Glowing avalanches

Glowing avalanches (nuées ardentes) resemble ash flows in mechanism, though often not in origin. Some of them result from very voluminous fall-back of hot tephra onto the flanks of a volcanic mountain. The fragments, buoyed up by expanding hot air and gas between them, rush down slope as hot avalanches which attain speeds at least as great as 100 km/hour, and may travel more than 10 km. This is known as the Soufrière type of glowing avalanche (fig. 12), because they were first recognized during the 1902 eruption of Soufrière on St. Vincent (West Indies). Others result from the collapse of the edge of a dome or thick lava flow at the summit or on the flank of the volcano. In this, the Merapi type of glowing avalanche (named after Merapi Volcano in central Java), the fine material is largely the result of comminution of the hot blocks in the avalanche, and the mobility is probably largely the result of the cushioning effect of expanding entrapped air. Speeds of Merapi-type avalanches are commonly 50 to 80 km/hour, but may exceed 100 km/hour. Still other glowing avalanches result from explosions directed at a low angle, commonly augmented by collapse of a dome induced by the explosion. These Pelée-type avalanches were first recognized during the 1902 eruption of Mt. Pelée, on Martinique, when low-angle explosions at the base of a dome in the summit crater precipitated great volumes of ash and blocks from the collapsing edge of the dome through a low notch in the crater wall into the head of the valley of the Rivière Blanche (fig. 13). The avalanche rushed to the sea at an average rate of about 160 km/hour. The driving force certainly was largely gravity, as in the Soufrière and Merapi types, but seems to have been increased by the explosion.

In all three types the flow consists principally of the avalanche, travelling along and close to the ground, and very largely directed by the topography. But above the avalanche rises a great cloud of dust, black in daylight, but glowing dull red at night. It is this cloud of glowing dust that gave rise to the name "nuée ardente". The dust cloud may spread considerably beyond the edges of the avalanche proper, and is far less controlled by topography. At Hibok-Hibok, Philippines, in 1951, the dust cloud extended at least a kilometer beyond the edge of the avalanche. Although less drastically destructive than the avalanche, the dust cloud also can be deadly. The destruction of the city of St. Pierre during the eruption of Mt. Pelée was wholly the result of the upper part of the ash cloud, which continued straight across the ridge bounding the Rivière Blanche Valley while the avalanche followed a bend in the valley. The avalanche reached the sea nearly two kilometers from St. Pierre (fig. 13), but the hot dust cloud struck the city squarely, causing the near-instantaneous death of some 30,000 people.

It has been suggested that it might be possible to divert glowing avalanches from specific localities by means of barriers such as those proposed to divert lava flows. Certainly, to some extent the possibility would depend on the size of the avalanche when it reached the barrier. In general, however, three factors seem to make the success of such diversion unlikely. First, most volcanoes that are likely to produce glowing avalanches have been somewhat eroded, and the avalanches of all three types usually follow valleys, from which it would be impossible to divert them. Secondly, because of its great velocity, the avalanche probably would climb over any barrier of practicable height; and thirdly, even if the avalanche itself were diverted, the overlying ash cloud probably would continue straight on for some distance beyond the barrier. The possibility of diversion is greatest in the case of Merapi-type avalanches, because they commonly are smaller than those of the Pelée and Soufrière types, because in some instances their speed appears to be less, because the overlying ash cloud tends to be less voluminous, and because the point of origin and path of the avalanche is more predictable. But even for Merapi-type avalanches, the hope of successful diversion is small.

