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CALDERA ACTIVITIES IN NORTH BALI, INDONESIA

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Abstract

One of the most serious natural hazards is largescaled Plinian eruption that forms caldera. Although the probability to have such large-scaled eruption is very low, the result will be catastrophic if it happens. Thus, it is important to clarify features of caldera system including eruption timing, scale of eruption, precursor activity, etc. With enough scientific information, we may be able to mitigate such very rare but extremely large-scaled geohazard. In Bali Island, Indonesia, there are two caldera systems; Batur caldera and Buyan-Bratan caldera. Batur caldera was previously well studied (e.g. Sutawijaya, 2009), whilst Buyan-Bratan caldera's geological and volcanological features have not been examined at all. The Buyan-Bratan caldera is about 6 km × 11 km in size and contains three caldera lakes. Wellformed several post-caldera cones are covered by thick soil and vegetation and developed from central to southern part of the caldera. Buyan-Bratan caldera and post-caldera cones are thought to be older than Batur caldera activities. Geothermal manifestation is confirmed within the caldera. Geological features of the Buyan-Bratan caldera and post-caldera cones were clarified by petrographic and petrochemical analyses. Also, KAr ages were obtained for each volcanic edifice in Buyan-Bratan caldera system.

Keywords: *Caldera, Plinian eruption, Buyan, Batur, volcano hazards*

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1 Introduction

About 10% of world population live at the adjacent of active or potentially active volcanoes. In the 21th century more than 500 million people are predicted in the risk of direct and indirect volcano hazards (Tilling, 2005; Peterson, 1986; Tilling and Lipman, 1993). During the period of 17th to 19th entury, most of fatalities are caused by indirect volcano hazards such as tsunami (e.g. Krakatau, Indonesia in 1883) and famine disease (e.g. Tambora, Indonesia in 1815). In contrast, during the 20th century, most of casualties are due to pyroclastic flow (e.g. Mt. Pelée, Martinique in 1902; El Chichón, Mexico in 1982) and lahar (e.g. Volcan Nevado del Ruiz, Colombia in 1985) (Tilling, 2005 and references there in). All of the above-mentioned eruptions are related with explosive style of eruption, especially Plinian type of eruption that may form caldera structures.

The event of Plinian eruption is usually limited from a few minutes to a few hours characterized by the formation of high convective eruptive column, discharging hot eruptive mass into the atmosphere. During this phase, the mass consisting of gas and particles (juvenile and wallrock) in various size is discharged from vent(s) at velocities between 100 and 400 m/s. The volume of ejected material ranges typically between 0.1 to 10 km^3 (magnitude 10^{11}–10^{13} kg) with mass discharge rates (MDR) of 10^6–10^8 kg/s (Cioni et al., 2000). The eruptive column then collapses to form pyroclastic flow, surge and tephra fallout. In term of geohazards, this phenomenon is potential for both direct and indirect volcano hazards.

Plinian type eruption is commonly resulted by the fragmentation of evolved magma of dacitic to rhyolitic, though there is also a possibility of andesitic magma e.g. Masaya (Wehrmann, 2005), the 1886AD Tarawera eruption (Walker et al., 1984; Houghton et al., 2004), the 122BC Etna eruption (Coltelli et al., 1998; Houghton et al., 2004). This type of magma is commonly formed in the subduction zones of island arc and continental arc. Therefore, countries like Indonesia, Philippines, Japan and other countries in the Pacific Ring of Fire have a high risk of volcano hazards. During history era the most catastrophic eruption happened in Indonesia such as Krakatau (1883) and Tambora (1815) with casualties more than 36,000 and 92,000 people respectively (Beget, 2000; Sigurdsson, 2000). Before this era, there were some volcanic catastrophic event, e.g. Vesuvius (79 AD, and Avellino during Bronze age, 3780 yr B.P) the Minoan eruption of Santorini, Greek (1645 BC).

