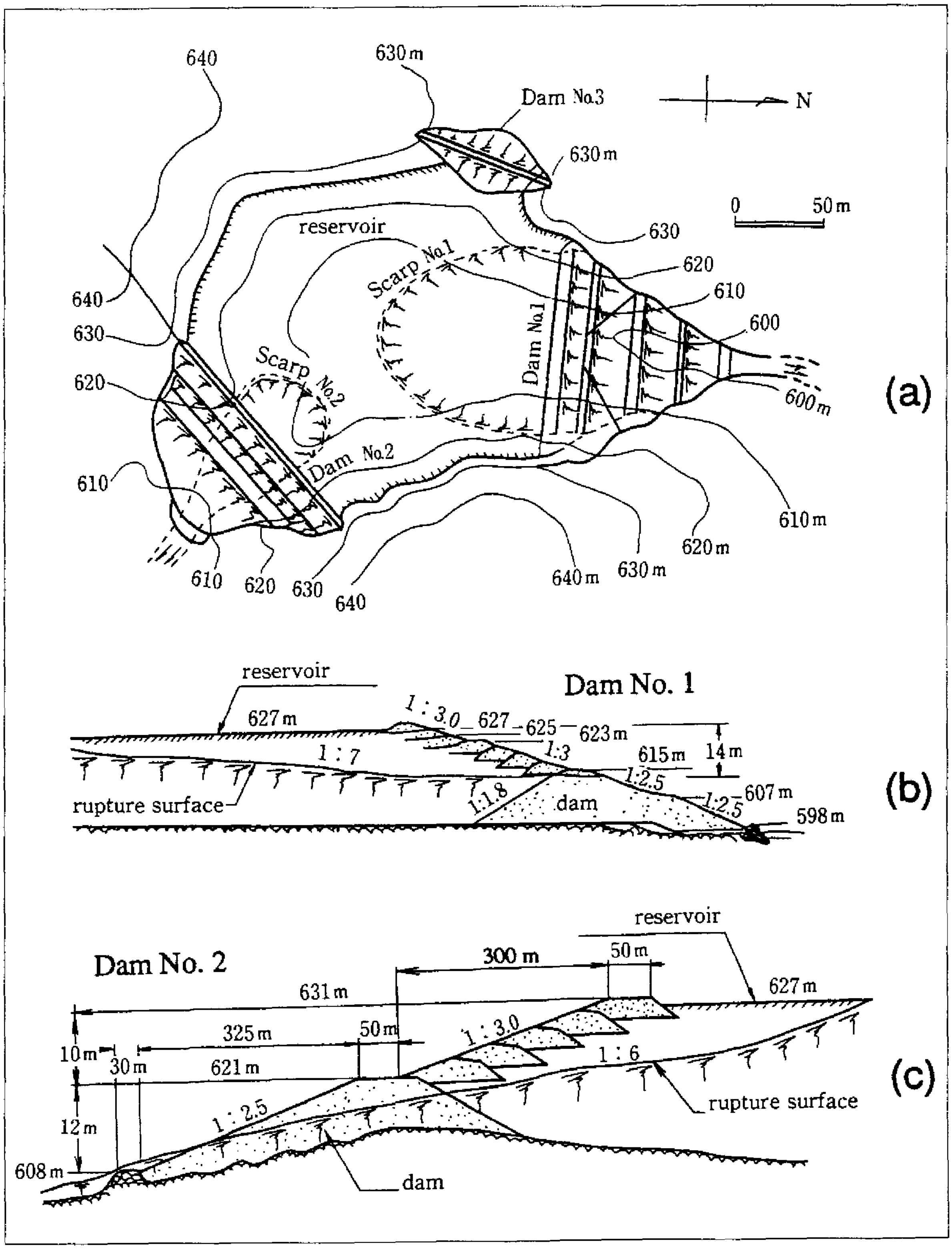


FIGURE 8.23 Liquefaction of sludge which had been retained by the tailings dams in Hozuki Valley, Shizuoka, Japan: (*a*) Layout of the dams; (*b*) Cross-sectional profile of dam No. 1; (*c*) Cross-sectional profile of dam No. 2.

