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Characterization of volcanic deposits and geoarchaeological studies from the 1815 eruption of Tambora volcano

IGAN SUPRIATMAN SUTAWIDJAJA*, HARALDUR SIGURDSSON**,
and LEWIS ABRAMS**

Center for Vulcanology and Geological Hazard Mitigation,
Jln. Diponegoro 57 Bandung, Indonesia*

University of Rhode Island, Kingston, RI 02881, United States of America**

ABSTRACT

The eruption of Tambora volcano on the island of Sumbawa in 1815 is generally considered as the largest and the most violent volcanic event in recorded history. The cataclysmic eruption occurred on 11 April 1815 was initiated by Plinian eruption type on 5 April and killed more than 90,000 people on Sumbawa and nearby Lombok. The type plinian eruptions occurred twice and ejected gray pumice and ash, to form stratified deposits as thick as 40-150 cm on the slopes and mostly distributed over the district west of the volcano. Following this, at about 7 pm, on 11 April the first pyroclastic surge was generated and progressively became greater extending to almost whole direction, mainly to the north, west, and south districts from the eruption center. The deadliest volcanic eruption buried ancient villages by pyroclastic surge and flow deposits in almost intact state, thus preserving important archaeological evidence for the period. High preservation in relatively stable conditions and known date of the eruptions provide approximate dating for the archaeological remains. Archaeological excavations on the site uncovered a variety of remains were relieved by ground penetrating radar (GPR) to map structural remains of the ancient villages under the pyroclastic surge and flow deposits. These traverses showed that GPR could define structures as deep as 10 m (velocity 0.090 m/ns) and could accurately map the thickness of the stratified volcanic deposits in the Tambora village area.

Keywords: plinian eruption type, pyroclastic surge, pyroclastic flow, pyroclastic airfall, geoarchaeology, GPR, ancient village

SARI

Letusan Gunung api Tambora di Pulau Sumbawa tahun 1815 merupakan kejadian letusan gunung api terbesar dan merusak dalam catatan sejarah. Letusan paroksisma terjadi pada 11 April 1815 yang diawali dengan letusan tipe plinian pada 5 April dan menewaskan lebih dari 90.000 jiwa penduduk Sumbawa dan sekitar Lombok. Tahap awal terdapat dua endapan letusan tipe plinian berupa abu dan batuapung abu-abu, membentuk perlapisan endapan setebal 40-150 cm menutupi hampir seluruh lereng dan juga tersebar ke bagian barat di luar wilayah gunung api. Letusan puncak terjadi pada pukul 19.00 WITA, 11 April dimana sernakan piroklastik sangat dahsyat mengalir hampir ke segala arah, terutama ke arah utara, barat, dan selatan dari pusat letusan. Endapan letusan gunung api yang sangat mematikan ini mengubur perkampungan purba pada daerah yang terlanda, dan menyimpan bukti arkeologi penting dalam periodenya. Penyimpanan arkeologi yang cukup baik dalam kondisi relatif utuh serta tanggal letusan yang diketahui memberikan perkiraan penanggalan bagi bahan-bahan arkeologi. Penggalian sekitar lokasi arkeologi yang terkubur memberikan berbagai macam peninggalan yang digambarkan oleh ground penetrating radar (GPR) berupa peta struktur peninggalan perkampungan purba di bawah endapan dan aliran piroklastik. Penjajakan GPR ini dapat memperlihatkan struktur sedalam 10 m (kecepatan 0,090 m/ns) dan dapat memetakan secara seksama ketebalan urutan perlapisan endapan di sekitar Kampung Tambora.

***Kata kunci**: letusan tipe plinian, sernakan piroklastik, aliran piroklastik, geoarkeologi, GPR, perkampungan purba*

Introduction

The Tambora expedition took place from 15 July to 30 August 2004 which was emphasized to study of stratigraphy and geoarchaelogy from the great 1815 explosive eruption of Tambora volcano on the island of Sumbawa in Indonesia. Tambora volcano occupies most of the Sanggar peninsula in the northern part of Sumbawa Island (Figure 1) in the Indonesian volcanic arc. It is well-known as the largest eruption in historical time. This event has an unprecedented impact on the earth's atmosphere as huge quantities of erupted ash and volcanic aerosols inferred with incoming solar radiation to the earth, causing global climate changes for one to two years. These changes were particularly well documented in temperate latitudes of the northern hemisphere. This catastrophic eruption was documented by a handful of British resident agents, sea captain, and army officer who were scattered in the Indonesian Archipelago. The available accounts were immediately solicited and published by Raffles, the British Lieutenant-Governor of Java at that time, and by the London editors of the Asiatic Journal. Some of these accounts were reprinted from the Java Government Gazzette (Slothers, 1984).

