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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 21.3°N and 105.95°E.

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.

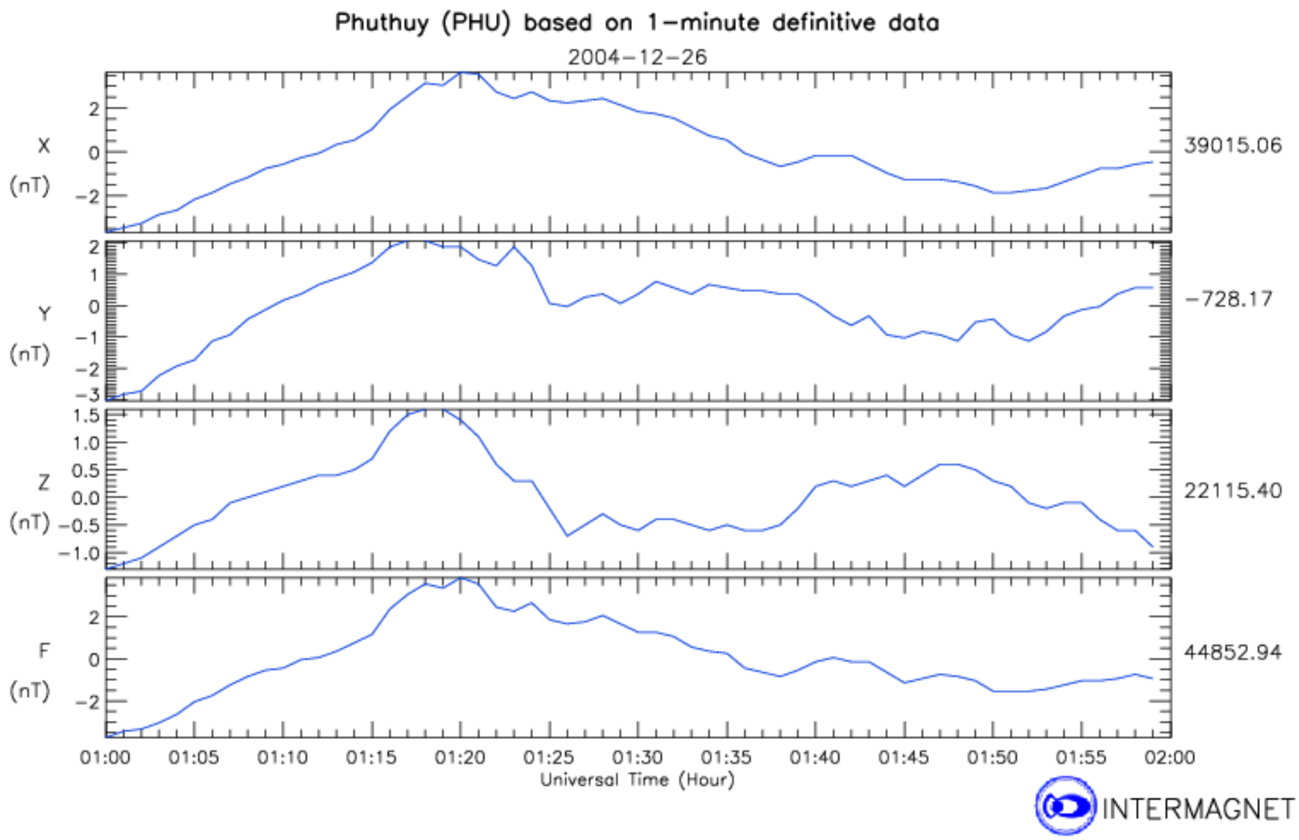

Figure 1. Magnetogram from INTERMAGNET for the 2004 Aceh event recorded at station PHU about 2300 km away from the epicenter, showing the observed vertical component of $b_z \approx 1.8$ nT.