The following is an eyewitness account of a geophysicist who happened to be in Yungay and narrowly escaped the huge Huascaran debris avalanche of 1970:

When the earthquake shaking began to subside, I heard a great roar coming from the Huascaran. Looking up, I saw a cloud of dust appear, as though a large mass of rock and ice was breaking loose from the peak. My immediate reaction was to run for the high ground of Cemetery Hill about 200 m away . . .

Beginning to run, I noticed that many others in Yungay were also running to Cemetery Hill. When I was about halfway up the hill, the debris avalanche reached the bridge above Yungay. It was like a huge breaker, estimated to be at least 80 m high. At that time, I observed hundreds of people in Yungay running in all directions. When I reached the area near the top, the avalanche struck the hill. I saw a man just a few metres downhill caught in the mud. Looking around, I counted 92 persons who had saved themselves by running to the top of the hill.

8.2.2. Izu Peninsula, Japan (1978)

On 14 January 1978, an earthquake of magnitude 7.0 on the Richter scale triggered a mudflow, which contained poisonous chemicals and heavy metal compounds, on the Izu Peninsula in south-central Japan. This mudflow event was the result of the collapse of one of the three dams belonging to the Hozuki Valley plant of a gold-mining operation (*Fig. 8.23*).

This initial earthquake, which occurred at 1224 hours on 14 January caused dam No. 1 to fail. The dam breached with a tremendous roar, and within 6 minutes a mudflow containing 80,000 m^3 of sludge had travelled as far as 2 km downstream (*Fig. 8.24*).

A second earthquake hit the same region at 0735 hours the next day and caused dam No. 2 to fail. This dam, however, began to breach slowly, and it was not until 1300 hours that the entire dam body collapsed and generated a mudflow with a volume of 3,000 m^3 and a speed of as much as 0.6 m/sec.

A similar dam at the Noro Valley sludge basin was also affected by the earthquakes, but they caused only a few cracks on the lower slope of the dam (*Fig. 8.25*).

Why were there differences in the modes of failure of the three dams? The downstream faces of dam No. 1 and dam No. 2 were stepped, and were built with materials whose characteristics and properties may have been inappropriate for the purpose. The dam in the Noro Valley basin, however, was on a firm foundation, equipped with a stable wall and provided with facilities to drain the dam body.

8.2.3. Mt. Ontake, Japan (1984)

At around 0900 hours on 14 September 1984, an earthquake of magnitude 6.8 on the Richter scale triggered a massive landslide on the southern slope of Mt. Ontake Volcano (3,060 m high) in central Japan. The epicentre was located just below the village of Otaki. The landslide was 1,300 m long, 420 m wide and 160 m in depth (*Fig. 8.26*). The landslide developed into a huge debris avalanche with a volume of 34 million m^3, and caused 29 deaths. The avalanche blocked the flow of the Otaki River and created a natural dam. About two thirds of the moving mass flowed down the river at high speed. The one third remaining initially dammed the upper reaches of the valley and then passed rapidly down the river.

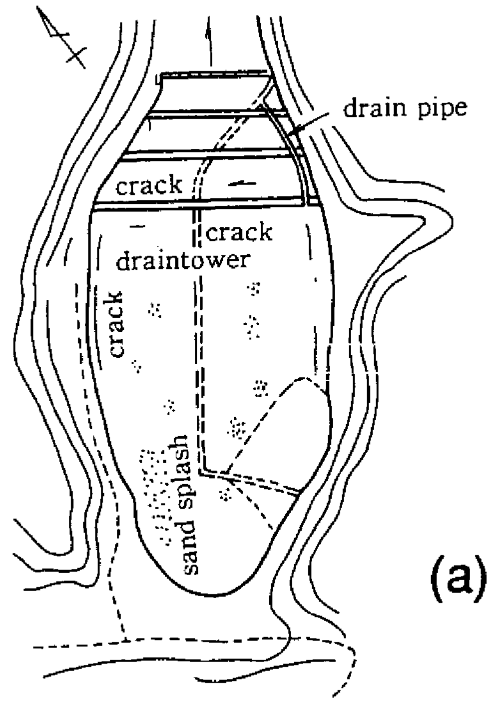
The following questions arose:

(*a*) Why did the landslide occur precisely where it did when the same conditions (rainfall followed by an earthquake) affected an extensive area?

