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Geothermal System as the Cause of the 1979 Landslide Tsunami in Lembata Island, Indonesia

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Abstract - A tsunami landslide which caused hundreds casualties and lots of damage took place on Lembata Island in 1979. In order to understand the characteristics of the landslide mechanism, a field survey was conducted in 2013 which sampled both the origin soil and landslide material, and the water from hotspring around the landslide site. The physical properties of the soil obtained show that the original soil has dominantly coarser grain than the landslide material (80.5% coarser grain compared to 11.8% coarse grain respectively) which indicates that the soil has become finer and softer. Hot spring analysis indicated that the mineral content of the water was 99.48% SO_4. This shows that magmatism processes are involved which caused the soil to become acidic and may have fragilised the system. Results of X-ray Diffraction Mineralogy Analysis (XRD) show that the original soil is composed of minerals of cristobalite, quartz, and albite, while the landslide material consists of clay minerals such as quartz, saponite, chabazite, silicon oxide, and coesite which are typical minerals in a hydrothermal environment. Based on these results, it can be concluded that the area was influenced by an active geothermal system that could be the main source mechanism behind this disastrous event.

Keywords: Lembata Island, landslide, sample analysis, clay minerals, geothermal system

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Introduction

Background

On July 18, 1979, Lembata Island, located in East Nusa Tenggara Province, Indonesia, was struck by a sudden tsunami, induced by a massive landslide. Fifty million cubic meters of material was displaced and one third of it tumbled into the sea and generated a 7 - 9 m height tsunami which spread along the Waiteba Bay (Hadian *et al*., 1979; Lassa, 2009). Four villages were buried by the landslide material and 539 of inhabitant were reported killed by both landslide and tsunami. This event is not well known by most Indonesian people, even though newspapers "KOMPAS" of 21 July 1979 and "Herald Tribune" 24 July 1979 reported this event (Lassa, 2009; Arif, 2010).

Lembata is an 80 x 30 km island that hosts numerous massive volcanic edifices, three of which remain active: Ili Lewotolo in the north and Ili Labalekan and Ili Werung in the south (Figure 1). Most of these edifices extend to the sea, exposing steep slopes and unconsolidated material. Adding regular heavy rain falls, and the

