Geotech Geol Eng (2017) 35:425–432
DOI 10.1007/s10706-016-0117-4

ORIGINAL PAPER

Field Investigation of the November to December 2015 Earthquake Swarm in West Halmahera, Indonesia

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Received: 12 April 2016 / Accepted: 22 October 2016 / Published online: 25 October 2016

Abstract The West Halmahera Swarm (WHS) event occurred from November to December 2015. A seismic station located in Ternate City detected at least 1000 shocks of magnitude (M) ≥ 1 and 11 shocks of $M \geq 4.5$. Our estimation yields a cumulative seismic moment of 3.87×10^{21} N m, which is equivalent to a single M 8.3 earthquake. We conducted a field survey after the swarm event and found that roads and residents' houses experienced cracks, while some parts of buildings were destroyed during the event. We find that the 2015 WHS was located just below the Jailolo volcano and was strongly associated with volcanic activity.

Keywords 2015 West Halmahera Swarm · Earthquakes · Jailolo volcano

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1 Introduction

West Halmahera, Indonesia, is considered a tectonically active region located at the convergence of three major plates, namely the Eurasian plate, Philippine Sea Plate, and Australian Plate (Lallemand et al. 1998). Socquet et al. (2006) suggested that the western region of the Molucca Sea is part of a micro block called the Manado block. The Philippine Sea plate, located in the eastern part of the Molucca Sea, dips to the west, and Nichols et al. (1990) suggested that the Philippine Trench terminates to the northeast of Halmahera. To the south, the Australian plate moves northward toward Eurasia and interacts complexly with the NW–SE convergence between the Sundablock and the Philippine Sea Plate (Widiwijayanti et al. 2004).

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The surface thrusts on the west and east sides of the Molucca Sea are directed outwards towards an adjacent arc associated with the Halmahera Thrust and the Sangihe Thrust (McCaffrey 1982). Evidence for the Halmahera Thrust can be found in the southern Philippines, while the Sangihe Thrust cannot be traced northward towards Mindanao Island (Hall 2002). The collision between the Sangihe and Halmahera arcs resulted in westward and eastward thrusts over the Sangihe and Halmahera volcanic arcs (Hall and Wilson 2000). The 2014 magnitude M_w 7.1 Molucca Sea earthquake is an example of a seismic event associated with crustal deformation in this region (Gunawan et al. 2016a). Figure 1 shows the tectonic background of the study area.

In November 2015, the Indonesian Agency for Meteorological, Climatological, and Geophysics (BMKG) reported a series of earthquake events with $M \leq 5$ in West Halmahera. The West Halmahera volcanic arc is composed of 13 volcanoes ranging from north to south, namely Dukono, Tobaru, Ibu, Gamkonora, Todoko-Ranu, Jailolo, Hiri, Gamalama, Tidore, Mare, Moti, Kiebesi (Makian), and Tigalalu (Fig. 2). Following Supriatna (1980), the physiography of western Halmahera is characterized by the presence of an alignment of volcanic cones, which extends from Jailolo city in the south to Galela city in the north, where the Dukono, Ibu, and Gamkonora volcanoes are still active at present. Apandi and Sudana (1980) defined the Quaternary volcanic arc in the west of Halmahera, which is mostly formed by volcanic island cones and is the site of the Gamalama and Kiebesi volcanoes, which remain active. These five active volcanoes are classified as A type volcanoes, which means they have erupted at least once since 1600.

Here we present in detail the seismicity of the 2015 West Halmahera swarm (WHS) evolution during the period from November to December 2015. Also, we present the results of our field survey in West Halmahera, Indonesia, after the November to December 2015 earthquake swarm. Hereinafter, we then refer to the entire earthquake swarm sequence as the 2015 WHS.

2 Seismic Activity and Observation

2.1 Earthquake Swarm

Between November and December 2015, an earthquake swarm was recorded in West Halmahera by a seismic station located in Ternate City, which was installed and maintained by the BMKG (Fig. 2). Seismic activity began on 2 November in West Halmahera, and by 6 November the swarm had concentrated below the volcanic area of Jailolo. The swarm occurred intensively on 7 and 8 November, before significantly reducing in activity, only to restart intensively on 16 November. The swarm activity reached its peak on 19 November, and reduced the next day. On 1 December, the activity again increased and since then has been reduced. Figure 3 shows the daily earthquake swarm evolution from November to December 2015.

