Multi-geohazards of Ende city area

Igan Supriatman Sutawidjaja[1] and Sugalang[2]

[1]Center for Volcanology and Geological Hazard Mitigation,
Jl. Diponegoro No. 57, Bandung
[2]Center for Environmental Geology, Jl. Diponegoro No. 57, Bandung

Abstract

The Ende City is a steep mountainous area, of which the height of their peaks are above 1500 m asl. It has the limited extent of plain places, without coastal plains. Due to this condition, large parts of the area are vulnerable to mass-movements mainly debris flows, rock-falls and shallow translational and rotational landslides. On the other hand, Flores Island is a segment of the Banda Arc that contains eleven very active volcanoes and numerous inactive volcanic cones. Two of them, Mount Iya and Mount Kelimutu are included to Ende Regency. The northern foot of Mount Iya is only about 1 km away from the southern outskirts of Ende city. But the presence of Mount Meja and Mount Roja as the barrier, and the orientation of the active crater (K2), the highly explosive eruption of Iya Volcano may not directly endanger the city of Ende. Most pyroclastic flows of previous eruptions and other eruptive material emplaced into the sea, but due to a short horizontal distance between Mount Iya and Ende City, the ejected rock fragments can endanger the city of Ende especially its southern parts. A crack has developed around the active crater (K2) of Iya Volcano. It seems that the crack indicates a major weakness within the volcano, which could result in a giant landslide, entering the sea in future eruptions of Iya Volcano. The kinetic energy which is transmitted through the water may probably generate a tsunami. The Ende City also experienced significant damages in the 1992 earthquake. Luckily this city is located on a solid rock instead of alluvial sediments which can potentially undergo liquefaction.

Keywords: debris flow, rock-fall, pyroclastic flow, landslide, tsunami, liquefaction

Sari

Wilayah kota Ende merupakan pegunungan yang curam dengan puncak-puncak yang mempunyai ketinggian lebih dari 1500 m d.p.l. Wilayah pedatarannya sangat terbatas, kecuali di beberapa tempat yang sempit, dan tidak mempunyai pedataran pantai. Sehubungan dengan kondisi tersebut, sebagian besar wilayahnya berpotensi mengalami gerakan tanah, terutama banjir bandang, guguran batu, rayapan, dan longsoran rotasi. Di pihak lain, Pulau Flores merupakan bagian dari jalur vulkanik Banda, yang mempunyai sebelas gunung api aktif dan sejumlah kerucut gunung api tidak aktif. Dua dari gunung api tersebut, Gunung Iya dan Kelimutu, termasuk ke dalam Kabupaten Ende. Kaki bagian utara Gunung Iya berjarak 1 km dari tepi selatan kota Ende. Tetapi karena adanya Gunung Meja dan Gunung Roja sebagai penghalang, serta arah bukaan kawah aktif (K2), kegiatan letusan Gunung Iya tampaknya tidak membahayakan kota Ende secara langsung. Pada letusan terdahulu, semua aliran piroklastika dan material lainnya yang diletuskan arahnya mengalir ke laut, tetapi karena jarak horizontal cukup pendek antara Gunung Iya dan Kota Ende, lontaran material letusan dapat membahayakan kota Ende, terutama kota bagian selatan. Sebuah rekahan telah berkembang sekeliling kawah aktif (K2) Gunung Iya. Hal ini mengindikasikan bahwa rekahan tersebut merupakan suatu zona lemah di dalam gunung api, yang kemungkinan dapat mengakibatkan longsoran besar ke arah laut pada saat letusan Gunung Iya yang akan datang. Energi kinetik yang ditumpahkan ke air laut, kemungkinan besar akan menimbulkan tsunami. Kota Ende mengalami kerusakan besar pada saat terjadi gempa bumi 1992. Beruntung letak kota ini tidak terletak pada sedimen aluvium, tetapi sebagian besar pada batuan masif, sehingga tidak menimbulkan pelulukan.

***Kata kunci**: debris flow, guguran batu, aliran piroklastika, longsor, tsunami, pelulukan*

Introduction

In attempt to face a natural hazard, a cooperation between the Indonesian and the German Government was set up to assist the Republic of Indonesia in disaster management. The project was implemented in 2003 and 2006. The project aimed to give a comprehensive summary of the baseline data on spatial information and the assessments and evaluations related to potential geo-hazards took place in the Regency of Ende, Flores Island, East Nusa Tenggara Province (Figure 1).

Earthquakes, volcanic eruptions, landslides, debris flows, erosion and tsunamis are geo-hazards that occur in the Ende Regency, generally in Indonesia. They potentially threaten people; each year they cause a lot of material and casualties losses, and they affect social and economic activities over the area. Most of these disasters have one thing in common, usually they occur suddenly and unexpected. To reduce the victims and property loss caused by natural hazards, several mitigation efforts have been carried out. To implement these programmes, several institutions were involved to issue laws and regulations. Numerous hazard and risk assessments have been carried out by the Centre for Environmental Geology (CEG) and the Centre for Volcanology and Geological Hazard Mitigation (CVGHM) which cooperated with the German Federal Institute for Geoscience and Natural Resources (BGR).

The project activities were to identify the geo-related hazards that threated the local people in the Ende Regency, to evaluate their risk potential and to work out appropriate countermeasures in order to improve the safety of the people's life and property. Developing a sustainable approach for risk reduction, will not be possible without coordinating with local communities, political decision-makers and other local stakeholders. Only by combining the scientific-technical geo-related issues with the social, economical and ecological aspects of disaster management it would be possible to work out suitable measures to reduce the threat to the people.

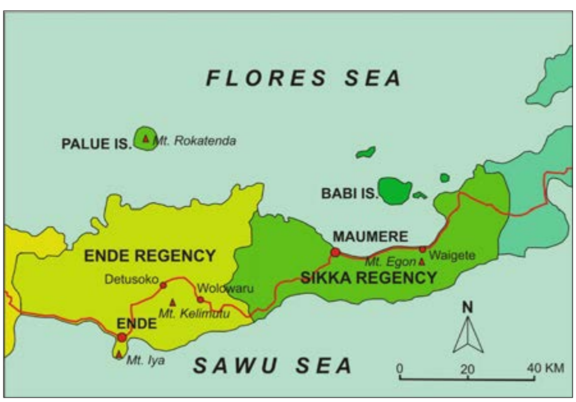


Figure 1. Geographic overview of Ende Regency in Flores.

General Features of Ende Regency

The Ende Regency is one of five regencies on the island of Flores in East Nusa Tenggara Province. The island stretches in east - west direction about 500 km long, and 80 to 12 km wide (Figure 1). Since it is a segment of the long volcanic Banda Arc, it contains fourteen very active volcanoes and numerous inactive ones, which have undergone a certain degree of erosion. Due to this condition, the whole island is extremely mountainous consisting of many peaks of above 1500 m asl and only few plains with limited extent, except small places, without coastal plains.

The slopes are mostly very steep ranging between 45^{o} to 60^{o} even sometimes more. As most high peaks especially in Ende Regency are located in the southern part of the island, even at some places only about 10 to 15 km from the coast, the slopes are generally steeper than in the northern part of the studied area. The drainage pattern is parallel to the length of the island. In areas where volcanic cones are well-defined, radial drainage patterns are well developed.

The valleys developed in accordance with the terrain conditions, V-shaped valleys are commonly found in the upper streams where the slope is steep, but further downstream the valleys become wider in U-shape. Off the south coast, the underwater relief of the sea floor steeply drops into a great depth, whereas in the northern part, it becomes less steep and up to a distance of 1 to 25 km from the coast.