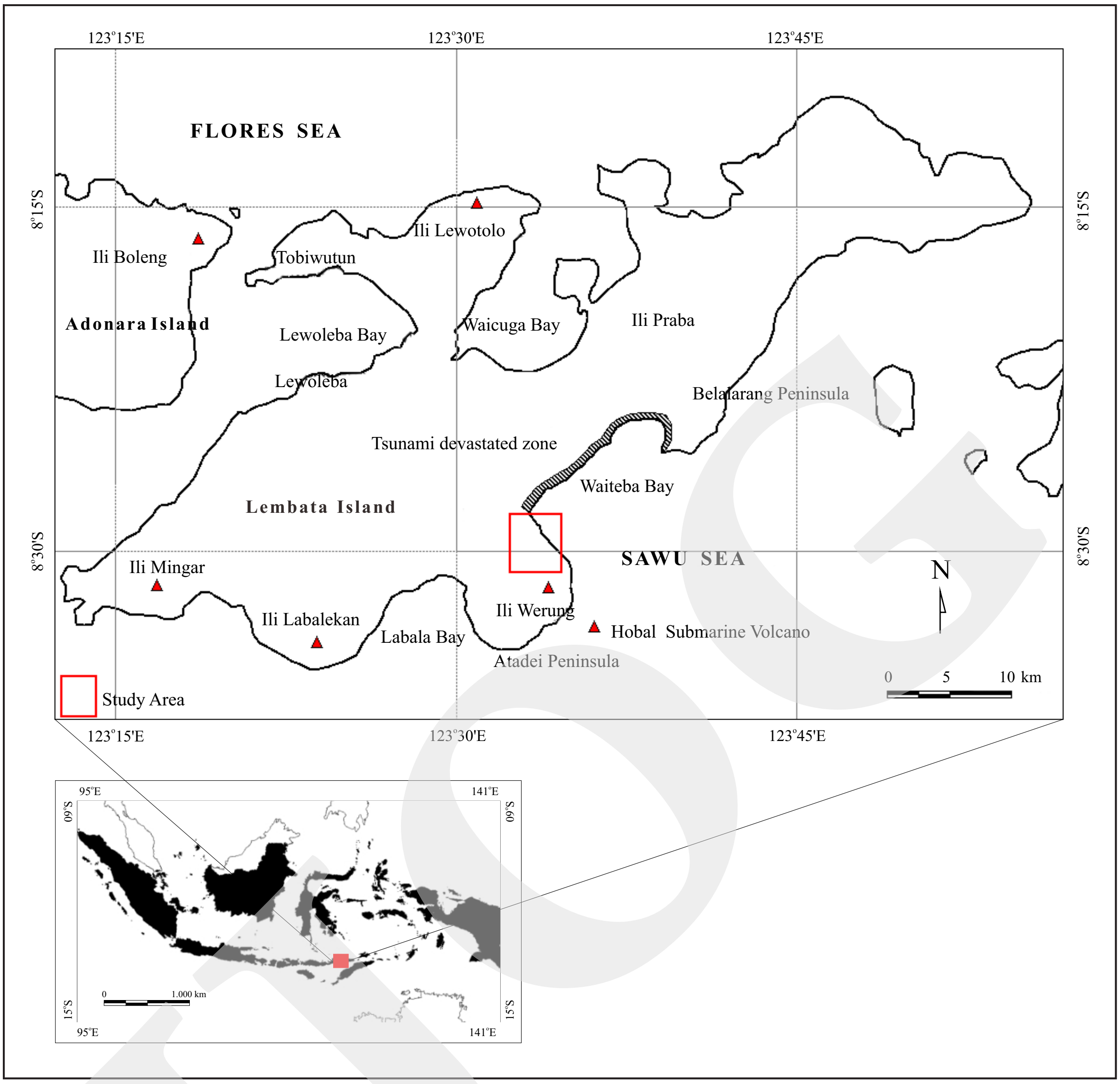

Figure 1. Top: Lembata Island showing active volcanoes (red triangle), study area (red square) and tsunami affected area. Bottom: Location of Lembata Island within Indonesia.

intense tectonic activity in that region, Lembata Island thus possesses many factors capable in triggering land displacement with a significant potential for landslide-tsunami. The 1979 event being the unfortunate example.

To gain further insights into the origin of the disastrous 1979 event, a field investigation was carried out in April 2013, observing landslide material and the surrounding edifice morphology, evaluating potential links to volcanic activities and determining tectonic structures in the study area. Soil and water samples were taken for laboratory analysis to constrain the physical properties of the landslide materials (soil density, specific gravity, cohesion, shear friction, and the nature of expanded soil) and other factor influencing the system.

The landslide site is located at 08°28'44"S - 123°33'34.3"E, a hill ca. 200 m above sea level, while the landslide material reach the sea of 08°28'30.8"S - 123°33'24.7"E (Figure 1).

According to the reports published in 1979 and compiled in Lassa (2009), the Volcanological team from Bandung reported that there was no volcano activity during the two days preceding the landslide (16 - 17 July 1979), while meteorological and geophysical teams noted no earthquakes during that time either. According to Lamanepa (2013), in the month of July 1979 the Lembata Island and its surroundings were in a rainy season and had heavy rainfall in some areas of East Nusa Tenggara. The study is intended to understand what caused this landslide given that lack of an obvious triggering mechanism.

Scientific Review

Geologically, the region where the landslide site is located consists of a Tertiary lithological unit called Kiro Formation, lying beneath the Quaternary old volcanic rocks and Quaternary young volcanic products (Koesoemadinata and Noya, 1990). Old volcanic rock units consist of lava, breccia, agglomerate, volcanic sandy tuff, and pumiceous sandy tuff as products of volcanoes which are no longer active, such as Wikiriwak, Ili Lewung, Ili Minggar, Ili Ujolewung, Pura, Ternate, and Treweg. These volcanoes form high mountains along the southern Lembata Island. There are also locally younger volcanic rocks, consisting of lava, agglomerates, bombs, sands, and volcanic ashes which are products of younger active volcanoes, such as Watuomi, Ili Boleng, Ili Lewotolo, Ili Werung, Ili Topaki/Sirung, Batutara, and Komba (Figure 2).