(*b*) What caused the landslide to occur at this particular site where no landslide had previously occurred?

A detailed survey carried out following the disaster provided the answers. Regarding question (*a*), the slope of a V-shaped valley of the ancient volcano was overlaid by an unconsolidated pumice stratum. This stratum was,

FIGURE 8.24 Hozuki Valley: Collapse of sludge dam No. 1. *Photo: S. Hatano.*



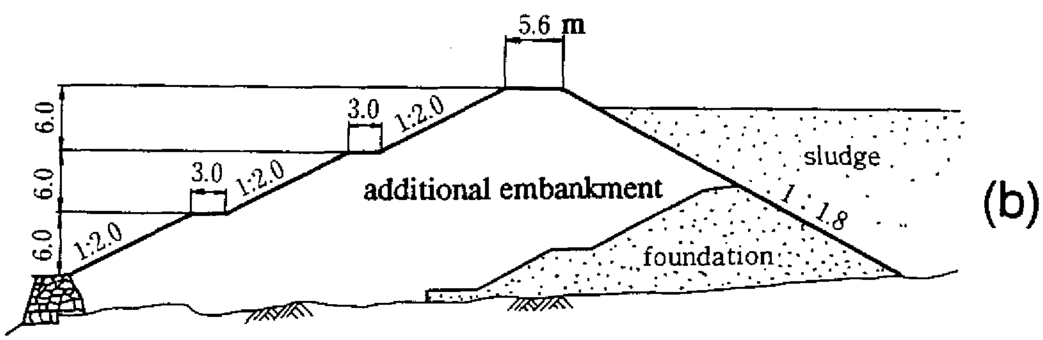


FIGURE 8.25 Noro Valley sludge basin, Japan: (*a*) Plan view showing cracks in the dam after the 1978 earthquake; and (*b*) Section through the dam.

FIGURE 8.26 Mt. Ontake, Nagano, Japan: (*a*) before the debris avalanche of 1984. *Photo*: *Taiyo Air Survey.*

FIGURE 8.26 Mt. Ontake, Nagano, Japan: (*b*) after the debris avalanche of 1984.

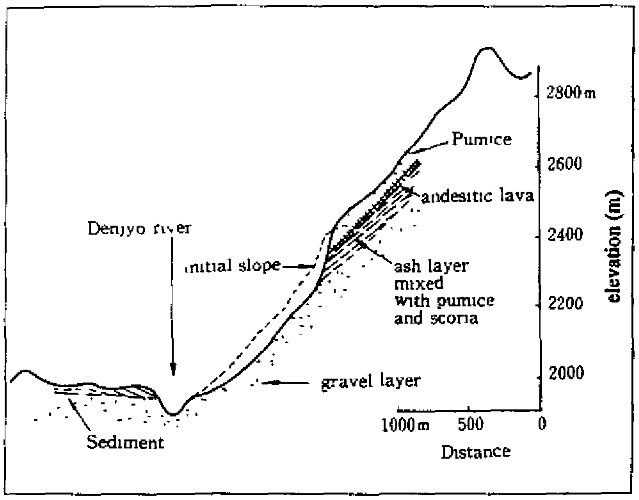


FIGURE 8.27 Cross-section of 1984 Mt. Ontake, Japan, landslide (Kitazawa. 1986).

in turn, overlaid by alternating strata of lava and pyroclastic material to form a long, ridge-shaped convex slope. This slope butted onto, and was stabilized by, the lava strata which had passed down the valley (*Fig. 8.27*). The underlying pumice layer was probably liquefied by the earthquake tremors and served as the sliding surface. These conditions apparently did not exist to the same extent elsewhere in the area affected by the earthquake.