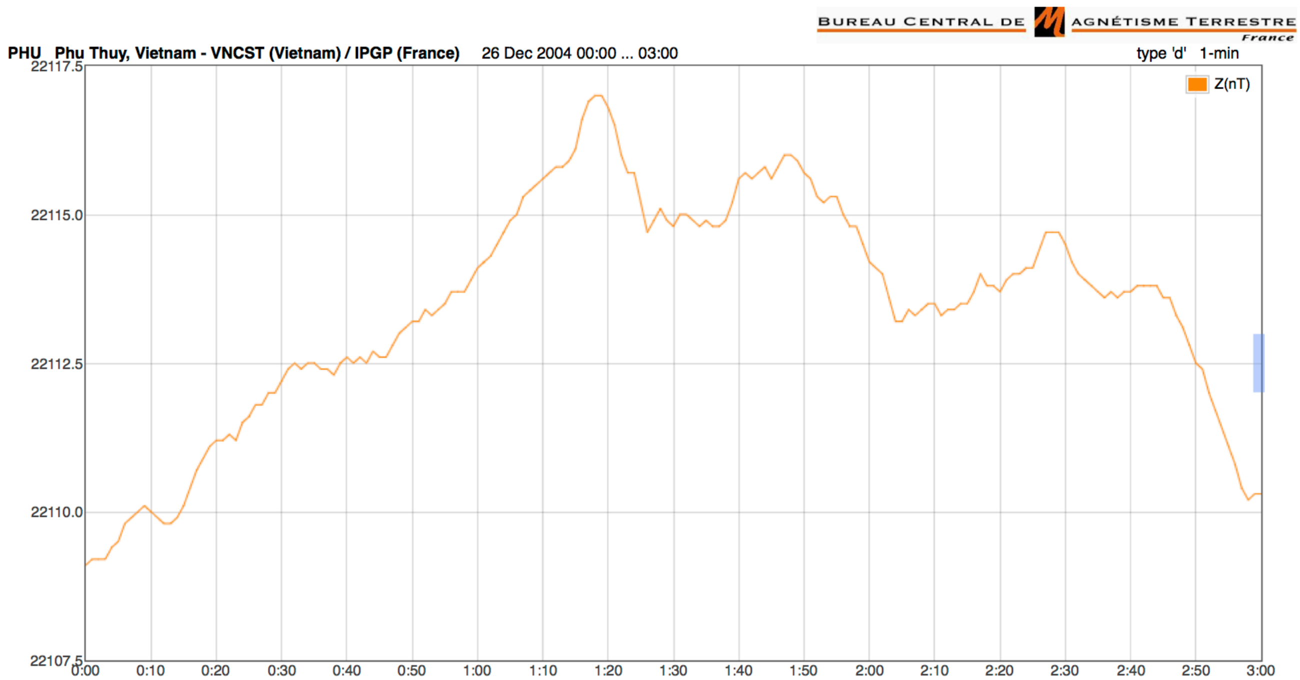

Figure 2. Magnetogram from BCMT for the 2004 Aceh event recorded at station PHU about 2300 km away from the epicenter, showing the observed vertical component of $b_z \approx 2.0$ nT.

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.