The eruption of Tambora volcano in 1815 is generally considered as the largest and most violent volcanic event in recorded history. Estimate of the loss of life on Sumbawa and nearby Lombok are about 92,000 and the volume of the erupted tephra has been estimated to be about 150 km^3 (Slothers, 1984; Self, 1984; Sigurdsson and Carey, 1989). Fall out ash deposit was recorded at least 1,300 km from source and the sound from explosions was heard to 2,600 km. A region extending up to 600 km west of the volcano was plunged into darkness up to three days. Slothers (1984) noted that tsunami of relatively modest height struck the shores of the Indonesian islands on 10 April. The wave rose to a maximum height of 4 m at Sanggar for a short time around 10 pm, and reached Besuki in East Java (500 km away) with a height of 1 to 2 m, before midnight. Travel time for a wave between Tambora and Besuki was estimated to be about 2 hours; therefore its average velocity must have been of 70 m/sec. The tsunami was also observed in Maluku islands with a wave height of over 2 m. The physical cause of the tsunami was probably the sudden entry of the pyroclastic flows into the sea that was reported to have taken place in the three coastal towns; Tambora, Sanggar, and Bima. Another tsunami reached Sumenep on Madura at 7 pm on 11 April with a height of about 1 m.

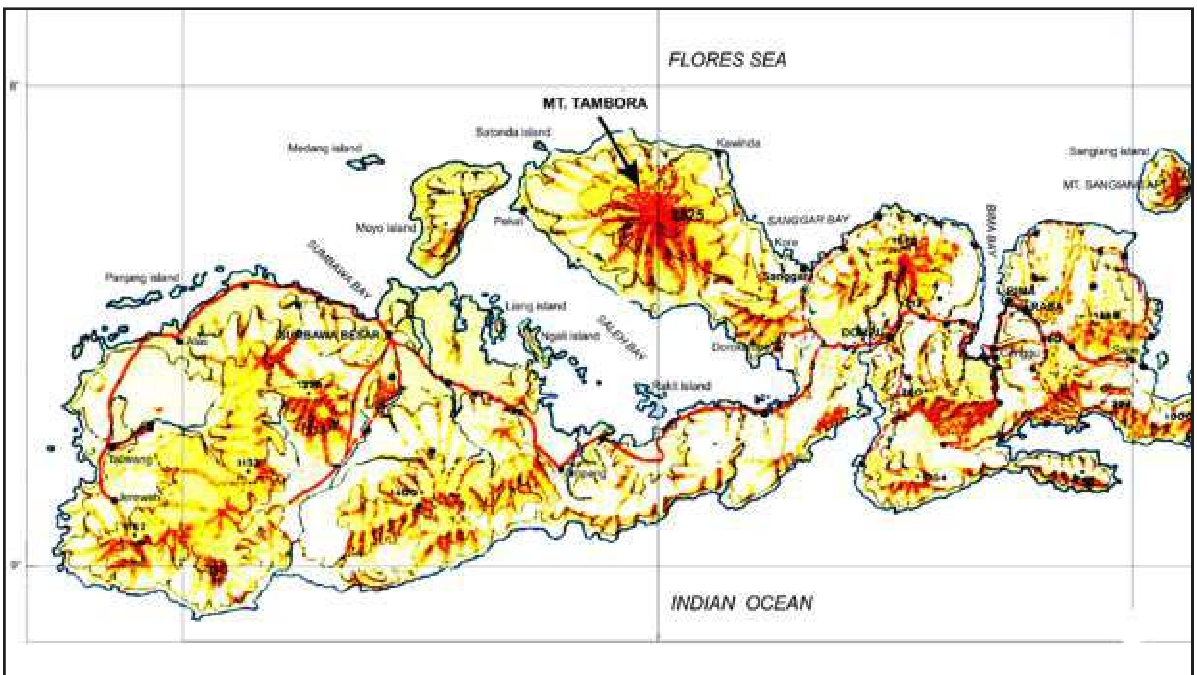

Figure 1. Tambora volcano occupies most of the Sanggar peninsula northern part of Sumbawa Island.