There are two major geological structures in Lembata Island, which have trends of southwest-northeast and northwest-southeast. One of them is a normal faulting in a northwest-southeast direction from the Plio-Pleistocene age which has produced a scattered hotsprings near to the landslide site that may influence the soil condition (Figure 2).

There is also a lineament showing a volcanic chain which has moved to the southwestward, and a submarine volcano named Ili Hobal at the end of faulting which has been observed since 1972.

A dense distribution of epicentres around Lembata Island indicates that the area is seismically very active. One earthquake which occurred in 1977 (USGS, 2013) and located nearby the landslide site resulted in a surface rupture. This may have fragilised soil at the site, although the earthquake magnitude was less than five (Figure 3).

According to the eruptive history around the Lembata Island, the last eruption occurred on Ili Hobal started in 1972 and ended in 1974. The Ili Hobal is a volcano located at the southern end below the sea (CVGHM, 2013 in http://www.volcano.si.edu/).

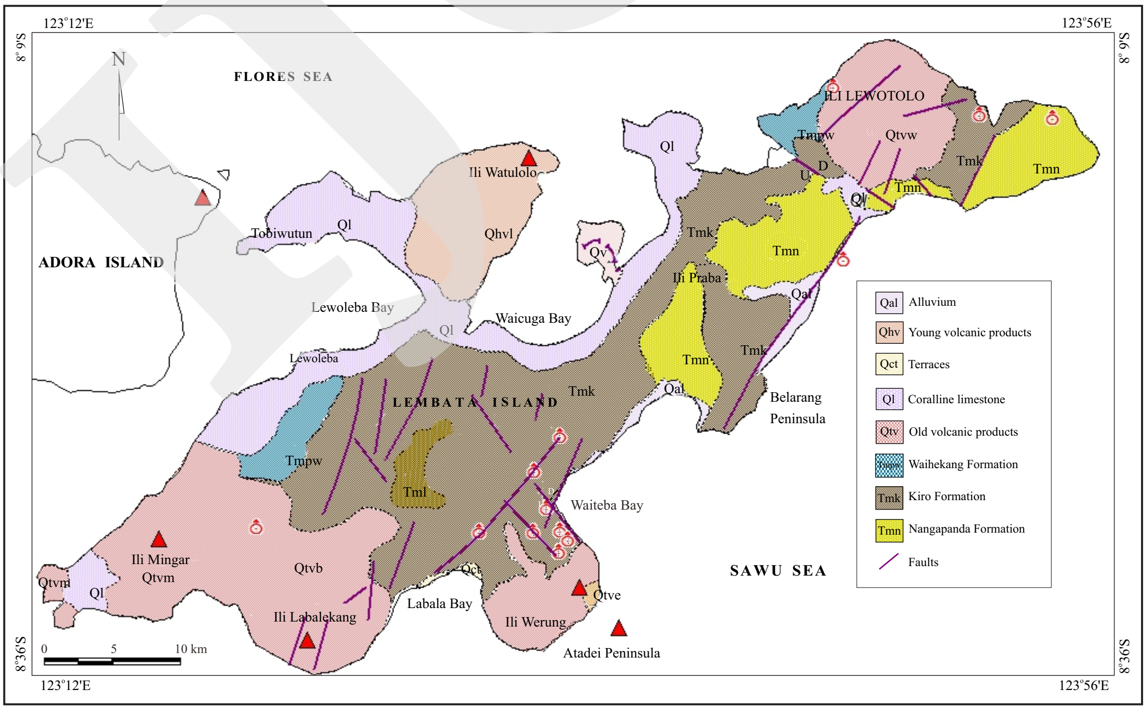

Figure 2. Geological Map of Lembata Island and location of hotsprings (vents) (Koesoemadinata and Nova, 1990).