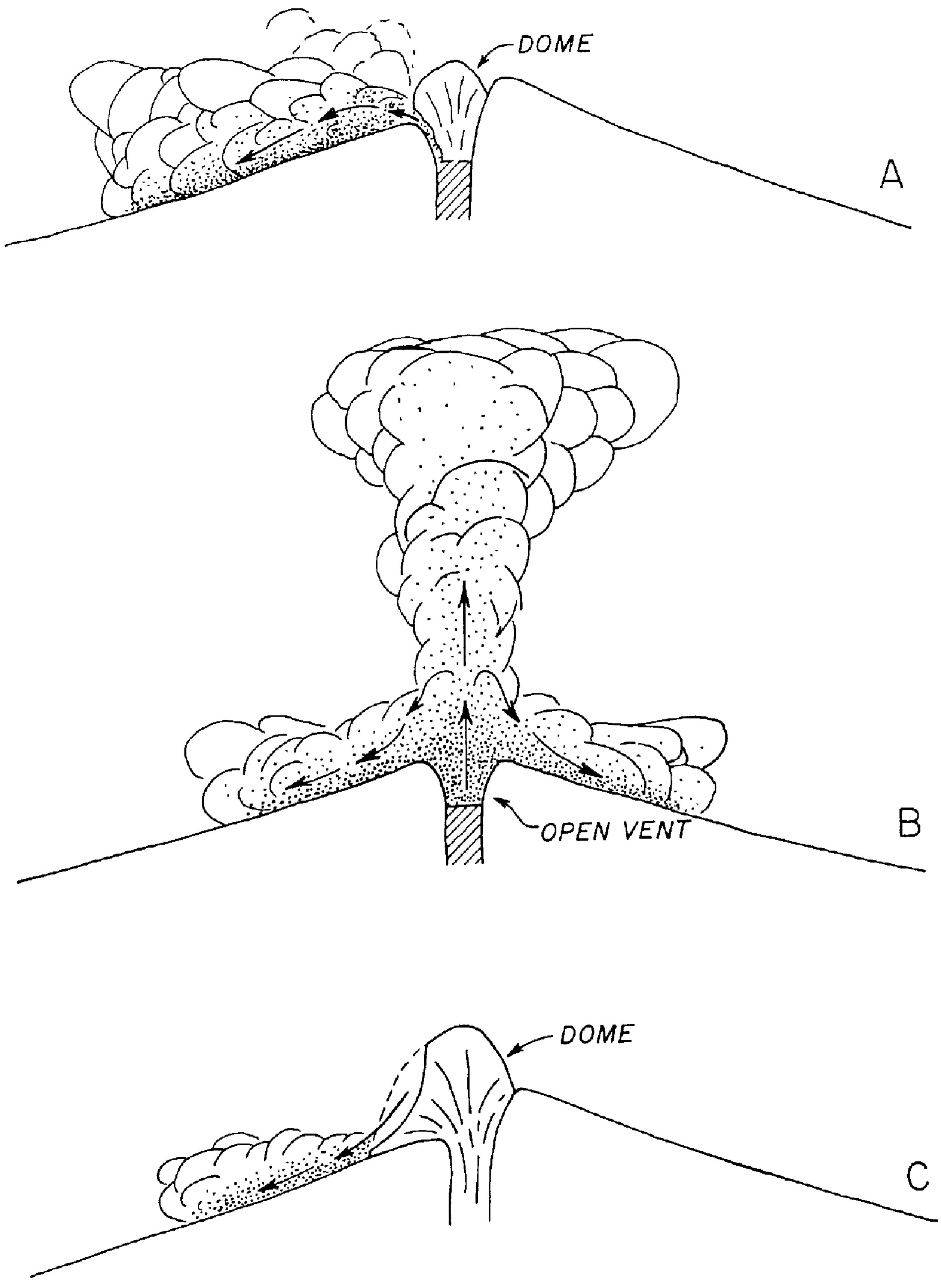

Figure 12. Diagram illustrating the principal types of glowing avalanches:
A - Pelée type, B - Soufrière type, C - Merapi type.
(From Macdonald, 1972).

