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and Sataputu and the whole town of Saleaula except for two houses (Fig. 5.2). The Samoan houses in the villages were built of thatched roofs supported on wooden poles, but the churches at Sataputu and Saleaula and Bartley's house near the latter were substantial stone buildings. The lava flowed around these three buildings, partially burying them but without causing the walls to fall. In each case, however, the interior was burned and gutted. At Sataputu the church was buried by 8–11 meters of lava but the tower still stands. At Saleaula, the church was near the edge of the lava which entered through the windows covering the floor to a depth of more than a meter (Anderson, 1910: 633-634).

The area covered by lava flows during the 1914 eruption of Sakura-jima is shown on Figure 3.19. Yokoyama and Akamizu villages on the western side and Seto, Waki and Arimra villages in the south western part of the island were overrun by lava. In these five villages all houses, a total of 1272, were destroyed (*Kobe Herald*, 1914: 12). Although Omori (1922: 513) gives the total number of houses burnt in the eruption as 2067 plus 1790 other buildings, it is clear from his earlier text (Omori, 1916b: 215) that not all these losses can be attributed to lava flows (see also Chapter 5, Sections 3, 4).

The extent of the lava flows and the approximate locations of the buildings destroyed in the 1955, 1960 and 1983 eruptions of Kilauea (Table 5.2) are shown on Figure 4.1. The progressive destruction by fire of the Kapoho school in 1960 is illustrated in Figure 5.3. Other buildings were ignited directly from adjacent vents (Fig. 5.4). The 1944–1945 lava flows from Parícutin also destroyed many buildings in the villages of Parícutin and San Juan Parangaricutiro (see Fig. 4.4). Part of Parícutin village was evacuated in June, 1944, in the face of an advancing aa flow (Fig. 5.5). In San Juan most of the village was buried but the masonry church tower remained intact (Fig. 5.6). The 1973 eruption in Heimaey also buried and/or burnt many houses (Fig. 5.7). By late March, 1973, two months after the eruption had started, 60 to 70 houses had been buried by lava. By early May, 300 buildings had been covered or gutted by fire, though many of the fires resulted from pumice fall (Clapperton, 1973; Williams and Moore, 1973). In all these examples the advance of the lava flow was sufficiently slow that evacuation of nearly all possessions was possible. However, at Heimaey, and no doubt elsewhere, personal property suffered severe damage during evacuation and transportation by ship to Reykjavik. Furniture and white-enamelled refrigerators seemed particularly damage-prone. Some families had up to half their personal possessions ruined by the time they reached the "mainland" (Gunnarsson, 1973: 56-58).

Numerous observations have indicated that lava flows with low yield strengths may be diverted by masonry walls and other resistant structures. Most protective measures involve diversion of the flow to another route and can only be successful if vacant land is available for the diversion, a point well illustrated by Rittman: "The first recorded attempt to divert a flowing lava stream was made by Diego Pappalardo during the greatest eruption of Etna, in 1669; unfortunately he was too late, since the lava had already penetrated into the town of Catania and not much