In order to reduce the risk of volcano hazards, it is important to provide scientific data that clarifies features of caldera system including eruption timing, scale of eruption, precursor activity, etc. Even though the Plinian type of eruption is devastating, some studies suggest that inhabitant in the area near the volcano can be evacuated safely. In order to succeed the evacuation, we must work on their timeline of the eruption, so we must understand the precursor of Plinian eruption that commonly alerts people in days to months before the cataclysmic event. This early phase of a Plinian eruption may not be fatal, even the location is close to the volcano (Mastrolorenzo et al., 2006).

In order to understand the mechanism of eruption, we may conduct a study by inverting the pyroclastic deposits product of the Plinian eruption that is available in Bali Island, Indonesia. There are two calderas in the northeastern part of Bali, i.e. Buyan-Bratan and Batur Calderas (Figure 1). So far, Batur Caldera has been studied intensively by some researchers (Sutawidjaja, 2009; Marinelli and Tazieff, 1968; Kusumadinata, 1964; Wheller and Varne, 1986; Yokoyama and Siswowidjojo, 1970; Reubi and Nicholls, 2004), in contrast, there is limited study that has been conducted in Buyan-Bratan caldera.

This study is aimed primarily to reveal the development of magma beneath BuyanBratan Caldera using petrographic and petrochemical analysis of each volcanic edifice in Buyan-Bratan Caldera. Furthermore, we compare our result to the Batur Caldera system to evaluate the possible risk of volcano hazards in Bali Island.

2 Tectonic setting

Bali Island is situated in the eastern part of Sunda volcanic arc that is formed due to subduction of northward-moving oceanic plate of Indo-Australia beneath Eurasian plate extended from Andaman Island to the East through Sumatra, Java, Bali until Flores Island (Hamilton, 1978). The thickness of Eurasian plate beneath Sumatra and Java is about 20 to 30 km (Ben-Avraham and Emery, 1973; Curray et al., 1977; Whitford, 1975) and is around 18 km close to Bali. The subducting plate is an oceanic plate with the age from ˜80 Ma to ˜130 Ma, ranging from Sumatra to Java (Plank and Langmuir, 1998; Widiyantoro and van der Hilst, 1996).

Subduction rate of Indo-Australian plate beneath Eurasia is 6 – 7 cm/year (DeMets et al., 1990; Tregoning et al., 1994; Simandjuntak and Barber, 1996).

There are two different configurations of this subduction system, which are: during Cretaceous, the subduction extended to Sumatra-Central Java-East Kalimantan, then since Early Tertiary to Recent the subduction extend to the East of Java continuing to Banda arc. Volcanism in Bali Island, therefore, appears to have occurred since Middle-Late Tertiary (e.g., Katili, 1975; Hamilton, 1979; Carlile and Mitchell, 1994; Metchalfe, 1996). Therefore, some researcher believe that the overriding plate in western Java is continental crust of Sunda land while the eastern Java to the East is transition to oceanic crust (Miyazaki et al., 1998; Carlile and Mitchell, 1994; Simandjuntak and Barber, 1996).