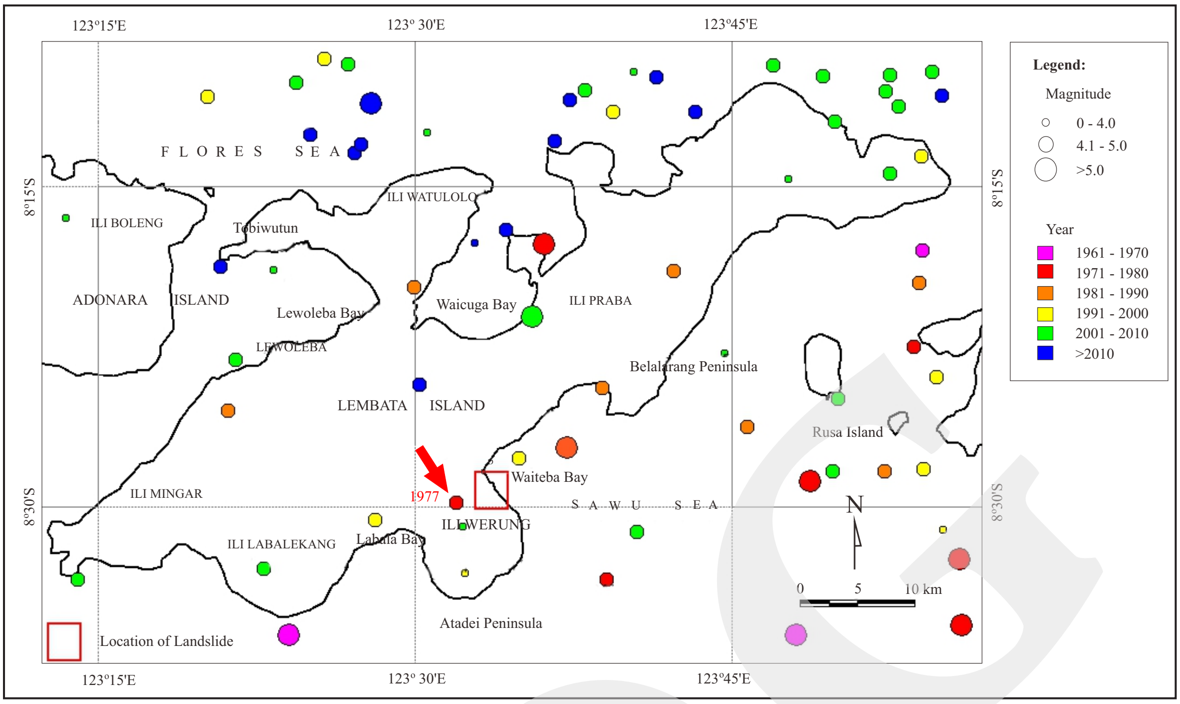

Figure 3. Seismicity in Lembata Island and its surroundings (USGS, 2013). Red arrow indicates the epicentre of the earthquake that occurred in 1977 close to the landslide site.

Landslide Induced Tsunami

Based on the scientific report related to the landslide and tsunami incident of 18 July 1979, the event occurred in the middle of the night and the landslide swept four villages that were located at the coast of the Waiteba Bay. (Hadian *et al.*, 1979). Geological condition shows that the site is composed of alluvium with loose sand and gravel. Both land and the seafloor near the shore are morphologically very steep and easy to be eroded. The eyewitnesses said that the landslides were observed at the site since 1976 and occurred progressively until 1979 when the biggest event occurred (Hadian *et al.*, 1979). The landslide body has a length of 3000 m along the slide direction starting at elevation of 500 m and width of 300 m to the east-southeast. Part of landslide material had tumbled down into the sea, generated the tsunami wave that came about three times on land and devastated about 50 km along the Waiteba Bay (Figure 4). Remnants of these landslides can still be traced from natural features observed in the field (Figure 5 and 6) and satellite images.