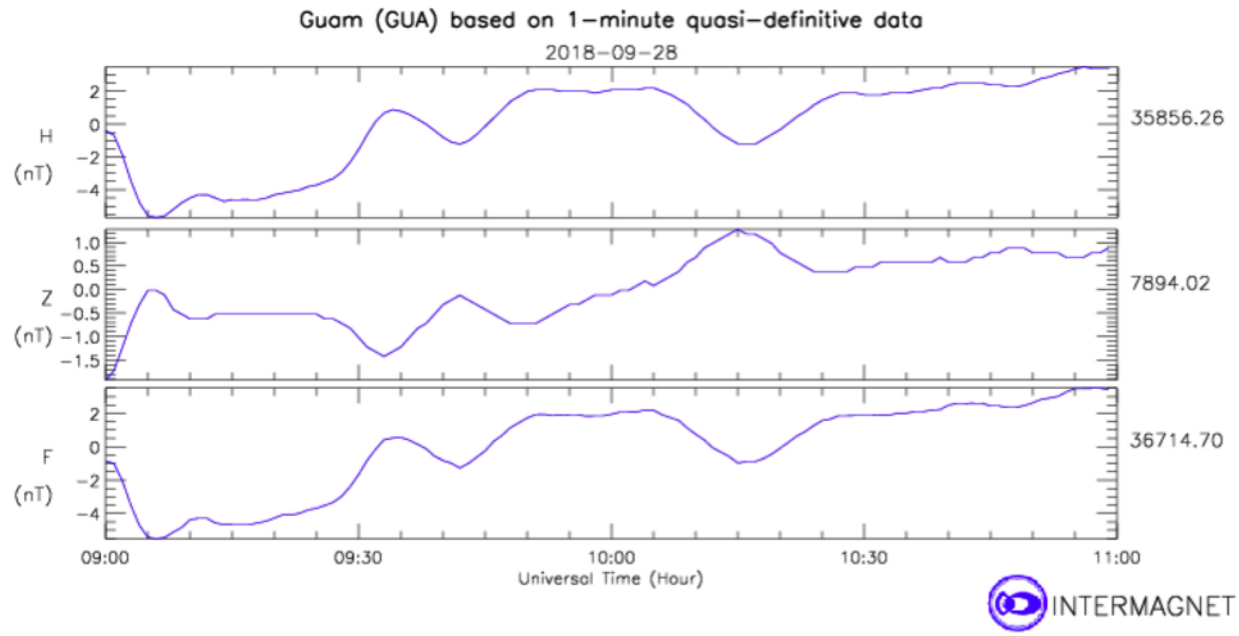

Figure 3. Magnetogram from INTERMAGNET for the 2018 Palu-Donggala tsunami showing the *H* and *Z* signals with *F* is the total field observed at GUA about 3200 km away from the epicenter.

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.