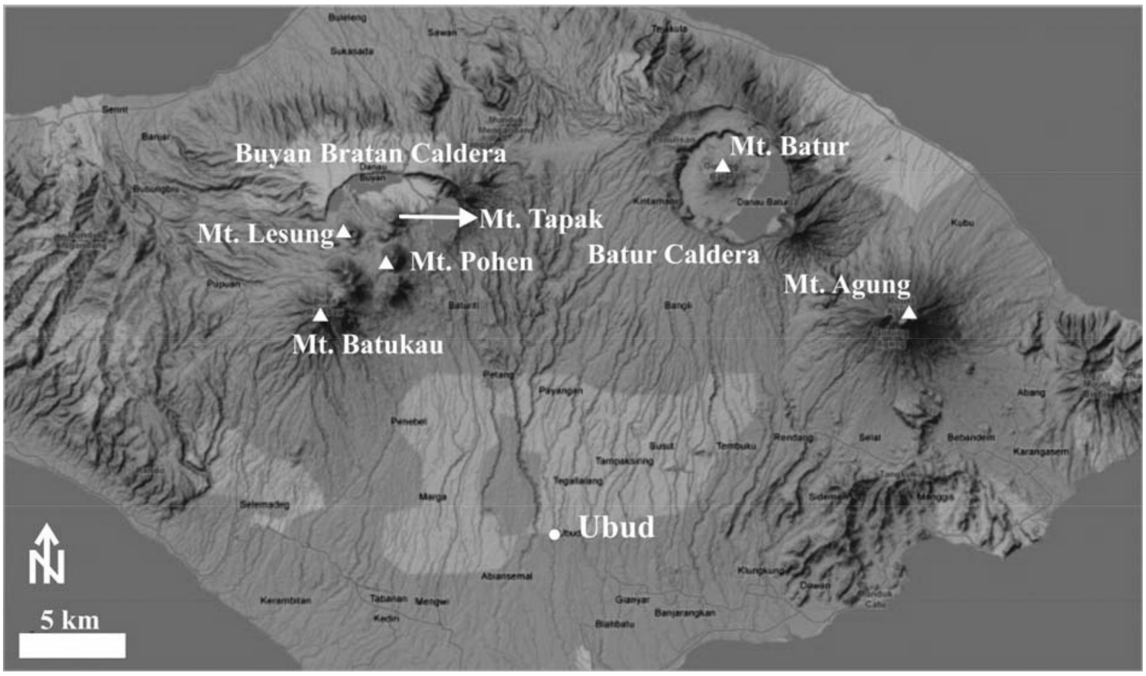

Figure 1: Terrain of Bali Island showing the two caldera, Buyan Bratan and Batur Calderas

3 Volcanic activities in Bali island

Purbo-Hadiwidjojo (1971) suggested that the exposed oldest rock in Bali Island is the Lower Miocene Ulakan Formation composed of volcanic rocks of lava flow, breccia and tuff intercalated with calcareous sandstone. However, Kadar (1972) determined that the oldest rock unit in Bali are calcareous sandstone of Late Miocene in age. Whilst, Wheller and Varne (1986) defined the oldest volcanic rocks in Bali to be pillow basalt of Late Pliocene. Those pillow basalt is included as a member of Ulakan Formation by PurboHadiwidjojo (1971). On the surface, the most widespreaded rocks are Quaternary volcanic rocks product of Buyan-Bratan Caldera (Bratan, Batukau), Seraya volcanoes and recently active Batur and Agung volcanoes (Figure 2). It is difficult, however, to distinguish the volcanic rocks product of Buyan-Bratan Caldera from the volcanic rocks product of Batur. Based on geological data, the researchers defined that the caldera-forming eruption of Buyan-Bratan is earlier than that of Batur. It is difficult to find the volcanic rocks that is unequivocally result of caldera forming eruption of Buyan-Bratan, since most of the Buyan-Bratan product is covered by deposit product of younger eruption. The last volcanic activity occurred in Bali was in 1963 when Agung volcano erupted.

3.1 Buyan-Bratan Caldera

Buyan-Bratan Caldera (BBC) is featured by the circular depression structure open to the South. The diameter of the structure is about 10 km trending east-west and open to the South. At the northeast side there is caldera wall of the BBC. This topography is the highest remaining caldera wall. Inside the caldera, there are several younger volcanic edifices such as Tapak, Lesung and Pohen. A little bit to the South, probably already outside the caldera, there are Sengayang and Batukau volcanoes. Those cones have crater at the top of the cone indicating that each young volcanic cone inside the caldera has erupted at least once.