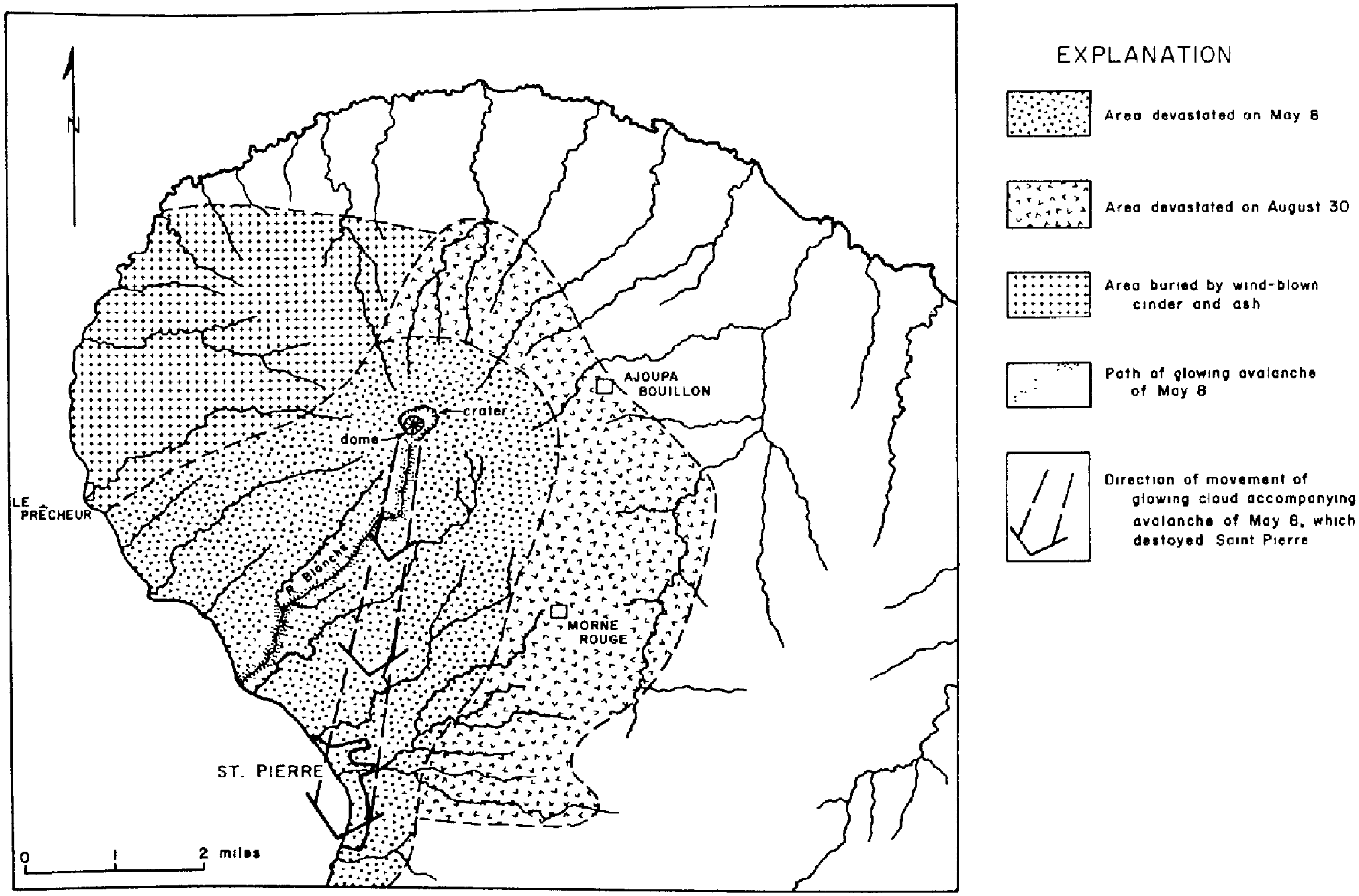

Figure 13. Map of part of the island of Martinique, showing the locations of Mt. Pelée and the city of St. Pierre, and the paths of the glowing avalanche and glowing dust cloud of May 8, 1902.

(Modified after Lacroix, 1904)

The possibility of impounding glowing avalanches behind dams also has been suggested. Small dams across valleys generally would not be effective, because of inadequate volume in the storage basin, and the tendency of the avalanche and ash cloud to jump the dam. Large reservoirs behind high dams certainly could contain small glowing avalanches, though probably not all of very large ones. Even if the avalanche is contained, however, the ash cloud may continue across the surface of the lake in the reservoir and far beyond the dam. Also, the avalanche entering the lake will displace water, and the impact of the avalanche may set up a big water wave (as the non-volcanic landslide did in Lituya Bay in 1958), with the result that if the reservoir is nearly full a large volume of water may be driven over the dam, causing flooding and perhaps mudflows in the valley beyond it, and possibly eroding and undercutting the face of the dam enough to lead to its collapse. If an eruption that may send glowing avalanches into the reservoir is anticipated, the water in the reservoir should be drained to a low level in order to reduce the risk of displacement of water over the dam, (Crandell and Waldron, 1969).

In most cases, protection against glowing avalanches must depend on prediction of their occurrence and their paths, and evacuation of the affected area. The possibility of Merapi-type avalanches can be foreseen where a dome or thick lava flow is forming on the flank of the volcano or has extended beyond the crater rim. Since the probable point of origin is known, the path of the avalanche can be forecast from the topography down slope from it. The extent of the avalanche is more difficult to forecast, and probably the best approach is to assume that it may travel at least as far as any previous avalanche on similar slopes. The possibility of Pelée-type avalanches exists wherever a dome has extended beyond the crater (as at Hibok-Hibok in 1951), or is growing in a crater with a low notch in the rim. Again, the probable course of the avalanche can be foreseen. In predicting the area likely to be affected by either type of avalanche, it should be remembered that the area covered by the ash cloud is greater than that of the avalanche itself, and that the ash cloud may continue straight ahead when the avalanche turns to follow a valley.

Prediction of Soufrière-type avalanches is more difficult, because they do not depend on an already-growing structure and commonly take place at the very beginning of the eruption. The problem is first to predict the eruption itself, and then to anticipate its nature. The general prediction of an eruption depends on the methods discussed later. Beyond that, perhaps it is safest to assume that any eruption of a mature volcano, particularly one that has had violent explosions in the past, may generate Soufriere-type avalanches. The area that may be affected is difficult to forecast, because the avalanches may travel down any or all sides of the cone. Their extent depends on the volume and violence of the explosions, on the steepness of slope, and on other factors such as the surrounding topography and the amount and size of forest; again, the best indicator seems to be the extent of previous avalanches, if any, as indicated by their deposits, but making due allowance for the greater spread of the ash cloud, the deposits of which may soon become difficult or impossible to identify. The only safe procedure seems to be, if an eruption is expected, to evacuate the entire cone and the surrounding area to a distance that must be decided in a rather arbitrary manner.

Reclamation of the surfaces of glowing avalanche deposits may be rendered difficult by the large number of large blocks that commonly litter it. If the larger blocks can be removed from its surface, the deposit should respond to treatment much like an ash-fall deposit. The economics of the situation may commonly forbid the removal of the blocks, and in that case consideration should be given to afforestation with marketable timber.

Smaller avalanches of mobile hot ash are quite common on the flanks of volcanoes during explosive eruptions. During the 1906 eruption of Vesuvius some of these traveled as much as a kilometer, at speeds of several tens of kilometers per hour. Similar avalanches of hot scoria were reported (Johnson, et al., 1972) on the flanks of Ulawun Volcano, New Britain, during the 1970 eruption. The possibility of avalanches of this type should be foreseen wherever hot ash or scoria accumulate to a considerable thickness on a steep slope. In general, they do not extend much beyond the base of the cone, and will not affect persons other than scientific observers or sightseers on the cone itself.