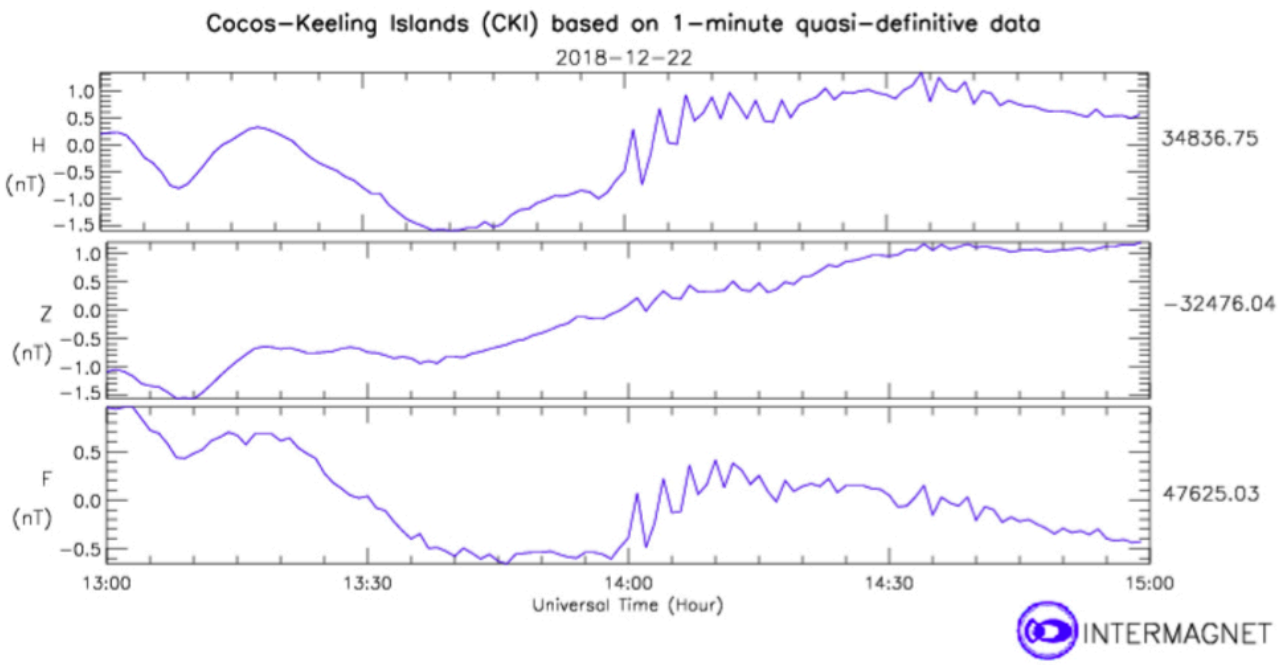

Figure 4. Magnetogram from INTERMAGNET for the 2018 Sunda Strait event, showing the *H* and *Z* signals with *F* is the total field observed at CKI about 1100 km away from the epicenter.

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.

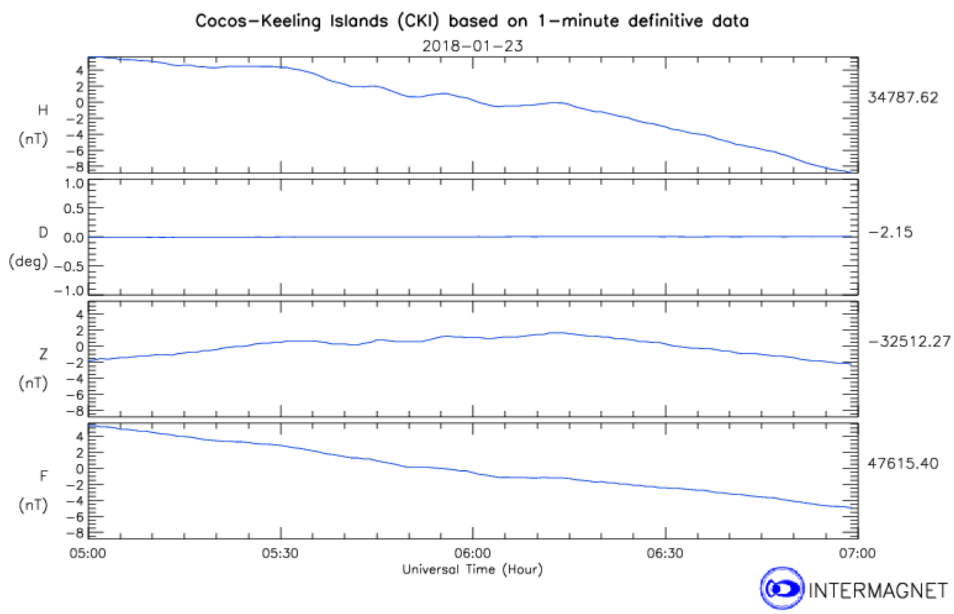

Figure 5. Magnetogram from INTERMAGNET for local earthquake with magnitude of M_w 6.1 in Banten on 23 January 2018 recorded at 6:34 UTC by CKI, where declination D is seen flat, confirming no tsunami generation.