Geochemical and petrological data of rocks representing the volcanic edifices inside the Buyan-Bratan caldera was reported by Yamanaka et al. (2009). Geochemical analysis revealed that the rock composition of those edifices are in the wide range of SiO_2 concentration from 45% to 63% or from basaltik to andesitic. So far, only rocks collected from caldera rim

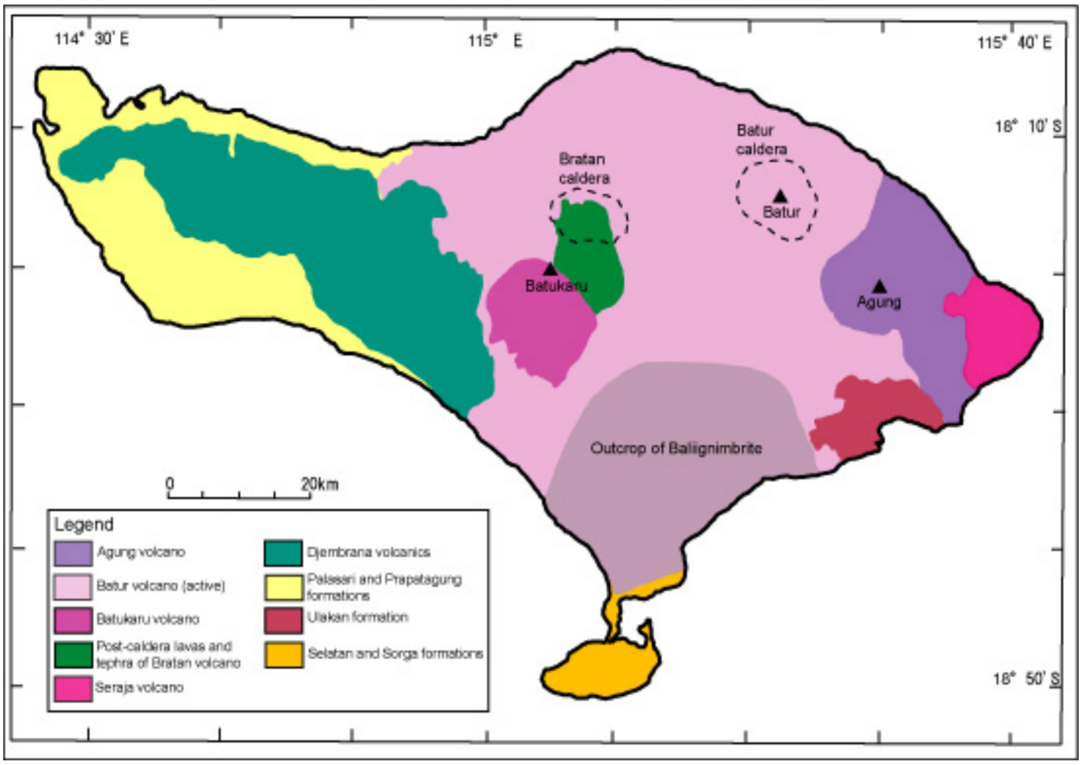

Figure 2: Geological map of Bali showing that Bali Island is covered mainly by volcanic rocks (after Wheller and Varne,1986)

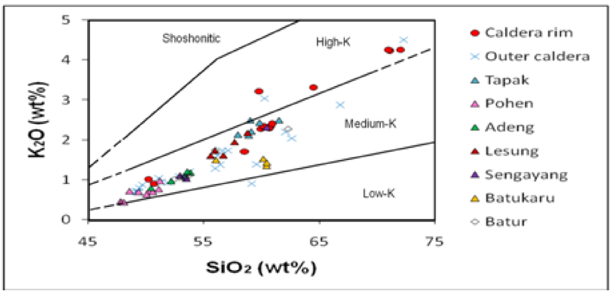

Figure 3: K_2O vs SiO_2 composition of each volcanic unit at Buyan-Bratan Caldera. The boundary of affinity is following Peccerillo and Taylor (1976).

having high SiO_2 concentration from 65 to 72% or from dacitic to rhyolitic composition (Figure ??). The affinity of magma is gradual from low-K to medium-K (Figure ??). Thin section analysis revealed that most of eruption product from BBC are composed of similar mineral assemblage of plagioclase, pyroxene, magnetite and olivin (Table 1).