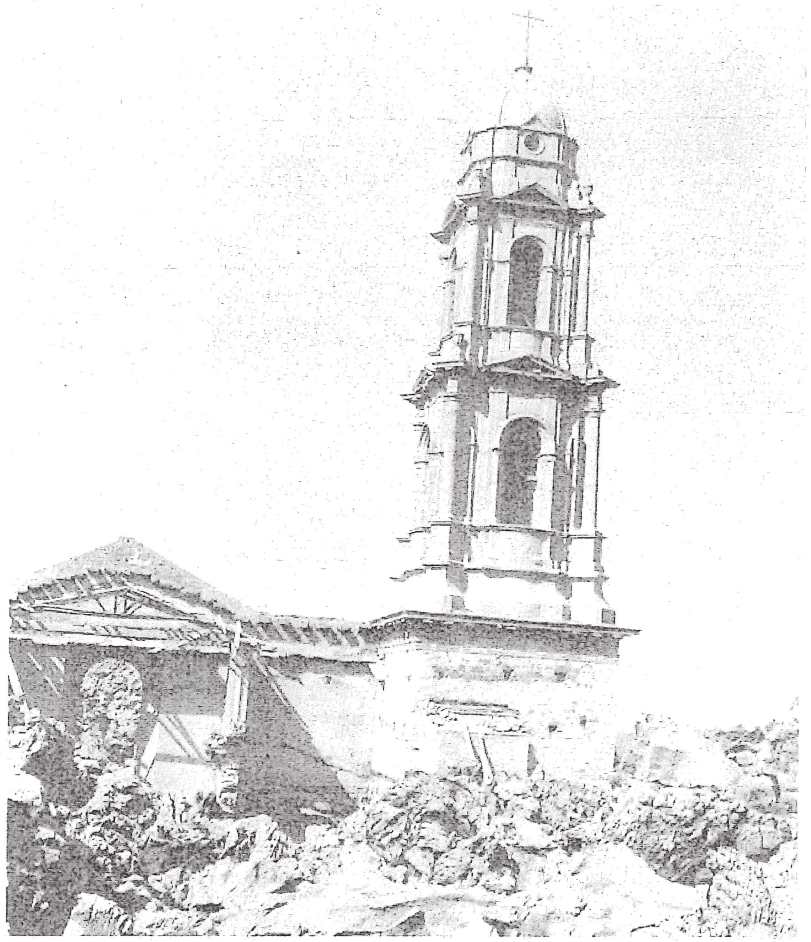

FIG. 5.6 Partial destruction of the church in San Juan by lava flow (Smithsonian Institution Archives, Record Unit 7281, William F. Foshag Papers, 1923-1965 and undated, F282, January 24, 1945).

remained to be saved. Under Pappalardo's leadership half-a-hundred men turned out, protecting themselves against the heat with wet hides, and proceeded to hack a breach with picks and axes through the western lateral moraine of the lava flow above the town, so that the molten river should flow away to the side. Had this attempt to divert the lava been made earlier, when it was still some distance from the town, it might perhaps have been more successful, since the lateral outflow would have reduced the pressure at the snout of the flow and thus slowed its advance. At all events, the scoriaceous covering was indeed broken through, and the