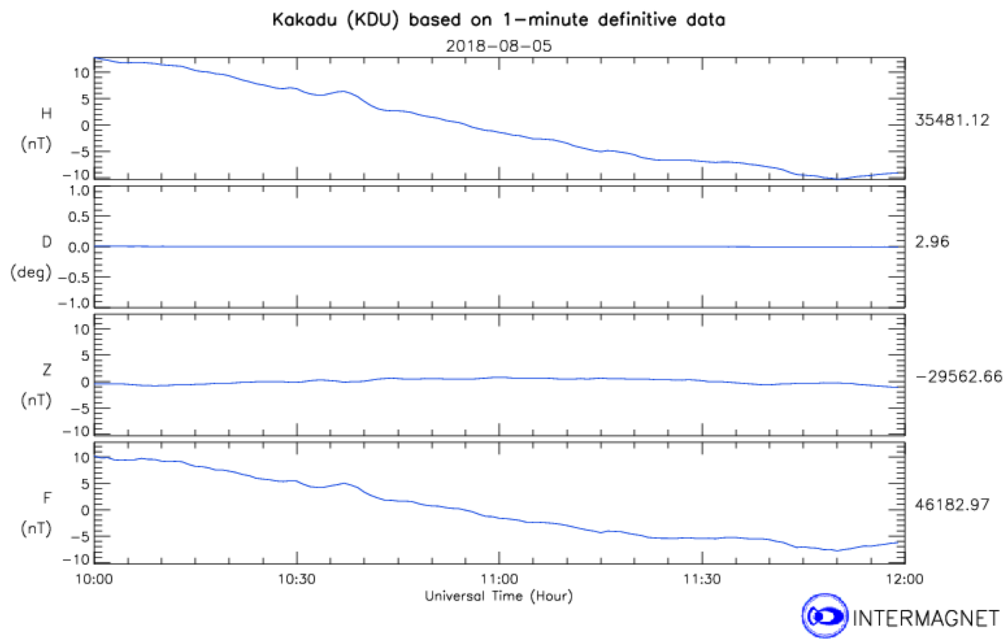

Figure 6. Magnetogram from INTERMAGNET for local earthquake with magnitude of M_w 7.0 in Lombok on 5 August 2018 recorded at 11:46 UTC by KDU, where declination D is seen flat, confirming no tsunami generation.

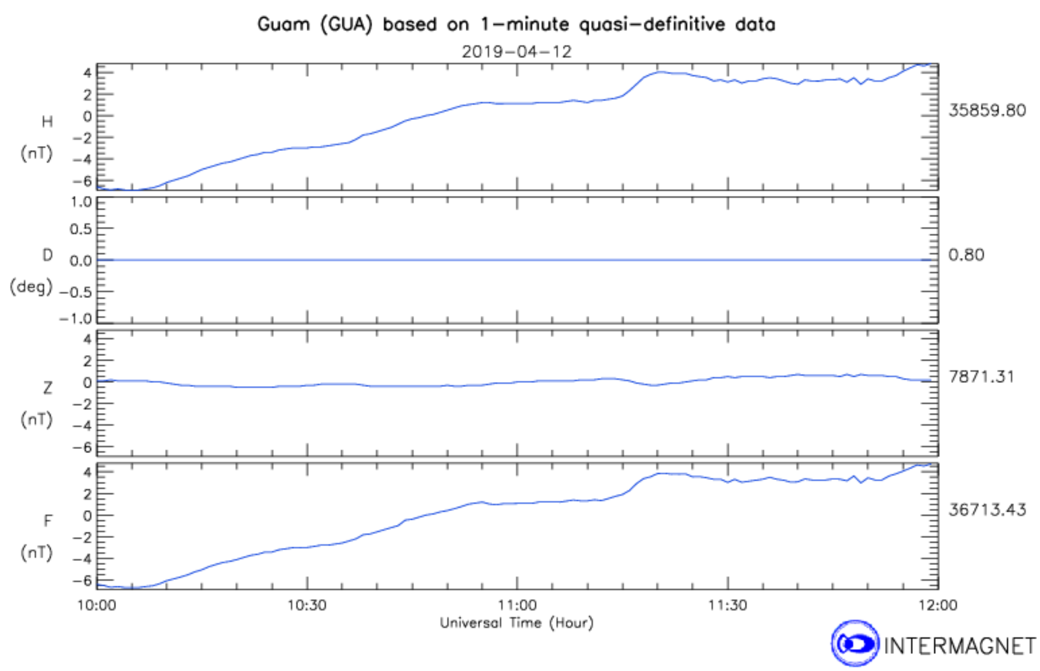

Figure 7. Magnetogram from INTERMAGNET for local earthquake with magnitude of M_w 6.8 in Central Sulawesi on 12 April 2019 recorded at 11:40 UTC by GUA, where declination D is flat, confirming no tsunami generation.