Geology and Tectonics

East Indonesia and the eastern part of the Sunda Arc-trench system as part of the greater Eurasian

Plate possess a complicated tectonic setting. It is affected by the combined processes of the northward drift of the Australian Plate and the westward thrust of the Pacific Plate (Katili, 1973). These movements occurred during the Cainozoic. The Indian Australian Oceanic plate converges northward towards SE-Asia indicated by the magnetic anomalies (Sclater and Fisher, 1974), and the oceanic lithosphere is being subducted normal to the predominantly enigmatic of the Sunda Arc. The very active Benioff zone was mapped by Hatherton and Dickinson (1969) and updated by Hamilton (1978). The seismicity in the Sunda Arc sector extends to a maximum depth of about 600 km in the Jawa and Flores Seas, and the major cross-cutting Sumba fractures separate Sumbawa from Flores (Audley-Charles, 1975). The magmatic rocks formed above the Benioff zone are intermediate and mafic, and the crust beneath the volcanic arc is thin and young and is flanked on both sides by oceanic crust. The plate boundaries are broadly defined as zones of active seismicity (Isacks *et al*., 1968). The subduction system during the Tertiary had caused volcanism in the Lesser Sunda.

The Tertiary rocks of Flores are represented by three formations: (a) the Kiro Formation; it is volcanics, comprising andesitic to basaltic breccia, lavas, sandy tuff and tuffaceous sandstone of Early Miocene age; (b) the Tanahau Formation is also of volcanic origin but unlike Kiro Formation, it is dacite and both interfinger with the Nangapanda Formation whereas the facies is entirely different; (c) the Nangapanda Formation is composed of sandstone and limestone with intercalation of marl lenses, locally brecciform and siltstone (Suwarna *et al*., 1990).

In some places the Kiro and Tanahau Formations are intruded by granitic, granodioritic, and quartz dioritic stocks and dykes. The age of the intrusive rocks are Late to Middle Miocene. The Nangapanda and Tanahau Formations uncomformably underlie the Laka and Waihekang Formations, consisting of tuff with locally tuffaceous intercalation and some intercalations of tuffaceous sandy limestone of Late Miocene to Early Pliocene age. The Waihekang Formation is of limited extent. Patches of the size of only some tens of meters can be found to the east of the Pedang Bay.

Suwarna *et al*. (1990) implied that volcanic activity in Flores continued until the present day. The volcanoes are well developed both on mainland of Flores and on the islands nearby. The youngest rocks are the coral limestone along the coast, coastal terraces, and alluvial and coastal deposits. All of these units were deposited unconformably on the pre-existing formations.

Climate

As the other islands of the Indonesian Archipelago, the climate of Ende Regency has followed characteristic features: only slightly different in temperature between dry and rainy seasons (isothermic); absolute dominance of convective precipitation (thunderstorms); high frequency of thunderstorms; the zone of highest amounts of rainfall is located at altitude of lower than 1500 m above sea level; and the local distribution of rainfall strongly depends on the seasonally prevailing wind.

The whole region is strongly influenced by a seasonal pressure change between two continents, Asia and Australia. From November to February, high pressure air from Asia that contains water vapour blows across the Lesser Sunda Islands in W-E direction towards low pressure air in Australia causing rainy season. Due to rugged topography and the westward facing of the slopes, the western part of Flores receives the highest amounts of rainfall in the Flores Island. Although during the investigation, the prevailing wind may be from W to E, local wind systems (sea-land, lowland-highland) may locally affect rainfall distribution.

During May to September, the Australian high pressure crosses over the Lesser Sunda Islands resulted in a clear sky with almost no rainfall and slow wind speeds. The traditional months (March/April to October) may be influenced by one of the climatologic settings. Local isolation, convection and moisture patterns therefore strongly determine the rainfall (thunderstorms) distribution. For geohazards mitigation it has to be considered, that thunderstorm-cumulus clouds frequently form over mountainous areas and that most rainfall occurs in an altitude between 1100 to 1300 m above sea level (Weischet & Endlicher, 2000).

Due to its location, the island susceptibility to tropical cyclones is pretty low, since the threshold latitude for sufficient Coriolis Force is about 10 degrees from the equator. Nevertheless, according to the World Map of Natural Hazards, the Lesser Sunda Islands may be hit by tropical cyclones with windspeeds up to 153 km/h. This indicates that the outer rims of tropical cyclones centred south of the Indonesian archipelago may touch the islands, but would not lead to comparable destruction than in neighbouring Australia.

The El Nino/Southern Oscillation phenomenon, which is going hand in hand with a cooling of surface waters in the region is likely to cause unusually dry conditions like during the Super El Nino in 1997. These abnormally dry periods could last from several months to more then one year.

Unfortunately, there is not many rainfall data available for the project region itself. The only station datum was from Maumere airport, which was available on a daily bases from January 1998 to June 2006. In this period, Maumere received an average of 1145 mm of precipitation each year. Generally, the region around Ende with its mountainous relief receives more rainfall than the northern coast around Maumere.

Major Natural Disasters Within the Last 80 Years

An overview about disasters happened in Ende area that nearly all major disaster events is covered and should give an impression of the region high exposure and vulnerability.

1. The 1928 eruption of Rokatenda Volcano. Between 4th of September to 25th of October, Mount Rokatenda in Palue Island erupted (Neumann van Padang, 1930). The eruption from the central crater was characterized by an explosive eruption that produced pyroclastic flows, and the activity was ended by the formation of a lava dome. The eruption was accompanied by a tsunami that killed 160 people on the island, where the wave height reached 5 to 7 m. Also some villages on the north coast of Flores Island were hit by the tsunami. In Maurole, six persons lost their lives, and seven houses and five boats were destroyed. In Maka and Maosambi, four persons were killed and a few others slightly injured. Mount Rokatenda in Palue Island belongs to Sikka Regency, but the location is close to Ende Regency, so most of tsunami that is caused by the volcanic eruption will hit north coast of Ende Regency.
2. Landslide and debris flow disasters in the rainy season in 1938. Poor information about the landslide and debris flow disasters was obtained from the local people who still remember the events. According to this information, it is expected that the disasters were very similar to those in 1988 and 2003 (BPS Kabupaten Ende, 2001). The only reliable information on damages is that the bridge crossing the Lowo Nangapanda river at the village of Nangapanda, 8 km west of Ende city was destroyed (DPU-ITB, 1994).
3. The 1961 Flores earthquake. On the 16th of March 1961, a strong earthquake measuring VII to VIII on Modified Mercalli Intensity Scale shocked the region, damaging many villages in Ende. One person was reported killed. The epicentre was located at 8.1^{o} S and 122.3^{o} E.
4. The eruption of Mount Iya in January 1969. The eruption did not give a significant precursor, but it turned out to be an explosive one as the characteristic for Iya Volcano. The eruption occurred on January 27th, 1969, at 4 am, and at 11 am; continue crumbling sounds and spectacular glowing features were identified above the summit. This was followed by a steady ash eruption forming a black cauliflower-shaped column, rising as high as 4000 m above the summit. In this event it was reported that one casualty due roof collapsed, two casualties and ten injured mainly by lahar flows, severely injured by hot air and gases on Ende Island, 177 houses collapsed, fifty houses damaged, six mosques collapsed, three schools collapsed, one hospital damaged, and 30,000 coconut trees and other plantation and agriculture damaged.
5. The Mount Rokatenda eruptions in 1980 and 1981. In November 1980 and October 1981, Mount Rokatenda in Palue Island erupted with two main periods of activity. The first period occurred between November 5th, 1980 till the end of January 1981, and the second period from August 22nd to November 5th, 1981 (Sumailani and

Sihat, 1985). During the first series of eruptions, ash columns rose 1000 m above the summit and volcanic bombs of about 60 cm in diameter fell nearby, 2 mm thick of ash was deposited 1 km westward. Bush fire occurred, mostly on the upper flank. A new crater measuring about 40 m in diameter was formed on the NNE flank of the mountain (Effendi & Chaniago, 1998). About 1850 people were evacuated from the hazard zone, but fortunately no casualties were reported (Kasturian & Wirasaputra, 1981). During the second eruption period, a new 200 m high lava dome with an estimated volume of 8.5 million cubic meters formed (Sutawidjaja *et al.*, 2000), which was then followed by the collapse of the dome. This activity led to the presence of pyroclastic and debris flows surging down the slopes, where 36 buildings were set on fire, but due to timely evacuation movements no casualties were reported. A three-component seismometer to observe the volcano was damaged.