Regarding question (*b*), the lava strata mentioned above had been eroded by running water for about 10,000 years. The ridge-shaped slope had therefore lost its stability because of the removal of the lava mass at its foot, which had been serving as a counterpoise. The erosion of the valley bed had been progressively exposing the pumice stratum over this long period of time, and a slight external impact was sufficient to cause the mass of material constituting the ridge-shaped slope to move.

A geomorphological examination of this landslide provides a valuable picture of the mechanism of such phenomena and a key to analysing the stability of potentially dangerous slopes.

8.3. Mudflows (lahars) caused by volcanic eruptions

- *Mt. Agung, Indonesia, 17.03.1963.*
- *Mt. Kelut, Indonesia, 1919, 1951, 1966.*
- *Mt. St. Helens, USA, 18.05.1980.*
- *Nevado del Ruiz, Colombia, 13.11.1985.*
- *Mt. Pinatubo, Philippines, 15.06.1991.*

8.3.1. Mt. Agung, Indonesia (1963)

Mt. Agung is an active volcano located in the eastern part of the island of Bali, Indonesia. It rises to a height of 3,142 m, which is 3,000 m above the fertile fields of Amrapura, the capital of the Karangasem region. The average population density of the area is 350 per km^2 with the greatest density being located south of the volcano. Cultivated land reaches up to 1,000 m.

Not much is known about the past volcanic activities of Mt. Agung, except that the mountain erupted in 1808 and 1843. A long period of dormancy of more than a century had led the general population and local officials to believe that the volcano posed no threat. On 18 February 1963, a weak eruption occurred, followed by more volcanic activity which increased in intensity day by day.

During the initial phase of the 1963 eruption, only minor lahars were generated, which ran along existing river courses. This was the main reason why the community was not aware of the danger of the lahars. People felt that they would still have time to evacuate if and when bigger lahars approached. A systematic warning system had not yet been established and there was no volcanic observatory in the area at that time.

The religion of the local population is mainly Balinese Hinduism. To pay homage to their god, the people have built hundreds of temples, not only at the foot of the volcano, but also up to a height of 1,000 m. On 17 March 1963, at the moment when the volcanic activity of Mt. Agung reached its peak, the Balinese people were preparing for the "Eka Dasa Rudra", a ceremony held once every century and centred around the main temple of Besaki on the south-western slope of the mountain (*Fig. 8.28*). The people did not want to miss a ceremony held only once in a lifetime. Even though the Besaki Temple had been vacated because of the dangerous situation, people continued the ceremony in small temples around the volcano This is one of the reasons for the relatively high death toll (200) caused by the 1963 eruption.

On 21 March 1963, four days after the first major eruption, heavy rain fell on the south-west flank of Mt. Agung causing the newly deposited ash, sand and pyroclastic flow deposits to move. The hot ladu formed a hot secondary lahar after mixing with the rainwater. The lahar flowed down the Krekuk River, which lies east of the village of Subagan. However, the flow was obstructed by trees and boulders which had been transported earlier by minor lahars. This obstruction, which was located at a bend 1.5 km north of Subagan, caused the lahar to move to the western part of the village (*Fig. 8.29*). Alerted by the noise of the oncoming lahar, people panicked and started running to the west, away from the Krekuk River, not knowing that the lahar had meanwhile changed its course. Only a few people who managed to climb to the top of a nearby hill in time survived.

Following the 1963 eruption, a hazard map of the area surrounding Mt. Agung was produced and regulations for warning and evacuation were drawn up prior to the next rainy season. Certain lahar-prone areas are bordered by a lahar-prone river on one side and by a lahar-free river on the other. To facilitate evacuation, bridges have been constructed over the lahar-free river, new

FIGURE 8.28 Eruption of Mt. Agung, Bali, Indonesia, 1963. Besaki Temple is in the foreground. *Photo: I. Suryo.*