The 2015 WHS included at least 1000 shocks of $M \geq 1$, with 11 shocks of $M \geq 4.5$. We estimated that the total cumulative seismic moment of the swarm was 3.87×10^{21} N m, and thus our estimation is equivalent to a single M 8.3 earthquake. We find that seismic energy released by the 2015 WHS was much higher than the seismic energy released during the March 1996 earthquake swarm event at the Akutan volcano in Alaska, USA (Lu et al. 2000). Figure 4 shows the time series of the number of earthquakes per day with $M > 1$ and the cumulative seismic moment during earthquake swarm events for 34 days since 1 November 2015.

2.2 Field Observations

We conducted a field survey in West Halmahera Regency, North Maluku Province of Indonesia in December 2015 to observe the environmental effect and the building damage caused by the 2015 WHS. West Halmahera has an area of 2.612 km^2 with a population of more than 100,000 inhabitants. We focused mainly on the region surrounding Jailolo volcano, where the Government of Indonesia received reports of damage to infrastructure. Our field survey location is shown in Fig. 5.

During the 2015 WHS, residents in Jailolo city reported continuous ground shaking as well as cracks in their houses, and parts of some buildings were also destroyed during the event (Fig. 6). In response to this situation, the Government of Indonesia, through the Local Agency for Disaster Management (BPBD), prepared a basecamp for organizing support for residents affected by this disaster (Fig. 7).

During our field survey, we observed several cracks resulting in damage to roads, houses, and other