6. The landslide and debris flow disasters in 1988. During November 5th and 7th, 1988, abnormal rainfall with up to 350 mm/day triggered landslides and debris flows in the surroundings of Ende. The affected area can roughly be described with a 26 km radius around the city of Ende. In this event, 72 people were killed, mainly by debris flows sweeping through villages.
7. The earthquake in Maumere 1989. Although the earthquake occurred in Maumere, Ende town was affected as well. On July 31st, 1989 an earthquake hit the region around Maumere. The epicentre was located in 8.05° S and 121.38° E, at a depth of 14 km. The magnitude measured 6.3 on the Richter scale, and the intensity reached V to VI on the MMI scale. Only minor damages to buildings were reported in Maumere, and nobody was injured.
8. The earthquake and tsunami in 1992. On December 12th, 1992, at 13:29 local time, an earthquake of magnitude 6.8 on the Richter scale occurred off the north coast of Flores. This shock was also felt on the island of Bali, 700 km to the west. It set off a series of tsunami, which arrived on the shores of Flores within two minutes after the initial shock, and it reached the north shore within five minutes. The epicentre was located approximately 35 km NW of Maumere. The fault which produced the earthquake lies between the epicentre near the Cape of Batumanuk and the Cape of Bunga on the northeastern tip of the island. The fault is approximately 110 km long and about 35 km wide. Over 1000 aftershocks were recorded by a field survey team from Japan during the week-long period from the December 30th, 1992 to January 5th, 1983 (Matsutomi, 1992). The island of Babi is located about 40 km NE of Maumere City. It is a round island of 2.5 km in diameter, surrounded by a coral reef, with a mountain of 351 m high rising up in the Centre (DPU-RI, 1994). There is almost no flat land on the coast, except on the south coast, facing Flores Island about 5 km to the south. Two villages are located on this flat land. The population of the island is 1,093, of which 263 were victims of the tsunami. Maximum run up on the island was measured at 5.6 m in the eastern village. The earthquake also triggered many landslides in the Centre of the island and along the road between Ende and Maumere. Twenty people died in Ende Regency due to the collapse of buildings. Some parts of Ende city, mostly the area around the western harbour were affected. In total, 1690 Flores islanders died, and the tsunami destroyed approximately 18,000 houses.
9. The landslide and debris flow disasters in 2003. Heavy rainfall from March 31st to April 2nd, 2003 caused flash floods, landslides and debris flows in the Ende, Sikka, and Larantuka regions. The areas that suffered most from heavy rains were the following sub-regencies in Ende Regency: Ende, Detusoko, Ndona, Nangapanda, Maurole, Wolowaru and South Ende. The road from Ende to Bajawa was blocked because the bridge crossing the Lowo Nangaba, 8.2 km west of Ende collapsed in a debris torrent. The road connecting Ende and Maumere towns was blocked by landslides and debris flows in several places. Seventeen houses in the Ndungga Village, 10 km in distance along the road from Ende to Maumere towns were swept away by a debris flow carrying boulders of more than 100 tons in weight and covering the village with 3.5 m of

debris, and 27 people were killed in this event (Figure 2). A big portion of the Ende airport was flooded up to 1 m deep and covered by debris. The airport could not be used for several days. The city of Ende was isolated from the outer world for about one week, since the roads to Bajawa and Maumere cities were blocked and the airport inundated.

Figure 2. The debris flow deposits in the village of Ndungga/ Detumbawa. The picture shows the formerly populated area, 27 people lost their lives in this event. The big block to the right was also carried by this debris flow and was estimated to weight more than 100 tons on April 2nd, 2003.

Assesment of Geohazards

Most of the following information and data were collected during the Georisk Project fieldwork to Sikka and Ende Regencies between July to August 2003, and September 2006.

Landslide Processes

Because of the very mountainous relief, large parts of the project area are potentially prone to mass-movements predominantly, rock falls, shallow translational landslides, and debris flows.

Rock falls

Falling rocks are hazards for areas located below very steep slopes and rock faces. In the project area a problem arose in many parts of the road between Ende city and Detusoko and the road between Ende city and Wolowaru (Figure 3). In those places the road was cut into the natural relief, producing steep and unstable slopes. Although rock falls are not a direct threat to settlements, boulders and gravels frequently block the roads, hampering transportation and economy. Additionally, passing vehicle and people can be subject to falling. Rock falls cannot be precisely predicted, but in the mapped road segments they occurred frequently, so people using the road should be aware of this danger to react accordingly. Therefore, road signs indicating the risk and warning the people should be installed before and at the

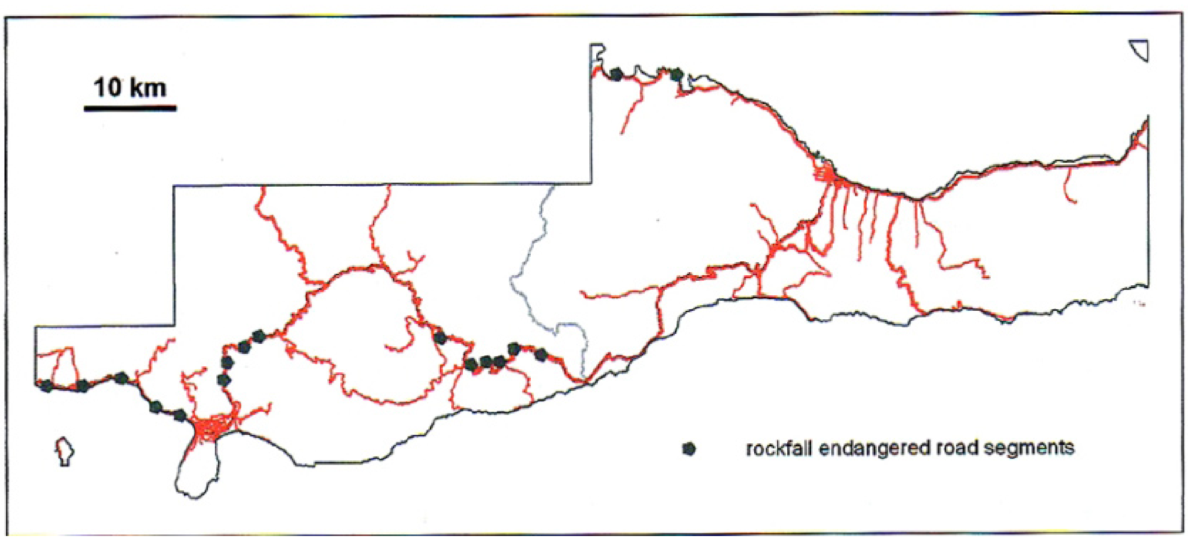


Figure 3. The rock-fall endangered segments of major road.

affected road segments. Because rock falls may also block the road, sufficient equipments to clear and repair the road should be available and functional in major settlements.

Landslides

The term of landslide is often used for all gravitational mass-movements, including rock falls, debris flows and others. Another term is defined as rotational and translational movements of soil. The speed of the movements might range from a few centimetres per year to one meter per second. Therefore, landslides can cause damage to buildings and lifelines (linear infrastructure) gradually, but may also rapidly destroy settlements. In most cases, landslides are triggered by earthquakes and intensive rainfall events soaking the soil. 10% of the settlements in Ende area are located in highly vulnerable areas, 22% in the moderate vulnerable ones, and only 40% of the settlements can be considered as entirely safe from landslide hazard (Figure 4). According to those hazards, during the rainy season thousands of people live at high risk to be affected by disastrous landslides.