Lahars

A lahar, or volcanic mudflow, consists of a slurry of fine material and water, often containing a large proportion of coarser debris. Most lahars are cold, but some are warm, or even at a temperature approaching that of boiling water. Lahars rush down the slopes of volcanic mountains with speeds as great as 100 km/hour, and have been known to travel along river valleys for as much as 300 km from their source (as at Cotopaxi, Ecuador, in 1877). Some cover areas of several hundred square kilometers. Thus, the Osceola lahar (fig. 14), which originated on Mt. Rainer about 5,700 years ago, had a volume of more than 2 km^3 and covered an area of more than 300 km^2, near Puget Sound in the State of Washington, United States of America (Crandell and Waldron, 1969). A similar lahar in the same area today would result in a major disaster. Because of their frequency, lahars rival or even surpass glowing avalanches as the prime volcanic agent of destruction. During the last few centuries they have caused many millions of dollars worth of damage and have taken many thousands of human lives.

Lahars can originate in several ways (Anderson, 1933; Macdonald, 1972, p. 171):

1. By ejection of the water of a crater lake by explosive eruption.

2. By release of the water of a crater lake by breaking down of the crater wall.

3. By rapid melting of ice or snow on the slope of the volcano.

4. By explosion-induced avalanches of old rock debris into streams.

5. By descent of glowing avalanches or ash flows into streams.

6. By entrance of autobrecciated lava flows into streams.

7. By brecciation of lava flowing over snow, ice, or very wet ground on the slope of the volcano.

8. By earthquake-initiated movement of water-saturated ash or soil down the slope of the mountain.

9. By extrusion of water and rock material already brecciated in the volcanic conduit before reaching the surface.

10. By heavy rains on loose material on the mountain slope.

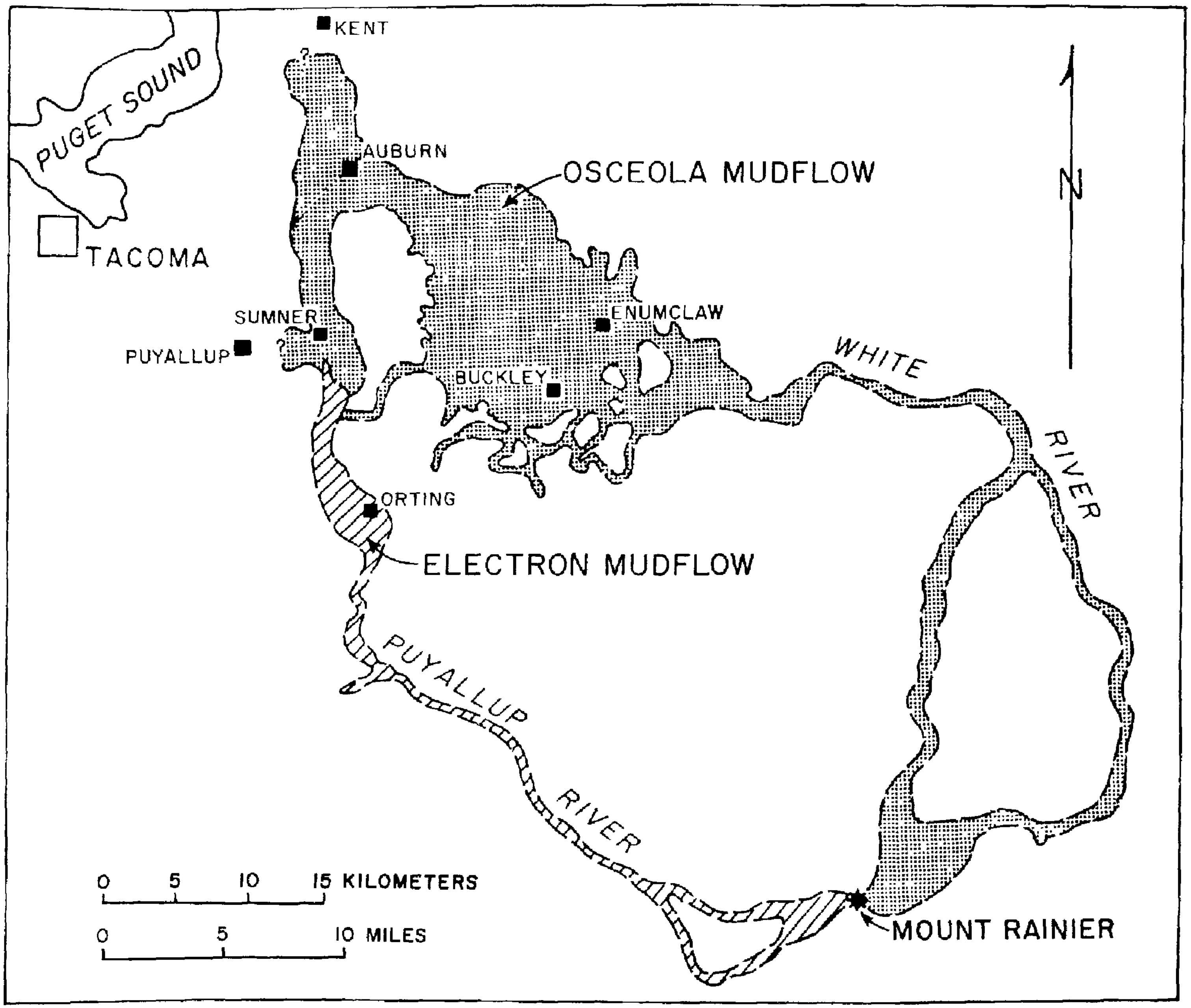

Figure 14. Map of the region near Mt. Rainier, Washington, showing the areas of the Electron lahar (about 500 years ago) and the Osceola lahar (about 5,000 years ago). (From Macdonald, 1972, after Crandell and Waldron, 1969).

