems, radio communication, multi-hazard early warning towers, media, and the normal telephone systems. Alternative countrywide communication systems have already been established and with these improvements, DMC ensures that there will be a mechanism to inform the vulnerable communities immediately. These include the Nation-wide Emergency Communication System, which will be used to provide information, shown on this diagram.



IOTWS (Indian Ocean Tsunami warning and Mitigation System) is the main key warning centers for the Tsunami early warnings. INCOIS (Indian National Centre for Ocean Information Services), Aus. MET (Australia Meteorology) and the Indonesian MET departments are working together to send more technical information to the DMC and MET in Sri Lanka. Several Methods were integrated with an early warning system from the national level up to grass root level. EOC (Emergency Operation Centre) was strengthened with Police and tri-force units at the national level with their co-education equipment. [5]

6.3. Early Warning System Introduced by the Disaster Management Centre

The disaster management centre has introduced the steps listed below (see Figures 4, 5, 6)
- Maintaining and operating Early Warning Towers and other early warning dissemination equipment.
- Dissemination of Early Warning Messages and ensure the receipt at remote vulnerable villagers.
- Co-ordination of donor assistance to strengthen the capacity of technical agencies for early warning.
- Working out strategy and policy in the given area of activity.
- Initiating awareness on activities related to early warning among the various agencies and public.
- Guiding District Disaster Management Units in coordinating and implementing warning dissemination related activities in the Province, District, Local Authority, Division, GN level/village, and community level. [5]

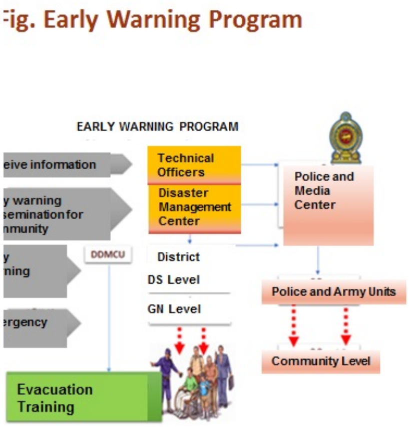
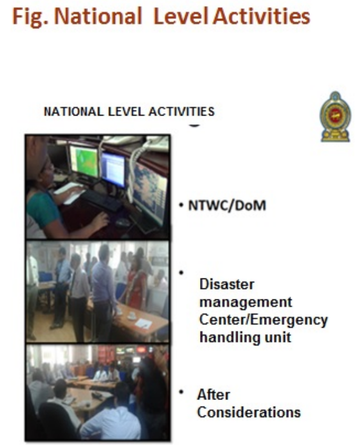
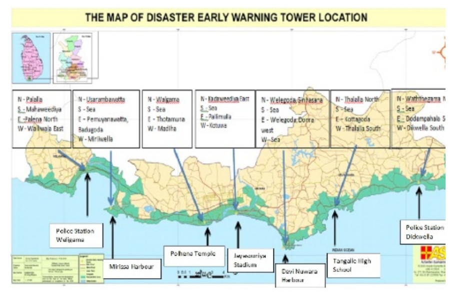
		

Fig. 4. Early Warning Program	Fig. 5. National level activities	Fig. 6. Locations of early warning towers on Southern Coast line

6.4.Community Level Communication Systems and Last-mile Dissemination

At the community level, emergency communication system by DMCwhich will be used, will provide the early warning information as shown on the following diagram.

Telephones / CDMA/ GSM → Police Vehicles – Announcements NGOs and CBOs → PA Systems → Sirens (Hand and Electric) → Temple and church bells → Riders/ Push Bicycle & Motor Cycles/Messengers → SMS / Cell Broad cast → Early Warning Towers → Media → Traditional and Religious methods → Early Warning Committees (Door to Door)

Furthermore, from the all locations (district/divisional/local authority/GN levels or other identified specific locations) onwards, the dissemination to the communities is effected through the following various methods: Personnel and agencies such as Local authority officials, GN's, Local Police, CBO's, NGO's, Military, Police and Volunteers. All listed will be involved in the warning dissemination activities. The effectiveness of the methods will be different in different locations depending on the location-specific characteristics. [5]

7. EXISTING EVACUATION SYSTEM FOR MIRISSA GN DIVISION

7.1. Annual Evacuation Drills

According to the interviews conducted with community members and GN division head officers, ongoing evacuation procedures are as follows: By February 2019 the latest evacuation drill program had been conducted on 2018.08.20 at Mirissa GN division parallel to the National evacuation program for the coastline. The Disaster Management Unit of Matara District Secretary office conducted the Mirissa program.

A general announcement had been issued to the community before the drill. Evacuation warning had been disseminated by the areas' Tsunami tower siren, on the day. The community had started to evacuate to places/shelters, which they have been designated in general, such as high grounds/ hilltops, a school, and a temple (Fig.10). Evacuation routes and evacuation shelters had been decided randomly by some evacuees during the drill, as they had less awareness of the systematic evacuation route/ shelter guidance at the community level.