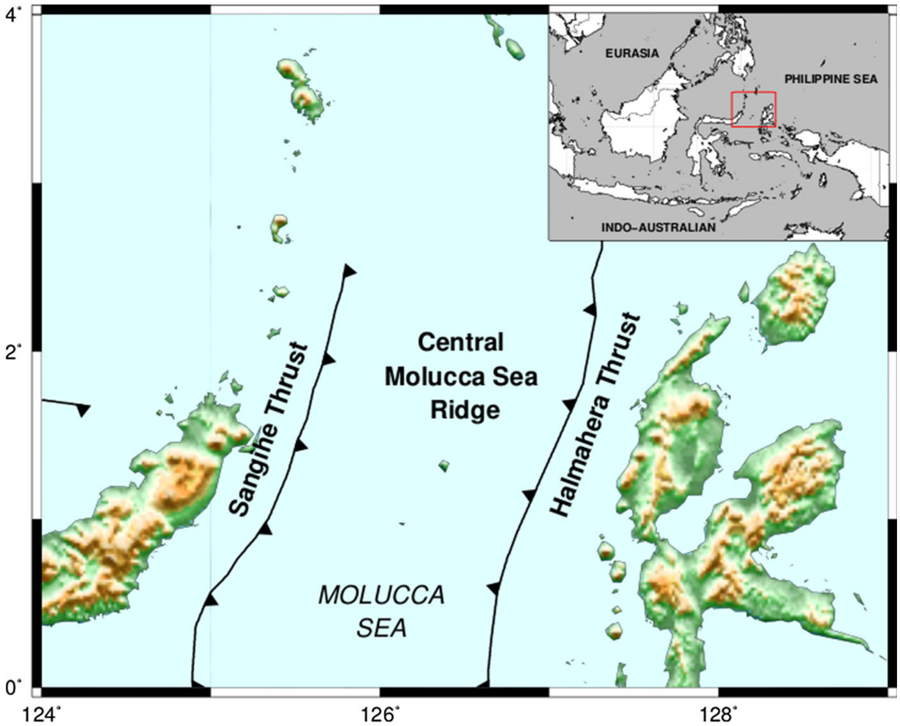

Fig. 1 Tectonic background, with the *inset* showing the larger regional setting

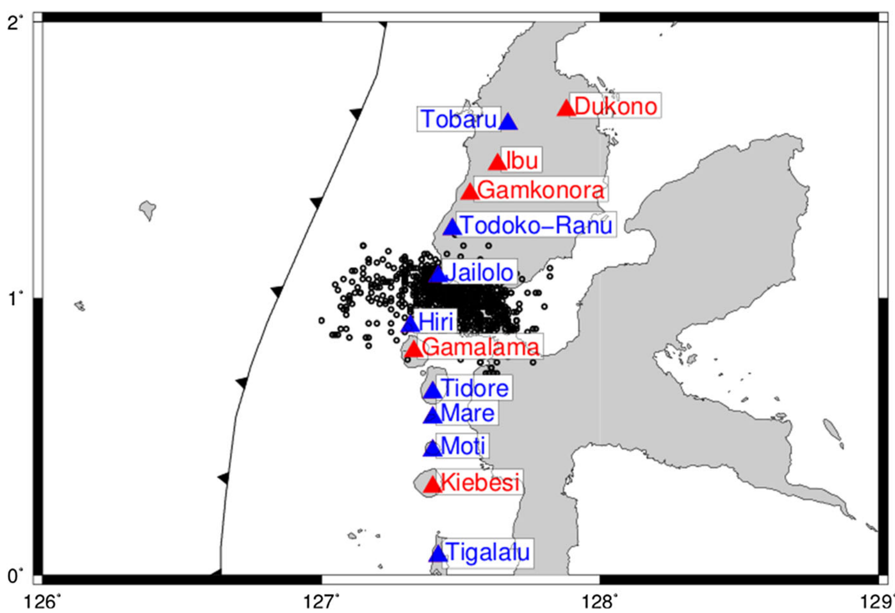

Fig. 2 The epicenters of the earthquake swarm are shown by *black dots*. The *red triangles* locations of A type volcanoes, while the *blue triangles* non-A type volcanoes

infrastructures. In the Bobanehena region, we observed a significant crack along the road that continued towards residential buildings (Fig. 8). This crack continued towards the shoreline, where a new hot spring had appeared. Cracks resulted in damage to the floor and the walls of the local buildings. Several houses were also destroyed by the event. Due to continuous activity of the swarm, the residents chose to sleep outside using tents provided by the BPBD. The Indonesian National Board for Disaster Management (BNPB) reported as many as 1593 buildings with damage induced by the 2015 WHS event.