As examples, lahars of the first type were produced during the eruption of Soufrière in 1902, that of Galunggung, Java, in 1822, and during several eruptions of Kelud, in Java. Those at Kelud, in 1919, took about 5,000 human lives in villages near the base of the volcano and destroyed about 200 km^2 of agricultural land. The lahar at Galunggung was steaming hot. The water of some crater lakes contains a considerable amount of sulphuric and hydrochloric acid, and in 1817 explosive ejection of the crater lake of Kawah Idjen, Java, produced a lahar that was sufficiently acid to cause chemical burns.

Crater walls may become weakened, sometimes as a result of chemical alteration of their rocks, and sometimes by thinning or undermining by explosions, and may collapse, releasing the water of a crater lake. Earthquakes may induce or trigger the collapse. An example is the collapse that occurred at Kelud in 1875. In 1953 movements, perhaps caused by crevassing of the overlying ice mantle, caused collapse of part of the rim of the inner cone in the crater of Ruapehu Volcano, New Zealand, resulting in a sudden flood of water from the crater lake. The flood rapidly enlarged the breach in the cone and a tunnel through which the water flowed beneath the ice into the head of the Whangaehu River. Rushing down the river, the flood gathered up loose fragments and became a lahar which partly destroyed a railroad bridge, leading to derailment of an express train and the loss of 154 lives.

The most effective means of eliminating or controlling lahars caused by release or ejection of crater lakes appears to be partial or complete draining of the lake. After the disastrous lahars of 1919 at Kelud, Dutch engineers constructed a series of tunnels in the mountain successively close enough to the lowering lake surface so that water could be lifted by a siphon and drained through an outlet (fig. 15). The water level was eventually lowered 56 m, and the volume of the lake reduced from about 65 million to 3 million m^3. As a result, during the next eruption, in 1951, most of the water was evaporated harmlessly in the crater and no large destructive lahars were generated. However, the entrances to the tunnels were destroyed by the eruption and the crater was deepened some 70 m, with the result that the lake began to grow, eventually reaching a volume of about 40 million m^3. A new tunnel 20 m lower than the previous lowest tunnel was driven, but stopped before it reached the crater wall, in hopes that seepage through the rock into the tunnel would be sufficient to lower the lake to near tunnel level. The attempt was unsuccessful, and in 1965 Zen and Hadikusumo pointed out that the situation was again extremely dangerous. As predicted, the next eruption (in 1966) threw out a large part of the lake, generating lahars that killed several hundred people. In 1967 a new tunnel drained the lake to a low level.

Another attempt to reduce and regulate the amount of water in the crater lake was made by Dutch engineers at Kawah Idjen, where a sluiceway was constructed at the lowest part of the crater rim.

Rapid melting of ice and snow on a volcanic mountain may release large enough volumes of water to cause potentially damaging lahars. The melting may be caused by warm weather or warm rains unrelated to eruptions, as happened at Mt. Shasta, California, in 1926 and 1931. Rapid melting may also result from lava flows, as at Mt. Lassen, California, in 1915, at Cotopaxi, Ecuador, in 1877, and at Villarica, Chile, in 1963. Hot ash falls probably do not cause sufficient melting to generate lahars (Finch, 1930). Whether or not glowing avalanches or ash flows may cause enough melting to form lahars is less certain, and probably depends to a large extent on the location of the snow or ice. High on the mountain the avalanche or flow may pass rapidly over the snow with little deposition of material and little melting, whereas on the lower,