Methods

In order to understand the nature of the landslide and what caused this event, a field survey was carried out in April 2013. Visual observations were made and samples were taken from both disturbed (*i.e.* landslide) and undisturbed (origin) soil material. This was followed by soil mechanic tests to obtain the physical properties of both the original soil and the landslide material.

XRD Analysis was undertaken on the origin soil and landslide material to obtain the mineral content, which can prove the involvement of hydrothermal system and an ion chromatograph analysis was conducted on water samples taken from geothermal sites scattered around the study area to confirm that evidence.

Result

The landslide area is located at an old crater of Iliwerung complex. The crown of landslide is found at Atakore Village, named Bauraja Hill (Figure 5). The Bauraja Hill forms a cliff that is

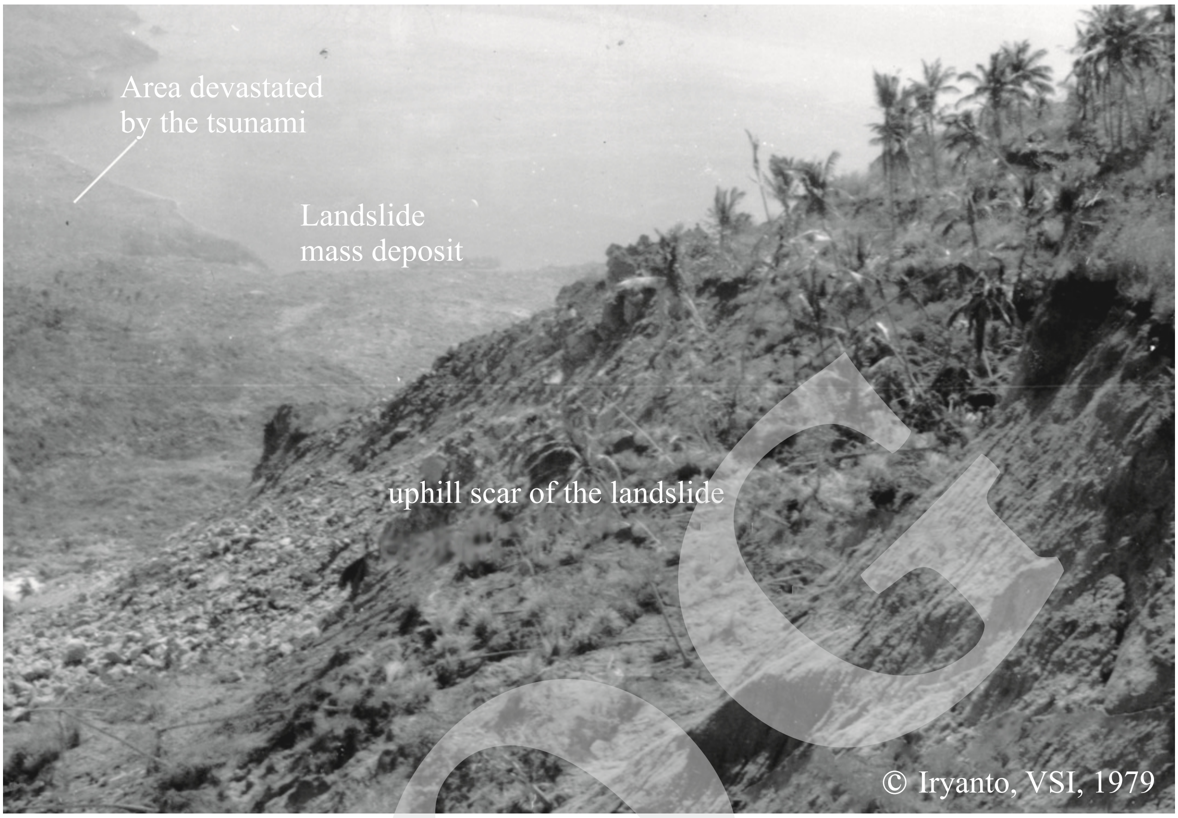

Figure 4. Location of landslide and tsunami impacted areas (taken from Iryanto, 1980).