Fig.7. Existing Unsafe Communities and Unsafe Houses on Mirissa Coastline

3.1. Shortcomings of the Existing Evacuation System

Shortcomings in the evacuation include insufficient knowledge by a community to receive sufficient understanding of when and where its citizens need to evacuate for safety. Another shortcoming involves a community's difficulties in selecting evacuation shelters and routes, even after the participation in several evacuation drills. Part of the difficulty is to find a significant improvement of evacuation time based on a repeat of the 2004 tsunami disaster. (Fig.11. & Table-1.) Further community participation in evacuation activities is still very low at present time and more active participation in community evacuation programs is needed, such as in developing hazard maps, designating evacuation routes and other steps that need to be taken (Table-1.) The proposed evacuation map is tentative and presents difficulties, and it does not include detailed information on evacuation routes and places/shelters –all needed for a clear idea on safe evacuation. (Fig. 8.)

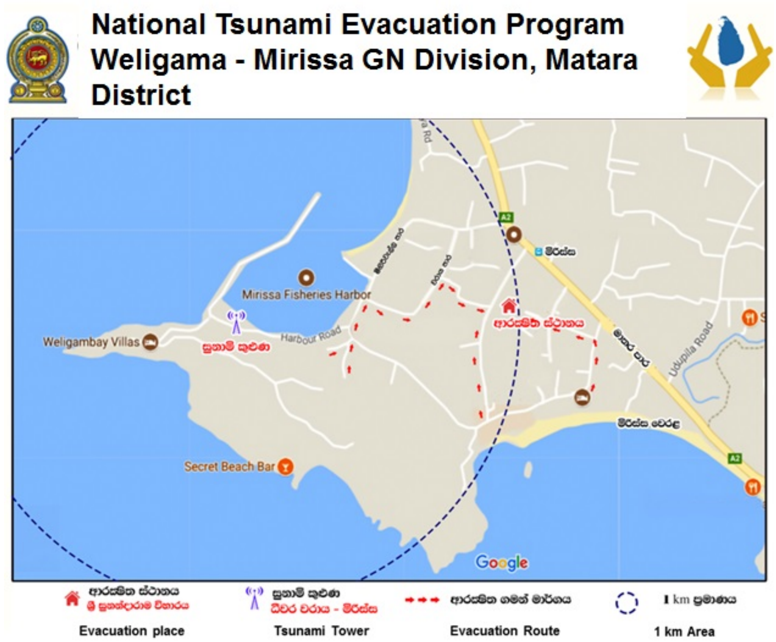


Fig. 8. Proposed Tentative Evacuation Route map for Mirissa GN Division
Source: Disaster Management Center –Matara District Secretarial Office

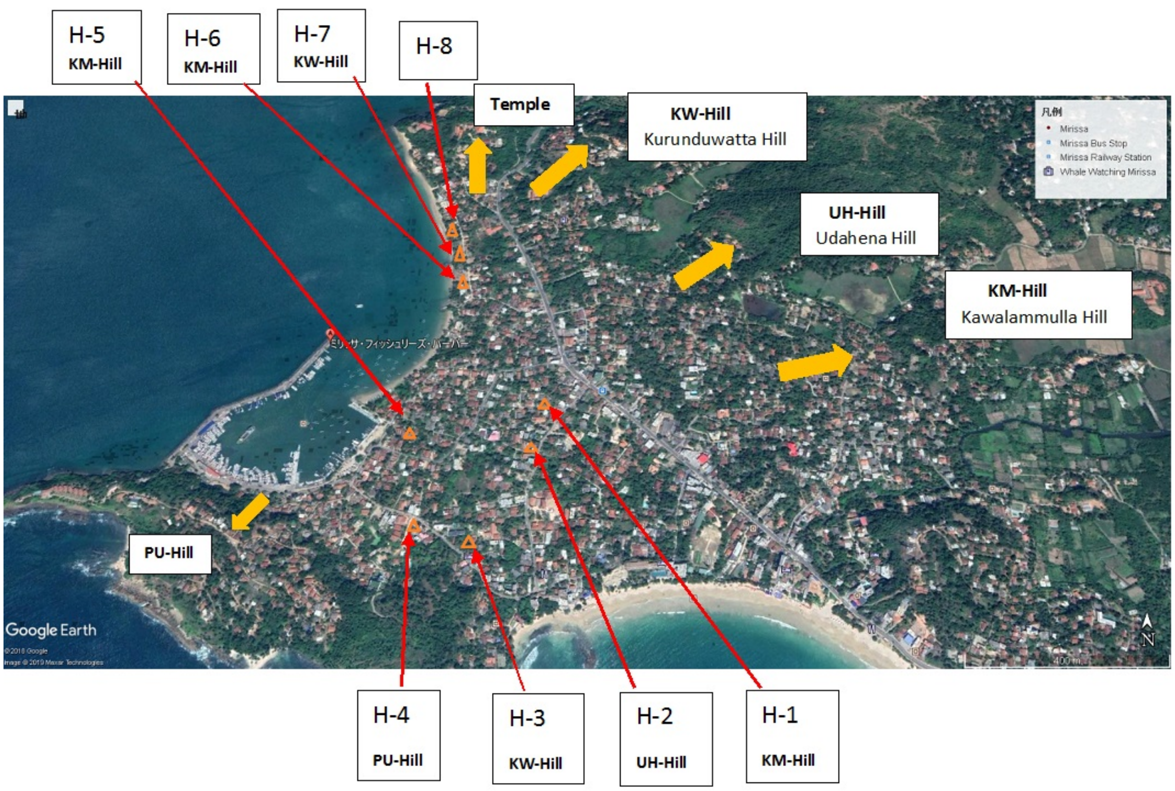


Fig.9. Locations of Interviewed Houses and Evacuated Places

Fig.10. Community Organization of Mirissa GN Division and Identified Evacuated Places/Shelters