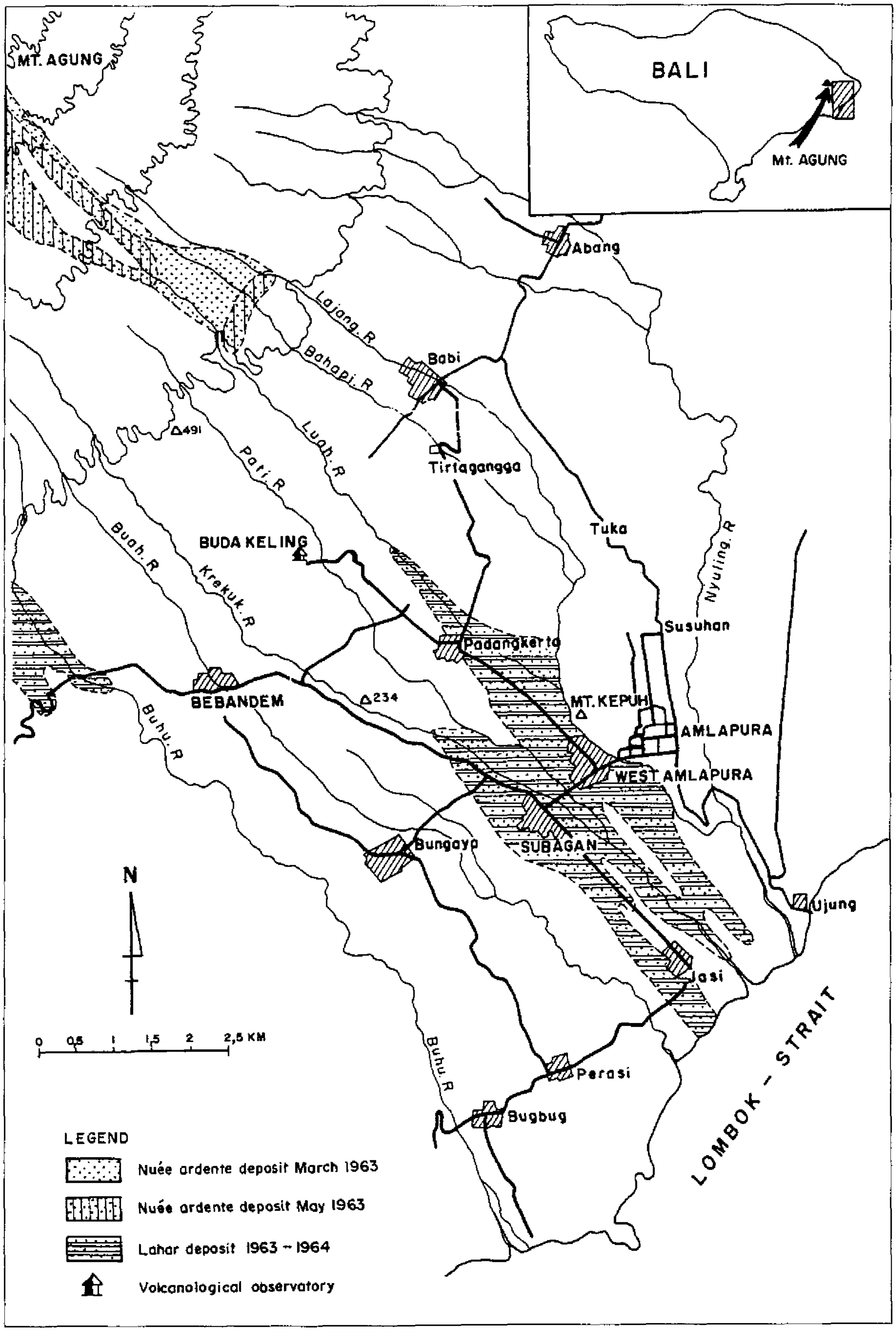


FIGURE 8.29 Map of lahar-affected south-east sector of Mt. Agung.