Tectonic Setting and General Geology

Tambora volcano is located on Sumbawa Island in the eastern sector of the Sunda arc, which extends for about 4,500 km. More than 100 Quaternary volcanoes have developed along the Sunda arc. These are caused by the northward subduction of the Australian plate beneath the Eurasian plate (Hamilton, 1979). Just to the east, however, the tectonics is complicated by a change in the nature of the subducting plate from oceanic to continental. The existence of back arc thrusting from Bali to Flores islands, including Sumbawa Island has been reported by Hamilton (1979). The thickness of the crust from Java to Bali islands is estimated to be about 20 km (Silver *et al.*, 1983).

Sumbawa Island is composed of Early Miocene volcanics, Middle Miocene (20-15 Ma) reef limestones and sandstones (Takada *et al.*, 2000), Pliocene volcanoes (5-3 Ma), Early Pleistocene volcanoes (1.7-1.1 Ma) and coral reef limestones, and Middle Pleistocene to Holocene volcanoes (Barberi *et al.*, 1983). Tambora volcano, which is younger than 200 ka, overlies coral reef limestone on its western foot, and cover an older volcano, here called Kawinda Toi volcano (410 ka) on the northern foot (Takada *et al.*, 2000).

Before the 1815 eruption, the height of Tambora volcano is about 4,300 m and 4,000 m respectively reported by Raffles (1835) and Petroeschevsky (1949). Self *et al.* (1984) and Slothers (1984) guessed that the height of Tambora volcano was quite high, because the volcano could be seen from Bali Island. According to the people on Sanggar, there were three Kingdoms surrounding the Tambora volcano, *i.e.* Sanggar Kingdom on the northern foot, Tambora Kingdom on the western foot and the Pekat Kingdom on the southern foot of Tambora volcano before 1815.

Morphologically, Tambora has a shield profile but its summit is occupied by a great caldera that was formed during the 1815 eruption (Figure 2). The caldera is about 7 km in diameter and is 1,100 m deep (Figure 3). A small ephermeral lake is present on the caldera floor and numerous fumaroles are active along the lower caldera walls; and the small cone of the post-caldera activity, called Doro Api Toi has a height of about 100 m on the caldera floor. The flanks of Tambora have twenty parasitic scoriae-cones (Sigurdsson and Carey, 1989), some of which have elevations of 1,000 m, undissected morphology. Most of these parasitic vents have produced lavas and pyroclastics that fall into three main groups (Foden, 1986; Barberi *et al.*, 1983), *i.e.*, high-MgO ne-trachybasalts, low-MgO ne-trachybasalts, and ne-trachyandesites which were erupted during the 1815 activity.

Stratigraphic Relations of the 1815 Deposits

Pyroclastic deposits from the 1815 activity of Tambora show that there were two major eruptive phases, the first produced four tephra fall deposits, while the second generated large volume pyroclastic flows and surges. A representative stratigraphic section of the tephra fall layers can be found at Tambora village, 12 km west of the Tambora caldera.

Pyroclastic fall deposits

The initial ash and pumice falls are found on the Sanggar peninsula, the central and northwestern coast of Sumbawa (Self, 1984), and on the islands west of Tambora as far as Lombok 150 km from the volcano. On most parts of the initial tephra fall layer sequences is overlain by a thick section of pyroclastic flows and surges (Figure 4). The sequence begins with four widespread fall layers which are locally overlain by up to eight pyroclastic flow deposits (Sigurdsson and Carey, 1989), and falls were identified as: F1, minor phreato-magmatic fall deposits produced during weak explosions prior to 5 April 1815, and possibly beginning in 1812; F2, a plinian pumice-fall from an eruption column with an estimated height of 35 km. The deposit is correlated with the large explosive event of 5 April 1815, which resulted in ash-fall on Java island; F3, a series of minor phreato-magmatic ash-falls from low-level activity between 5 and 10 April 1815; and F4, the major plinian pumice fall from the great 10 April 1815 explosion, deposited from a 43 km high eruption column. On the volcano's flanks, these fall deposits are overlain by up to eight pyroclastic flow deposits and surges. In distal areas, the plinian and phreato-magmatic falls, representing co-ignimbrite ash fall from the pyroclastic flow-generating phase of the eruption beginning on 10 April. Best exposures of the proximal 1815 deposits are found along the western part of the caldera wall. Here there is a nearby unbroken exposure of Tambora volcanic deposits, with aggregate thickness of over 1,000 m. The 1815 deposits