er	H-1 65yrs/F	H-2 60yrs/F	H-3 55yrs/F	H-4 58/F	H-5 50/M	H-6 35/F	H-7 61/F	H-8 52/F
om Sea	300m	300m	300m	200m	100m	35m	35m	35m
s by mi	No	Housing & Property loss	Housing & Property loss	Property loss	Housing & Property loss	Housing & Property loss	Housing& Property loss	Housing& Property loss
using	No loss- covered property	Minor damages/6 m flood	Minor damages/ 6m flood	Minor damages/6 m flood	Partially Damaged	Partially Damaged	Partially Damaged	Partially Damaged
Place	KM-Hill	UH-Hill	KW-Hill	PU-Hill	KM-Hill	KM-Hill	KW-Hill	Unattended
elect	Just followed others	Own decision	Just followed others	Just followed others	Just followed others	Just followed others	Own decision	-
	No specific	No specific	No specific	No specific	No specific	No specific	No specific	-
ch to Place	About	About	About	About	About	About	About	About
ami on drill	15 min 15 min	30 min 30 min	20min/bus 30 min	15min/run 30 min	45 min 40 min	40 min 30 min	20 min 20 min	- 10 min
other later	No	Yes Temple	Yes Temple	No	No	No	No	No
r dren/	Didn't support	Cuddle children	Didn't support	Didn't support	Didn't support	Didn't support	Didn't support	-
Stuff	No	No	No	No	No	No	No	-
of ami	Yes	Yes	Yes	No	No	No	No	Yes
under on	No children	Yes By School	No children	No children	No children	Younger children	Younger grand children	No children
uation ture	Same place	Temple (not sure)	Same place	Temple (un- confident/ 40 mints)	Same place	Same place	Temple	Temple (not sure)
map ated in	Haven't	Haven't	Haven't	Haven't	Haven't	Haven't	Haven't	Haven't
work	No	No	No	No	No	No	No	No
on	yes	yes	yes	yes	yes	yes	yes	yes
on of Drill	2 times	no	2,3 times	4 times	3,4 times	2 times	2,3 times	1,2 times

Table-1. Questionnaire Summary

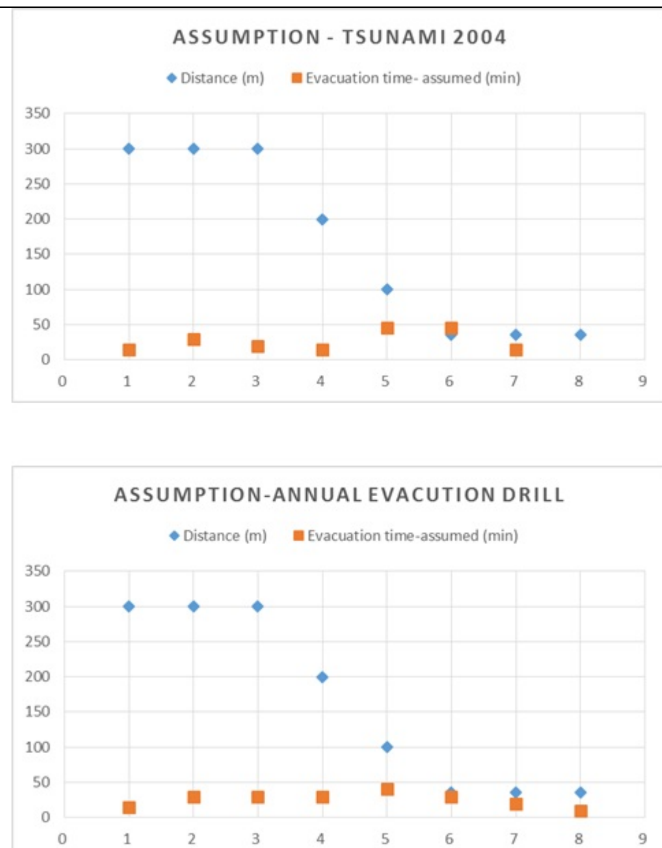


Fig.11. Comparison of Evacuation Time and Distance to Evacuation Shelter/Place.

4. CONSIDERATIONS AND RECOMMENDATIONS

4.1. Suggestions for Top-level Administration

To emphasize the importance of obtaining advance knowledge on the future possible risk and variations of risk-levels by earthquakes and Tsunamis for top-level decision-makers, due to unpredictable source regions of active seismic faults. It would be helpful for administrators to conduct risk assessments and evacuations programs in a more accurate and active manner, considering hazard-levels and safe evacuation times, particularly for coastline communities.

It is important to increase each community's awareness of the future Tsunami risk and of the procedures for safe evacuation. This could be achieved by increasing the understanding of potential risk areas, of methods for disaster mitigation and with the adoptation of proper educational programs, for each vulnerable community.

4.2. Suggestions for Community-level Administration

The present study identifies the necessity for strategic evacuation plans/programs, and suggests the reconsideration of the existing programs, to properly addresses all safety/DRR aspects. Such plans should be ready to be in action in a short time, and with affordable, long-term and fruitful solutions for coastal communities.

4.3. How to Develop a Strategic Evacuation Plan/Program at the Community-level

It could be accomplished by community-level Hazard Mapping and by developing functional networks of evacuation routes to proper evacuation shelters/places. Active community participation should include educational programs for school children, as this is important for them to individually recognize their risk and what they need to do for their own safety.