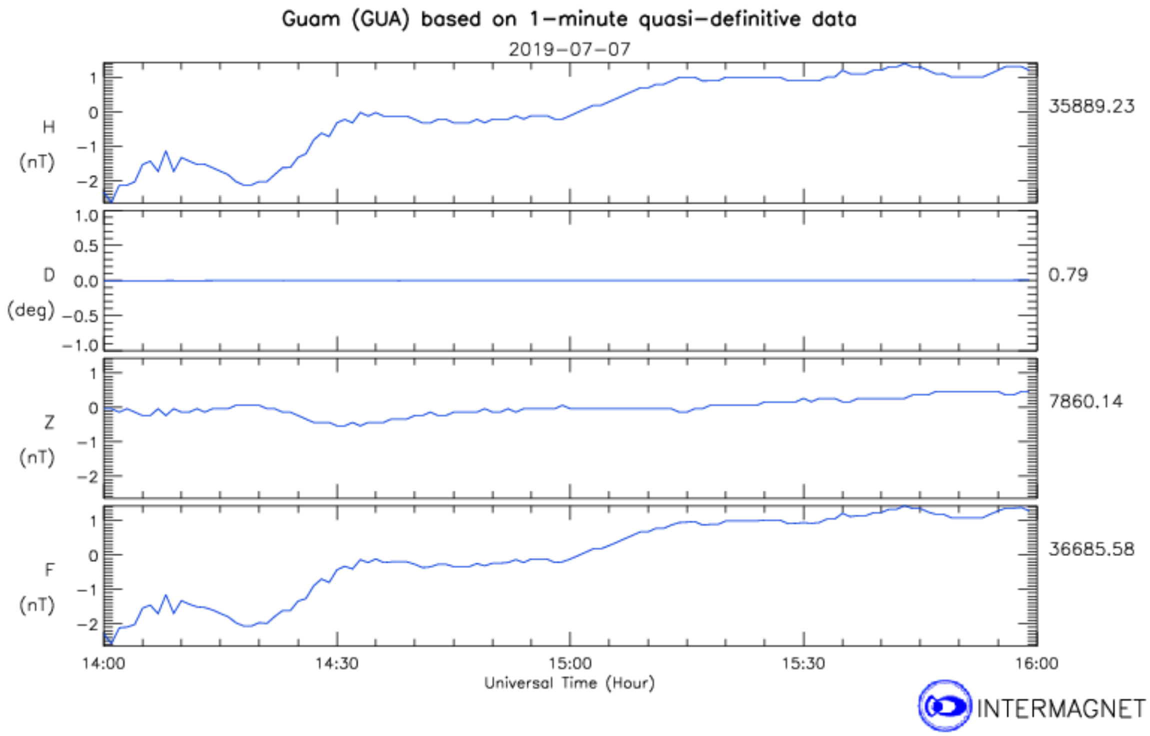

Figure 8. Magnetogram from INTERMAGNET for local earthquake with magnitude of M_w 7.0 in North Maluku on 7 July 2019 recorded at 15:08 UTC by GUA, where declination D is flat, confirming no tsunami generation.

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.