The activities of BBC system was earlier than Batur Caldera (BC). As the distance of those caldera is close, it is possible that the volcanic product of BBC is covered and concealed beneath volcanic product of BC. The outcrop of the volcanic product of BBC is limited or unclear. Field observation identified the product of BBC exposed at Gitgit waterfall. Major outcrop in and around the waterfall is several lava flows showing columnar joint. These lava flows are most probably result of pre-caldera activities. This lava is overlain by weathered tuff breccia. This deposit is a result of pyroclastic flow, though the mechanism cannot be defined clearly. Inside the caldera most of the area is covered by ash to lapilli size scoria resulted from pyroclastic fallout. The scoria deposits can be found surrounding Tapak and Lesung. At Tapak, there are at least five layers of scoria that are separated by paleosoil (Figure 4). The deposit may resulted from the strombolian eruption and to form the young cone inside the caldera such as Lesung, Tapak and Pohen.

Geochemical analysis reveals that the scoria composition is basaltic similar with the composition of rocks from Pohen. Whilst, the lava

Table 1: Mineralogy of each volcanic edifice

Volcanic Edifices	Minerals
Caldera rim	plagioclase, clino pyroxene, ortho pyroxene
Tapak volcano	plagioclase, clino pyroxene, ortho pyroxene
Pohen volcano	plagioclase, clino pyroxene, ortho pyroxene, olivin
Adeng volcano	plagioclase, clino pyroxene, ortho pyroxene, olivin
Lesong volcano	plagioclase, clino pyroxene, ortho pyroxene, olivin
Sengayang volcano	plagioclase, clino pyroxene, ortho pyroxene, olivin
Batukaru volcano	plagioclase, clino pyroxene, ortho pyroxene

Figure 4: Photo of the out crop of scoria layers at the foot hill of Pohen edifice.

composition has a wide range from basaltic to rhyolitic. The variation diagram show that the composition has a linear relationship, indicating that fractionation process is responsible for the wide range of the composition. Rhyolitic rock is found near Tamblingan Lake. It is a welded tuff, resulted from intracaldera ash flow. Unfortunately, the outcrop is not possible to climb.

3.2 Batur Caldera

Batur caldera is located in the eastern part of Bali Island, with the size of about 14×10 km^2 consisting of three construction periods and two caldera formation periods indicated by the appearance of two caldera rim. The volcanic activity at Batur Caldera started at least 500 ka BP with the building of a basaltic to andesitic stratovolcano (Penulisan volcano) (Wheller and Varne, 1986). The description of BC ignimbrite is based on the report published by Sutawidjaja (2009). Magma erupted from Batur has wide range in composition from basaltic to rhyolitic indicating there is mature evolution of magma and progressive development of a shallow magmatic system resulted in catastrophic caldera-forming eruptions.

Sutawidjaja (2009) reported his work on

stratigraphy of the ignimbrite as well as radiometric age dating using ^{14}C of the ignimbrite. The radiometric dating revealed that the first caldera eruption produced Ubud Ignimbrite in 29,300 years BP, the second eruption occurred 20,150 years BP and the third occurred in 5500 years BP. Furthermore, He distinguished the deposit into four units of ignimbrite result of BC i.e. Ubud Ignimbrite, Gunung Kawi Ignimbrite, Batur Ignimbrite and Blingkang Ignimbrite.

