GEOLOGIC HAZARDS IMPACT ANALYSIS
OF
POTENTIAL GEOTHERMAL RESOURCE AREAS

Circular C-107

1959

State of Hawaii
DEPARTMENT OF LAND AND NATURAL RESOURCES
Division of Water and Land Development

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Honolulu, Hawaii
September 1984

STATE OF HAWAII
1959

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PREFACE

Act 296, Session Laws of Hawaii 1983, as amended by Act 151, SLH 1984, requires that the Board of Land and Natural Resources examine various factors when designating subzone areas for the exploration, development, and production of geothermal resources. These factors include potential for production, prospects for utilization, geologic hazards, social and environmental impacts, land use compatibility, and economic benefits. The Department of Land and Natural Resources has prepared a series of reports which addresses each of the subzone factors. This report analyzes the major geologic hazards and their resultant effects within potential geothermal areas. Effects include risks to people and property. Available hazard mitigation techniques will also be described.

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The same volcanic activity which provides the source of geothermal heat may also create a hazard to people and property. Volcanic hazards include lava flows, pyroclastic fallout, ground deformation, cracking, and subsidence. With proper evacuation planning, lava flows should not be a great danger to people because of their usually slow speed and somewhat predictable paths; however, substantial property damage is a possibility. The table below summarizes past eruptive activity.

Historic Eruptions Within Geothermal Resource Areas

Location	Number of Eruptions Since 1750	Average Area (km^2)
Kilauea Upper East Rift*	21	6
Kilauea Lower East Rift*	5	11
Kilauea Southwest Rift	5	7
Mauna Loa Northeast Rift	7	37
Mauna Loa Southwest Rift	7	34
Hualalai	1	46
Haleakala Southwest Rift	1	6
Haleakala East Rift	0	--

A significant phenomenon is unique to Kilauea: the southern flanks of its rift zones are much more prone to be covered by lava flows than are the north flanks due to topography. This is clearly depicted by the chronological maps in figure 9 and by the graph in figure 10.

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*An imaginary line extending approximately north of Kalapana distinguishes the lower and upper east rift zone. Caldera eruptions were not considered.

Earthquakes hazards include ground shaking, cracking, and subsidence. Several tectonic earthquakes above magnitude 6 have been reported on the island of Hawaii; particularly in the coastal and saddle areas. Less powerful, volcanic earthquake swarms commonly occur in rift zone areas.

Geothermal developments near coastal areas should consider the possibility of damage from tsunami and ground subsidence.

Several mitigation methods are described which may reduce the risk from geologic hazards. These methods include strategic siting, special construction designs and fortifications, evacuation planning, decentralization of power plants, and giving development investors a clear economic incentive to utilize mitigation methods by having them assume a major portion of the associated risks of loss.

In the past, several attempts have been made to restrict the flow of lava in Hawaii, Italy, and Iceland. These examples are provided to illustrate the effectiveness of the technology used and the costs involved. In those situations, governmental authorities spent large amounts of money, sometimes millions of dollars, in efforts to protect communities threatened by lava flows.

The past history and nature of geologic hazards can provide a valid guide to the probable course of future activity; although it is not possible to detail the specific time and location of such activity.

GEOLOGIC HAZARDS IN HAWAII; THEIR DESCRIPTION AND EFFECT

LAVA FLOWS

Lava flows are generated in most volcanic eruptions in Hawaii and can cover extensive areas extending out to more than 10 km from the source; be they from a vent or a long linear fissure or crack. Lava tends to flow freely in a fairly predictable course determined by ground slope. However, ridges built by cooling lava on the sides of a flow may create channels and divert lava from the steepest slope. Flows from earlier phases of an eruption can quickly change the topography and expected course of the flow. In a somewhat similar manner, other natural and man-made obstacles can divert lava flows.

Most lava flows are thin, about 1 meter in near vent areas increasing commonly to about 5 meters in its distal part; although some individual flows (e.g. Pu'u O) have been significantly thicker. Structures more than 5 meters high are not immune from burial by lava. There is a strong tendency for many lava flow units to be generated during a single eruption. These flows will superpose upon one another, particularly near the vent where accumulations over 10 meters thick may be constructed by accretion of many individually thin layers.

Lava flows vary in their flow behavior. Thick distal aa flows tend to bulldoze, crush, bury, and burn any surface structures in their path. The more fluid, newly erupted, proximal (near-vent) lava tends to flow around obstacles. A fluid flow could enter buildings and may not cause much structural damage beyond igniting flammable materials and softening and distorting some of the metalwork. In principle, fluid pahoehoe lava could subsequently be removed and the building reoccupied. In principle this would also apply to flows covering protective well cellars and thin pahoehoe flows surrounding transmission piping (see mitigation below).

Removal of cooled lava would be feasible if the flows were sufficiently thin and friable, and if the eruption was not lengthy. Using Kilauea as an example, since 1800, the average duration of an eruption has been about 60 days, with many lasting only one day and some, such as the Mauna Ulu and the current Pu'u O eruptions, lasting years.

Since the crust tends to insulate underlying lava, cooling time for lava increases exponentially with the thickness of the flow. It would take about 200 days for 1 meter (1000 days for 4 meters) of lava to cool to 200°C (extrapolated from Peck, 1974). However, cooling time can be significantly reduced if great amounts of water are applied to a cooling flow area. (See section on lava cooling effort at Heimaey Island, Iceland.)

Thus, recovery from a deep or long enduring flow could take many months. Mitigation techniques may significantly reduce risk from flows. A long recovery time would not be acceptable to a damaged electric utility power plant unless sufficient reserve capacity were available.

Past volcanic activity can suggest future activity, however it is not possible to detail the specific time and place of future eruptions. Summit swelling and increasing swarms of volcanic earthquakes can warn of impending eruptions.

PYROCLASTIC FALLOUT

Explosive eruption fountains may eject rock fragments of many sizes and types. The weight and depth of fallout can be appreciable as far as even 500 or 1000 m away from an eruptive vent or fissure. Large fragments tend to fall close to the vent building cones that may be tens of meters high. Smaller particles can form a long, narrow, blanket many feet thick downwind of the vent. Figure 1 shows a pumice blanket originating from Kilauea Iki vent. Cones tend to be higher and fallout more extensive on older volcanoes, such as Haleakala than on Mauna Loa or Kilauea; some cones on Haleakala exceed 100 meters high.

The probability of an eruption being powerfully explosive (with resultant increased debris) increases as the coast is approached and is near 100% for a vent within about 1 km of the coast. Steam generated by magma from the near-surface groundwater promotes such explosiveness. An example of potential damage from pyroclastic fallout is given by the 1960 Kapoho eruption where some buildings were destroyed because of the weight of cinder and ash upon their roofs (Macdonald, 1962). Other dangers from fallout include lung irritation, poor visibility, anxiety or panic, blockage of escape routes, and severe cleanup problems.

GROUND CRACKS

Cracks, which may open as much as several feet, can be the surface expression of dikes that fail to reach the surface. These cracks can produce a surface graben several meters wide and deep in which the ground is let down between two parallel cracks. This type of cracking related to magma movements is concentrated in volcanic rift zones which are clearly defined and narrow features (see figure 2). Cracks could also open outside a rift zone; not enough information is available to access the probability, but it decreases rapidly as the distance from the rift zone increases.

Ground cracking can also be associated with earthquakes, resulting from tectonic activity. Their formation is often accompanied by a relative vertical or lateral displacement of the ground on either side. Tectonic ground cracking is usually localized in definable zones; e.g. the Hilina and Koae fault systems at Kilauea (see figure 3).

Ground cracking across a geothermal plant could cause a suspension of operation, depending on the extent and location of damages.

Pipes carrying steam between the wells and plant are likely to remain undamaged by moderate ground cracking, since they are designed with expansion joints at regular intervals.

Ground cracking close to a well bore might open up an alternate path for the steam and cause its loss from the well. It is unlikely for a crack to intercept a well bore due to the vertical pitch of most cracks.

GROUND SUBSIDENCE

On the mainland, subsidence due to contraction of clay or sand formations may result from the withdrawal of geothermal fluids in those formations. In Hawaii, subsidence from geothermal fluid withdrawal is not likely to be problem; since the islands are generally composed of dense, yet porous, self-supporting basaltic rock, especially in geothermal production zones. Of more concern is the volcanic or tectonic subsidence which usually occurs on or about active rift zones, e.g. Kilauea.

Small to large grabens may result with the subsidence of rock blocks (usually rectangular) which are downthrown along or between cracks, e.g. 1960 Kapoho graben (see section on ground cracks).

Subsidence and cracking may also be associated with tectonic earthquakes, e.g. subsiding slump blocks in Hilina fault system at Kilauea (figure 3).

Collapsing pit craters and lava tubes can result in very severe localized subsidence. Pit craters usually occur within a summit or upper rift zone of a volcano. Figure 4 explains their formation which can result in subsidence up to hundreds of feet. Fragile, near-surface lava tubes (usually found in pahoehoe flows) are subject to collapse from heavy surface activity. A geologic site survey could reveal these hazards.

Aside from the immediate effects subsidence may have on the foundation and contents of a power plant; subsidence also increases the hazards from lava flows since flows usually seek lower areas.

EARTHQUAKES

Most earthquakes in Hawaii are volcanic; resulting from near-surface magma movements. They are small in magnitude and usually cause little direct damage. Larger earthquakes tend to be tectonic, generally resulting from the movement of large rock bodies.

The largest Hawaiian earthquake occurred on the island of Hawaii in 1868, having a magnitude of 7.5.

Major earthquake shaking can easily damage buildings; especially those poorly constructed. Indirect damage may be caused by the smaller but more frequent volcanic earthquakes; e.g. collapse of lava tubes, landslides, and compaction (Mullineaux and Peterson, 1974). It is recommended that power plants be constructed to withstand shaking from a 7.5 magnitude earthquake (Stearns).