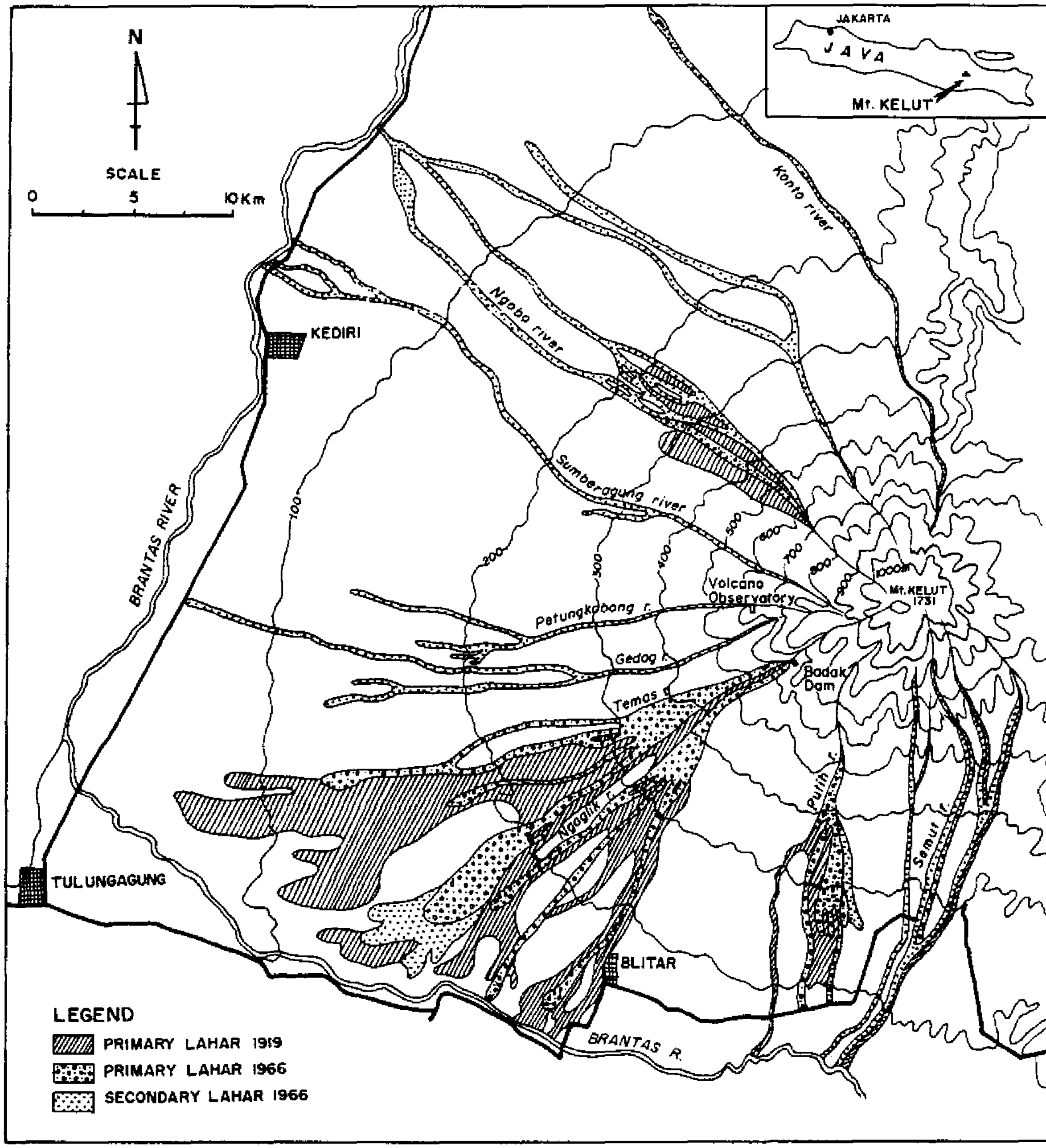


FIGURE 8.30 Mt. Kelut, East Java, Indonesia. Map showing the distribution of primary and secondary lahars.

roads leading to the bridges and safe refuge areas have been built, and existing roads have been improved.

The areas of maximum danger from which no escape would be possible in the event of a lahar have been permanently abandoned. A secondary danger zone is reserved for agricultural use only. The villages in this zone, which have not been affected by lahars, need not be evacuated. The expansion of the existing villages and the establishment of new settlements in this zone are, however, prohibited.