It is important to consider the following recommendations in re-considering the existing programs and plans as summarized in Figure 12:

1. Introduction of best evacuation place at household level in each community.
2. Introduction of additional long-distance and short-distance escape routes and evacuation shelters at a community-level.
3. Identification of existing Tsunami resistant buildings at the community-level for emergency evacuation.
4. Increase community responsibilities and participation through community member leaderships and involvement of school children and for help of disabled persons/children, and other vulnerable groups.

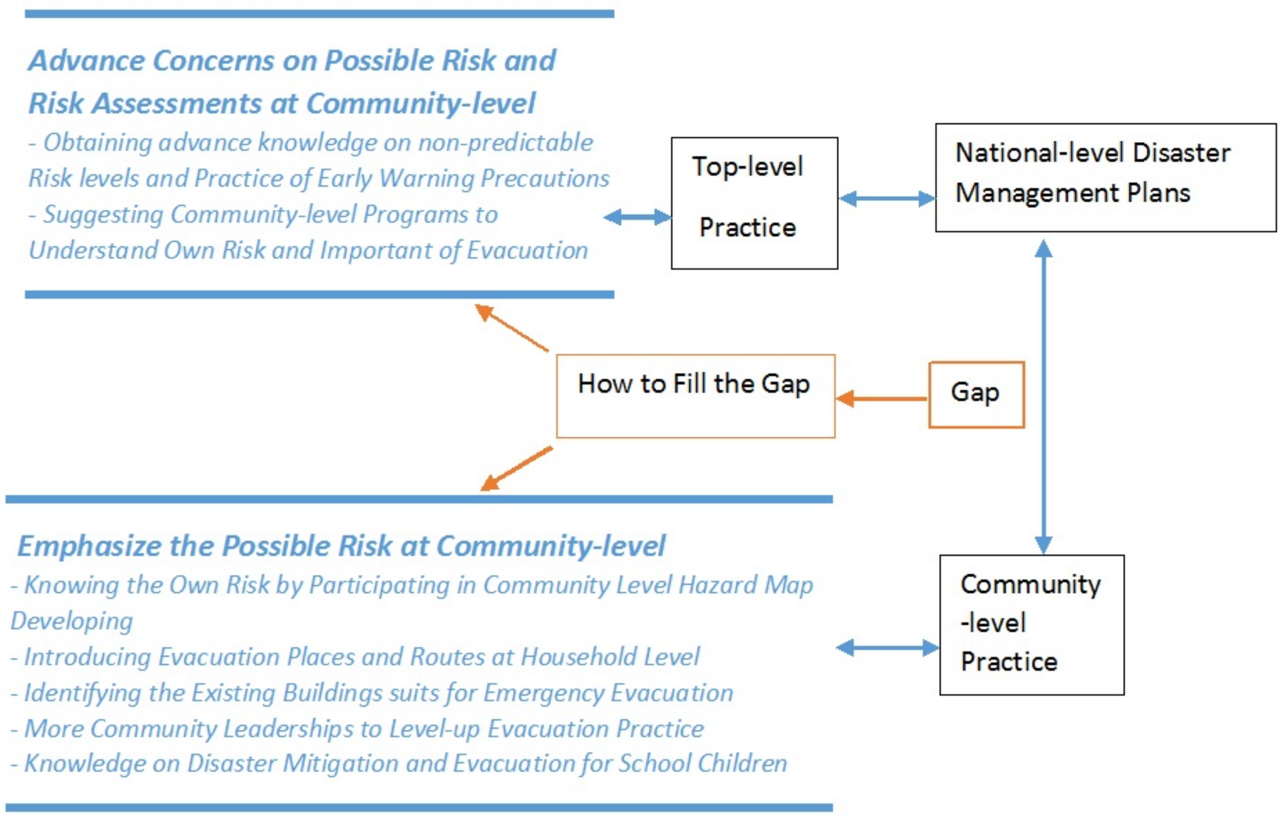


Fig.12. Consideration and Recommendation Summary Chart

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Notes: Acronyms

DMC - Disaster Management Centre

GN division - *Grama Niladari* division-Village officer division of Sri Lanka

GS division - District Secretariat division

DRR - Disaster Risk Reduction

IOTWS - Indian Ocean Tsunami Warning and Mitigation System

INCOIS - Indian National Centre for Ocean Information Services

EOC - Emergency Operation Centre

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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.

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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.