TSUNAMI

Tsunamis are large sea waves usually generated by movement of large submarine rock masses although some are caused by volcanic eruptions. These devastating waves can travel great distances at speeds of almost 500 mph and move on shore turbulently or merely rise quietly. The highest reported wave of 60 feet above sea-level resulted from a local earthquake on the island of Hawaii in 1868 (Macdonald et al, 1983). Much larger tsunamis have been reported elsewhere.

Thus tsunami hazard is probably localized to a zone of land at most 2 km wide around the coast, and at elevations below about 75 feet. This should not pose a significant danger to geothermal developments which are likely to be situated at higher elevations.

MEASURES TO MITIGATE DAMAGE FROM GEOLOGIC HAZARDS

Various methods which could be used to mitigate dangers from geologic hazards are listed below. No attempt is made to prioritize methods since priorities may differ with the risks at each specific site. A survey should be conducted on each development site to closely examine topography and structural integrity of the surface and sub-surface areas.

- Keep the power plant as far outside the rift zone as is possible since volcanic activity is concentrated there, e.g. lava flows, lava tubes, cracking, subsidence, pit craters, grabens, swelling. The piping distance from the well field to the power plant is limited due to increased thermal losses with distance; for example, the Kahauale'a site development map shows a maximum distance of about 2½ miles from its farthest well to a power plant.

- Power plants and wells should be constructed on the highest ground available. Even a very small hill or ridge could offer considerable protection from lava flows. Channels and valleys should be avoided, even if upslope, as lava flows tend to be channeled into and be deepest in these relatively low areas.
- If a sufficiently large hill is not available, a plant or well could be protected by constructing an earth-and-rock platform several meters high. Depending on the perceived risk from flow hazard, wells or plants can be sufficiently fortified to withstand almost any lava flow (Mullineaux and Peterson, 1974). A cost/risk analysis would have to be made.
- Another well-protection alternative is to enclose the well-head in a concrete cellar allowing the lava to flow above rather than around the well-head. Recovering a well covered with a thick flow could be quite arduous and time consuming. The precise effect the lava's heat would have on the well-head mechanisms is not known.
- To complement the platform a berm or wall could be constructed to divert lava flows. The embankment should be several meters high around the upslope and cross-slope sides of the structure. (See section on diversion walls below.)
- Available information indicates that the northern flank of Kilauea's rift zones are safer than the southern. For example, ground movements are more frequent on the Kilauea east rift zone's southern flank. By referring to figure 9 it is apparent that over the past 250 years the vast majority of erupted lava on Kilauea's rift zones has flowed over the southern slopes. Figure 10 depicts the percentage of ground covered by lava in the past 30 years, as distance varies north and south of the Kilauea east rift zone axis. A similar relationship does not appear to apply to volcanoes at other proposed geothermal areas in Hawaii.

- A geologic survey may identify near-surface lava tubes which could collapse under construction.
- Power plants should be modular and somewhat portable so that, if all fortifications fail, units might be salvaged and reused. This tends to encourage use of smaller decentralized plants.
- Steam transmission piping may be protected from a thin, fluid pahoehoe flow by installing downslope support structures. Thick aa flows would probably disrupt surface piping. Underground piping may offer more protection but installation and maintenance would be quite costly.
- Comprehensive evacuation plans should be designed to assure worker safety. Warning time prior to inundation can be as little as one hour (Moore, 1984). Procedures should be established to protect equipment. Multiple access roads should be provided in the event one gets covered by a flow.
- The development should coordinate contingency planning with government field geologists (e.g. Hawaiian Volcano Observatory) and local civil defense authorities to ascertain when an eruption appears imminent and what subsequent action should be taken. Escape and abandonment procedures may be flexible but should be predetermined and clear. The developers have been giving this area their attention.
- If a lava flow is impending during well drilling, the well can be fitted with a pressure and temperature resistant "bridge plug" to safely isolate and protect the lower, resource-bearing, portion of the well. These plugs can be installed in one hour (Niimi, 1984).
- Trip wires, placed in the expected path of a lava flow, can alert development personnel as to the distance and speed of the oncoming flow. The crew can then take appropriate action in accord with their preexisting evacuation plan (Niimi, 1984).
- Protecting structures or machinery against damage by pyroclastic fallout might be achieved by enclosing those parts vulnerable to abrasion or contamination. Building roofs should be strong, having a sufficient pitch so that pyroclastic fallout does not

accumulate. Access to roofs should be easy so that, if necessary, they can be manually kept cleared of pyroclastic material.

- Plant generators can be specifically designed to be adjustable to some ground surface tilting or subsidence (Capuano, 1984).
- Steam transmission piping can be made with expansion joints to accommodate appreciable subsidence and ground movements.
- Plants should be constructed to withstand an earthquake of 7.5 (Stearns).
- Power plants should not be constructed in coastal regions, if risk from tsunami is to be avoided.
- In extraordinary and particular situations, bombing a lava channel may cut the feed to a flow-front and prevent or slow further advance in the front area (see section on bombing lava channels).
- If warranted by volcanic risk, adequate spacing between developments should be maintained so that one eruption would not likely endanger more than one development. It is a common utility practice to maintain reserves sufficient to prevent a major blackout. Reserve requirements (and associated costs) may be limited by using small decentralized power plants rather than one large plant.
- If geothermal development investors assume a major portion of the economic risk of loss resulting from geologic hazards, then developers would have a clear economic incentive to utilize appropriate mitigation measures and to select sites which offer the optimum balance of safety and productivity.
- It is generally assumed that the resource developers will bear the risks of loss associated with their activities. However, if the utility owns the power plant, there may be some question as to whether the investors or the rate-payers will bear the risks of loss. This assumption of risk would be reflected in the cost of electricity from geothermal plants. It may be better that this cost be apparent "up front" rather than be delayed and possibly deferred to rate-payers in the event of a catastrophe. In the past, there have been some instances where hazard losses were recovered by the utility from rate revenues (e.g. Hilo tsunami of

1960). Policy regarding assigning and clarifying risks of loss may be implemented by imposing conditions to be met by development investors prior to the granting of a geothermal resource permit by the State (conservation district) or Counties (urban, rural, or agriculture districts).

PAST ATTEMPTS TO MITIGATE GEOLOGIC HAZARDS

CONSTRUCTION OF WALLS TO RESTRICT LAVA FLOWS IN KAPOHO, HAWAII

Macdonald (1962) wrote an excellent article on walls built to restrict lava flows during the 1959 and 1960 Kilauea eruptions. The 1960 eruption resulted in a flow of 113 million m^3 of lava, burying about 6 km^2 of land including most of Kapoho village. Both dams (which tend to impound flows) and diversion barriers (which alter flow course) were constructed. Diversion barriers are more likely to be successful in most situations.

Some of Macdonald's conclusions regarding the effectiveness and nature of the walls are presented:

- Walls must be constructed of heavy materials; not cinder as lava tends to burrow under it. Lava-rock is preferred; especially aa clinker since it is easily bulldozed and its spiny character allow them to bind well.
- Walls must have a broad base and adequate height to prevent overflow; e.g. if flow is 10 m thick, the base should be about 30 m wide.
- Outwide walls should be gently sloped to lessen erosion should an overflow develop.
- If the wall is a diversion barrier, a smooth unobstructed path or channel should be along the inside of the wall to promote diverted flow. In addition, the channel must also have sufficient slope to promote flow, i.e. at least 2 percent.

- Yielding of walls to lava pressure was limited to only a few places where wall was built from light cinder.

Macdonald summarizes the success of the Kapoho walls by noting that "they have demonstrated that properly constructed walls will endure the thrust of even thick lava flows without yielding; and that walls with adequately sloping clear channels behind them will successfully change the course of a flow." Others believe that "structures of sufficient size and strength could be constructed to divert lava flows as large as any historic flow...if the need were great enough a carefully planned, small-scale system might be feasible and effective" (Mullineaux and Peterson, 1974).

USE OF LAVA DIVERSION WALLS AND EXPLOSIVES ON MOUNT ETNA, ITALY

In 1983, lava flows from Mt. Etna in Italy threatened two towns downslope of an active vent (Figure 16A). In response to the situation, a lava diversion program was initiated to mitigate damages from the lava flows. This included two diversion barriers and the use of explosives.

With explosives, it was intended to create a significant diverting leak in a channel supplying lava to the flow front. A portion of the lava channel was removed by heavy equipment to provide for proper placement of the explosives (Figure 16B). It was observed that efforts to cool the drill (using water and dry ice) cooled the lava, thereby reducing the cross-sectional area of the lava tube and causing the lava to "back-up" and overflow the lava tube; this resulted in some unintended but welcomed lava diversion. 400 kg of explosives were finally inserted and detonated which caused a small lava flow away from the main lava tube.

The diversion barriers were quite substantial (Figure 16C); one being 150,000 m^3 and 500 m long, the other 120,000 m^3 and 300 m long. Work continued while lava was accumulating on the interior of the diversion wall. The first barrier, though eventually overtopped, caused major channels to be diverted from one town. The second barrier also succeeded in diverting the lava away from a second town.

This effort was quite substantial, utilizing 100 pieces of major equipment and over 100 men (working 90 hours per week), at a cost of $3 million. However, savings due to prevention of property loss were estimated at $5-25 million. (See Williams and Moore, 1977.)

PUMPING WATER ON LAVA FLOWS IN KAPOHO, HAWAII

Water may chill and partially congeal a flow margin. During the 1960 Kapoho flow, the Hawaii Fire Department pumped water on the flow margin. Macdonald (1962) found that "it was possible to locally check the advance of the flow margin. Although the check is temporary, it is sometimes possible in that way to gain the short time--up to several hours--that may be needed to remove furnishings or other materials from a building, or even to remove the building itself."

This has obvious application to a geothermal development. If warranted, a sufficient supply of water might be kept on hand for lava cooling purposes; possibly from the same source as the power plant cooling water. The amount of rainfall in geothermal areas should also be considered (e.g. figure 5).