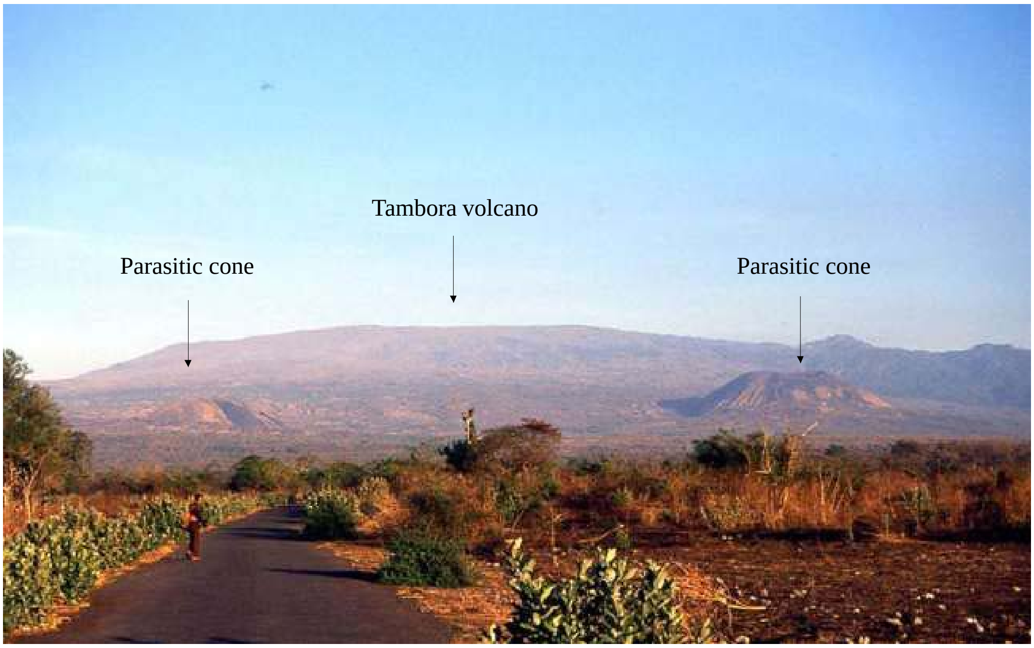

Figure 2. Tambora volcano with shield-shape which was reconstructed of about 4,300 m a.s.l. before 1815. Two parasitic cones are in foreground.

Figure 3. Tambora caldera having a diameter 7 km and 1,100 m deep.

are up to 140 m thick in the western caldera rim, but nowhere less than 40 m.

The F1 ash fall from the 1815 eruption within the early caldera is 7 to 23 cm thick, silty-sandy, and grayish-brown in color, the F2 plinian pumice fall similarly shows a great range in thickness, as much as 1 m or more, within the early caldera as a result of slumping. It contains abundant obsidian fragments, possibly from an early dome extrusion. In F2, the diameter of pumice clasts are average 30 mm and lithics 29 mm, whereas in the west flank, 2 km west of the caldera have a typical fragments of pumice-clasts and lithics in diameter average 68 and 148 mm, respectively. The F3 ash fall in intra-caldera sections is often in three lithologic units, with total thickness of 10 cm. All units are reddish to rusty-brown due to thermal effects from the overlying pyroclastic flows. They are relatively poorly sorted, sandy-silty, finely laminated ashes but with some lenses of coarse pumice-rich fall, and the F4 is similarly re-deposited and over-