Ubud Ignimbrite is the oldest ignimbrite of BC and mainly exposed at Ubud area about 30 km from the center of Batur Volcano. It is distributed around 1200 km^2 with the volume of about 84 km^3. It is composed of common black pumice, crystal poor. At the proximal part it contains lapilli size of pumice and is partially welded. In contrast, the distal facies shows typical columnar joint with thickness more than 120 m.

The second caldera forming eruption produced the deposit called Gungkawi Ignimbrite. The Gunungkawi Ignimbrite is younger and more mafic in composition than Ubud Ignimbrite. This ignimbrite can be distinguished into two cooling unit. The lower unit consists of fine-grained and densely welded ignimbrite, while the upper part is composed of very coarse and partially welded. The typical outcrop of Gunungkawi Ignimbrite is located at Gunungkawi, Tampaksiring, north of Ubud.

The proximal part of the second eruption deposit is known as Batur Ignimbrite. It consists of densely welded dacitic ignimbrite. Most of the Batur Ignimbrite is distributed inside the caldera, constituting the caldera wall II and rarely found outside caldera. The thickness of the Batur Ignimbrite varies from 50 to 200 m, as it is controlled by irregularity of initial topography inside caldera. Pumice block composition is dacitic.

In his study, Sutawidjaja (2009) suggested that Blingkang Ignimbrite is a result of third Plinian eruption at Batur Caldera. It is based on the ^{14}C dating result of charcoal from Blingkang Ignimbrite of 5500 yr BP. The ignimbrite consists of pale brown to grayish brown basal non welded sheet of 1 to 4 m thick containing pumice clast and pumice ash matrix.

4 The impact of Bali's volcanoes eruption to environment

The geochemical and petrological studies have been conducted intensively on BC, whilst they are limited on BBC. Those data may revealed the eruptive process in magma chamber. Wheller and Varne (1986) and Reubi and Nicholls (2004) identified complex magmatic process beneath BC. There is a differentiation process resulted in a wide range of magma composition from basaltic to rhyolitic.

The fragmentation of magma is interpreted as a main factor to induce Plinian eruption. Magma fragmentation will result in a porous and fine pyroclast. Pyroclastic deposit of BC show the change of color of the pyroclast from light gray into dark gray, implying a change of magma composition that became more mafic during the eruption. The pyroclastic deposit at the flank of volcanic that came inside the BBC is blackish scoria layer that is interpreted as a result of fragmentation of basaltic magma. If we compare with BBC in which we found rhyolitic rock on the caldera wall we may suggest that the caldera forming eruption at BBC is also due to fragmentation of rhyolitic magma.

Study of pyroclastic deposit of BC shows that pyroclastic density current (PDC) of the Plinian eruption can reach distance up to 30 km. The volume of the deposit is about 84 km^3 with distribution across 1200 km2. This size of pyroclastic deposit is much more massive than the eruption of Avellino eruption during Bronze Age (3780 yr BP) of about 4 km3. This distance is almost the same as the distance of PDC of 79 AD Vesuvius eruption, Minoan eruption. The temperature of the PDC at the distance up to 25 km is modeled less than 100ºC, with the velocity 1 to 10 m/s. An analoguous catastrophic eruption would make devastation of present day of Bali Island. Age dating indicates that the Plinian eruption may occur repeatedly, such that happened at BC; there were at least three large scaled eruption of 29,300 yr BP, 20,150 yr BP and 5,500 yr BP (Sutawidjaja, 2009). Other example is the eruption of Vesuvius at Italy at 3,780 yr BP and 79 AD (Mastrolorenzo et al., 2006).

In order to minimize the victims of the eruption, we should know the precursor of large scaled eruption of Plinian phase. Study of the eruption of Avellino 3780 yr BP (Mastrolorenzo et al., 2006) was interpreted that there was an exodus of inhabitant during that eruption. This meant that those people are probably safe. In order to mitigate victims from the Plinian eruption, the evacuation scenario must be planned. Since the pyroclastic surge can reach 25 km away from the vent, we must pay the attention more to the area in the 25 km radii (Figure 5). Assuming that the speed of the pyroclastic surge is 10 m/s, it will reach 25 km in less than 1 hour.