PUMPING WATER ON LAVA FLOWS ON HEIMAEY ISLAND, ICELAND

In 1973, when lava flows threatened a coastal town on Heimaey Island, Iceland, a program was designed to: (1) slow advancing lava by pumping great volumes of seawater over the flow and (2) divert the lava flow using a diversion barrier. The water-pumping program was the largest ever attempted. Seventy-five men working at times around the clock, sprayed approximately 7.3 million cubic yards of seawater onto the lava flow at a cost of $1.5 million. The pumped water converted 5.5 million cubic of molten lava into solid rock, cooling the lava 50 to 100 times more rapidly than self-cooling. A specialized system of pumps and piping was utilized. (See Lockwood, 1983.)

BOMBING OF LAVA CHANNELS ON MAUNA LOA, HAWAII

This technique can only be used in appropriate situations, i.e. to break-down walls of near-vent lava channels, clogging them, thereby lessening the supply of lava to distal lava flow fronts. This would promote spreading of the flow in the bombed areas. Bombing of Mauna Loa flows was tried twice; but was not particularly useful in those situations (Macdonald, 1962). The legal ramifications of damages caused by diverting flow paths should be explored.

EMERGENCY PLANNING AT THE GEOTHERMAL DEVELOPMENT IN KRAFLA, ICELAND

In 1975 an emergency situation developed at Krafla, in Northern Iceland. A geothermal power plant under construction was located within 1 km of the locus of ground deformation and seismic activity of the type that proceeds volcanic eruptions. This activity continued for over five years with construction proceeding normally though several small lava eruptions occurred within 2 km of the plant. Careful contingency plans were designed for the evacuation of site workers, but the lava flows did not directly contact the power plant. On one occasion lava did rise into one of the well bore-holes without significant effect. Construction was concluded and the geothermal development is now operating.

This particular development is sited in a rift zone similar to the Hawaiian rift zones. Detailed emergency planning should draw upon the contingency plans which resulted from this experience in Iceland (see Tryggvason, 1973).

GEOLOGIC HAZARD ANALYSIS

MAUI

A Maui volcanic hazard map has been prepared by D. Crandell (1983) which describes the frequency of past eruptions.

Haleakala Southwest Rift Zone

Flows range from 200 to 20,000 years old. Six flows have erupted in this area within the last 1000 years. Based on past activity, the average rate of eruption is one per 150-200 years. The last flow occurred in 1790 by the coast; it was the largest (6 km^2) of the more recent flows. See figures 6 and 7.

Haleakala East Rift Zone

The most recent flow on the east side of Haleakala is just north of this geothermal resource area between Olopawa and Puu Puou; it is about 500 years old. Based on past activity, the average rate of eruption is one per 10,000 years.

The above risk from volcanic hazards includes dangers from lava flows and other attendant phenomenon such as pyroclastic fallout, cracking, subsidence, swelling, and emission of volcanic gases.

The most recent earthquake near Maui occurred in 1938, 40 miles off the northern coast of East Maui. Some damage to roads and buildings on Maui and Molokai was reported (Macdonald et al, 1983). Cracking and subsidence may also be associated with large earthquakes.

Crandall (1983) states that although Haleakala's "eruptive history suggests that an eruption could occur on Haleakala within the next hundred years, there is as yet no way to predict a specific time or place of the next eruption."

HAWAII

Figures 8 through 11 show the locations of historic lava flows and fault systems. Figures 12 through 15 show relative zones of risk from flows, fallout, subsidence, and ruptures.

Hualalai

The only historic eruption of Hualalai occurred in 1801. It produced two large flows covering 46 km^2 east and north towards the ocean.

Several thousand earthquakes, from a source beneath Hualalai, shook the island in 1929. This may indicate subsurface magmatic movement or a readjustment or settling of the mountain.

Eruptions and earthquakes (and associated cracking, fallout, subsidence, etc.) may occur here in the future but it is not possible to predict the precise time and place of future activity.

Mauna Loa Southwest Rift Zone

- There have been 7 eruptions on the southwest rift zone since 1832; an average of one eruption every 22 years.
- The latest and largest flow occurred in 1950 covering an area of 91 km^2. The average flow has been about 34 km^2.
- Hawaii's largest earthquake (magnitude 7.5) occurred in 1868 near the southern tip of the island.
- Eruptions and earthquakes (and associated hazards of ash fallout, ground deformation, cracking, and subsidence) are likely to occur here in the future but it is not possible to predict the precise time and location of future activity.
- There is no danger from tsunami in this geothermal resource area since its lowest elevation is about 1500 feet.

Historic Eruptions of Mauna Loa Southwest Rift

Date	Duration (days)	Repose since last eruption (months)	Altitude of vent (m)	Area of flow (km^2)	Volume (m^3)	Average thickness (m)
Mar. 1868	15	--	990	223.7	140,000,000	5.9
Jan. 1887	10	226	1710	29.4	220,000,000	7.5
Jan. 1907	15	240	1860	21.1	75,000,000	3.5
May 1916	14	112	2220	17.2	60,000,000	3.5
Sept. 1919	42	41	2310	23.9	255,000,000	10.7
Apr. 1926	14	77	2280	34.8	110,000,000	3.2
June 1950	23	290	2400	91.0	440,000,000	4.8
Total	95	986		241.1	1,300,000,000	
Average	14	164 (13.7 yrs)	1967	34.4	186,000,000	6.3 (21 ft)

Source: Modified after Macdonald, et al, (1983).

Mauna Loa Northeast Rift Zone

- There have been 7 eruptions on the northeast rift zone since 1832; an average of one every 22 years. Most eruptions originated at elevations higher than the proposed 7000' resource area cut-off; but flows commonly travel into this area.
- The largest flow, in 1880, covered an area of 62 km^2. The average flow has been about 37 km^2.
- The most recent flow, in Spring 1984, covered an area of over 30 km^2 and stopped close to Hilo, Hawaii.
- Earthquakes with magnitudes above 6 have occurred in the saddle area between Mauna Loa and Kilauea, e.g. magnitude 6.7 in November 1983.
- Eruptions and earthquakes (and associated hazards of ash fallout, ground deformation, cracking, subsidence, etc.) are likely to occur here in the future but it is not possible to predict the precise time and place of future activity.

- There is no danger from tsunami in this geothermal resource area since its lowest elevation is about 3500 feet.

Historic Eruptions of Mauna Loa Northeast Rift

Date	Duration (days)	Repose since last eruption (months)	Altitude of vent (m)	Area of flow (km^2)	Volume (m^3)	Average thickness (m)
Feb. 1852	20	--	2520	28.6	100,000,000	3.5
Aug. 1855	450	40	3150(?)	31.7	110,000,000	3.5
Nov. 1880	280	288	3120	62.4	220,000,000	3.5
Jul 1899	19	215	3210	42.1	145,000,000	3.5
Nov. 1935	42	435	3630	35.9	115,000,000	3.2
Apr. 1942	13	76	2760	27.6	75,000,000	2.7
Mar. 1984	--	503	3600	30+	300,000,000	4.8
Total	824	1557		258+	1,065,000,000	
Average	137 (4.5 mo.)	260 (22 yrs)	3141	37	152,000,000	3.5 (11½ ft)

Source: Modified after Macdonald, et al, (1983).

Kilauea Southwest Rift Zone

- There have been 5 eruptions on the southwest rift zone since 1750; an average of one every 47 years.
- The largest flow, in 1919, covered an area of 13 km^2. The average flow has been about 7 km^2.
- The most recent volcanic activity occurred in 1982, when magma moved into the rift zone. This caused ground cracking but no lava erupted.
- The southern flanks of Kilauea's rift zones are more prone to be covered by lava flows than are the north flanks due to its topography (see Figure 9).

- Earthquakes with magnitudes above 6 have occurred in the saddle area between Mauna Loa and Kilauea, the largest being of magnitude 6.7 in November 1983.
- Eruptions and earthquakes (and associated hazards of ash fallout, ground deformation, cracks, subsidence, etc.) are likely to occur here in the future; but it is not possible to predict the precise time and place of future activity. Intervals between historic eruptions in the southwest rift zone have varied from 3 years (1971 to 1974) to 52 years (1919 to 1971).
- There may be some danger from tsunami and ground subsidence in the coastal portion of this geothermal resource area.

Historic Eruptions of Kilauea Southwest Rift

Date	Duration (days)	Repose since last eruption (months)	Altitude of vent (m)	Area of flow (km^2)	Volume (m^3)	Average thickness (m)
May 1823	Short	--	400	10	11,000,000	1.1
Apr. 1868	Short	539	770	.1	183,000	1.8
Dec. 1919	221	620	900	13	45,300,000	3.5
Sep 1971	5	615	1000	3.9	7,700,000	2.0
Dec. 1974	1	38	1080	7.5	14,300,000	1.9
Total		1812		34.5	78,483,000	
Average	Short	453 (38 yrs)	830	6.9	16,000,000	2.7 (9 ft)

Source: Modified after Macdonald, et al, (1983).

Kilauea Upper East Rift Zone

For purposes of this hazard analysis the east rift zone is divided into upper and lower segments. A line extending roughly north of Kalapana distinguishes these two areas (see line A-A, figure 8). Eruptions at the caldera area were not considered as a rift zone eruption.