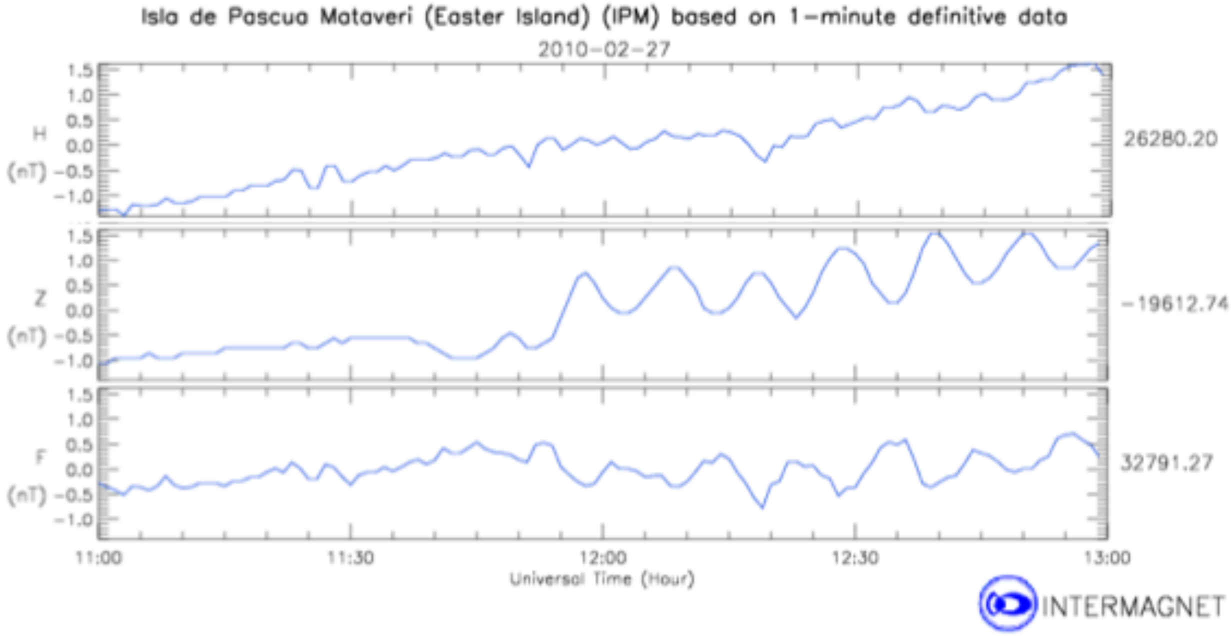

Figure 9. Magnetogram from INTERMAGNET for the 2010 Chilean tsunami, showing the H and Z signals with F is the total field observed at IPM about 3500 km away from the epicenter after approximately 5 hours-travelling across the Pacific.

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).