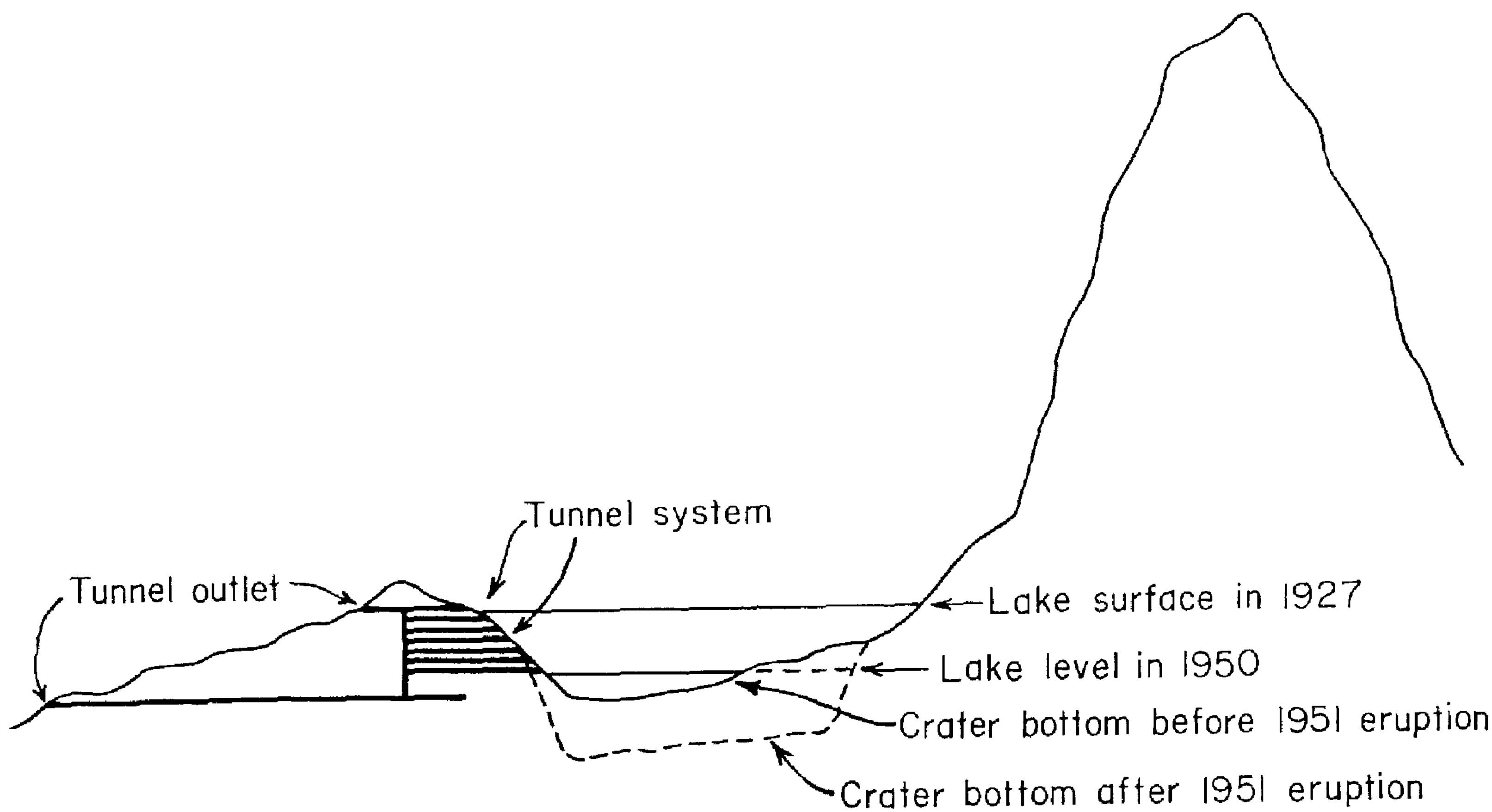

Figure 15. **Diagrammatic cross section of the tunnel system constructed at Kelud Volcano, Java, to drain the crater lake.**

(From Macdonald, 1972, after Zen and Hadikusumo, 1965).

gentler slopes deposited rock debris may result in large volumes of meltwater. Ash flows from Bezymianny Volcano, in 1956, melted about 2 m of snow from the lower slopes of the mountain. Furthermore, a blanket of ash or avalanche debris on snow, though causing little melting from its own heat, may result in increased absorption of radiant sun heat and increased melting. An ash blanket from Bezymianny brought about abnormally high rates of melting on the slopes of nearby mountains, with resultant lahars.

The formation of lahars by rapid melting thus can be expected whenever ash or avalanche debris blankets snow or ice on steep slopes, or when lava flows are extruded into or onto ice, especially if the underlying ground surface is littered with abundant loose material.

A glacier burst (jökulhlaup) is a sudden outburst of water from beneath or behind a glacier. It may be caused by volcanic activity beneath the ice, or by some other cause, such as a prolonged period of warm rain, that produces an accumulation of water behind an ice dam. Most of the water is meltwater, but some of it may come from condensed steam of subglacial fumaroles, or from hot springs. Commonly the outrushing water picks up enough solid debris to form a mudflow. The release of the water may be due to shattering of the ice dam by steam explosions or by earthquakes, or water accumulating behind the dam may in time become deep enough to force its way under the ice. The latter bursts may be totally unrelated to current volcanic activity.

Most floods or mudflows due to glacier bursts are relatively small, and damage from them is largely confined to the slopes of the volcano itself. In Iceland, however, glacier bursts reach enormous proportions. Some of those from the Myrdals Glacier have had flows of more than 92,000 m 3/ per second, and the total volume of water in a single burst has exceeded 6 km 3/. Bursts have issued from several different glaciers, but the most frequent have been those from the Myrdals and Vatna Glaciers. At both the melting appears to be caused by volcanic activity beneath the ice.

In the Vatna Glacier melting extends completely through the ice, forming a lake, Grimsvatn, visible at the surface. The lake level rises gradually and so constantly that it is probable that the melting is caused by continuous fumarolic activity rather than by occasional eruptions. By observing the lake level it is possible to predict when the critical level will be reached and the glacier burst will occur (Thorarinsson, 1953). Previous to 1934 the bursts often were accompanied by visible eruptions in the Grimsvatn crater, but it is not certain whether the eruptions brought about an increase in the rate of melting that triggered the burst, or if the rapid lowering of water level so reduced the pressure on the underlying magma column that it induced the eruption.

Katla Volcano is completely buried beneath the Myrdals Glacier, and thus far no surface indications have been recognized that make possible consistent predictions of the glacier bursts, though collapse basins form on the glacier's surface during and after the bursts. If the bursts result from actual eruptions, surface deformation and/or seismic observations may make possible the recognition of coming eruptions and prediction of the bursts.