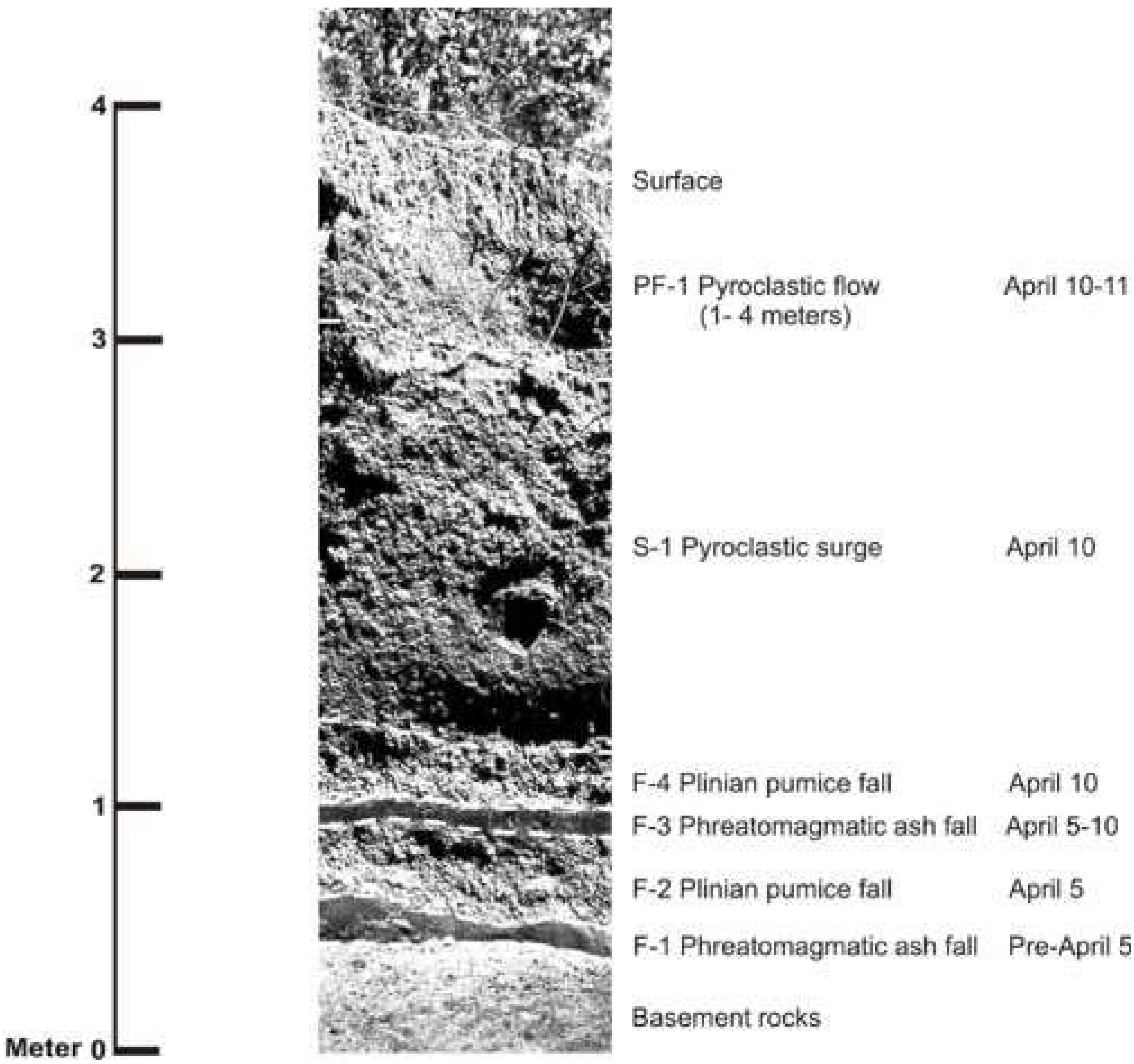

FIGURE 4. PYROCLASTIC STRATIGRAPHY OF THE 1815 TAMBORA ERUPTIVE PRODUCTS AT TAMBORA VILLAGE. DATES TO THE RIGHT OF THE STRATIGRAPHIC COLUMN INDICATE THE INFERRED TIMING OF THE DIFFERENT ERUPTIVE PHASES BASED ON HISTORICAL REPORTS.

thickened in the caldera wall due to slumping, with multiple pumice-rich lenses alternating with finer lapilli. The fall grades upwards from a grey pumice to dark-grey and nearly black pumice, which shows welding and flattening when in contact with the overlying pyroclastic flows.