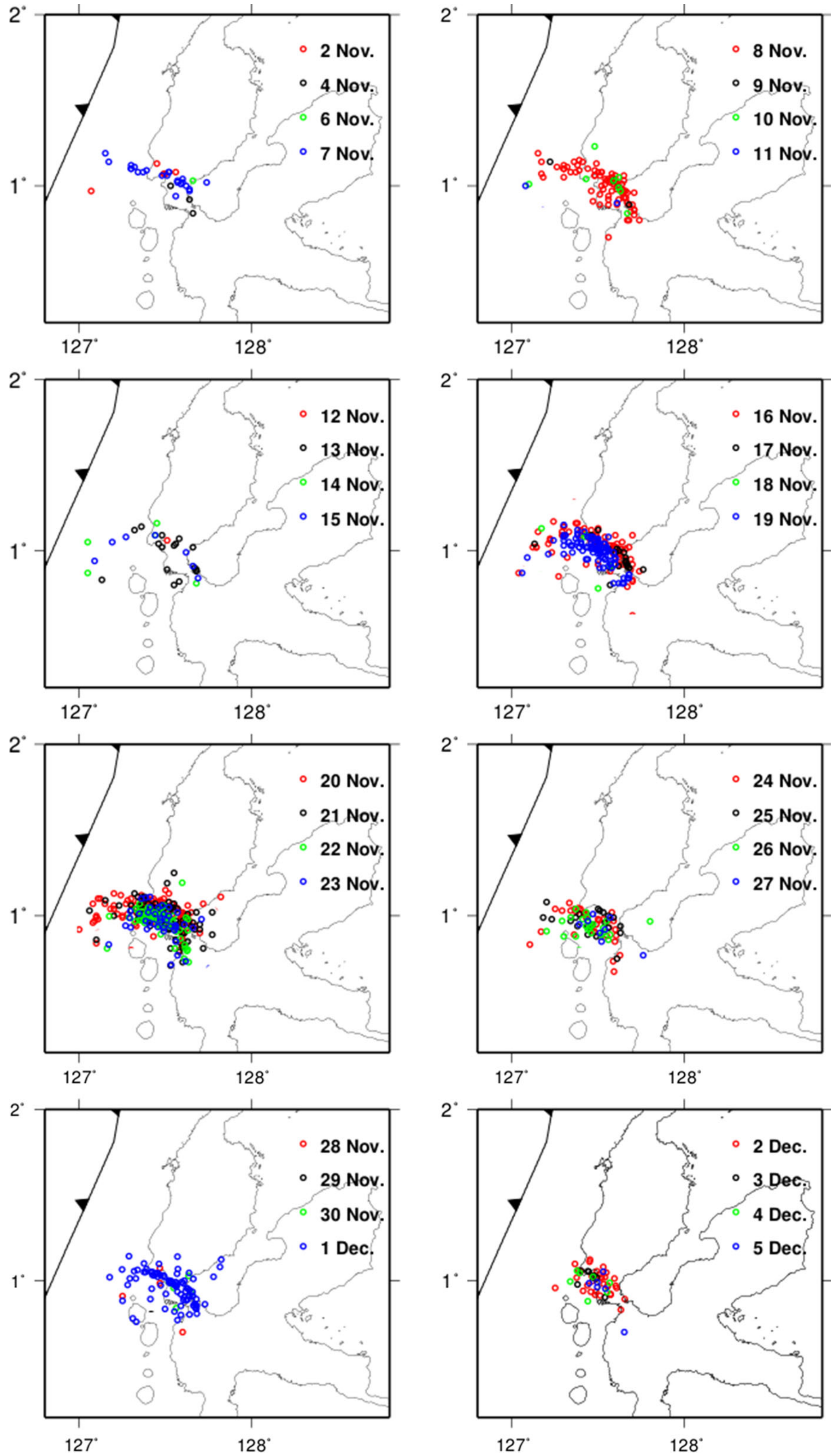

Fig. 3 The daily evolution of the studied earthquake swarm

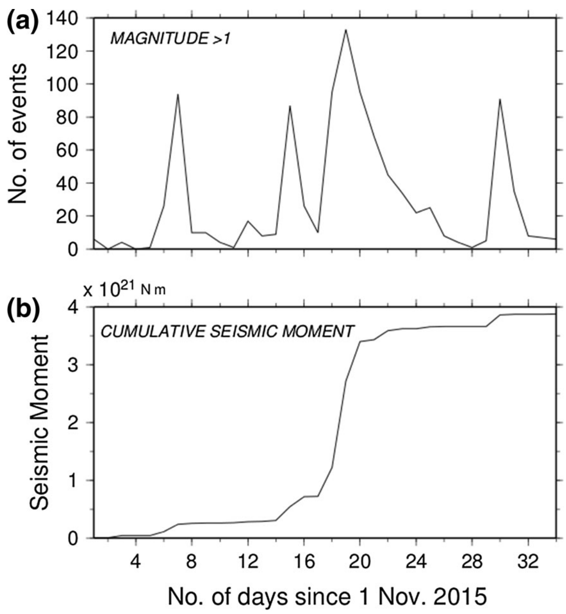

Fig. 4 Time series showing **a** the number of earthquakes per day with $M > 1$, and **b** the cumulative seismic moment during the earthquake swarm event for 34 days since 1 November 2015

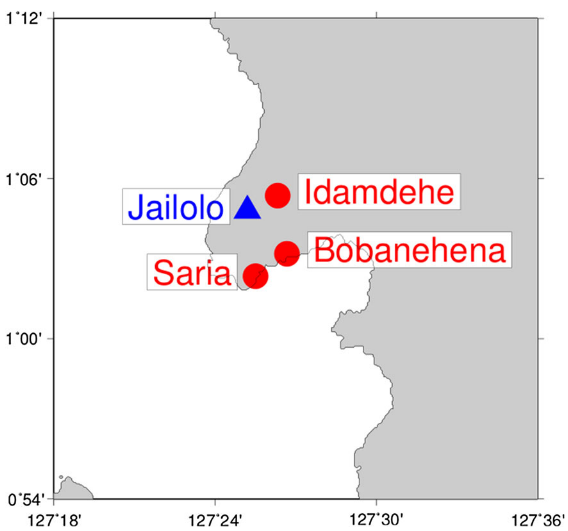

Fig. 5 Location of the field survey

Fig. 6 Crack in residential buildings induced by the 2015 WHS

Fig. 7 Basecamp for the 2015 WHS emergency responses

We found a crack in the Saria region, in the southern part of Jailolo. Because the crack occurred on a slope region, we suspect that this might indicate a future landslide location (Fig. 9). Residents also reported damage to their houses in the Idamdehe region to the north of Jailolo. However, when we went to this location, we found that the damage to buildings was minor and insignificant.