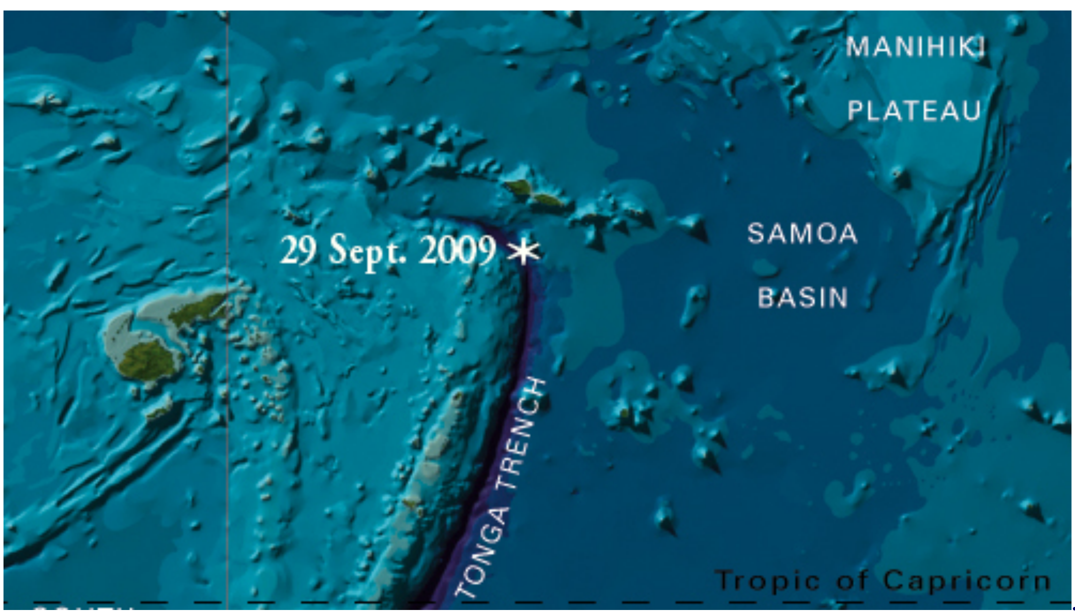

Fig 1. Epicenter of the 29 Sept. 2009 Earthquake at the northern end of the Tonga Trench.

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.

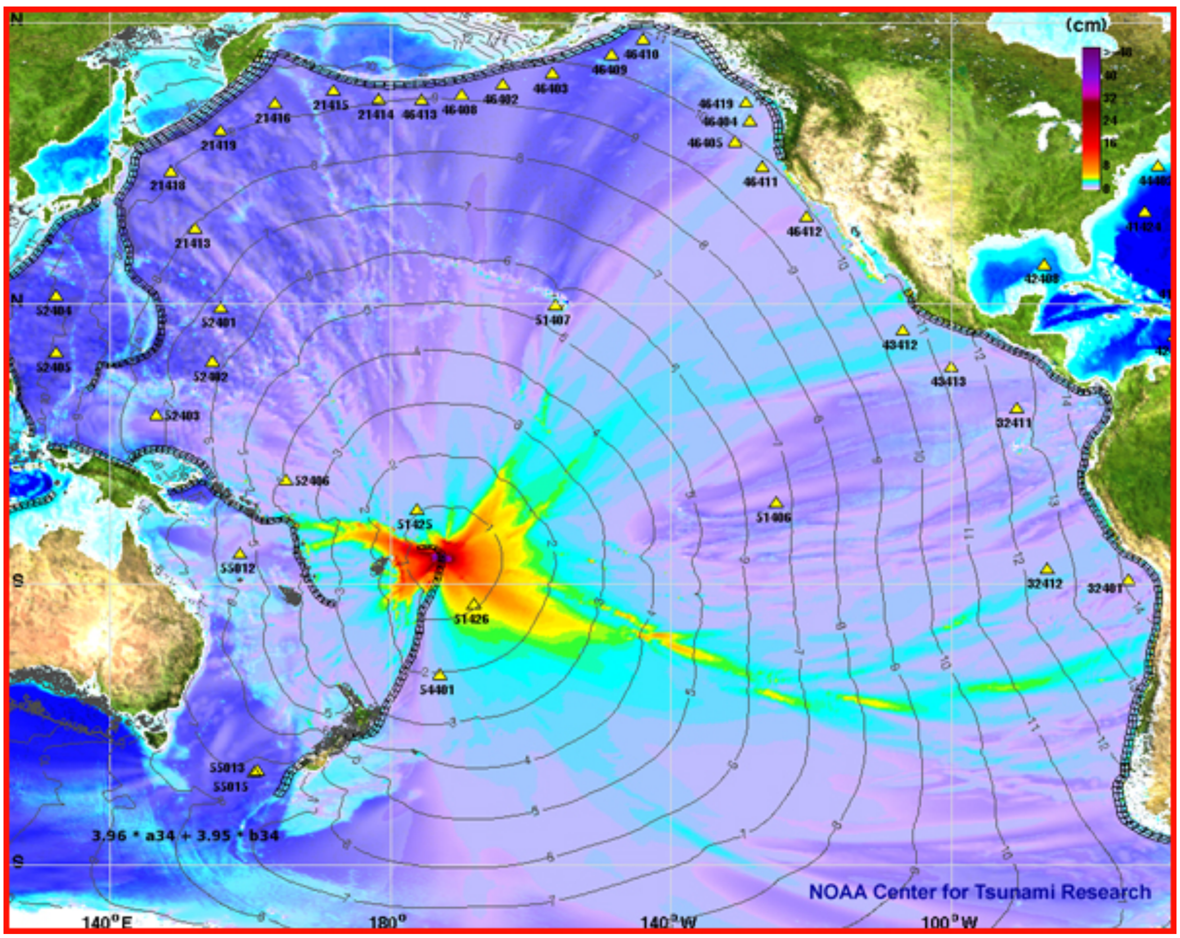

Fig. 4. The 29 September 2009 tsunami travel time chart. Location of DART buoys (Source: NOAA Center for Tsunami Research).

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.