Figure 5. Evidences of the 1979 landslide taken on April 2013, the crown (left) and the landslide body (right) (Yudhicara *et al*., 2013).

unstable and prone to landslide, particularly after a heavy rain. The study area is about 1.2 square km. It has many volcanic cones around and close to the landslide site, active faults cutting across it and is often subjected to a heavy rainfall. The study area has a hilly morphology with a very steep slope and is covered by dense forest and trees, however the landslide scar is still barren and not been revegetated.

Some insitu samples were taken around the hill in areas assumed to be undisturbed. Megascopic appearance shows that the soil has coarse sand to gravel grain size, yellow to reddish colour, loose, bad sorting, and open fabric. The landslide

Figure 6. The landslide product potrudes into the sea (red circle); location of water sample is shown by red arrow (Yudhicara *et al*., 2013).

material was taken nearby the sea (Figure 6), which has finer grain volcanic ashes, yellow to white colour, very soft, clayey, loose, slippery and easy to move.

Results of the soil mechanics analysis shows that the grain size curve of origin soil consists of 6.9% gravel, 80.5% coarser grain, and 12.60% the fine grain (Figure 7). This means that the soil is dominantly composed of coarser sandy grains. In contrast, the landslide material has fine grains composed 88.2% of soil, while the coarse grains represent 11.8% (Figure 7). This indicates that the soil has become to be softer, which can be differentiated from surrounding soil.

According to the physical properties of the original soil, it has cohesion value of 0.04 kg/cm^2 and deep shear angle of 33.72^o, so for the safety factor of 1.0, by this soil, it has potential to slide even without ground shaking on slope of 15^o to 24^o.

Some hot springs were found around the landslide site indicating a fumarole system. A water sample was taken from a hot spring at the foot hill of the landslide material at position of 08^{o}28'44"S - 123^{o}33'34.3"E (Figure 6), which coincides with a fault line. The mixing of water and hot material from inside can alter the rocks, and some of the material could be changed to be clay minerals that may fragilised the system and be responsible for the slide occurrence.

Results of ion chromatograph analysis on the hot spring water sample show that the SO_4 content is 99.48% of the total chemical content (Table 1). This indicates that this water is associated with the magmatism beneath the area and take the role in the hydrothermal system. It is also the reason why soil are fragile, loose, unconsolidated, and easy to move. The sulfate content of 3458.61 ppm contained in this hot water may also explain why vegetation cannot grow in the landslide material, even after 35 years. This is due to the high acidity properties of the soil in that location.

According to the result of the XRD analysis, the original soil contains minerals such as cristobalite, quartz, and albite (Figure 8), while the landslide materials contain minerals of quartz, saponite, chabazite, silicon oxide, and coesite (Figure 9). It seems that minerals in the original soil have altered and some of the altered minerals contain clay minerals that could influence the soil physical properties thus becoming loose.