5 Conclusions

Plinian eruption occurs due to fragmentation of dacitic to rhyolitic magma and results in huge ignimbrite and its subordinate. The eruption may expel about 84 km^3 of pyroclasts in various size distributed more than 25 km from the vent across area of 120 km^2. Plinian eruption may occur several times at a single volcano, such that occurred at Batur Volcano and other volcanoes worldwide. Therefore, care must be taken for both active and dormant volcanoes. Monitoring on the magma composition is important in order to know the process beneath the volcano. Bali Island has two active volcanoes and also several Plinian eruptions during Quaternary. Therefore, monitoring the two active volcanoes using different methods are strongly required as Bali Island is densely populated and is a famous tourism area.

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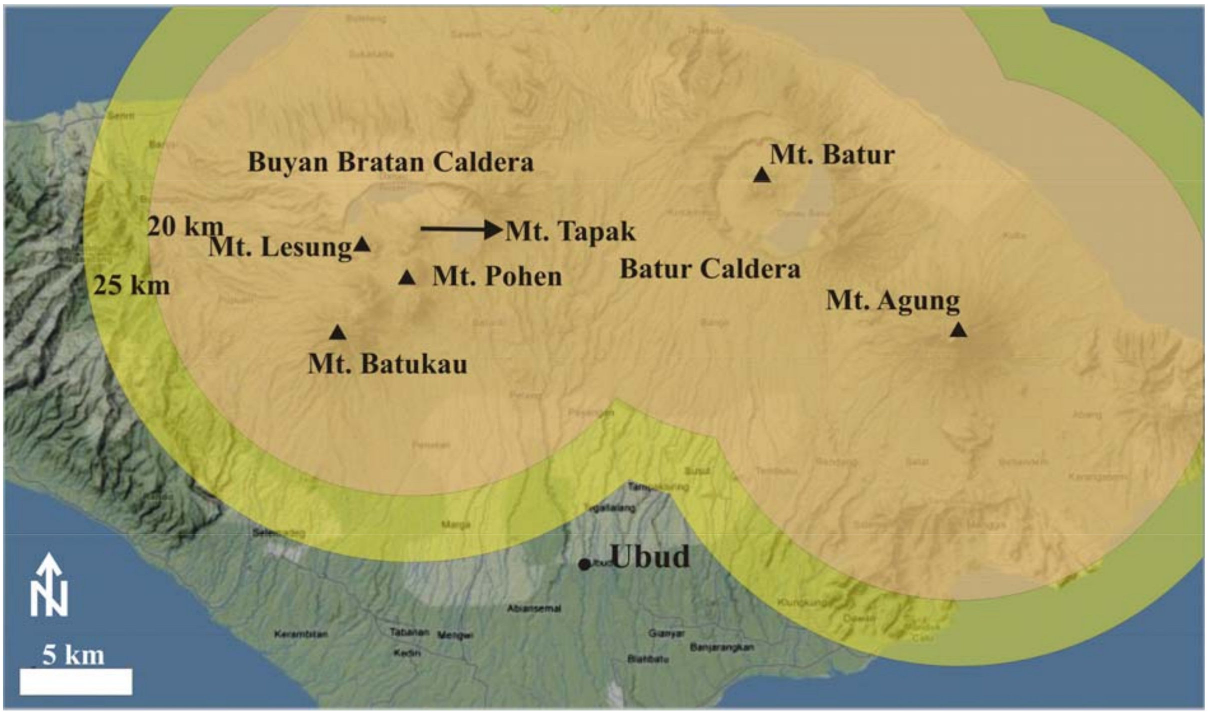

Figure 5: Map showing the area in the radii 25 km away from the vent. The pyroclastic surge may reach the area in one hour

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