Pyroclastic flow deposits

Pyroclastic flows from the 1815 eruption covered almost the entire Sanggar peninsula, reached to ocean in most directions from Tambora, and have extended the coastline to an unknown extent (Figure 5). The flows are generally well exposed along the coastline and in gullies inland and form six principal lobes or aprons. In the south a major lobe of pyroclstic flows extends from Hoddo to Ncanga crater. The lower most flow unit is a dark-gray, massive pyroclastic flow, with black scoriae and bread-crust blocks up to 1 m in diameter in a sandy-silty matrix. The third pyroclastic lobe extends northwestward from Doro Petie along the coast to Wontu Wa, with the dark-gray pyroclastic flow at the base containing very large scoriae blocks and carbonized tree logs. No pyroclastic flows of any importance have reached the ocean in the northwestern sector during the 1815 eruption. Thus, the Calabai and Nangamiro areas appear to have been in a "shadow" zone from pyroclastic flows, but five surges passed over this region.

Pyroclastic flows are present near Kenanga on the northern coast and form three small lobes on the coast between Kenanga and Nguwu Ponda. In Nguwu Ponda is found many large carbonized tree logs within the dark-grey pyroclastic flow containing very large scoriae blocks. Direct north of the caldera a major pyroclastic lobe occurs at Oi Mari peninsula. Here the basal flow is up to 6 m thick with common large, dark scoriae clasts up to 1 m in diameter, partly carbonized logs, and a welded basal part. The Oi Mari pyroclastic flow lobe pinches out west of Kawinda, which is in the "shadow" zone of the 2,300 m high Doro Nae peak, just northeast of the caldera. Further east, a major flow lobe forms the Katupa peninsula, again with the dark-gray pyroclastic flow at base. Here, up to 10 m long logs, 1-2 m in diameter is enclosed in the lower part of the flow along with 1-2 m dark scoriae blocks.

The lithology of pyroclastic flows is distinctly different from the underlying sequence of tephra fall layers and surges, as the flows are almost devoid of light colored pumice and glass shards. The darker color of glass in the pyroclastic flows is thus attributed to relatively slow cooling rate and growth of oxide microlites in the glass. The flows were not deposited on the upper and steeper slopes of the volcano, but left deposits on gentler slopes and the coastal plain. The distribution of pyroclastic flows on the slopes of Tambora was estimated in total deposition area on land of 820 km^2 and 874 km^2 for pyroclastic flows and surges, respectively, and all of the exposures show that pyroclastic flow deposits overlain surge deposits. The flows exceed a total thickness of 20 m, but average about 7 m, indicating a minimum subaerial volume of 5.7 km^3.

Stratigraphic Section and Excavation

A stratigraphic section of the 1815 volcanic deposits is shown in Figure 4. At Tambora village the first product of the Tambora eruptive sequence is a gray, silty to sandy ash fall layer (F1), which is distributed to the west of the volcano. It is 10-100 mm thick on the western flank of Tambora, eastern Moyo, and eastern Satonda and fades out near Medang Island. Continuous fallout of a pale gray-green plinian pumice deposit (F2) overlies the F1 ash fall and extends over a wide area to the west of Tambora. The layer is typically between 10 to 30 cm thicks on the slopes of the volcano. The third (F3) layer is a layer of

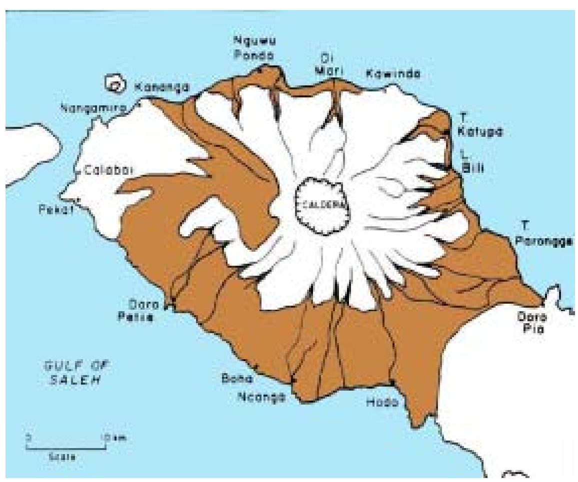

Figure 5. Map of Sanggar peninsula of Tambora island showing the distribution of 1815 pyroclastic flow deposits (shaded area) around the flanks of Tambora volcano (Modified from Sigurdsson (1989).