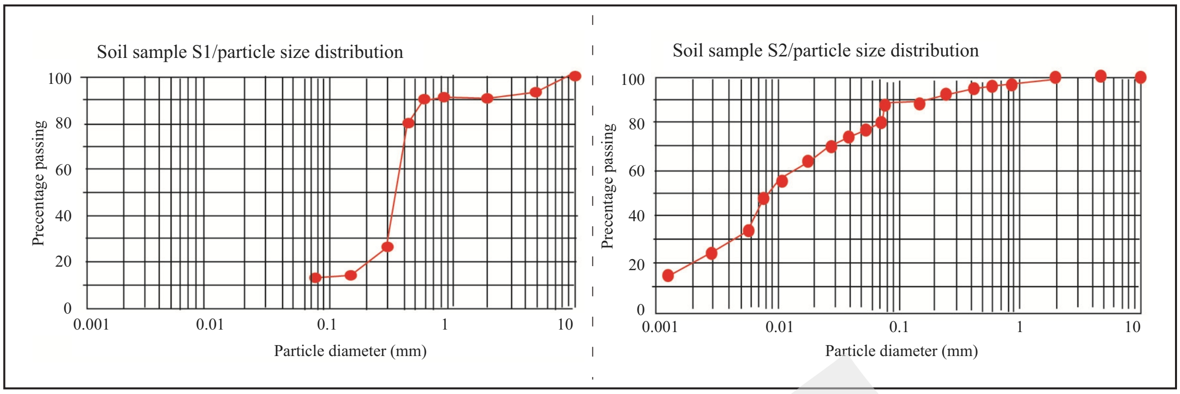

Figure 7. Grain size analyses of the original soil (left) and the landslide material (right).

Table 1. Chemical Content of Water Sample from Hotspring close to the Landslide Site

No	Ret. Time (min)	Peak Name	Heigh µS	Area µSxT	Rel. Area %	Amount ppm
1	3.09	F	0.097	0.012	0.09	1.54
2	4.57	Cl	0.402	0.059	0.43	10.36
3	11.91	SO_4	41.835	13.597	99.48	3458.61

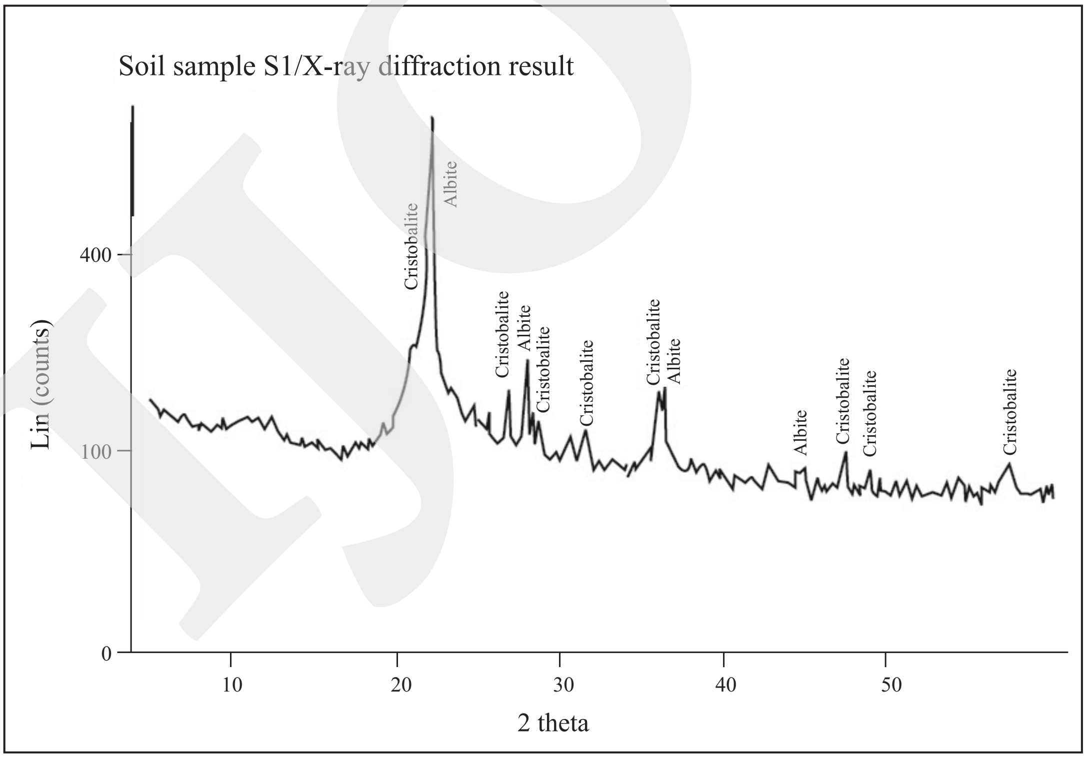

Figure 8. Spectral record of the original soil (Geological Agency, 2014).