A total of 36 lahar warning posts are set up each year before the start of the rainy season. These posts are equipped with tong-tongs (see *Fig. 8.8*) which are struck when lahars begin to flow. When rain starts to fall on the slopes of the volcano, the observers located at the posts strike the tong-tongs in accordance with rhythm codes specific to the hazard situation. The signals are relayed to the lower posts until the lahar-prone area is reached. After hearing the signal for "Run for safety", the population must be evacuated by the designated roads and bridges to the safe areas where barracks have already been erected.

8.3.2. Mt. Kelut, Indonesia (1919, 1966)

Mt. Kelut is a 1,731 m high active volcano, with a crater lake on its summit, located on the island of Java, Indonesia. Eruptions through the crater lake in 1919 and 1966 triggered highly destructive mudflows or primary lahars (*Fig. 8.30*).

The area around Mt. Kelut is densely populated with more than 500 inhabitants per km^2. The population density in the immediate danger zone is 327 per km^2. The Brantas River which runs along three sides (east, south and west) of Mt. Kelut receives the entire sediment load and threatens the industrial city of Kediri with seasonal flooding.

Since the greater part of the population lives by agriculture, the destruction of the agricultural land and the deterioration of the irrigation network by the eruptions had a far-reaching impact on their social and economic well-being. It took at least two years for the population to recover from the consequences of each eruption.

The eruptions of Mt. Kelut were not preceded by any reported precursor phenomena. The sudden eruptions and the resulting lahars did not give the population sufficient time to evacuate. Most of the fatalities were caused by people being taken unaware by the fast-flowing lahar mass.

The 1919 eruption released huge quantities (38 million m^3) of water. This produced a lahar that travelled 38 km. It devastated a large area (131 km^2) on the slopes and at the foot of the mountain, and killed 5,100 people. In 1923, a series of tunnels was constructed high on Mt. Kelut to reduce the volume of water in the crater lake from 38.5 million m^3 to 1.8 million m^3 (*Fig. 8.31*). In addition, the continuous crumbling of the inner crater wall caused the crater bottom to rise and further reduced the quantity of water in the lake. When an eruption occurred in 1951, there was only 1 million m^3 of water in the crater lake, and the resulting lahar did not cause any significant damage. The capacity of the crater lake, however, increased again as a consequence of the 1951 eruption.