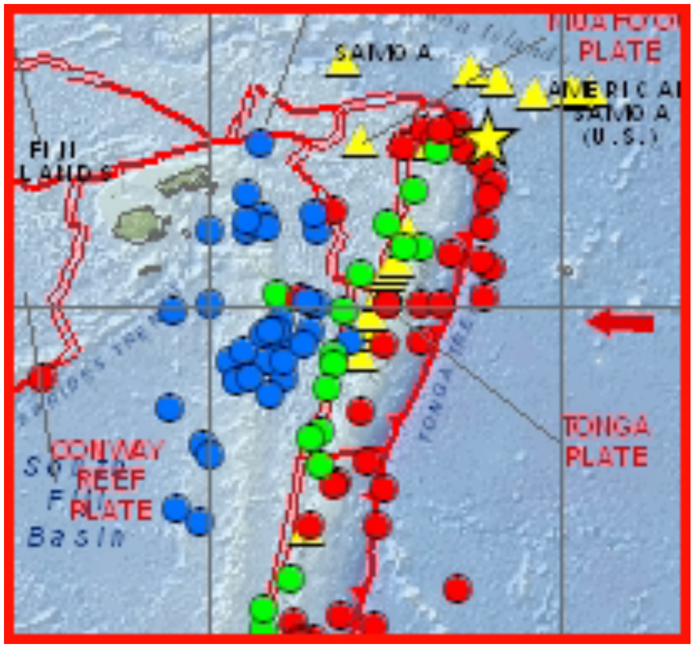

Figure 5. Epicenter of the 29 September 2009 tsunamigenic earthquake on the outer-rise of the northern end of the Tonga Trench and Arc.

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.

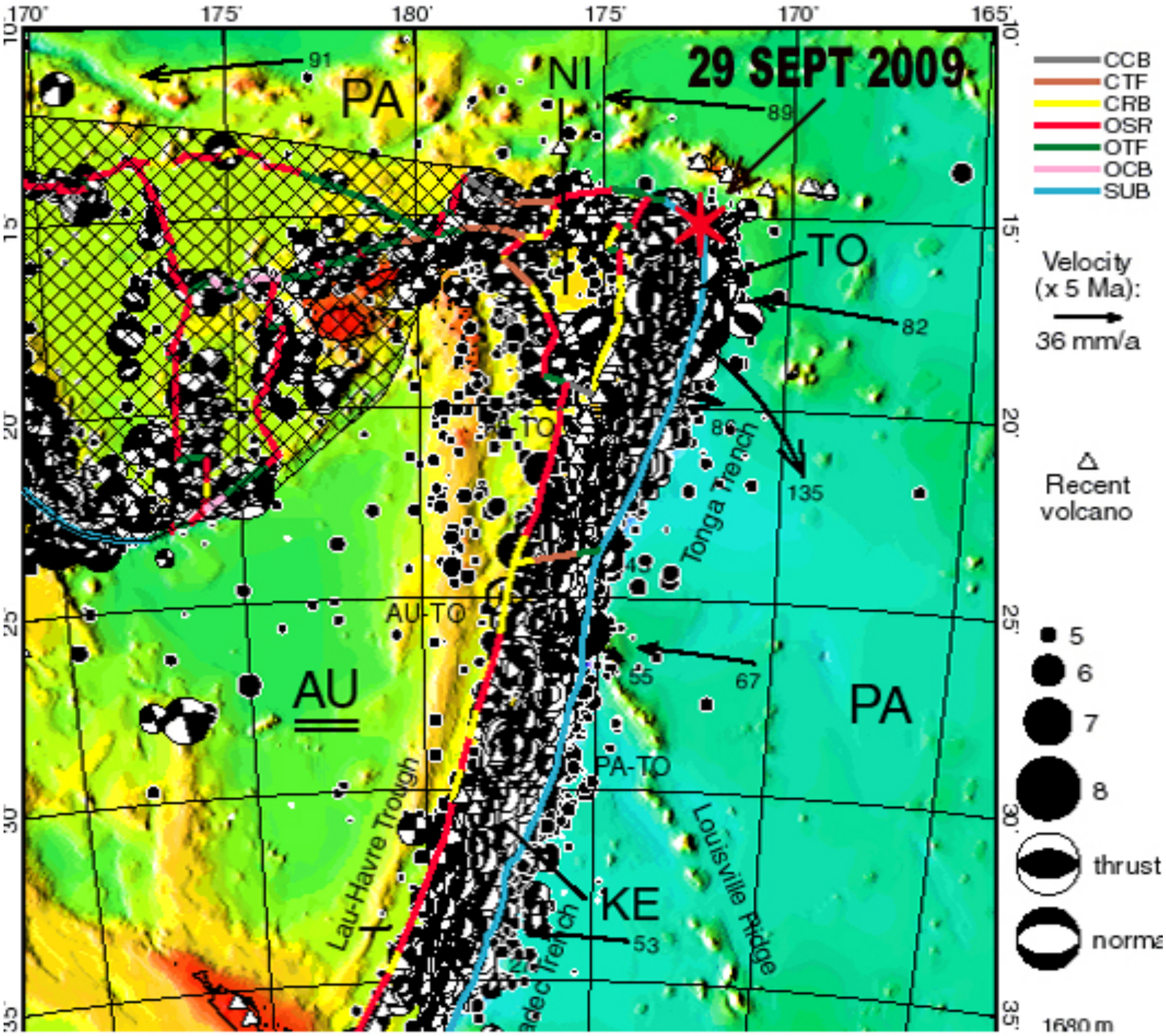

Figure 6. *The Tonga-Kermadec Trench and Arc. Seismotectonics, Kinematics and Plate Boundaries of the Tonga subplate seismic activity along the Tonga Trench and its northern boundary near the region where the 29 September Earthquake occurred. TO-Tonga plate, PA-Pacific plate. KE-Kermadec plate, AU-Australian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