Although it is widely accepted, that certain human activities (deforestation, cutting of slopes for constructions and others) increase the probability for landslides, these activities do not trigger a sliding process immediately. Therefore, all human activities in landslide prone areas have to be planned and handled carefully. Since it is not easy to predict the exact time of the onset of most landslides, all mitigation efforts strongly rely on probability calculations. Therefore, the project area was mapped using direct and indirect methods as described in the national standard operation procedure, dividing the region in to the following four hazard classes (Figure 4): (a) Zone of high susceptibility to landslides (red), wherein landslides occur frequently, while old landslides may be reactivated and the new ones induced by high rainfall or strong erosion processes; (b) Zone of moderate susceptibility to landslides (yellow). This zone is characterized by the occurrence of landslides, especially along riversides, scarps, road cuts or disturbed slopes. Old landslides may be reactivated especially when induced by high rainfall or strong erosion processes; (c) Zone of low susceptibility to landslides (green). In this zone, landslides rarely occur unless the slope is disturbed or old landslides are reactivated. Small-scale landslides may occur especially on riversides and stream channels; (d) Zone of very low susceptibility to landslides (blue). This zone has never been subjected to landslides. No features of old and new landslides were found, except some small areas on riversides.

Generally, there should be no further development within the red zone. In the yellow zone, development should be carried out only after con-

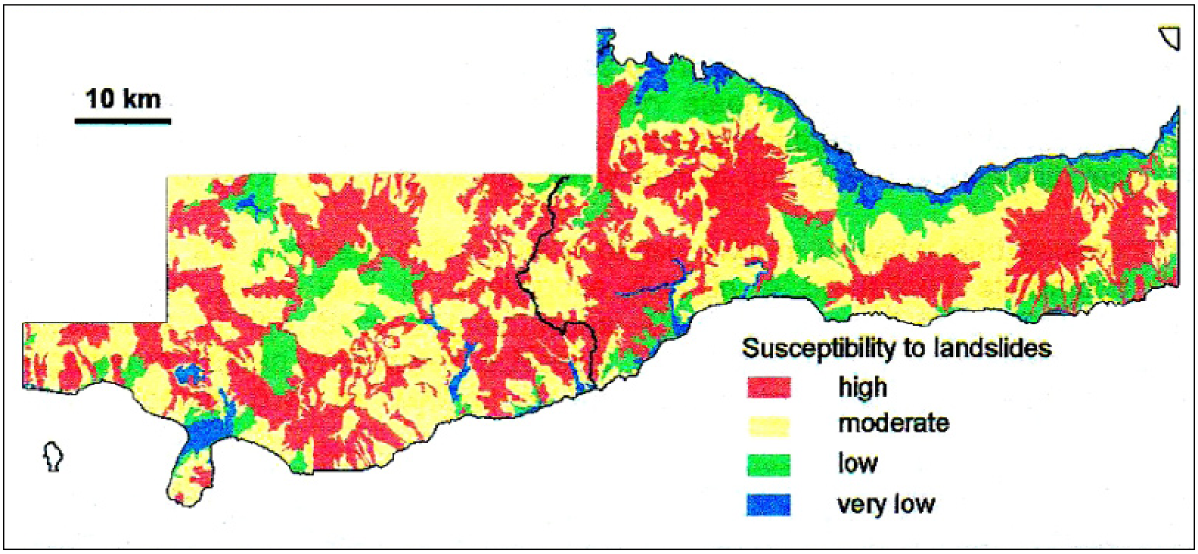


Figure 4. Landslide susceptibility map of the project region, which should be used as a bases for planning and emergency activities.

sultation with landslide experts. Settlements, which are located within the red and yellow zones should be protected or replanted by natural vegetation (forest) mainly on the slopes nearby the settlements and vital infrastructure, especially crucial infrastructure for possible cracking. Furthermore, the local people should frequently observe the slopes. In the case cracks occur, the people should plug them with clay to prevent water infiltration and evacuate the possible affected houses.

Debris flows and debris torrents

The most dangerous and unexpected types of mass movement within the project area are debris flows, which are generated in the very steep terrains with narrow and deep valleys (gorges). In general, the threshold slope angle of these gorges is about 30^o, but the run out of such debris flows frequently affects the lower reaches with less then 20^0.

Debris flows are generally defined as a dense mixture of water and sediment that surge down as a kind of continuous fluid in a predefined streambed. Such a debris flow disaster recently happened by the end of March 2003, 10 km north of the Ende town at Ndungga (Figure 2). The turbulent current must have had a height of 5 to 10 m according to the damages and scouring at the slopes of the valley. Similar debris flows happened in 1988 along the western tributary of the Lowo Wolowona at Rowo Reke, 8 km north of Ende city, and in the Ae Isa Village, 2 km northwest of Ende city. Until today, the lower part of the valley at Rowo Reke is covered 2 to 3 m thick of gravel and big boulders originated from the upper part of the 5 km long tributary valley. The deposits of the debris flow are now used for sand and gravel mining.

One debris flow generating mechanism is the damming of a gorge by rocks, soil and uprooted trees (maybe by another landslide, rock fall or gully erosion). During heavy rainfall, water quickly accumulates behind the dam and may cause bursting (Takahashi, 2000). When the natural dam is destroyed, the stored water and accumulated sediments are surging downwards with high speed in a turbulent current with a high destruction potential in and along the riverside. The speed of such turbulent currents can reach about 25 m per second. Although the described mechanism is very likely one within the investigation area, it has to be emphasized, that debris flows may also occur without previous damming in any tributary river that passes several hundred meters difference in altitude at a distance of only 1 to 2 km.

Debris torrents or hyper-concentrated flows are also triggered by heavy rainfalls and mark the transition between the material rich debris flows, and also in wider riverbeds, but they still need a considerable steep gradient, as typically found in mountain valleys. Debris torrents like debris flow carry all kinds of materials such as sand, gravels, soil, boulders and trees, but have much higher water content. In Ende Regency, the bridge over the Lowo Nangaba River, 8.2 km west of Ende city was destroyed by debris torrents in 1988 and 2003.

In the past, the most devastating debris flows occurred in the surroundings of the Ende city. Therefore, future mitigation activities should focus on settlements that are partly located along such gorges and valleys, which are especially prone to debris flow events. The characteristic of these events is the fact, that some places repeatedly experience the same damages like the bridge crossing the Lowo Nangaba River. It seems that there have been three major debris flow disasters in the region around Ende city within about 100 years (1938, 1988, and 2003). Due to landuse pattern changes and a higher population density, similar hazards may still occur in the future, and should be anticipated.

So far there is no early warning system for heavy rainfall that can trigger debris flows and debris torrents, such as: no reliable weather forecast for the region and the most affected villages do not have any communication facilities to receive early warning information. Although weather tendencies and data from official rainfall gauges should be considered for general alert level via radio, TV and others, a community based on an early warning and evacuation system is the most effective. Generally debris flows occur during rainy season. It seems that the existence of Sabo Dam are nor very useful, due to the presence of very powerful debris flows. The power of debris flows is impressively visualized in Figure 2. Generally, every development in dry river channels and dry creeks should be avoided, since they are potentially affected by debris flows and debris torrents.