Saponite belongs to the smectite group, which is mineralized by hydrothermal processes. Smectite is a clay mineral that can swell when immersed in water or some organic liquids, while chabazite belongs to zeolite group, a clay mineral which is formed in a volcanic complex. Coesite is an alteration mineral formed from quartz under high temperature and presure (Inoue, 1995).

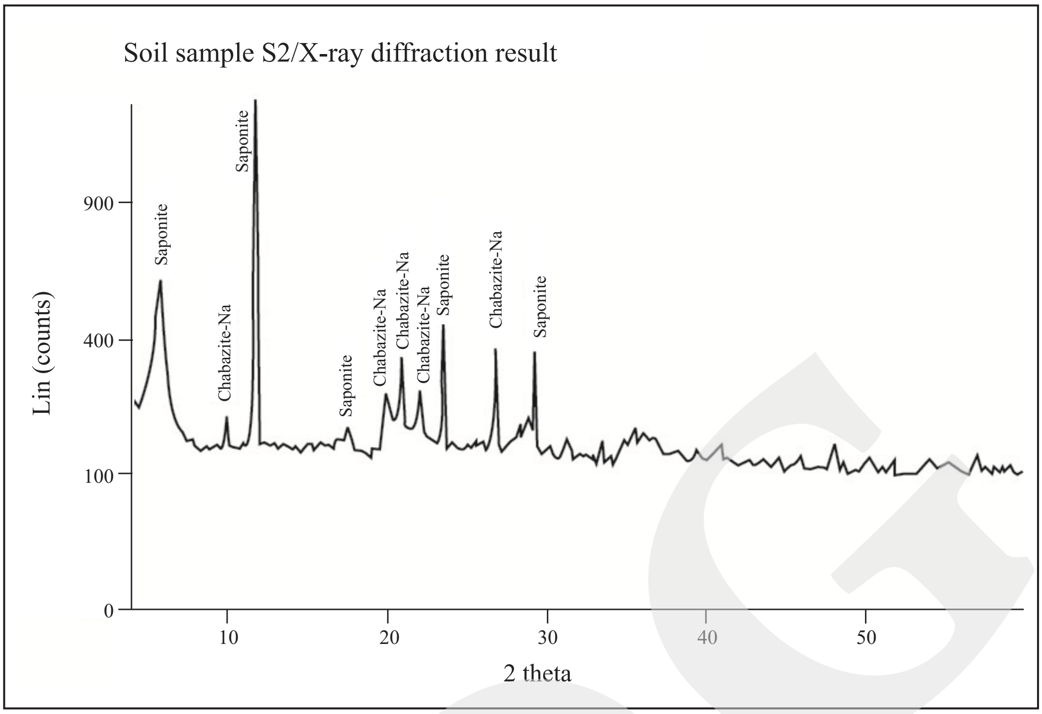

Figure 9. Spectral record of the landslide material (Geological Agency, 2014).

Discussion and Conclusions

In general, factors that may cause landslides include steep slope angle, earthquakes shaking, prolonged rainfall, and volcanic eruptions. These factors can all be found in the study area. The region is hilly with steep slope with relatively high rainfall. Despite the fact that earthquakes are common, before the landslide event, there had been only earthquake which occurred in 1977 with magnitude less than five. The last eruption which occurred before the landslide was Ili Hobal in 1976. Both earthquake and volcanic activities do not directly relate to the 1979 landslide events but they may have fragilised the system.

The Waiteba landslide area is located at a volcano complex where there are scattered geothermal fields, indicated by numerous hot springs. Rocks and soils which are altered by the geothermal activity could lose their underlying structure. The altered rocks are loose, slightly light and consist of clay minerals. Clay minerals expand when they absorb water, so in the season of heavy rainfall, the area would susceptible to landslide occurrence. Clay minerals content found in the landslide material, such as smectite and zeolite are typical minerals in hydrothermal environments. Hence, there is a high likelihood that the 1979 Lembata landslide and resulting tsunami was primed by hydrothermal alteration of the rocks and soil in the geothermal environment. This correlation should be kept in mind when assessing the hazard posed by landslides in other geothermally active areas.

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