- There have been 21 eruptions on the upper east rift zone since 1750; an average of one every 11 years.
- The largest flow, the Mauna Ulu flow of 1972, covered an area of 35 km^2. The average flow has been about 6 km^2. However, the greater volumes of the more recent eruptions may be a better guide to future events than the generally small-volume historic eruptions prior to 1969.
- The current Pu'u O eruption has covered an area over 30 km^2. This eruption began in January 1983 and has been through 23 phases so far. The localized present danger will subside after the Pu'u O eruption is determined to have ended by qualified geologists.
- The southern flanks of Kilauea's rift zones are much more prone to be covered by lava flows than are the north flanks due to its topography (see Figure 9). Figure 10 graphically depicts the percentage of ground covered by lava flows, from 1954 to 1984, as it varies with distance north and south of the rift zone axis.
- The largest recent earthquake (magnitude 7.2) occurred in 1975 about 5 km southwest of Kalapana. It resulted in cracking, subsidence, and tsunami (Macdonald et al, 1983).
- Most volcanic cracking and subsidence are centered about the rift zone. However, there is considerable faulting associated with the Koae and Hilina fault system south of the caldera (See Figure 3).
- There may be some danger from tsunami and ground subsidence in the coastal portion of this geothermal resource area.
- As Kilauea is highly active, eruptions and earthquakes (and associated hazards of ash fallout, ground deformation, cracks, subsidence, etc.) will occur here in the future; but it is not possible to predict the precise time and place of future activity. Intervals between historic eruptions in the upper east rift zone have varied from days apart (1973) to 38 years (1923 to 1961).

Historic Eruptions of Kilauea Upper East Rift*

Date	Duration (days)	Repose since last eruption (months)	Altitude of vent (m)	Area of flow (km^2)	Volume (m^3)	Average thickness (m)
May 1840	26	--	900	3.4**	41,000,000**	12
May 1922	2	983	800	.1	?	--
Aug. 1923	1	16	900	.5	73,000	.2
Sep 1961	3	456	500	.8	2,200,000	2.8
Dec. 1962	2	15	950	.1	310,000	3.1
Aug. 1963	2	9	900	.2	800,000	4.0
Oct. 1963	1	2	900	3.4	6,600,000	1.9
Mar. 1965	10	17	750	7.8	16,800,000	2.2
Dec. 1965	1	9	920	.6	850,000	1.4
Aug. 1968	5	40	650	.1	130,000	1.3
Oct. 1968	15	2	850	2.1	6,600,000	3.1
Feb. 1969	6	4	900	6.0	16,100,000	2.7
May 1969	867	3	940	12.5	176,700,000	14.1
Feb. 1972	455	4	940	35.1	119,600,000	3.4
May 1973	1	0	990	.3	1,200,000	4.0
Nov. 1973	30	6	925	1.0	2,700,000	2.7
Dec. 1973	203	0	940	8.1	28,700,000	3.5
July 1974	3	0	1040	3.1	6,600,000	2.1
Sep. 1977	18	38	550	7.8	32,900,000	4.2
Nov. 1979	1	25	970	.3	580,000	1.9
Jan. 1983	520+	39	750	30+	200,000,000+	6.7
Total	2172	1668		126	667,643,000	
Average	103 (3.5 mo.)	83 (7 yrs)	855	6	32,000,000	7.6 (25 ft)

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* In this report, a line extending roughly north of Kalapana distinguishes the lower and upper east rift zone (see Figure 8). Eruptions in the caldera area were not considered as a rift zone eruption.

**The 1840 flow occurred roughly 1/5 within the upper east rift and 4/5 within the lower east rift; the appropriate fractional portion is shown in the table.

Source: Modified after Macdonald, et al (1983).

Kilauea Lower East Rift Zone

- There have been 5 eruptions on the lower east rift zone since 1750; an average of one every 47 years.
- The largest flow, in 1955, covered an area of 16 km^2. The average flow has been about 11 km^2.
- The most recent flow, in 1960, covered an area of about 11 km^2 near and in Kapoho.
- The southern flanks of Kilauea's rift zones are much more prone to be covered by lava flows than are the north flanks due to its topography (see Figure 9). Figure 10 graphically depicts the percentage of ground covered by lava flows, from 1954 to 1984, as it varies with distance north and south of the rift zone axis.
- Intervals between historic eruptions have varied from 5 years (1955 to 1960) to 115 years (1840 to 1955). It is not possible to predict the precise time and place of future eruptions.
- The earthquake of 1868 on the southern tip of the island was the largest earthquake in this area (magnitude 7.5).
- There may be some danger from tsunami and ground subsidence in the coastal portion of this geothermal resource area.

Historic Eruptions of Kilauea Lower East Rift*

Date	Duration (days)	Repose since last eruption (months)	Altitude of vent (m)	Area of flow (km^2)	Volume (m^3)	Average thickness (m)
1750 (?)	--	--	510	4.1	14,200,000	3.5
1790 (?)	--	480	300	7.9	27,500,000	3.5
May 1840	26	605	350	13.8**	164,000,000**	11.9
Feb. 1955	88	1384	175	15.9	87,600,000	5.5
Jan. 1960	36	56	35	10.7	113,200,000	10.6
Total		2525		52.4	406,500,000	
Average	50	631 (53 yrs)	274	10.5	81,000,000	9.5 (31 ft)

* In this report, a line extending roughly north of Kalapana distinguishes the lower and upper east rift zone (see Figure 8). Eruptions in the caldera area were not considered as a rift zone eruption.

**The 1840 flow occurred roughly 1/5 within the upper east rift and 4/5 within the lower east rift; the appropriate fractional portion is shown in the table.

Source: Modified after Macdonald, et al, p. 64 (1983)

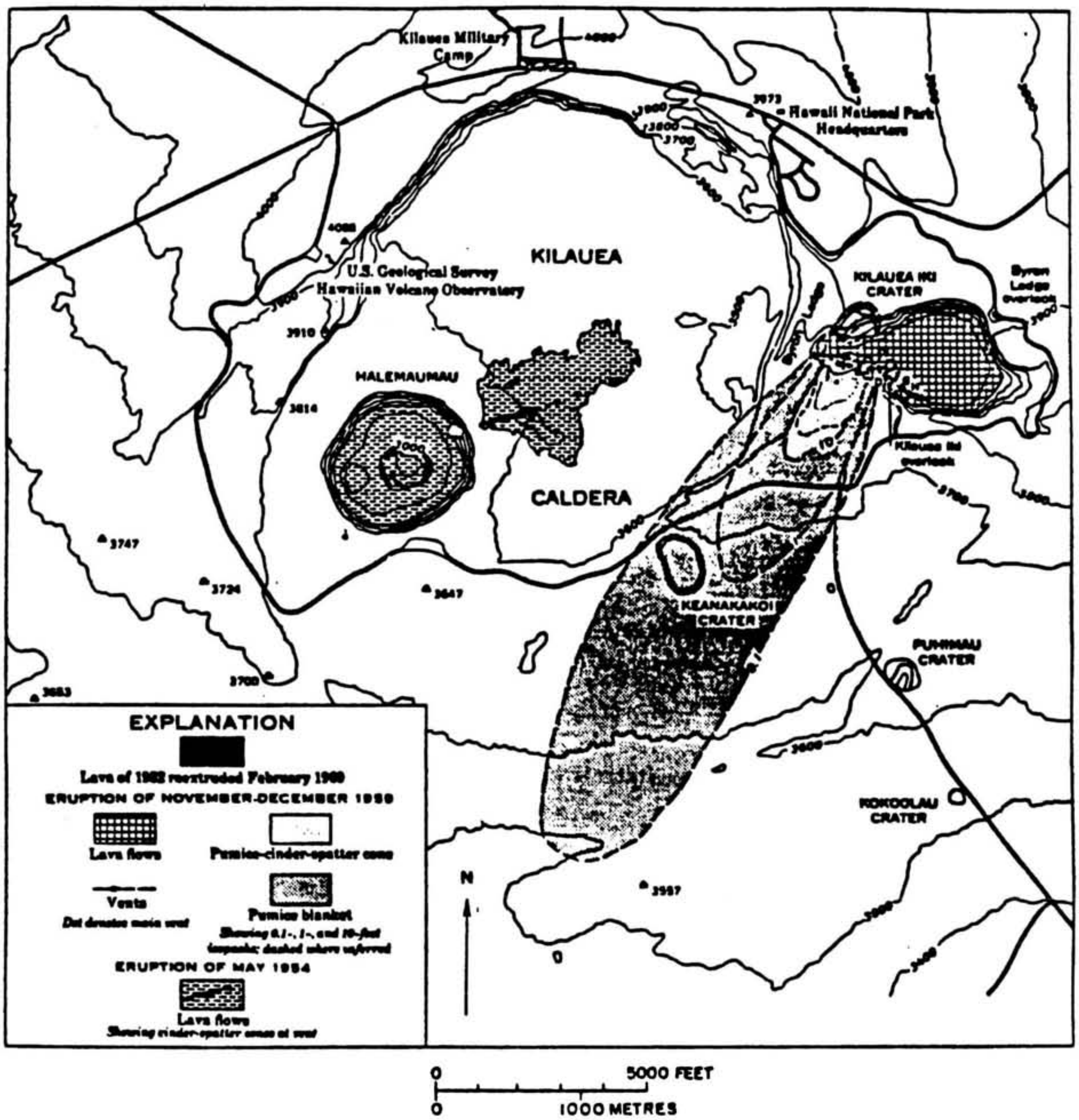


Figure 1. Map of the Kilauea summit area, showing extent of pumice blanket from Kilauea Iki vent in 1959. (In Mullineaux and Peterson, 1974, from Richter and others, 1970)