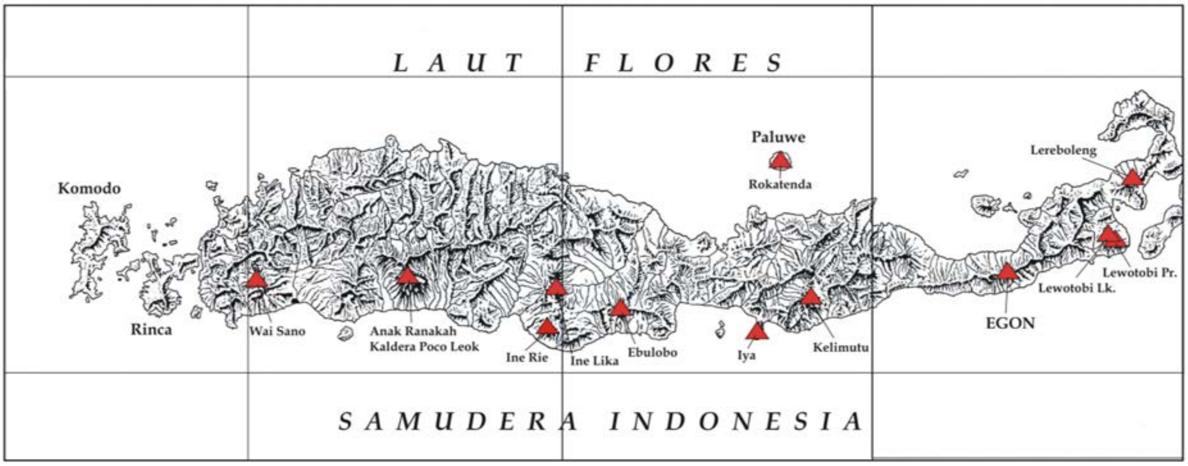


Figure 5. Locations of very active volcanoes (A-type) on Flores Island.

Volcanoes

There are eleven highly active (A-type) volcanoes in the Flores Island and another one at a nearby island (Mount Rokatenda) (Figure 5). A-type volcano is defined as a volcano that at least erupted once in historic times since 1600. The Ende Regency has two volcanoes, Mount Iya and Mount Kelimutu. Mount Rokatenda, although it is situated in the Sikka Regency, this volcano is located close to Ende area; thereby, most of its eruption impact always hit the north coast of Ende Regency, such as ash-fall and tsunami.

Mount Iya

Mount Iya strato volcano is situated within 8°03.5' S and 121°38' E. It occupies the southern tip of the peninsula stretching south of the Ende City. The northern foot of the volcano is only about 1km away from the southern outskirts of Ende city. Mount Iya is part of the peninsula row of volcanic cones including Mount Meja (+371m) in the north, Mount Roja (+425m) in the middle and Mount Iya (+655m) in the south (Figure 6). Mount Iya highest point, located about 1300 m in horizontal distance to the sea, occupies the northeastern rim of the original central crater.

The peninsula formation was initiated by Mount Roja, which grew offshore south of the area. Today, it is occupied by the city of Ende. Its eruptive products covered the Tertiary rocks in the surrounding of Ende city. Mount Meja is a parasitic cone located NNE of Mount Roja and very close to the city of Ende. Both, Mount Roja and Mount Meja show no volcanic activity during historic times and are not considered as active volcanoes anymore. At present, both volcanoes form a natural barrier between Iya Volcano and the city of Ende, so they shelter the city from various volcanic hazards including pyroclastic flows. The growth of Mount Iya significantly extends the peninsula southward. The whole volcano comprises alternating layers of lava and ash and other fragmented volcanic rock debris formed during explosive eruptions over thousands of years in the past.

Today, Mount Iya shows two craters, called Crater 1 (K1) and Crater 2 (K2) by Stehn (1940). The rim of K1 has a diameter of about 600 m and its crater bottom stretches about 300 m in NW-SE and

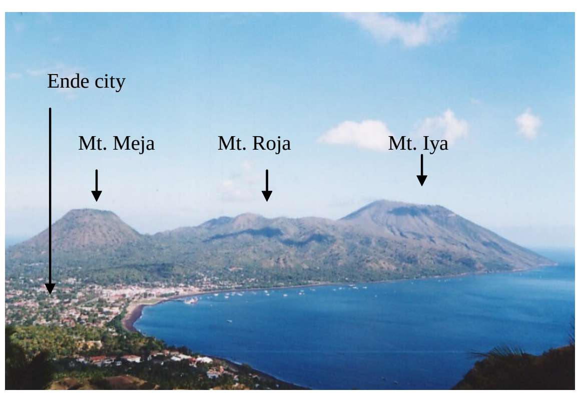


Figure 6. The growth of Mt. Iya significantly extended the peninsula to the south. Mt. Meja and Mt. Roja form a natural barrier between active Mt. Iya and the city of Ende.

150m in NE-SW direction. K2 is the active, lower lying crater with 300 to 400 m in diameter. The crater bottom is about 50 to 100 m in diameter with a depth about 75 m (Figure 7). K2 as the youngest crater is located SSW of K1 roughly halfway between the summit and the sea. According to Stehn (1940), this crater was formed by a large eruption that must have taken place SW of the main crater (K1), causing the collapse of part of its former crater wall. Since 1924 the coastline shifted backwards over probably more than 100 m. During historic times numerous explosive eruptions were recorded from Mount Iya in the years – 1671, 1844, 1867, 1868, 1871, 1882, 1888 (not recommended), 1953, 1969, and 1971 (not recommended). Although most of these eruptions were only a moderate one with a volcanic explosivity index (VEI) of 2 (about 0.001 km^3 of ejected tephra), the eruptions in 1671 and the 1969 were classified with VEI of 3 (about 0.01 km^3 of ejected tephra). The last major activity occurred in 1969 (Figure 8).

Due to its hidden location and the orientation of the volcano is the active crater K2, the highly eruptive Iya Volcano seems not to endanger the city of Ende directly, as during past eruptions, most pyroclastic flows and other eruptive material were emplaced into the sea. Only Rate Village northwest of the volcano is severely endangered by pyroclastic flows, but because of short horizontal distance, ejected rock fragments can endanger the city of Ende, especially its southern outskirts. The volcanic bombs could have diameters of more than 6 cm.

Ash-fall is another big danger for the city of Ende and its surroundings, even though this city was only covered by 1cm thick of ash fall during the 1969 eruption. This case was due to favourable wind-direction from east, which caused the ash to drift to the sea (Figure 9). In case of heavy ash-fall in and around the city, it has to be worried since it can cause disruption of all infrastructure facilities (air-, land-, and sea-transport, telephone communication, water supply, *etc*.) (Reksowirogo, 1969). Moreover, the people will strongly suffer from respiratory problems. Additionally, the heavy upload to buildings could easily result in its collapse as happened in Ende Island in 1969. Thick ash-fall in the mountainous surrounding the Ende city can generate lahar flows, that can endanger most villages located on mountain flanks. When a volcanic eruption takes place during a rainy season, all evacuation measures have to consider this aspect, if a village is used as evacuation barracks, otherwise it will endanger refugees.

Figure 7. The active crater (K2) of Mt. Iya showing solfatara acticities on the north crater wall.

Figure 8. The eruption of Mount Iya in 1969. (Photo Doc. VSI).

Another major threat from the Iya Volcano which was evaluated during the fieldwork in 2003 and 2006 was a well developed crack that runs across the active crater (K2) of Iya Volcano (Figure 10). Fumaroles appear along the crack where the temperatures ranged between 60° to 80° C. Thermal infrared photograph shows very active fumaroles along the crack (Figure 11). It is thought, that the crack indicates a major weakness within the volcano, which could resulted in the occurrence of a giant landslide surging into the sea during future eruption of Iya. A computer simulation of this possible landslide is shown in Figure 12, where about 70 million m3 of rock lies on the unstable area and prone to slide. Although this material will not directly threat the settlements (since the sliding direction will be south to southwest), the kinetic energy transmitted to the water column may result in the occurrence of tsunami. The amplitude of this tsunami depends very much on the speed and form of the fearfull sliding process. It is expected that the whole rock portion surges into the sea at once within minutes (worst case scenario), but it is also possible that the unstable volume would gradually slide down into the sea within weeks, months, or years. Although no further modelling was carried out to map the tsunami hazard along the coasts in Ende Regency, most of the coasts especially Ende Island should be informed about the alert level of Mount Iya and in case an eruption (before the eruption) occurs. Evacuation of people to higher places should be carried out.