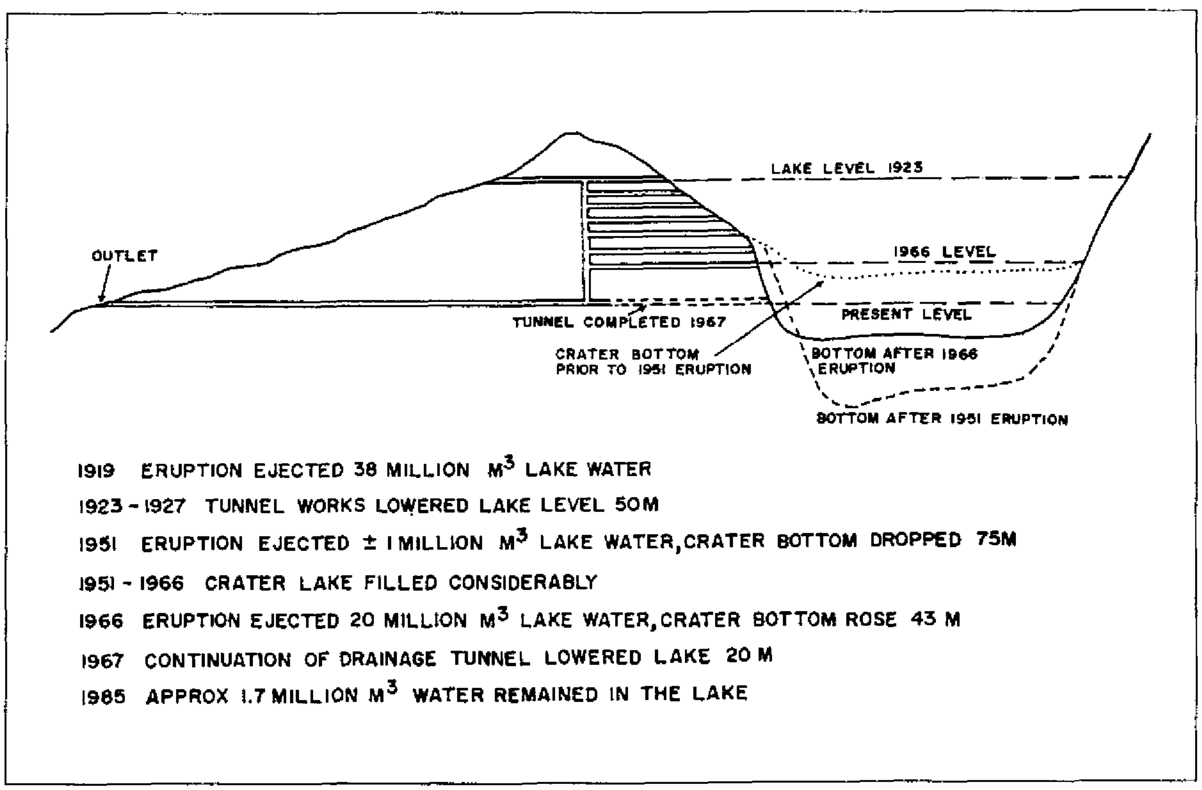


FIGURE 8.31 Section across the Mt. Kelut crater lake showing the drainage system (Suryo and Clark, 1985).

The next major eruption took place in 1966, without any noticeable precursor activity. Two days before the eruption, a routine check of the crater had been carried out by the observer from the office for volcanological surveys, but he did not observe any increased activity. After hearing the eruption at 1015 hours on 24 April 1966, the observer immediately informed local officials of the danger of lahars. The general population had already been alerted by the roar of primary lahars.

The eruption released 20.3 million m^3 of crater water, triggering the primary lahars, which moved to the south and west. According to eyewitnesses, the first crater water released by the 1966 eruption (and the earlier 1919 eruption) was not hot. Subsequent flows became mixed with hot pyroclastic material and generated the hot primary lahars. At a point 500 m high, the lahars overflowed the river banks and spread, invading villages and arable lands. Most of the population was able to evade the rapidly flowing lahars and escape to designated safe areas. A small number of mostly the aged, women and children were trapped, and 282 people were killed.

In contrast to the population around the Mt. Agung volcano (see Section 8.4) who had never witnessed an eruption, the people around Mt. Kelut had earlier experienced primary lahars. In general, they were more aware of the potential danger, and hence, they managed to evacuate even though the evacuation order did not reach them as early as would have been desirable.

An area of 45 km^2 was covered with volcanic material carried by the primary lahars. The lahar that reached the city of Blitar (*Fig. 8.32*) travelled at a speed of 43 km/h. Its average speed over the reach from Badak to Blitar City was 23 km/h.

The primary lahar is the most feared of all lahars, because within a short time huge volumes of hot materials surge down mountain slopes and spread over large areas. However, secondary lahars which are triggered by heavy rainfall and which are cold, in general, can be more harmful in the long run. During the year immediately after an eruption, the volume of material transported to the plain can be surprisingly large. Even though the volume of the discharged material decreases gradually year after year, the total quantity of material transported by the second and successive flows can often be bigger than that transported by the primary lahars, because of the development of gully erosion in the upper reaches.

The loose material carried down by the secondary lahars in Mt. Kelut raised the bed of the Brantas River (see *Fig. 8.32*). As a result, large areas are flooded during the rainy season. With a gradient of 1 per cent, the river bed

FIGURE 8.32 Brantas River. The bed level rose up to the ceiling level of a nearby house on the alluvial fan, after deposition by lahars from Mt. Kelut. Location: East Java, Indonesia. *Photo: M. Watanabe.*