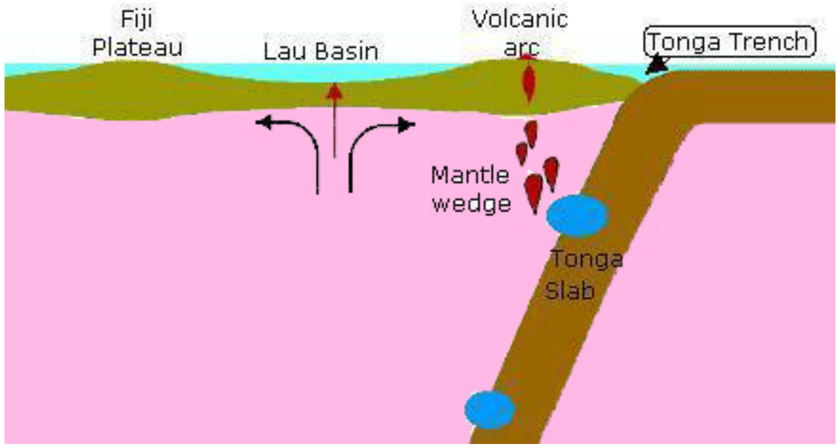

Figure 7. Illustrations of stresses along a cross-section in the middle segment of the Tonga trench from Pacific plate subduction and from the spreading center of Lau Basin (modified USGS graphic). Intra-oceanic convergence tectonics along the Tonga Trench and the adjacent forarc between 14 South and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

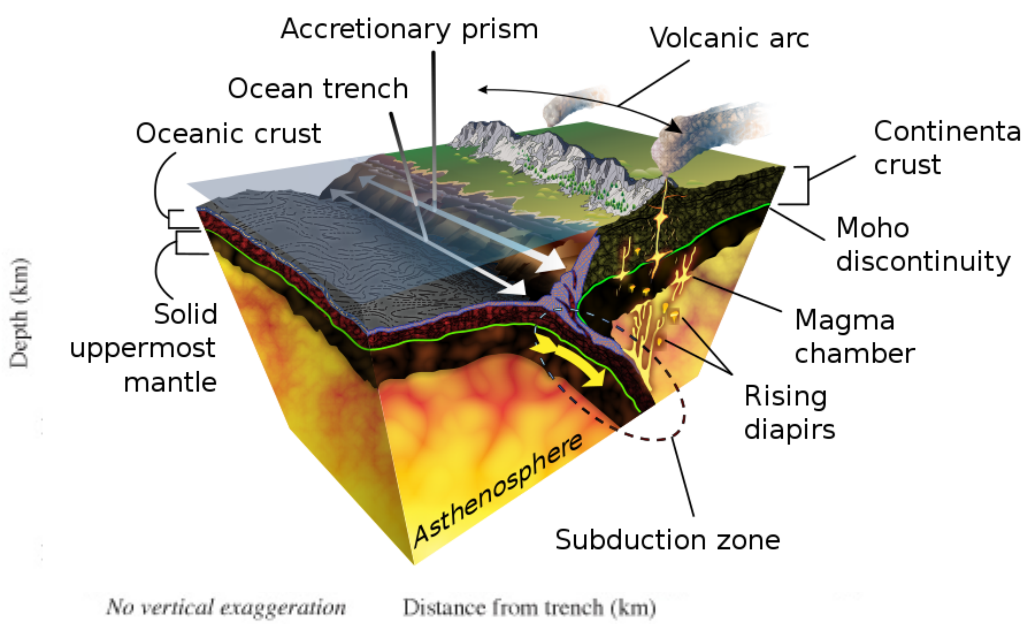

Figure 8. Schematic illustration depicting the intra-oceanic convergence tectonics in general (modified Wikipedia graphic).

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.

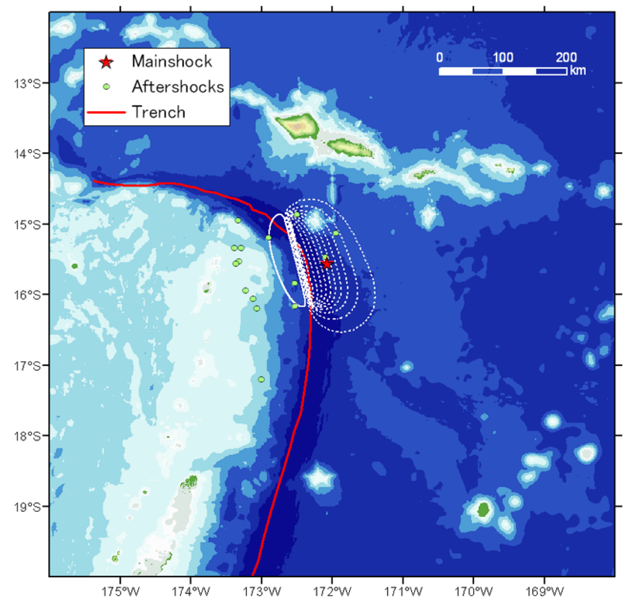

*Figure 10. Case 1. Tohoku University, (USGS data), Mo = 1.2 x 10**21 Nm; Fault Length / Width : 150 km / 75 km; Source Mechanism (Strike, Dip, Slip) = (345, 52, -61) Reference:USGS Dislocation: 3.6 m. http://www.tsunami.civil.tohoku.ac.jp/hokusai3/J/events/samoa_090930/source_case1.png*