sandy-silty ash fall. The contact between F2 and F3 layers is sharp at proximal sites but becomes increasingly gradational at sites more than 50 km from source. The coarsest and most extensive of all the early fall deposits from the 1815 Tambora activity is a plinian pumice fall layer (F4). This deposit is in excess of 20 cm over the entire western flank of Tambora. On neighboring Moyo and Satonda islands, it is over 10 cm thick, and the 5 cm isopach extends beyond Medang and Sumbawa Besar in the west and beyond Sanggar in the east. Fallout of pumice (F4) was interrupted by the emplacement of the first surge to affect the Tambora village area, west slope of the volcano. This surge damaged the village as evidenced by the occurrence of minor building fragments in the deposit. Most of the ancient-buildings were constructed by woods and bamboos which were easier to destruct and burn by hot pyroclastic flows and surges. Passage of the surge laid down predominantly massive, sandy layer, 2 to 4 m thick, poorly sorted in Tambora village area, swept over an area already blanketed by the previous pumice fall. The surge to reach Tambora village swept the area in the evening at 7 pm of 11 April 1815, and instantly buried the surrounding areas of the volcano, and killing people within a 7 to 10 km radius from the crater. The first surge spread over the south and west flanks of Tambora, overwhelming Tambora village on the west and Pekat area on the south. The effects of this surge were remarkably similar to the effects of the surges of AD 79 Vesuvius eruption in Italy, which devastated more than five towns and villages (Sigurdsson *et al.*, 1985). The first surge swept in to Tambora village at sufficient velocity to topple and to transport building rubble 2 to 4 m. It probably did not leave walls intact and completely stripped all buildings. Temperatures in surge were high enough to carbonized wood, fruit, rice (Figure 6), and others. As the hot surge entered the ocean and pushed sea water it caused the tsunami and the sea water to become boil and give off small steam explosions.

The excavation was initiated by using ground penetrating radar (GPR), mainly to investigate the volcanic deposits on Tambora village in order allowed us to establish the thickness of individual pyroclastic units and facies variations in areas where the deposits are unexposed (Figure 7). These traverses show that GPR can define structures as deep as 1 to 10 m with velocity 0.090 m/ns and can accurately map the thickness of the 1815 pyroclastic deposits around the Tambora village. In the excavation area, accumulation of pumice deposits had possibly collapsed roofs and the houses had been abandoned and were therefore still inhabited when the surge struck, as evidence by two human skeletons found inside (Figure 8). Continuing excavation has discovered a complete house-building at the depth of 2 to 3 m of pyroclastic flow and surge deposits (Figure 9). The original shapes of the beams, roof materials and bamboo-floors have been identified, but they were completely charred on very high-temperatures. The first carbonized- human skeleton was found in the kitchen area with stripped back position, and another human skeleton was very damage and charred that was very difficult to identified, but the leg-bone and back-bone could be identified. The other materials such as Chinese porcelains, potteries, and copper bowls were also found inside the house area.

FIGURE 6. CARBONIZED RICE HAD COMPLETELY CHARRED ON THE ORIGINAL SHAPE.

CONCLUSION

The volcanic stratigraphy of the 1815 Tambora deposits shows that the eruptive products consist of two distinct phases: an initial phase of at least four tephra fall episodes, and subsequent pyroclastic flow and surge phases, during which at least seven major flows were deposited. This volcanic stratigraphy can be generally correlated with contemporary accounts of the eruption by Raffles (1835). The eruption column during the two plinian eruptions was among the highest known for any historic eruptions, 33 – 43 km above the volcano. Sudden transition to pyroclastic flow and surge activity during the second plinian eruption occurred on 10 April and is tentatively attributed to increase mass eruption rate as summit collapse and early caldera formation resulted in widening vent and possible formation of new vents.

At least eight pyroclastic flows and surges were produced, and first surge swept against Tambora village, stripped down all buildings, and destroyed many villages and killing many people. The pyroclastic flows also triggered a tsunami which struck along the coast of mainly the eastern Indonesian archipelago. GPR studies of the volcanic deposits on Tambora village have allowed us to establish the thickness of individual pyroclastic units and to obtain facieses variations in unexposed areas.