An explosion on the flank of a volcano may undermine part of the flank, which may then collapse, causing a rock avalanche; and the avalanche may, in turn, enter a stream mixing with water to form a lahar. One such occurred at Bandai-san, Japan, in 1888. The low-temperature explosion took place in a fumarole area where the rock had been much altered. A portion of the mountain above the explosion craters collapsed, and the clay-rich debris moved rapidly down slope, entered a stream, and formed a lahar that travelled down the valley for 15 km, destroying villages and farmlands and killing more than 400 people. Lahars of this type cannot be predicted, except to the degree that the place and time of eruption can be forecast and by recognition of conditions that may lead to formation of explosion-generated avalanches and lahars.

The great Osceola lahar, mentioned earlier, resulted from collapse of a large segment of the upper part of Mt. Rainier in which the rocks had been much altered by fumarole gases (Crandell, 1973). Whether the collapse was wholly the result of the altered condition of the rock, or whether it was triggered by an earthquake or by a low-temperature explosion, is not certain.

In 1929 a glowing avalanche from Santa Maria Volcano, Guatemala, entered a river and was transformed into a lahar that travelled along the river about 100 km. Similar but smaller lahars have been generated by glowing avalanches at Merapi, and have done great damage and taken many lives. Ash and pumice flows from Bezymianny, in 1956, entered the Khapitza River and formed lahars that travelled down the river about 80 km. Owing to the sparse habitation of the country, they are not known to have taken any lives, but similar lahars in inhabited areas could be disastrous. Fragmental lava flows (block lava) entering streams are believed to have been responsible for many of the lahars that created the Mehrten Formation, in the Sierra Nevada of California (Curtis, 1954), and probably others elsewhere, though specific historic examples do not seem to have been recorded. Again, prediction of lahars of these types depends on prediction of the eruption and recognition of topographic conditions that favour their formation and direct their courses.

Enormous breccia deposits such as those in the ancient Absaroka volcanic field of Montana and Wyoming, and the Tuscan Formation of California, appear to have resulted at least in part from lahars that were generated within the volcanic conduits themselves (Parsons, 1967; Lydon, 1968), though again no historic examples have been described. The precise mechanism of the generation, and particularly the origin of the water, is still in considerable doubt (Macdonald, 1972, p. 176-181), and until it is better understood prediction of this type of lahar is probably impossible.

Although all of the foregoing mechanisms are important in the generation of lahars, the immense majority of lahars are the result of heavy rainfall. The formation of accretionary lapilli (volcanic pisolites) by raindrops falling through clouds of ash is well known. The falling mud drops may accumulate so heavily on vegetation that branches are broken from trees, doing considerable damage to orchards. During the 1963 eruption of Irazú, Costa Rica, the mud fell so abundantly that it coalesced into sheets that flowed down the mountainside, to some extent gathering up coarser loose debris, and damaging cultivated fields. However, lahars of this sort probably are always small.

Rain responsible for lahars may originate by condensation of steam in a volcanic eruption cloud, and in some instances it appears to result from condensation in water-saturated air carried rapidly upward by strong convection above hot volcanic vents or deposits. Most commonly, however, it results from ordinary meteorological conditions. Torrential monsoon rains are responsible for most lahars in tropical regions. Particularly during periods immediately following eruptions the mountain slopes are apt to be largely unprotected by vegetation, and often abundant fine ash decreases the surface permeability and results in an abnormally large proportion of runoff. The permeability may be further reduced by rapid cementation of the thin crust on the ash (Waldron, 1967). The flowing water encounters abundant loose debris, and is quickly transformed into a lahar. Commonly the debris is largely air-fall tephra; but in other instances, as at Mayon in 1968, the lahars (fig. 16) may be largely the result of rapid erosion of glowing-avalanche or ash-flow deposits (plate 8). At Mayon, the heavy rainfall appears to have been partly due to nucleation of droplets by dust particles rising from the glowing avalanches themselves (Moore and Melson, 1969).

Rain-saturated ash may be caused to flow by earthquakes. Particularly when it has been partly or largely altered to clay minerals, such ash may have a high degree of thixotropism - the ability to retain its original form so long as it is not disturbed, but to become liquid and mobile when it is jarred or shaken. An example of a lahar of this sort occurred on the sout part of the Island of Hawaii in 1868. Altered ash up to several metres thick on the upper slopes of valleys was saturated with water by several weeks of frequent rains. Shaken by a violent earthquake, it became liquified and flowed down two adjacent valleys, forming two lahars, one of them 3 km long, and burying a village. About 500 domestic animals and 31 persons were killed.

Lahars of all origins are closely controlled in their courses by topography. On little-eroded surfaces they may spread out to form broad sheets, but on hilly or mountainous terrains damage from all but the very large ones is restricted to the axial parts of valleys, close to the stream channels. If conditions are recognized to be such that lahars are likely to be generated, people, domestic animals and portable property can be moved away from the axial parts of valleys. Considerable loss of life and property could conceivably be avoided in this way. However, this depends on recognition of the potential for lahars, and in this respect much further study is needed in order to define better the conditions of danger, and to make warnings more reliable. As in other situations of potential danger, false alarms must be avoided, or all warnings will become ineffective.