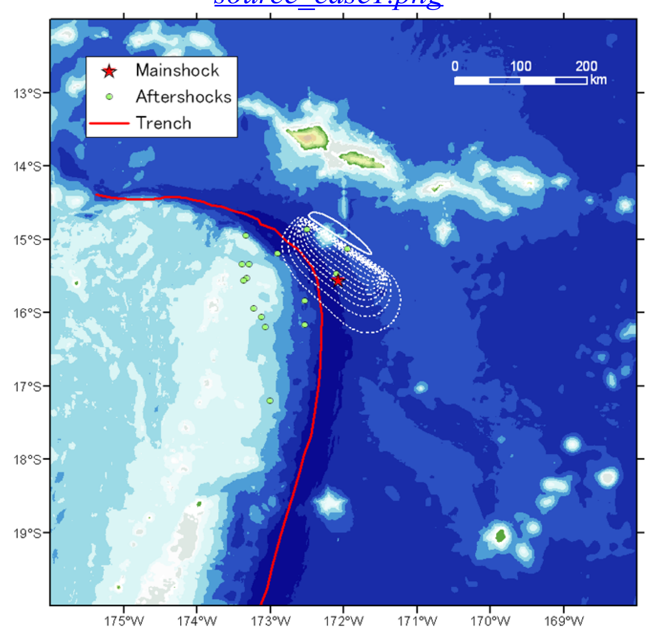

*Figure 11. Case 2 Tohoku University, (USGS DATA, Mo = 1.2 x 10**21 Nm Fault Length / Width : 150 km / 75 km; Source Mechanism (Strike, Dip, Slip) = (124, 46, -120) Reference :USGS Dislocation : 3.6 m http://www.tsunami.civil.tohoku.ac.jp/hokusai3/J/events/samoa_090930/source_case2.png*

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.

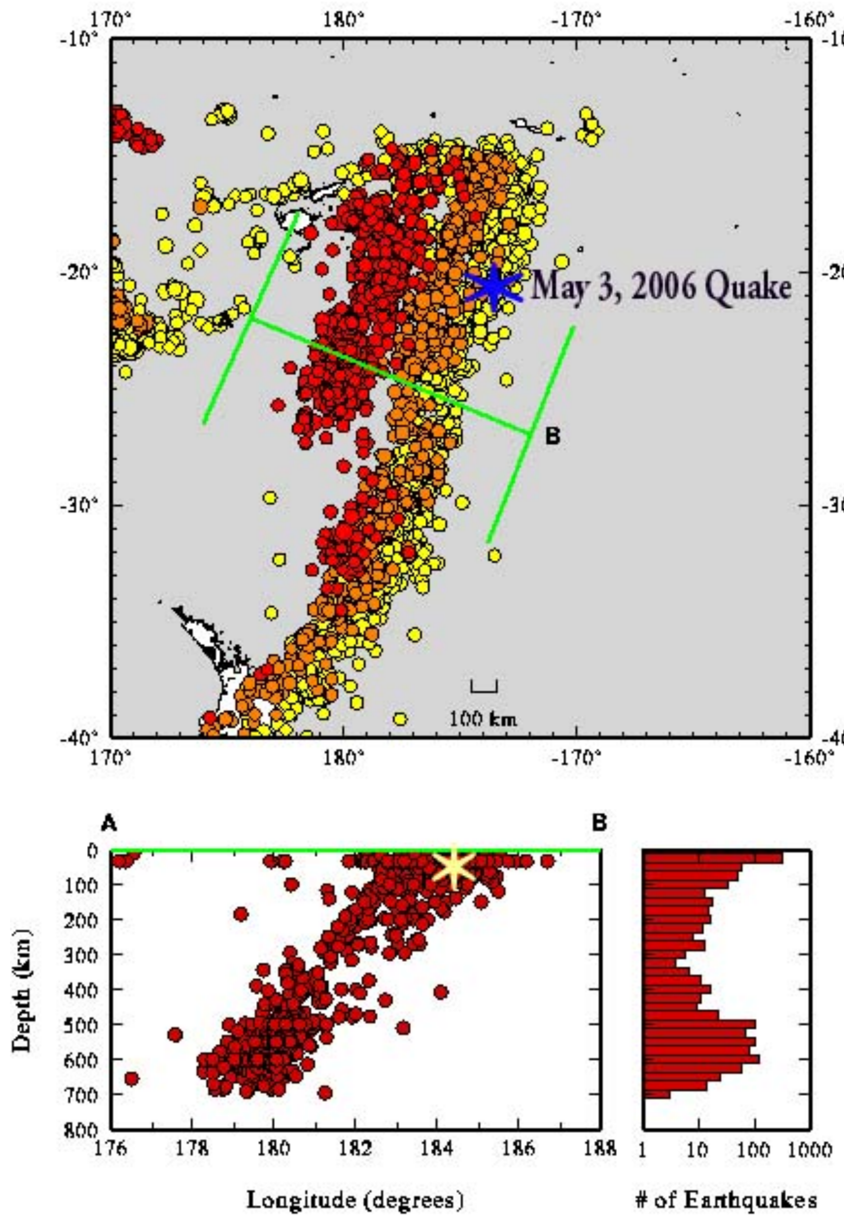

Figure 12. Cross-section along the southern Kermadec-Tonga Arc (modified graphic from www.seismo.berkeley.edu).

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.

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