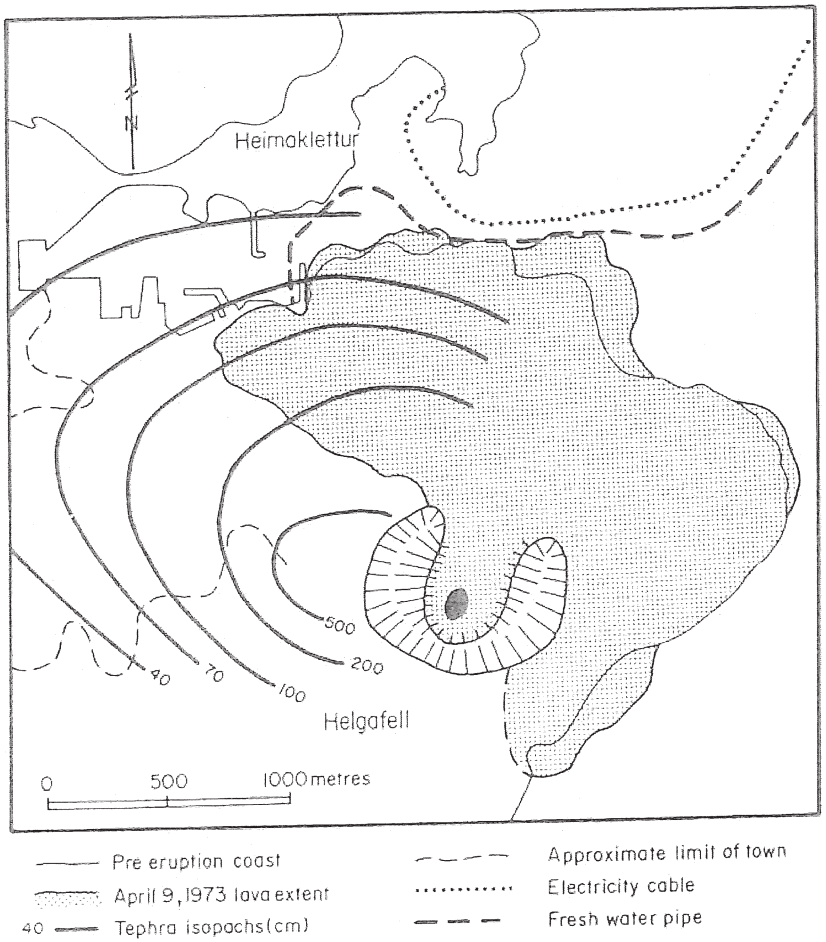

FIG. 5.7 Distribution of lava flows and tephra from the 1973 Heimaey eruption (modified after Clapperton, 1973a,b; Preusser, 1973).

lava induced to flow out laterally as planned. But when the people of Paterno heard of this, they feared that the diverted stream would threaten *their* town. And so, 500 heavily armed men turned out with trumpets and drums, and put Pappalardo and his helpers to flight" (1962: 54-55).

During the same eruption the walls of Catania held up the lava flow for 15 days before they were breached (Clapperton, 1972: 163). Diversons and/or damming of lava flows have been tried in a number of other situations with varying degrees of success. At Kapoho in 1960 bulldozers were used to build six walls with a total

length of 4500 m and a volume of more than 300 000 m^3 of old lava (Fig. 5.8) ripped from the surrounding area in 9.5 days. Although there has been some debate as to the effectiveness of these barriers (Macdonald and Abbott, 1970: 103) a great deal was learnt about wall construction techniques. Macdonald (1962: 292-293) concluded:

> 1. The wall must have a broad base. If the flow against the wall is in the order of 10 to 12 m thick, the base should be in the order of 30 m wide.
> 2. The wall must be constructed of heavy materials. Cinder is too light, and the lava tends to push it aside or burrow under it and heave it up.
> 3. The wall should have adequate height to prevent overflow, so far as possible. Even small overflows can be serious, because they may erode the face of the wall and eventually cut a gap through the wall.
> 4. The slope of the wall away from the lava should be gentle so that any overflows that do occur will move slowly down the side of the wall and erode it less than if the movement were rapid.
> 5. Sharp salients projecting into the flow should be avoided. Salients are equivalent to a low place in the wall, and invite overflows. If a salient is unavoidable, the wall should be built somewhat higher there than along the rest of its course.
> 6. If a wall is to act as a diversion barrier, an unobstructed path should be provided along the side of the wall toward the lava. This clear path is nearly as important in directing the course of the flow as the wall itself. All vegetation larger than grass and small bushes should be removed. Even the trails of rock fragments spilled from the edges of bulldozer blades in building the wall constitute a noticeable obstacle to the advance of the flow and should be cleaned away so far as possible.
> 7. Diversion barriers cannot operate successfully unless the gradient in the channel behind them is sufficient to cause the liquid lava to flow readily. The amount of slope necesary depends, of course, on the viscosity of the lava, more viscous flows requiring a steeper slope than less viscous ones. For flows of the sort ordinarily encountered in Hawaii, the minimum slope appears to be about 1.5 to 2 per cent.

In 1973 barriers built by bulldozers in Heimaey slowed the advance of lava toward the town. In 1977, a wall 3–4 m high was built around the diatomite factory at Namafjall near Krafla (Iceland) to divert lava flows (*BVE*, 1979, 17: 80). More recently, various plans for the construction of diversion barriers have been considered in order to protect Hilo from future lava flows from Mauna Loa (United States Army Corps of Engineers, 1980). It is worth noting that suburbs of Hilo requiring protection include those built on 1881 lavas!

Explosives were used in attempts to halt lava flows advancing toward Hilo from Mauna Loa in 1935 and 1942. Although Rittman (1962: 55) and others (for example, Macdonald and Abbott 1970: 64-65) have claimed that these aerial bombings were at least partially successful in diverting and/or stopping flows a detailed analysis by Lockwood and Torgerson (1980) indicates that the bombs had no significant effects. However, experiments on Mauna Loa in 1975–1976 using bombs up to 900 kg with fuse delays of 0.05 seconds and impact velocities of 250–275 m s^{-1} caused maximum flow disruption particularly where spatter cones were targeted.