Lahars can take place at any time during an eruption, and for several months after the eruption has ended, as long as abundant loose unstable debris remains on the mountainside not bound by vegetation. The presence of abundant loose debris at the advent of the monsoon season, or other times of unusually heavy rain, creates a hazardous condition and people should be advised of the possibility of having to move out of the axial parts of valleys, especially from areas known to have been invaded by earlier lahars. Where observatories exist on the upper slopes of the mountain, warnings for immediate evacuation can be issued when the rainfall reaches dangerous amounts. At Merapi, the warning is issued when the rate of rainfall reaches about 60 mm/hour.

If loss of life and property is to be minimized, crater lakes, particularly those with fragile walls, should be drained to a level low enough to ensure that the release or ejection of the remaining water will not create lahars large enough to damage the closest villages. This is especially important when the lake level is close to the crater rim, but even lakes far below the crater rim have been ejected with disastrous results. Voluminous lahars were caused at the beginning of the 1902 eruption of Soufrière, on St. Vincent, by the ejection of a lake that stood about 300 m below the crater rim. Watch should be kept for the development of domes or lava flows that may cause rapid melting of snow or ice, or conditions that may favour the occurrence of glowing avalanches over snowfields.

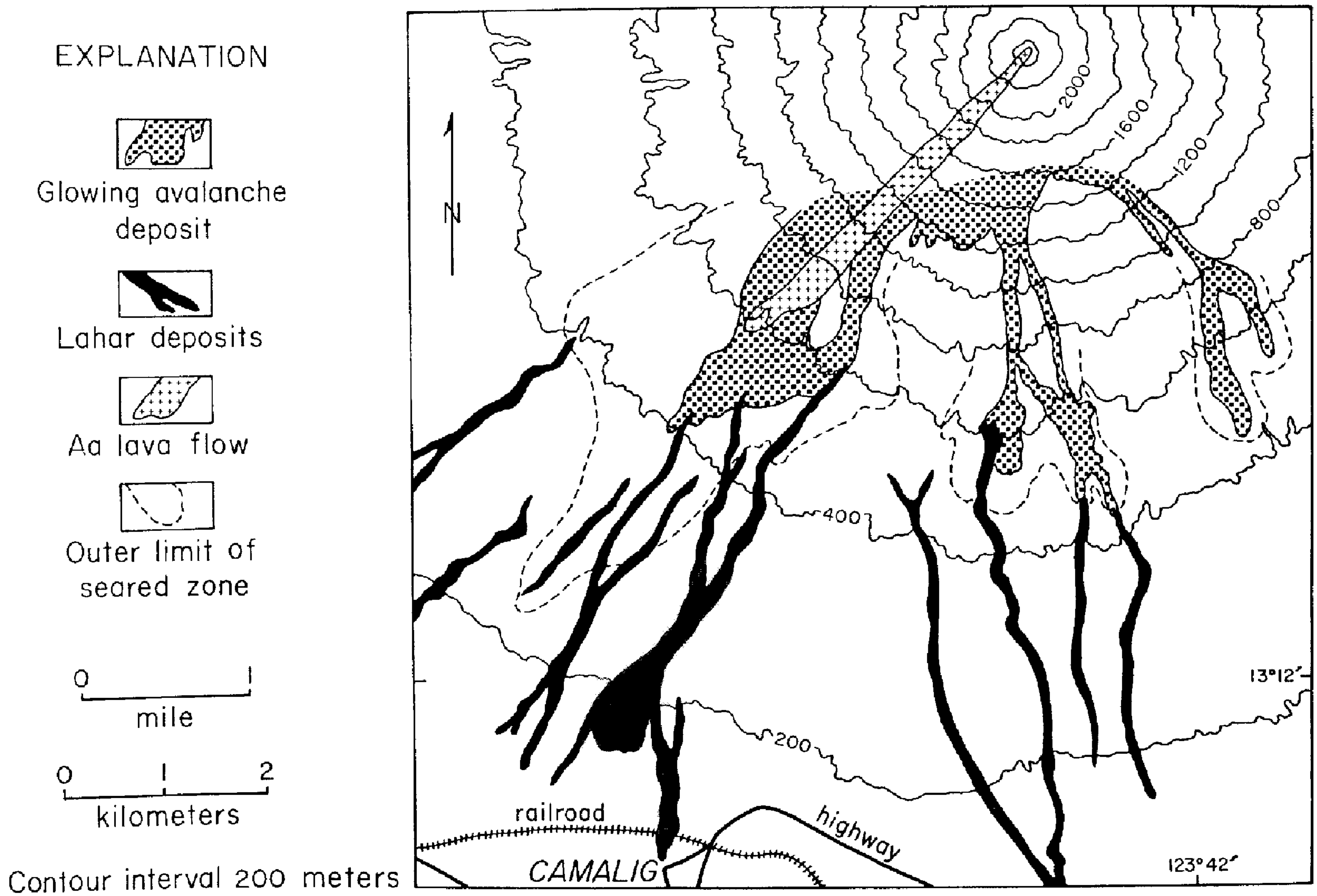

Figure 16. Map of Mayon Volcano, Philippines, showing the distribution of glowing-avalanche and lahar deposits during the eruption of 1968. (From Macdonald, 1972, after Moore and Melson, 1969)