Repose period from the previous eruptions for a moderate scale (VEI 2) can be estimated, where Mount Iya eruption took place within 18 years in average. Three months after the 1969 eruption, the Volcanological Survey of Indonesia (now is the Centre for Volcanology and Geological Hazard Mitigation – CVGHM/PVMBG) built an observation post in the Kampungbaru Village, on the northwestern side of the volcano. The volcano observatory, connected to the city of Ende by a good paved road, is equipped with electricity, a seismograph and a single-side radio communication. Two observers, permanently observing the volcanic activity in 12 hour shifts, re-

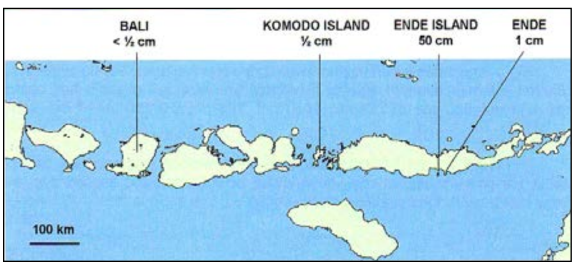
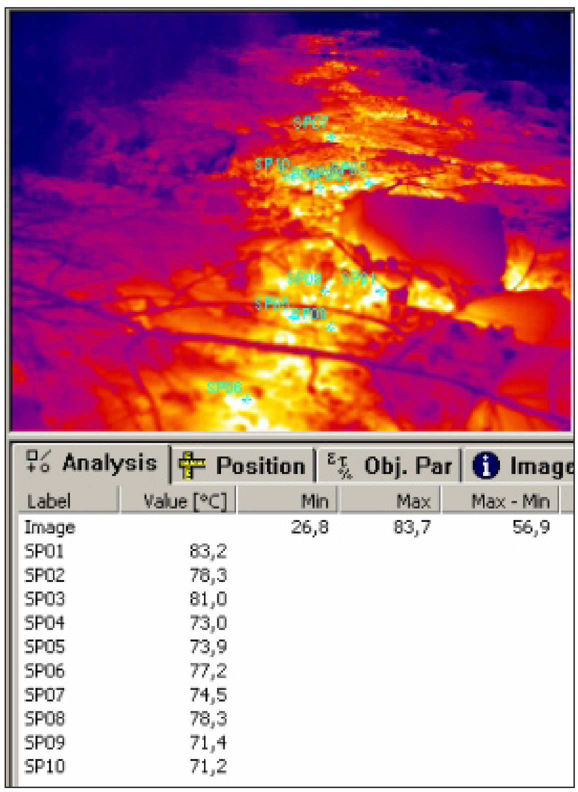


Figure 9. Distribution of ash-fall during the Iya eruption in 1969.

Figure 10. A well-developed crack (white arrow) runs all around the active lower crater (K2) of Iya volcano.



Label	Value [°C]	Min	Max	Max - Min
Image		26,8	83,7	56,9
SP01	83,2			
SP02	78,3			
SP03	81,0			
SP04	73,0			
SP05	73,9			
SP06	77,2			
SP07	74,5			
SP08	78,3			
SP09	71,4			
SP10	71,2			

Figure 11. Thermal infrared photograph of the crack showing the temperature of fumaroles along the crack range between 70 to 85 degrees C.

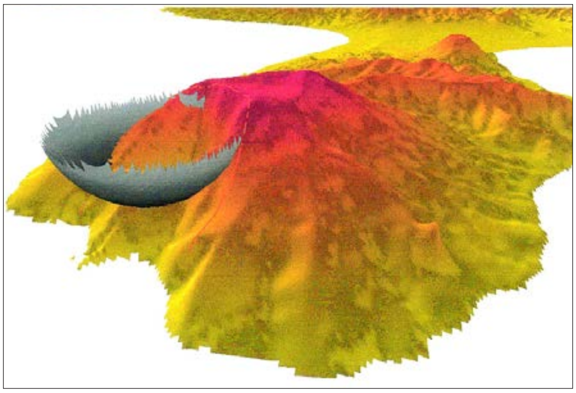


Figure 12. The computer model of Mount Iya simulating a landslide triggered by an eruption. The dash-red line indicating the crack.

port the activity to the CVGHM and Bupati (Head of SATLAK-PB). A cooperation programme between BGR and CVGHM has produced Volcanic Hazard Zone Maps of Iya (Figure 13), Kelimutu and Egon Volcanoes. The present activity of Mount Iya is shown by the existence of solfatar emission on the north wall of the crater (Figures 14 and 15).

Mount Kelimutu

Mount Kelimutu is an active volcano with the highest peak +1640m above sea level, at a geographic position of 8.76^o S and 121.83^o E. The summit area shows three spectacular crater lakes with different colours. The western lake, Tiwu Ata Mbupu (Lake of the Old People) showed dark blue colour, but it is currently dark green; the Tiwu Nua Muri Kooh Fai (Lake of the Young Men and Maidens) used to be green, pale green or white, and it is currently pale green; whilst Tiwu Ato Polo (Bewitched Lake) used to be red, dark red or brown, but it is currently dark brown. Both craters share the same crater wall. The crater lakes are famous for their unique colours.

The volcano is one of Indonesia's top tourist attractions and is the main reason why tourists are interested in visiting Flores. The tourists can drive up to a car park, and take a short walk, so the most popular viewpoints are found. These beautiful crater lakes give advantages to the local people who live in the surrounding villages. At present, the Tiwu Ato Polo crater (the red one) is located very close to Tiwu Nua Muri Kooh Fai crater (Figure 16). It is separated only by some meters of a thin wall, which is quite different from the condition in 1990, when the wall was still thicker, between 15 – 20 m. In case an eruption occurs in one of these two craters, the wall is likely to be damaged and the two lakes would merge to become a big crater. It seems that currently the three craters are very quite, and even the oldest craters (Tiwu Ato Mbupu) and Tiwu Ato Polo nearby, have almost no activity at all.

There is little known about the historic and prehistoric activities of Mount Kelimutu. This might be due to its isolated location and the lack of research carried out on this volcano as well. The recorded activities during the last decades, in the years of 1938, 1967, 1968, 1986 (increasing temperature of Tiwu Nua Muri Kooh Fai crater), 1989 (moderate degassing at Tiwu Ato Polo, the water lake changes from reddish (1986) to green (1989), and 1993 (increasing seismicity) (Kusumadinata, 1979). There was no eruption since 1968 and the only activities recorded were the presence of fumaroles and solfatars around the lakes of the young Tiwu Nua Muri Kooh Fai crater and the change of the lake water colours.

In case a big or medium eruption occurs, pyroclastic flows and lahars may affect the settlements northwest of the summit, and the priority should be given to evacuate the villages of Pomo, Kopoone, Sigo, Manukako, Nuabaru, Waturaka, Kombobewa and Watugana. The nearest village to the south of the summit is Toba which should be evacuated, too. In case of a major eruption, it should be considered to evacuate all villages on the southwestern, southern, and eastern slopes to Ende city and Wolowaru. Those places have good infrastructures with bigger capacities to cater refugees over a longer period.

The major hazard of Kelimutu Volcano is the poisonous gases that frequently accumulate above the crater lakes and can endanger incautious tourists as in 1995 when a Dutch tourist disappeared in one of the three crater lakes. Generally, poisonous gases accumulate when the weather is cloudy, wherein they are floating above the crater lakes mainly during wind-less periods. For this reason, a ranger-station on the road up to the summit is provided to prevent tourists to climb up the volcano during the night. During the daytime, rangers also remind the tourists not to enter the crater lakes.