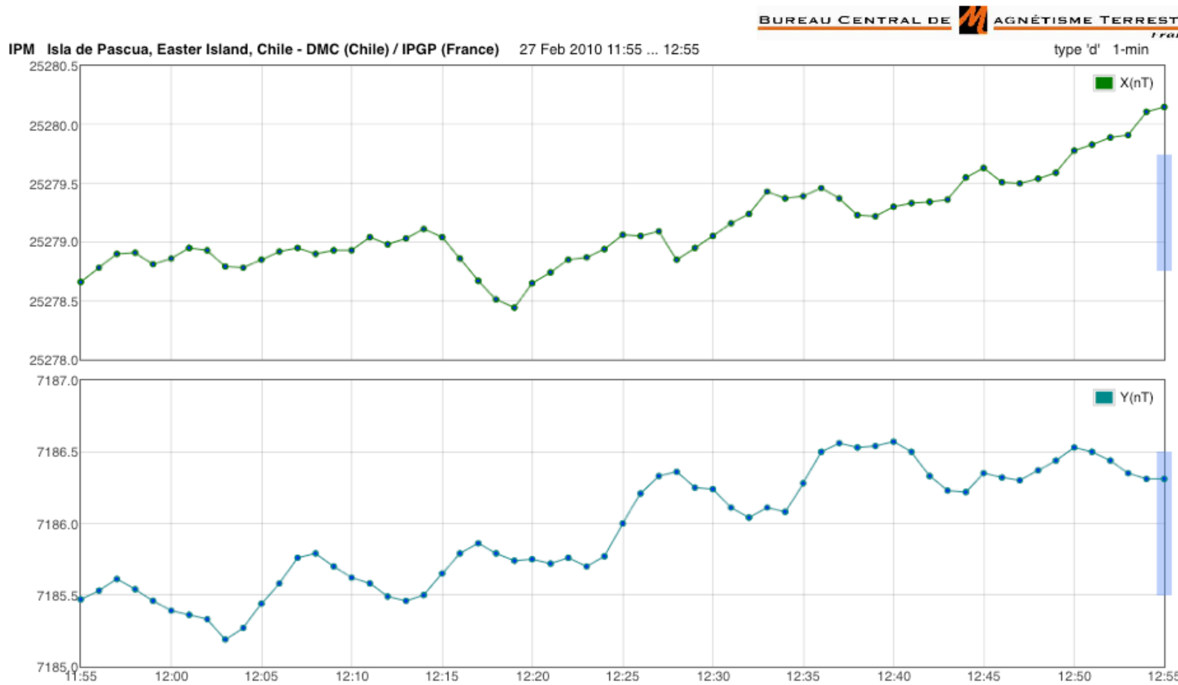

Figure 10. Magnetogram from BCMT for the 2010 Chilean tsunami, showing the *X* and *Y* signals observed at IPM about 3500 km away from the epicenter.

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.

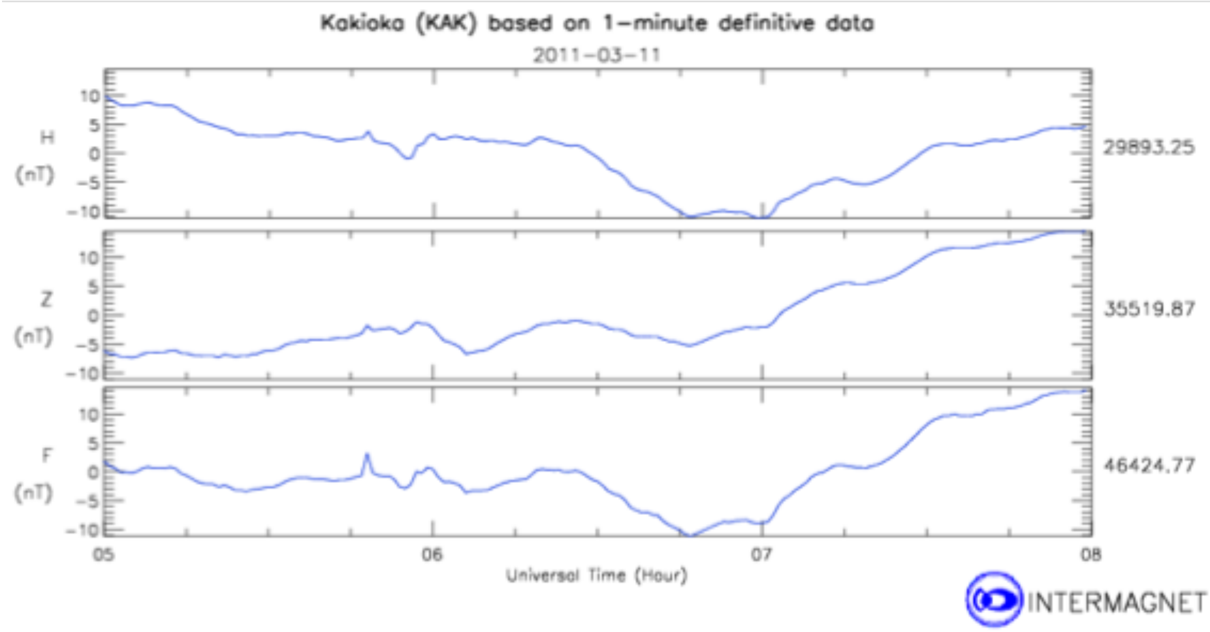

Figure 11. Magnetogram from INTERMAGNET for the 2011 Tohoku tsunami, showing the *H* and *Z* signals with *F* is the total field observed at KAK about 320 km away from the epicenter.

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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