Fig. 8 Crack on the road that continued towards adjacent residential buildings resulting in damage to floors and walls

Fig. 9 Crack on the southern side of the mountain that might be indicative of future landslides

3 Preliminary Analysis

Our seismic analysis suggests that the 2015 WHS was located just below the Jailolo volcano. This finding shows that the swarm was strongly associated with Jailolo's volcanic activity (Fig. 10). Jailolo is a stratovolcano with a height of 3707 feet. Even though Jailolo's cone and its surrounding area are composed of volcanic materials, there is no record of its activity since $\sim$1600. However, there seem to be remnants of old volcanic activity such as hot springs, traces of a young lava flow in the eastern part, a small caldera in the southwestern part of the volcano, and former craters.

Seismic activity of the earthquake swarm could become part of the volcano's eruption sequence process, as was in the case of swarm events in recent prior eruptions such as Redoubt volcano (Power et al. 1994) and Mount Spuur volcano (Power et al. 1995), both in Alaska. However, earthquake swarms are not necessarily considered as part of a volcanic eruption, as evidenced by the 1988 seismic swarm at Dutton

Fig. 10 Jailolo volcano: *Left* view from the South, and *right* view from the East

volcano in Alaska (Lu et al. 2000). Hence, one can investigate and analyze the tectonic process in the region using modern equipment, such as a dense Global Positioning System (GPS) network or seismic network.

GPS has become an essential tool for understanding the Earth's tectonic activity. It can be used to analyze deformation on a fault system (Ito et al. 2012; Meilano et al. 2012), strain accumulation during inter-seismic phases (Hanifa et al. 2014; Ohkura et al. 2015), co-seismic deformation (Ito et al. 2016; Gunawan et al. 2016b), post-seismic deformation (Anugrah et al. 2015; Ardika et al. 2015; Alif et al. 2016), and the rheological structure of a region (Gunawan et al. 2014).

The availability of a GPS network was important in the 2015 WHS case, and is crucial for the analysis of future hazards in relation to the swarm event. It is very interesting to determine if the 2015 WHS is related to the next eruption of Jailolo. Unfortunately, GPS stations are not available around Jailolo. One great example comes from dense GPS network of Japan, named the GNSS Earth Observation Network System (GEONET) (Sagiya 2004), which provides useful information as a base for analysis of the tectonic process during a swarm event (Toda et al. 2002). Using the Japanese case of the Izu Islands earthquake swarm of 2000, Nishimura et al. (2001) showed that GPS was capable of detecting subsidence and extension between stations. They showed that magma migrated up to 30 km distance. Considering that Indonesia is prone to earthquakes and other disaster activities, we strongly suggest the use of continuous GPS around Jailolo volcano, or any other potential natural disaster location in the country.

4 Conclusions

The seismic station located in Ternate City detected at least 1000 shocks of $M \geq 1$ and 11 shocks of $M \geq 4.5$ during the 2015 WHS event. Our estimation yields a cumulative seismic moment of 3.87×10^{21} N m, which is equivalent to a single M 8.3 earthquake. We conducted a field survey after the swarm event and found that roads and residents' houses experienced cracks, while some parts of buildings were destroyed. Our findings suggest that the swarm was strongly associated with the volcanic activity of Jailolo.

Acknowledgements We are grateful to two anonymous reviewers and the Editor for their helpful comments and suggestions. This study was partially funded by the Australian Department of Foreign Affairs and Trade (DFAT) for Graduate Research on Earthquake and Ministry of Research and Higher Education No. PN-7-06-2016. Some of the figures are made using GMT software (Wessel and Smith 1998).

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