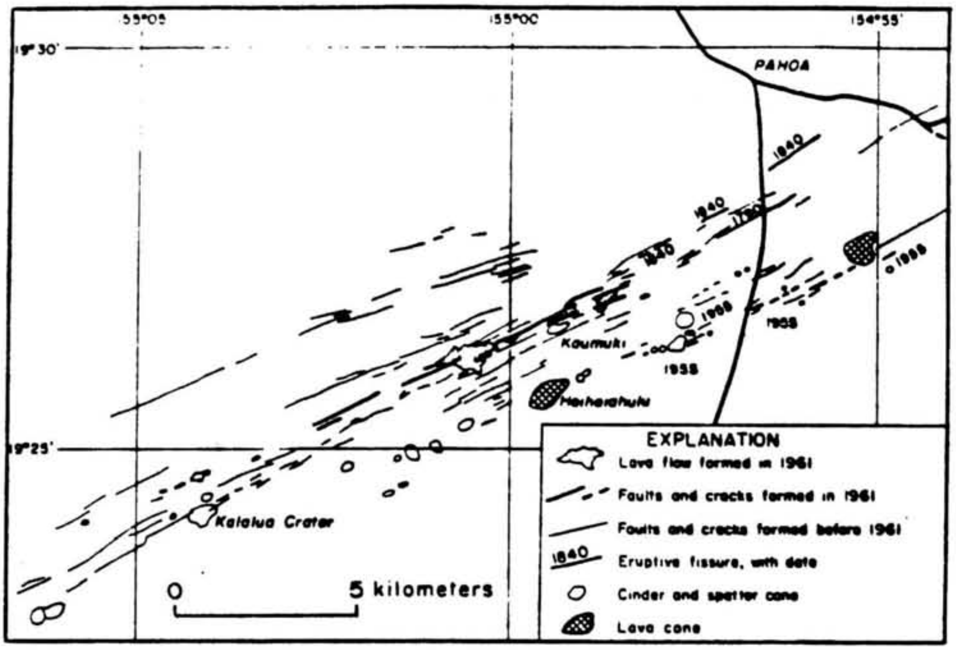


Figure 2. Map of part of the east rift zone of Kilauea showing faults, cracks, and lava flows formed in 1961. (In Holcomb, 1980; modified after Richter et al., 1964)

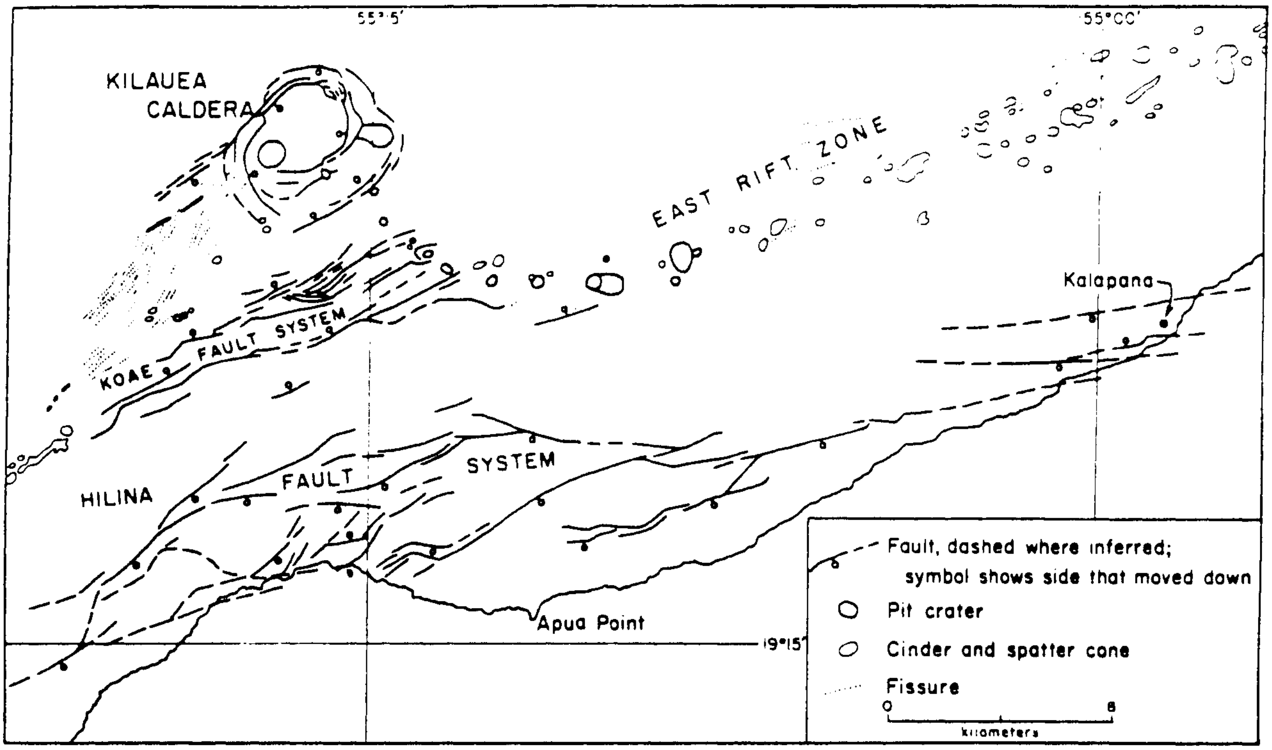


Figure 3. Map showing the pattern of faults in the Hilina fault system, on the southern flank of Kilauea volcano. (In Macdonald et al., 1983; modified after Stearns and Macdonald, 1946)

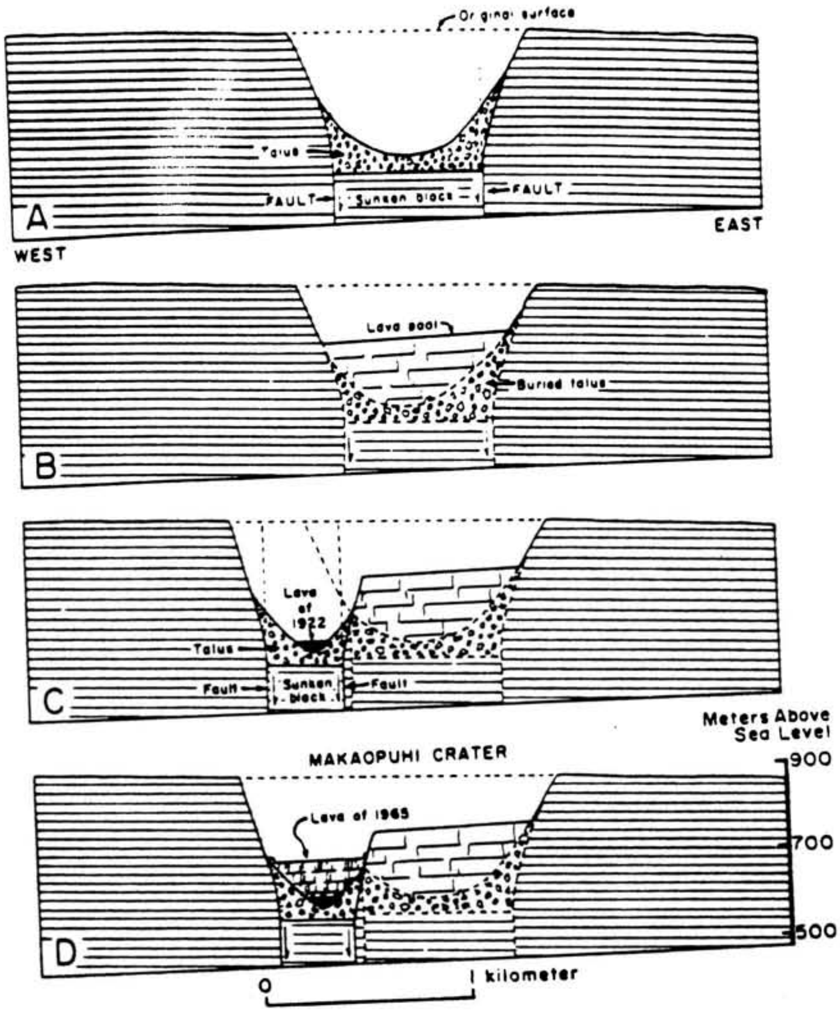


Diagram showing the manner of formation of Makaopuhi, a double pit crater. *A*, A subcircular fault block sinks, leaving a crater at the surface. (The position and attitude of the faults is hypothetical.) The upper walls of the crater collapse to form taluses (piles of rock fragments) that hide the lower walls. *B*, Lava pouring into the crater collects in a deep pool, the surface of which solidifies to form a nearly flat floor. *C*, A second block sinks, making a second crater that cuts across the western edge of the first one. The pool of lava in the bottom of the second crater is from a small eruption in 1922. *D*, A much larger eruption (in 1965) forms a pool 90 meters deep in the second crater. Note the slump scarps at the edge of the new lava floor, formed as lava in the central part of the crater drains back into underlying vents.

Figure 4. Formation of pit craters. (Macdonald et al., 1983)