An attempt on Etna to divert a lava flow using explosives was only partly successful. The main technical problem with this effort, in May, 1983, revolved around

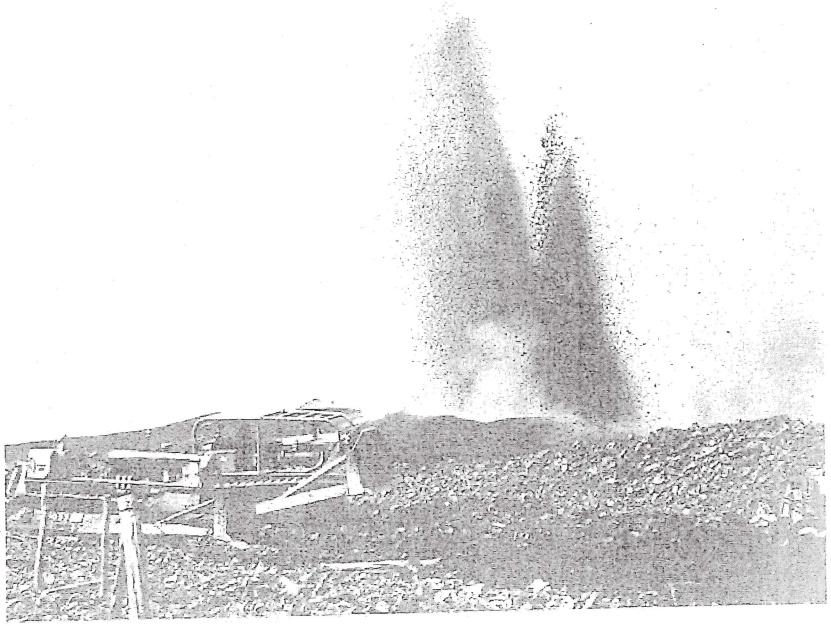

FIG. 5.8 Bulldozers work at constructing a wall of old lava fragments to dam a 1960 Kapoho flow while spectacular fire fountaining occurs in the background (Photo: American Red Cross).

the use of explosives which became unstable at temperatures of about 100°C to remove a rock barrier behind which lava flowed at temperatures of greater than 1000°C. Water jackets were used to cool the explosives but variations in lava flux and accretion on the barrier resulted in a diversion of only about 20% of the flow for a few days. However, other overflows slowed the lava front in the main channel (*Discover*, July, 1983; *SEAN Bulletin*, 865: 6).

Attempts have also been made to halt or slow the advance of flows by spraying cooling water onto the lava. It was noticed both at Matavanu in 1911 and at Kapoho in 1960 that lava advancing into the sea moved along the shore rather than continuing into deeper water, presumably because chilling increased the viscosity of the flow front. "Later in the 1960 eruption, on several occasions the Hawaii Fire Department tried artificial spraying of the flow margin to determine its effects. One example may be given. For several days the edge of the flow had been creeping slowly toward a wooden house. When the lava was about 6 m from the house volunteer firemen, who were not then otherwise occupied, turned two streams of water from 75 mm hoses onto the side of the flow. Within a few minutes the lava stopped moving, and it remained stationary for several hours. In short, it was found that

even with rather small amounts of water the spread of the flow could locally be checked for long enough to remove the contents of buildings, or even to move entire buildings to safety" (*UNDRO*, 1976: 7).

A much more substantial experiment was undertaken at Heimaey in 1973 where the harbor entrance was at risk (Fig. 5.7). At first the advancing lava was sprayed with 12 000 tonnes of water per hour from a ship. By late March, 30 high power pumps together with fireboats and ships' pumps were delivering 32 400 tonnes of seawater per hour to the lava surface (Williams and Moore, 1973; Clapperton, 1973: 628). It appears that these efforts were instrumental in saving the harbor entrance and much of the town. Large-scale pumping schemes have also been considered at Krafla and Hilo. In 1983 sea water was sprayed on the Miyake-jima flow front at 40 places. By the following day forward movement of the flow had halted at 38 of the 40 places (*SEAN Bulletin*, 8(10): 3).