The available data are not enough to calculate any statistical recurrence period, but since the last

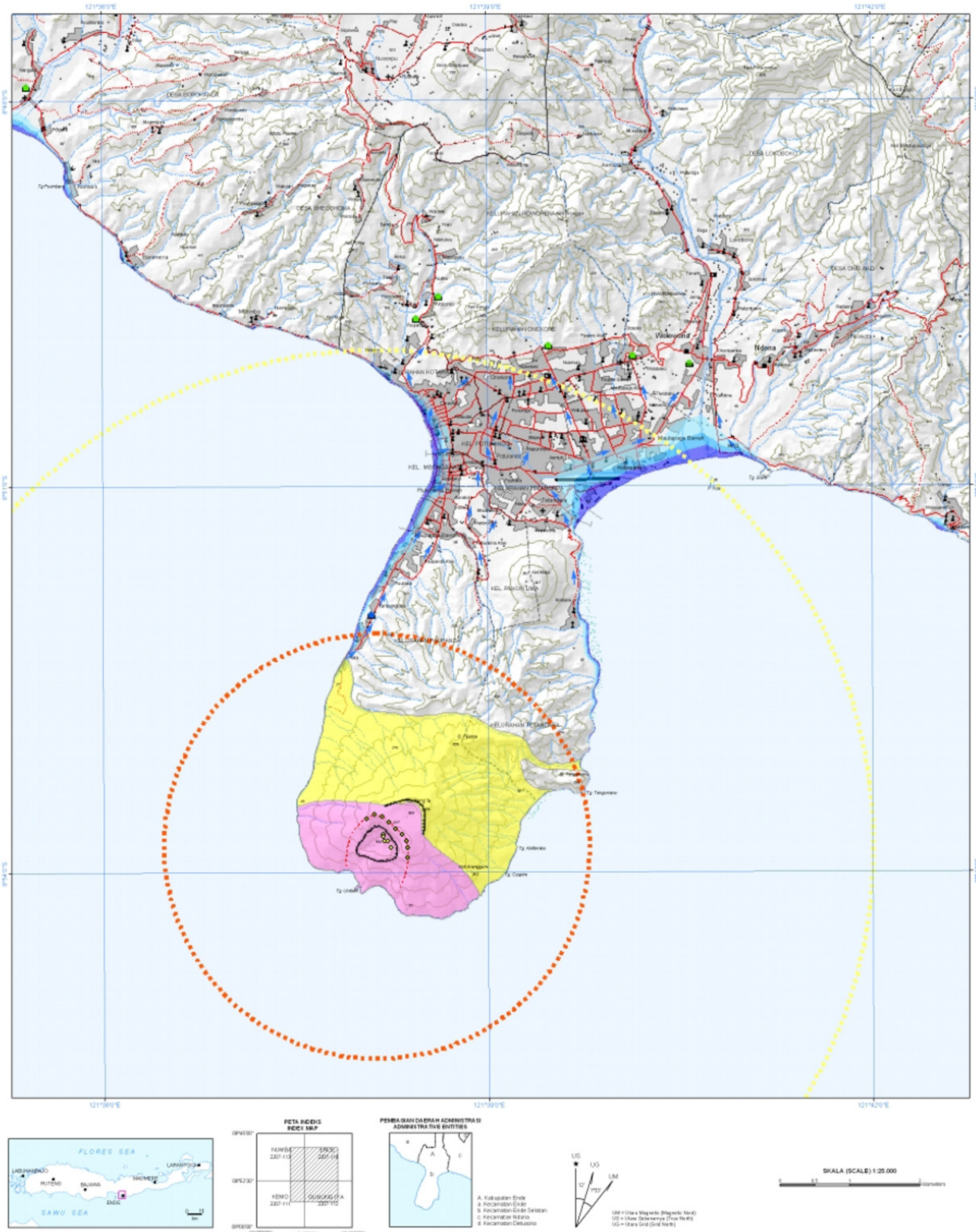


Figure 13. The Volcanic Hazard Zone Map of Iya Volcano.

Figure 13. Continued.

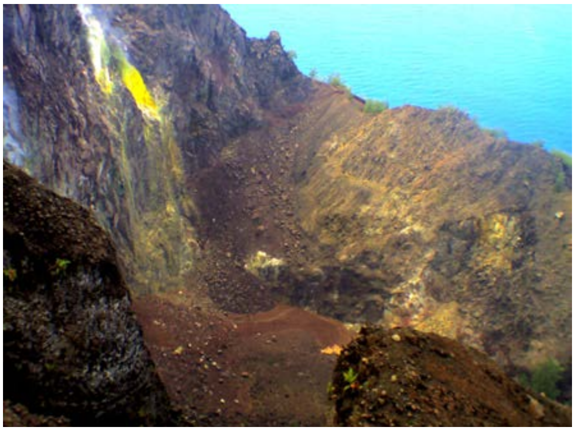


Figure 14. Digital photograph of Mount Iya crater.

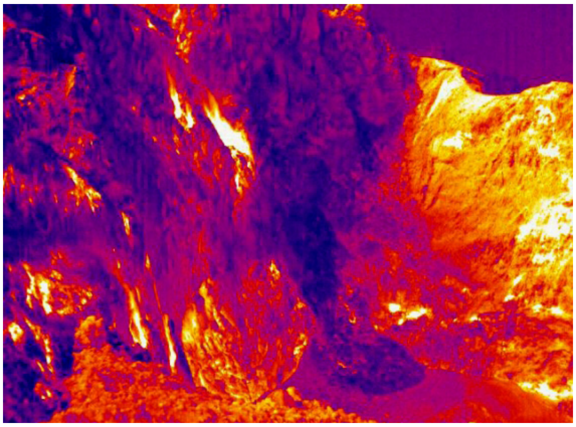


Figure 15. Thermal infrared photograph of Mount Iya crater.

Figure 16. Tiwu Nua Muri Kooh Fai crater is one of three different colors of Mount Kelimutu's crater lakes. In the background is Tiwu Ato Polo crater which has a brownish black color.

eruption dates back until 1968 it is thought that the Kelimutu Volcano accumulating its energy, and therefore a future eruption is potential. The Kelimutu observation post is located on the road to the summit between Liasembe and Saona Villages.

Earthquakes

According to modern plate tectonics, Flores Island is located on the Asian plate along the plate boundary between the Asian and Indo-Australian plates, where the latter subducting northwards beneath the Asian plate. This movement frequently causes earthquakes in most parts of Indonesia. The Maumere earthquake 1992 was the most disastrous event of the century in Indonesia. The past destructive earthquake in Maumere occurred in 1992, measuring 6.8 on the Richter Scale, and it was due to the city condition, geologically set on sediments instead of solid rock (Kertapati, 2001). Although the Maumere city experiences earthquake hazard in the project region, other areas may be affected as well. The Ende city for example also experienced significant damages during the 1992 shaking. Luckily, this city is not located on alluvial sediments but mostly on solid rock and so does not have to fear liquefaction.

Since the seismic data of the region is limited, no probability or return period for specific earthquake intensities could be calculated. Although the 1992 event is likely to be an event with a statistical return period of may be 100 years, the whole region should prepare with the incoming earthquakes, since less powerful (but more frequent) quakes are likely to cause considerable destruction.

Tsunami

The word "tsunami" comes from the Japanese language. Literally translated it means "great harbour wave". This is because tsunami waves can reach heights of around 40m when they proceed to coastal areas with lower water depths. The term contains a suitable description for one of the most threatening rapid onset natural hazards in the world. Tsunami can be caused by: (a) sudden movements or disturbances of the sea floor during an earthquake; (b) submarine volcanic eruptions; (c) landslide at the sea floor as well as landslides reaching the sea;

(d) impacts of large objects in the sea.