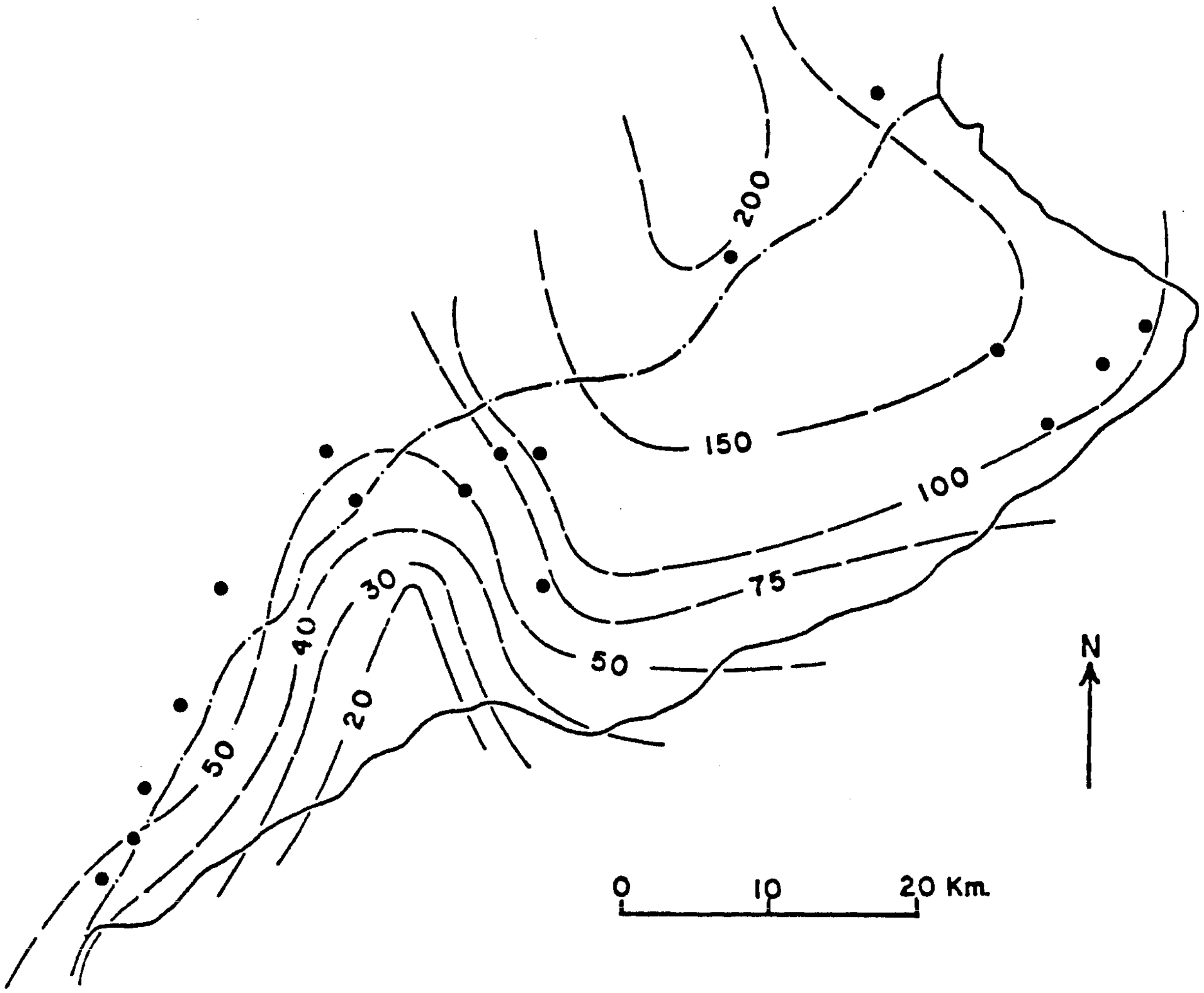


Figure 5. Rainfall of Kilauea. (In Holcomb, 1980; after Taliaferro 1959)

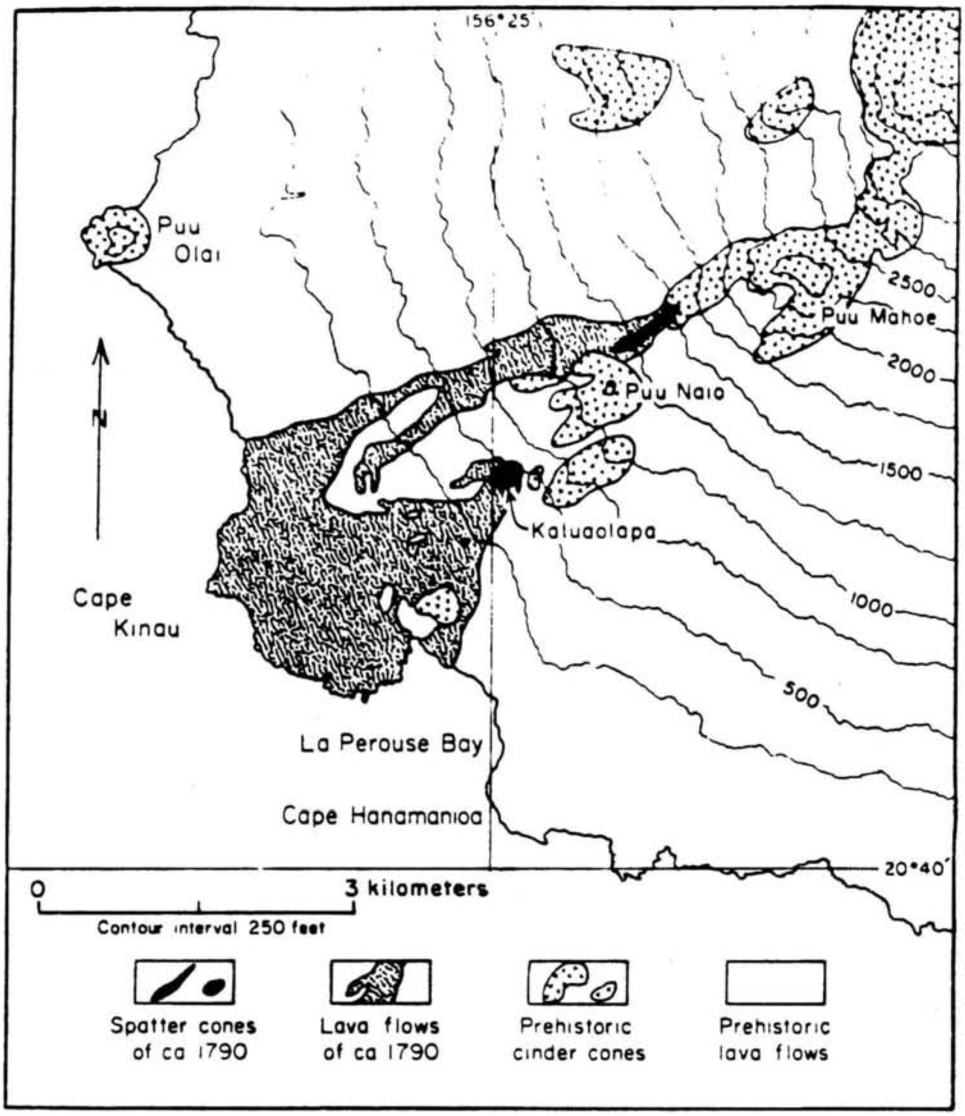


Figure 6. Map of the southwestern part of Haleakala volcano, island of Maui, showing the lava flows of the 1790 eruption and the spatter cones at their vents. (In Macdonald et al., 1983; modified after Stearns and Macdonald, 1942)

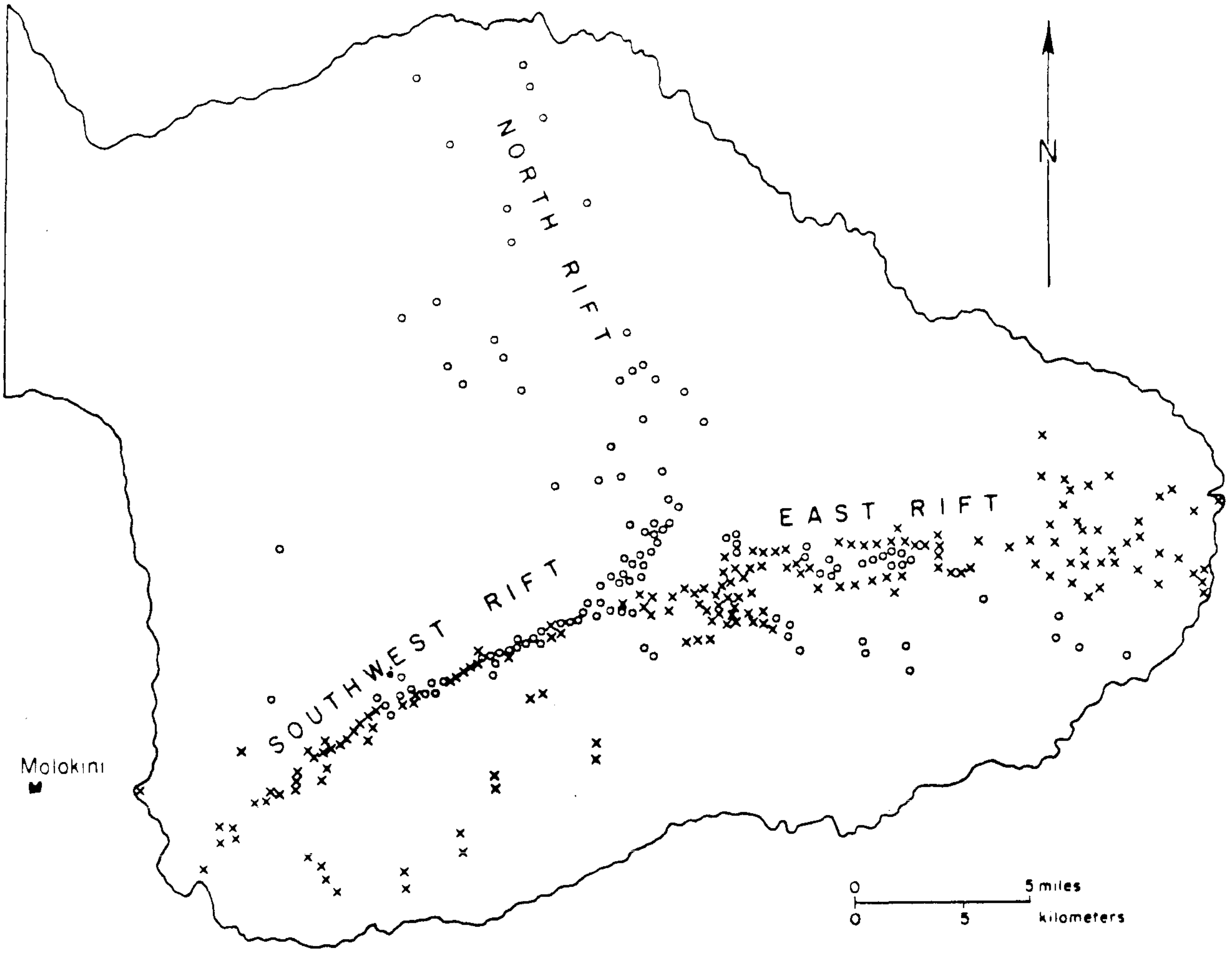


Figure 7. Map of Haleakala volcano, showing vents of the Kula (circles) and Hana (crosses) Volcanic Series. Molokini Islet is a tuff cone on the southwest rift zone of Haleakala. (In Macdonald et al., 1983; after Stearns and Macdonald, 1942)