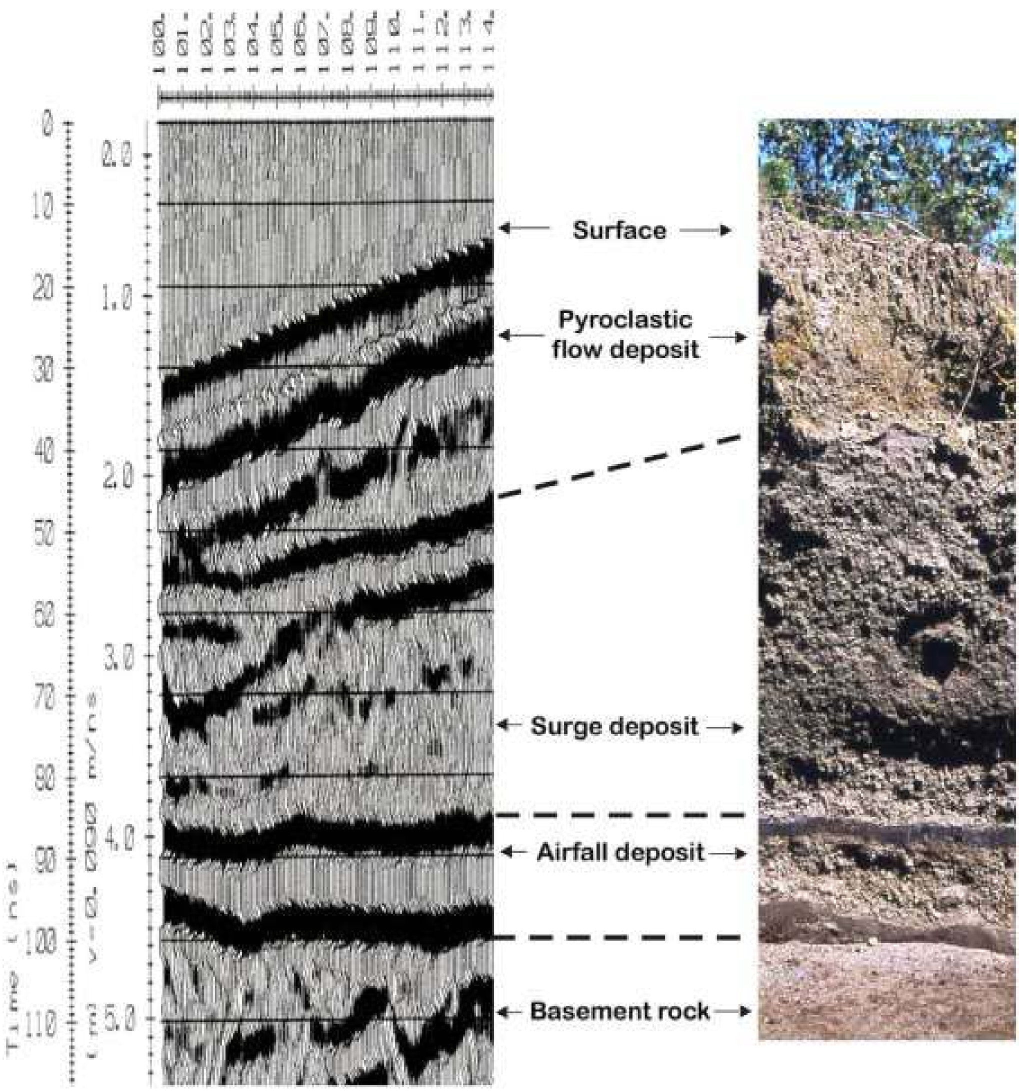

FIGURE 7. A RADARGRAM OF GPR SURVEY IN TAMBORA VILLAGE AREA CORRELATED TO THE CROSSED-SECTION OF THE 1815 TAMBORA DEPOSITS'S STRATIGRAPHY.

FIGURE 8. CARBONIZED HUMAN SKELETON WHICH WAS STRIPPED DOWN AND BURIED BY PYROCLASTIC SURGE. THIS HUMAN SKELETON WAS FOUND IN THE KITCHEN AREA.

FIGURE 9. CARBONIZED BUILDING MATERIALS THAT WAS COMPLETELY EXCAVATED NEAR TAMBORA VILLAGE AT THE DEPTH OF 2 TO 3 M BENEATH THE SURFACE.

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