In Flores Island, most coastal areas may experience tsunami, but due to the distribution of earthquake epicentres the northern coast areas are considered as more vulnerable. In the project region, the two coastal volcanoes Mount Iya and Mount Rokatenda and the submarine volcanoes northeast of Flores Island might also be able to cause tsunami when they erupt. Especially Mount Iya should be intensively monitored because of its 70 million cubic-meters of rock that can slide down into the sea. A simulation of an unstable area, which is likely to generate a tsunami wave seriously threatened the coastal areas of Ende City and the adjacent Ende Island. The eruption of Rokatenda in 1928 had caused a tsunami that killed more than 160 people (Neumann van Padang, 1930). By comparing the settlements in the north and the south coast, it is obvious that the Sawu Sea (south coast) is built further from shore which is protected from high sea tides. Therefore, there are many more structures should be produced, since the north coast is more potentially affected by tsunami.

For the Flores Island, the establishment of a central early warning system of tsunami seems to be difficult, since many earthquake epicentres are located only a few kilometres from the coast as it was the case in 1992. During this event, the tsunami reached the coast between 2 and 5 minutes after the main shock, a time-span, which is extremely too short for early warning. To cope this problem, people knowledge and education how to react and what to do when tsunami occurs is more effective. Especially, in the cases of Mount Iya and Mount Rokatenda, the volcanic early warning systems should also include tsunami early warnings for endangered settlements, primarily when paroxysm eruption is likely to occur.

Conclusions

Landslide and debris flow events triggered by abnormal high rainfall resemble similar events in 1988. It is remarkable that some places experienced the same damages as in 1988 like the village Nungaba, where the same bridge that crosses over the Lowo Nangaba was destroyed twice. Another example is the Lowo Wolowona valley NE of Ende city, which was severely damaged by debris flows and three known landslides.

The Mount Iya eruption in January 1969 surprised the local population, the political decision makers and the volcano monitoring observers of the Volcanological Survey of Indonesia (today the CVGHM, Bandung). It was due to that no precursor activities like earthquakes, smaller eruptions or else were recognized, and the fact that on that time there was no volcano observatory installed at Mount Iya as it is today. During the eruption it turned out again, that most settlements around the Iya Volcano are naturally well protected against pyroclastic and lava flows. The situation is much different for heavy ash-fall and lahar flows, which caused the major damages during this disaster. It is remarkable that the Ende city only received 1 cm thick of ash-fall compared to Ende Island with was up to 50 cm in thickness, and Komodo Island (more than 200 km to the west) with 0.5 cm thick and ash-fall still reported from Bali. This implies that a very dominant wind was from the east, so that most of the ejected ash fell into the sea and did not affect any settlements or infrastructure. Suppose the ash fallout would have covered the mountains north of Ende, a lot of casualties may occur, as the most refugees took shelters in villages located in the very steep slopes. The presence of thick ash deposits mixed up with heavy rainfall either during or after eruption can generate the presence of lahars, endangering many settlements in the area.

The existence of small and moderate wave heights of the tsunami in many locations along the north coast may cause another problem in mitigating the future hazard of tsunami events. Many people who survived from the tsunami without or with only little harm that based on their 1992 experience a tsunami possessed no serious threat for them. The understanding of the victims is often based on the assumption: “I survived once and I will survive in the future”. In their view there is no need for any action. This hampers the dissemination of precautionary measures and undermines long-term actions like relocation. There is a demand for information on tsunami and earthquake hazard and risk from local officials, but no institution is responsible to collect and store information and data from previous events in one central place and to distribute this information to other offices when needed. As a result, almost all scientific recommendation and advices given after the 1992 event disappeared and useless.

Acknowledgments—This paper is part of Georisk Project funded by BGR, German within the year 2004 and 2006. In this opportunity, the authors extend their gratitude to BGR Team for a solid cooperation that resulted from Georisk Project in East Nusa Tenggara. Thanks to all colleagues who have given the authors assistance and support.

References

Audley-Charles, M.G., 1975. The Sumba fracture; a major discontinuity between eastern and western Indonesia. *Tectonophysics*, 26, p.213-228.

BPS (Badan Pusat Statistik) Kabupaten Ende, 2002. Ende Dalam Angka 2001. Ende.

Bryant, E.A., 2001. *Tsunami*. The underrated hazard. New York.

DPU – ITB (Departemen Pekerjaan Umum Republik Indonesia dan Institut Teknologi Bandung), 1994. *Spatial planning for the island of Flores*. Bandung.

DPU (Departemen Pekerjaan Umum) Republik Indonesia, 1994. Data survai untuk petunjuk umum perbaikan kerusakan akibat gempabumi. Bandung.

Effendi, W. and Chaniago, R., 1998. *Geologi foto Gunungapi Rokatenda, Kabupaten Sikka, Propinsi NTT*. Direktorat Vulkanologi dan Mitigasi Bencana Geologi. Bandung.

Hamilton, W., 1978. *Tectonic map of the Indonesian region 1: 5,000,000*. Map I-875-D, US Geological Survey.

Hatherton, T., and Dickinson, W.R., 1969. The relationship between andesitic volcanism and seismicity in Indonesia, the Lesser Antilles and other island arcs. *Journal of Geophysical Res*earch, 74, p.5301-5310.

Issacks, B., Oliver, J., and Sykes, L., 1968. Seismology and the new global tectonics. *Journal of Geophysical Res*earch, 73, p.5855-5899.

Kasturian, P. and Wirasaputra, A.D., 1981. Pemeriksaan puncak dan pemetaan daerah bahaya G. Rokatenda. *Field Report*. Direktorat Vulkanologi, Bandung.

Katilli, J.A., 1973. Geochronology of west Indonesia and its implication on plate tectonics. *Tectonophysics,* 19, p.195-212.

Kertapati, E.K., 2001. *Seimic Hazard Map of Indonesia*. Geological Research and Development Centre. Bandung.

Kusumadinata, K., 1979. *Data dasar gunungapi Indonesia. Catalogue of references on Indonesian volcanoes with eruptions in historical time*. Direktorat Vulkanologi.

Matsutomi, 1992. Flores Island, Indonesia Earthquake of December 12, 1992. *JICA Preliminary Investigation and Recommendations*.

Neumann van Padang, N.M., 1930. *Tidal waves during Rokatenda volcano eruption, Paluweh island in 1928.*

Reksowirogo, L.D., 1969. *Komunike G. Iya I-III*. Direktorat Geologi.

Sclater, J.G., and Fisher, R.L., 1974. Evolution of the east central Indian Ocean, with emphasis on the tectonic setting of the Ninety East Ridge. *Geological Society of America, Bulletin,* 85, p.683-702.

Stehn, Ch.E., 1940. Vulkanologische onderzoekingen in Oost Flores. *Vulkanologie & Seismik Mededeelingen, Batavia*, 13, p.68-82.

Sumailani, A.R., and Sihat, E., 1985, Pemetaan situasi puncak G. Rokatenda, Pulau Palue, Kabupaten Sikka, Flores Tengah, Nusa Tenggara Timur. *Field Report*. Direktorat Vulkanologi dan Mitigasi Bencana Geologi. Bandung.

Sutawidjaja, I.S., Pribadi, A., and Taufiqurrohman, R., 2000. Pemetaan Geologi Gunungapi Rokatenda, Kabupaten Sikka, Nusa Tenggara Timur. *Field Report*. Direktorat Vulkanologi dan Mitigasi Bencana Geologi. Bandung.

Suwarna, N., Santosa, S., and Koesoemadinata, P., 1990. *Geology of the Ende Quadrangle, East Nusa Tenggara 1:250,000*. Geological Research and Development Centre, Bandung.

Takahashi, T., 2000. Initiation and flow of various types of debris flow. *In*: Wieczorek & Naeser (eds) Debris Flow Hazards Mitigation. *Mechanics, Prediction and Assessment*. Balkema, Rotterdam.

Weischet, W., and Endlicher, W., 2000. *Reginale Klimatologie – Die Alte Welt*. Stuttgart, Leipzig.