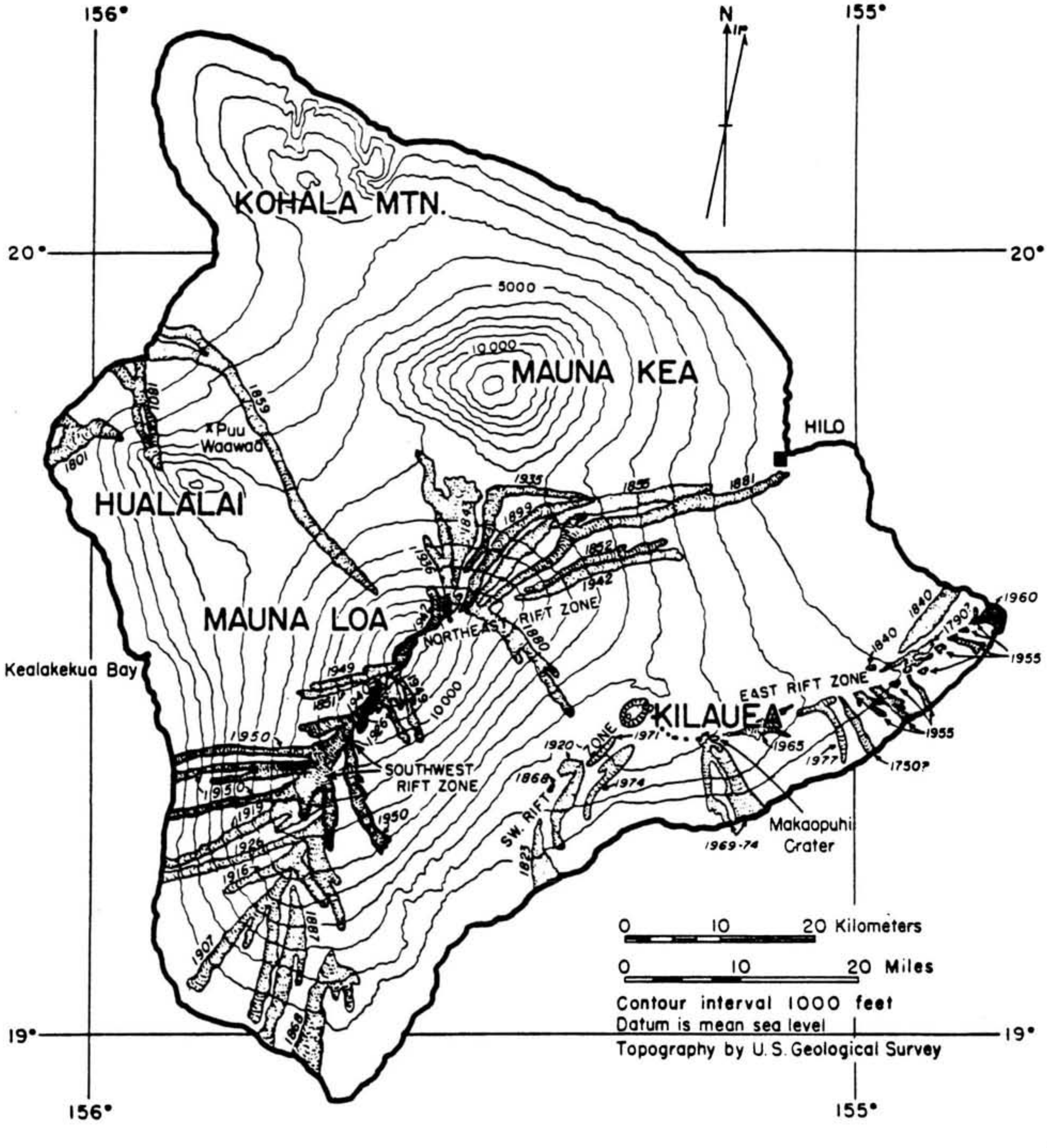


Figure 8. Map of the island of Hawaii, showing the five major volcanoes that make up the island, and the historic lava flows. (Macdonald et al., 1983)

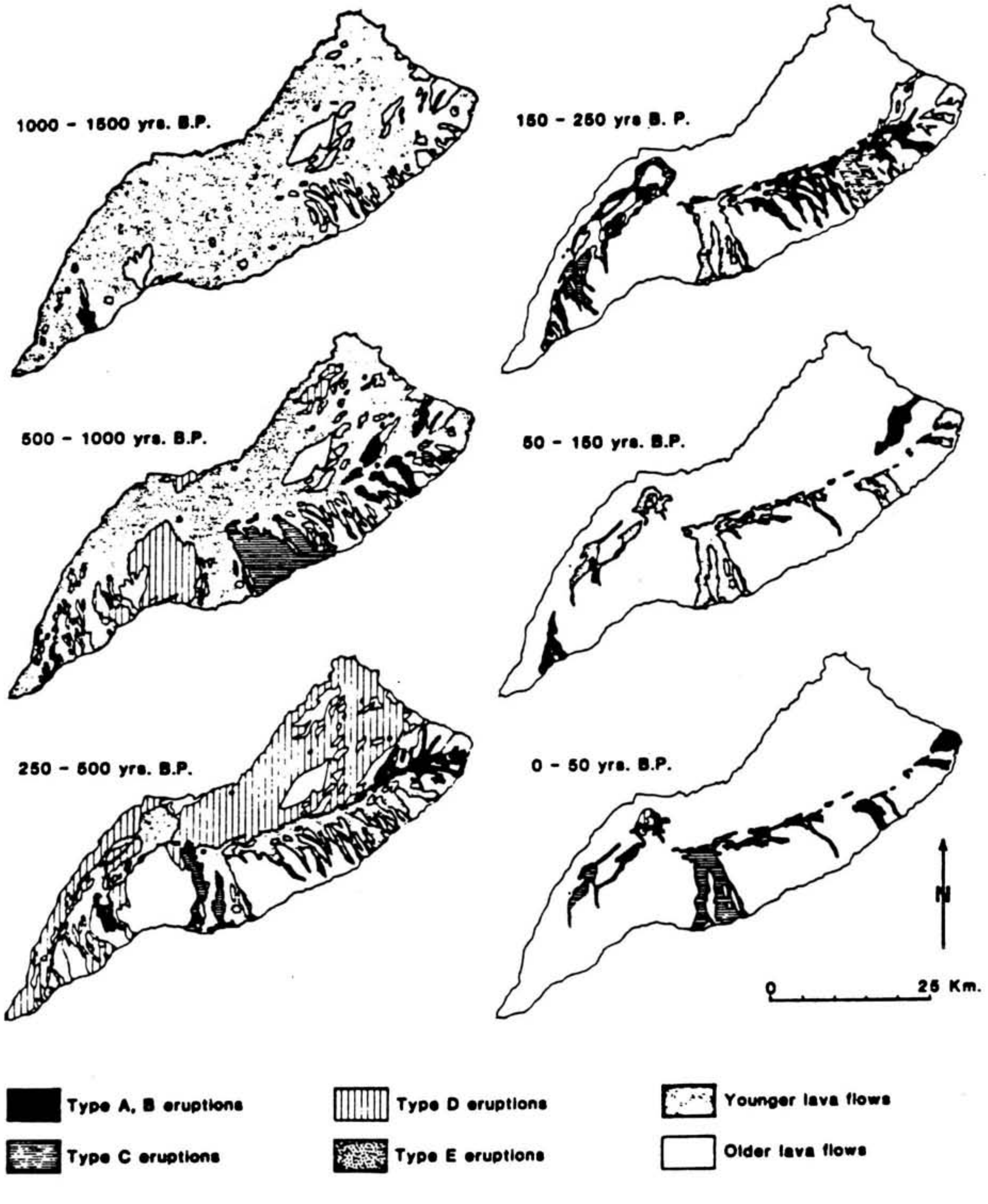


Figure 9. Summary of Kilauea's eruption history during the last 1500 years. (Holcomb, 1980)