While bombing, dams, walls and cooling of the lava provide valuable methods which may halt, slow or divert lava flow, non-structural methods of protection may be simpler and cheaper if applied early enough. The most important of these is land-use zoning. The 1980 estimate of the cost of a barrier to protect much of Hilo was $US3.5 million. Zoning, using the 1881 lava flow as an example, would have been much cheaper. Relocation of buildings may still prove cost-effective in some circumstances.

It is also worth noting that structural protective measures need to be considered within the cultural background of the affected residents. Human intervention may change lava flows from "Acts of God" to "human-caused events" with dramatic effect on insurance policy provisions (Barberi and Gasperini, 1976: 220). On the densely settled slopes of Etna diversion of lava flows is often impractical because other settlements will be placed at risk as indicated above. Attempts to divert a 1971 flow brought to light a seventeenth century law which forbade such efforts (*Newsweek*, 1971, May 17: 43; Booth, 1974: 317). During public hearings regarding the Hilo diversion barriers it became apparent that the goddess Pele (see Chapter 4, Section 8) was important in shaping some local attitudes to control measures: "... many believe it is possible to pray to dead relatives who have been dedicated to Pele to intercede with the goddess to direct a lava flow away from a particular piece of land. Pele beliefs also play a part in behavior associated with evacuation on the part of old Hawaiians. Such people may designate a flow as being Pele who 'can take anything she wants when she will', and when a lava flow approaches their property, they will do nothing, believing that to take any action would anger the goddess. During the 1955 eruption in Puna district [see Fig. 4.1], an old Hawaiian man refused to move his belongings, including a new television set and refrigerator, because of his beliefs. During the recent volcanic eruption and lava flow in the Kalapana area of south Puna in 1977, there was widespread local opposition to any form of experimental waterbombing by the Army to determine the effects on the flow of lava. The degree of opposition finally lead the Mayor of Hawaii County and the Governor of the State to informally request federal authorities to stop their experimentation" (US Army Corps of Engineers, 1980: 89).

5.3 TEPHRA FALL

As indicated in Table 5.1 the most damaging effects of tephra falls result from projectile impacts and roof loads leading to collapse. Secondary effects such as ignition of furnishings or, indeed, the destruction of the entire building by fire may result from penetration of the structure by hot projectiles or shortcircuiting of electrical systems by fine-grained tephra. Corrosion of some surfaces may result from contact with the acidic coatings on grains.

5.3.1 Projectile Impacts

Some of the effects of projectile impacts on buildings have been previously summarised by Blong (1981). Figure 5.9 illustrates the relationship between the penetration resistance of a variety of building materials and the impact energy of volcanic bombs of varying size, shape and density falling at terminal velocities (and hence with varying kinetic energies of impact = $0.5\ mv^2$; see Chapter 2, Section 2.1). The data presented in Figure 5.10 indicates:

A. Even 20 mm thick sheets of tempered glass will be penetrated by bombs of 10 g mass. Some bombs of only 2.5 g mass but with specific gravities greater than 1.0 g cm^{-3} can break some window glasses. All window glasses except laminated glasses will be broken by projectiles of greater than 25 g mass whatever the projectile shape.
B. Plywood, hardboard, fibre-cement, asphalt and cedar shingles, slate and clay tiles are all likely to be penetrated or at least damaged by projectiles of 50–60 mm diameter.
C. Steel cladding material could be damaged, particularly around fastenings, by projectiles of greater than 40–45 mm diameter (mass 250–500 g). Steel cladding can be penetrated by bombs of greater than 2.5 g cm^{-3} with masses of greater than 200 g (Blong, 1981: 410).

These results need to be treated with some caution. Impact energies have been calculated for normal (90°) impacts on buildings materials fastened in accordance with the codes extant in Australia and the United States. The penetration resistances of most building materials decline with age but sheet steel and asphalt shingle show increased resistance with increasing ambient temperature. Pointed projectiles will achieve higher penetration than spherical or cubical projectiles. The results shown on Figure 5.9 assume that volcanic bombs have cooled and solidified. While the penetration achieved by hot malleable bombs will be less than