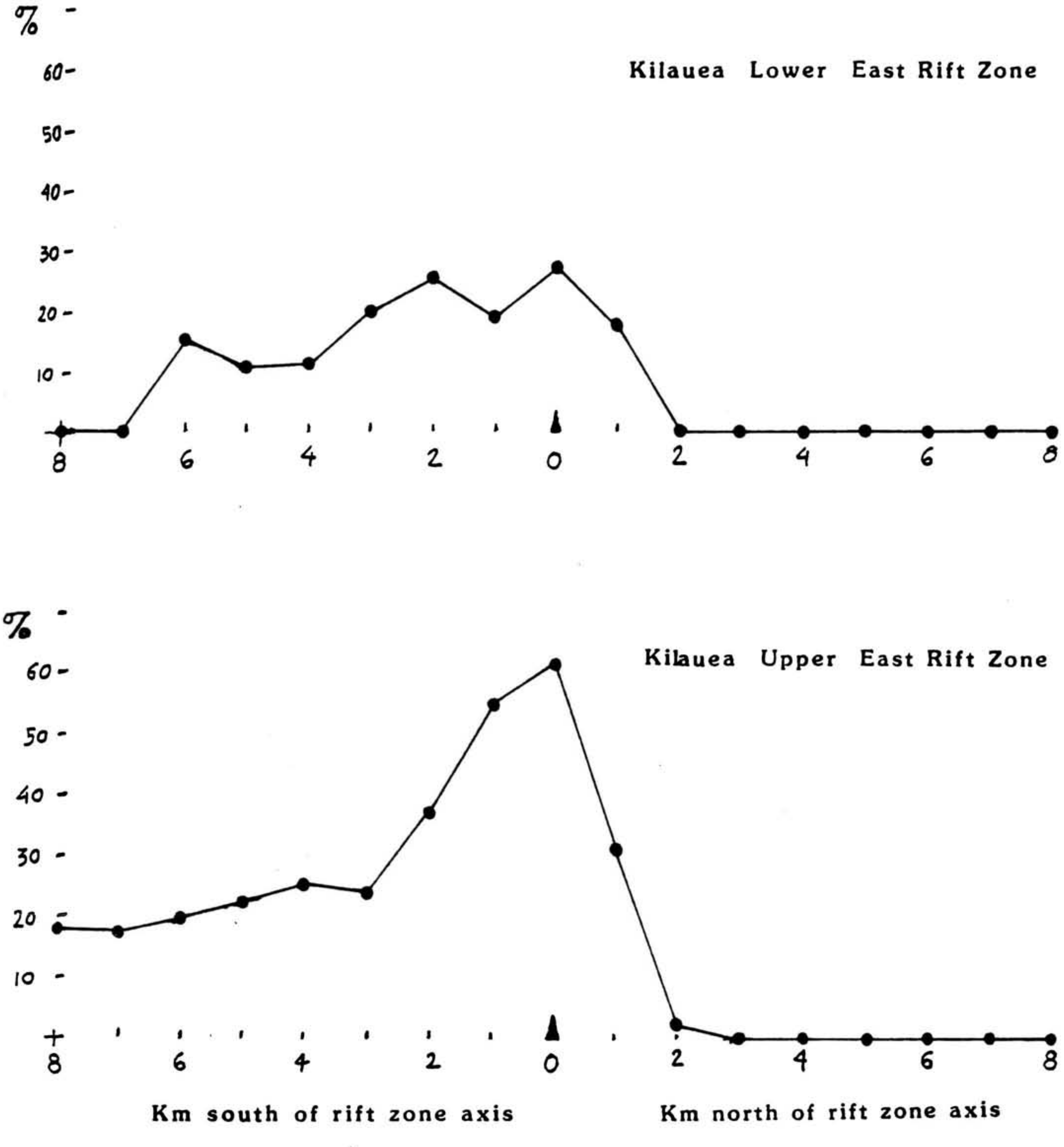


Figure 10. Percentage of ground covered by lava flows, from 1954 to 1984, as it varies with distance north and south of Kilauea's east rift zone axis. If 30 years is the assumed life of a geothermal power plant, these figures suggest the probability that sites may be threatened by burial during their lifetime, as based on Kilauea's history from 1954 to 1984.

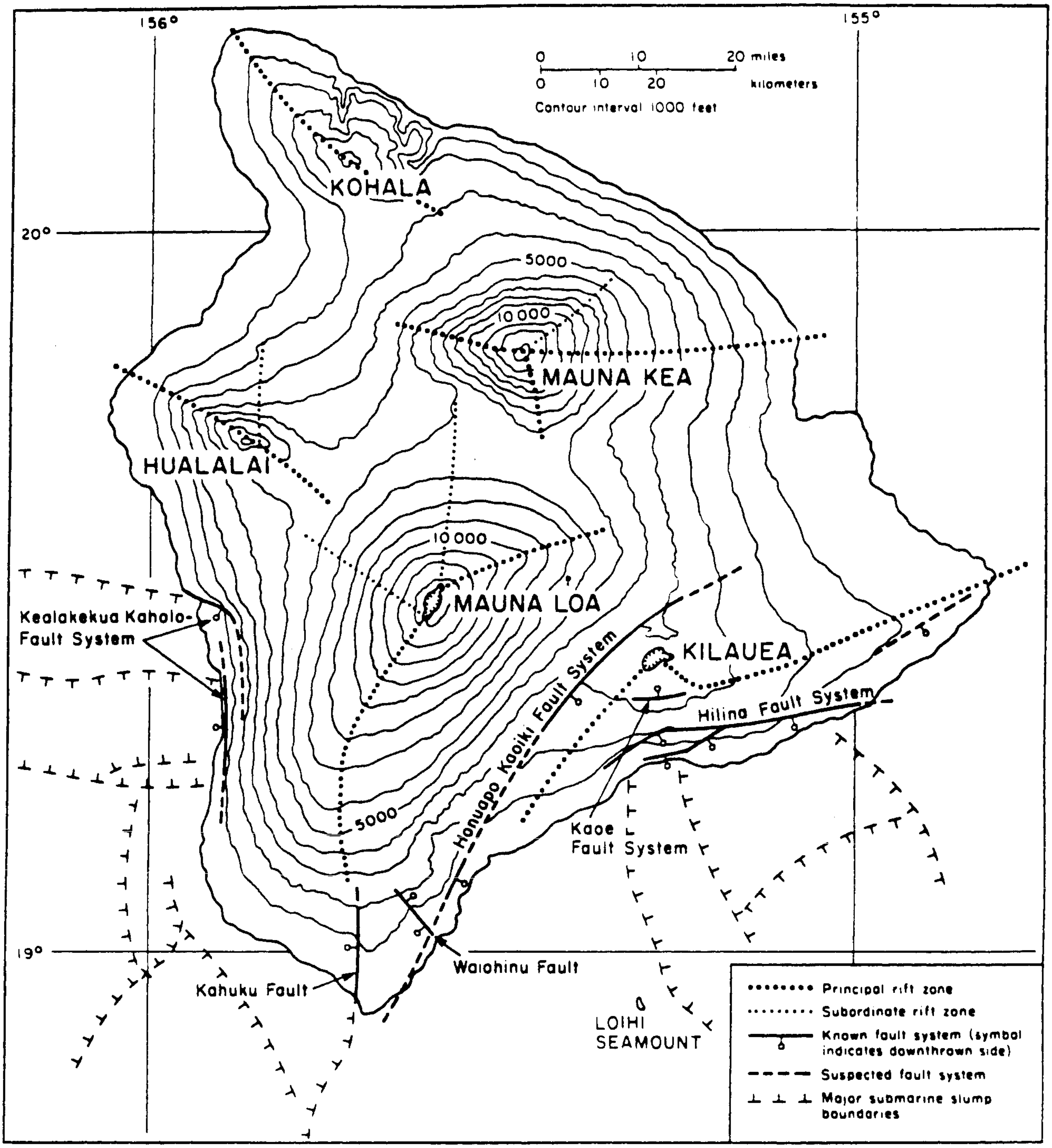


Figure 11. Map showing volcanic rift zones and faults on the island of Hawaii. (In Macdonald et al., 1983; submarine slumps after Normark et al., 1978)

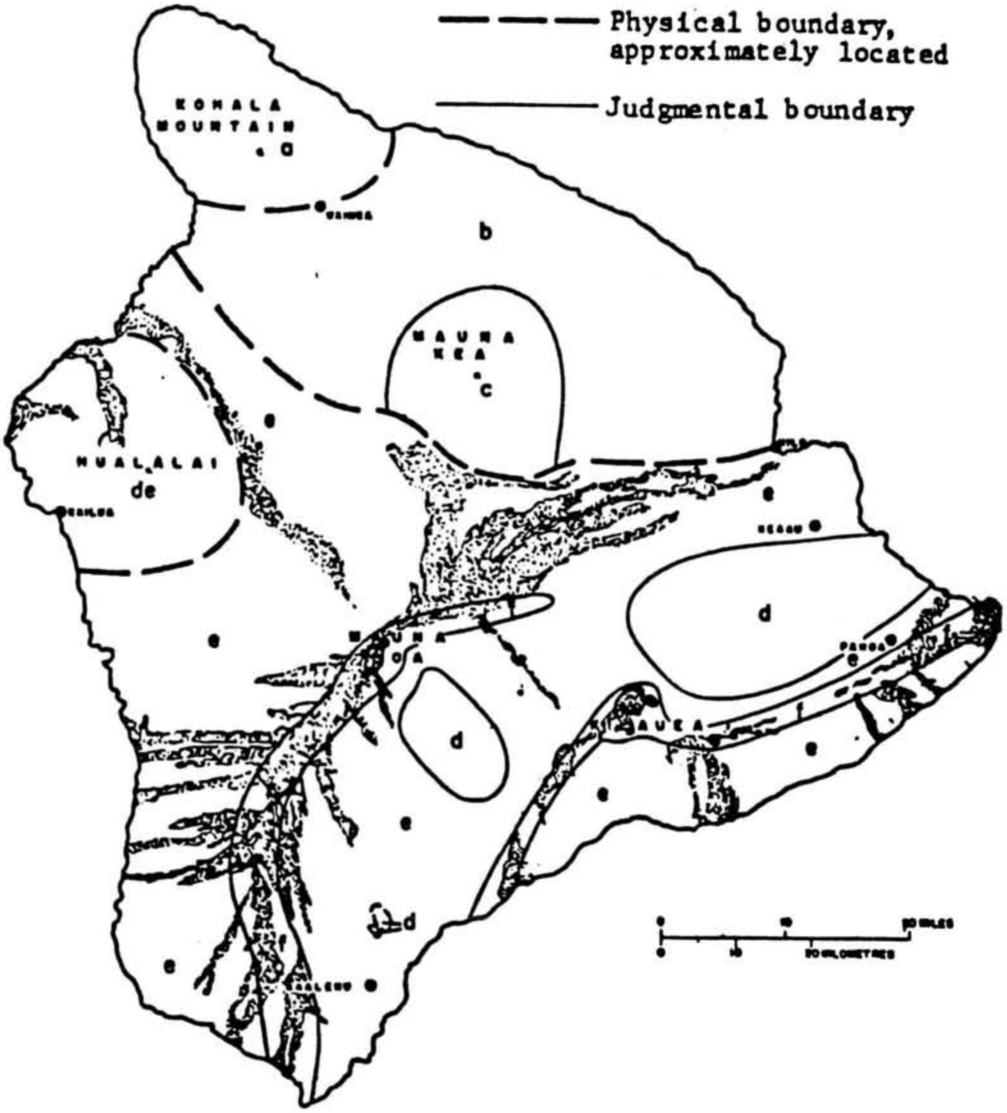


Figure 12. Zones of relative risk from lava-flow burial. Risk increases from "a" through "f". (Mullineaux and Peterson, 1974)

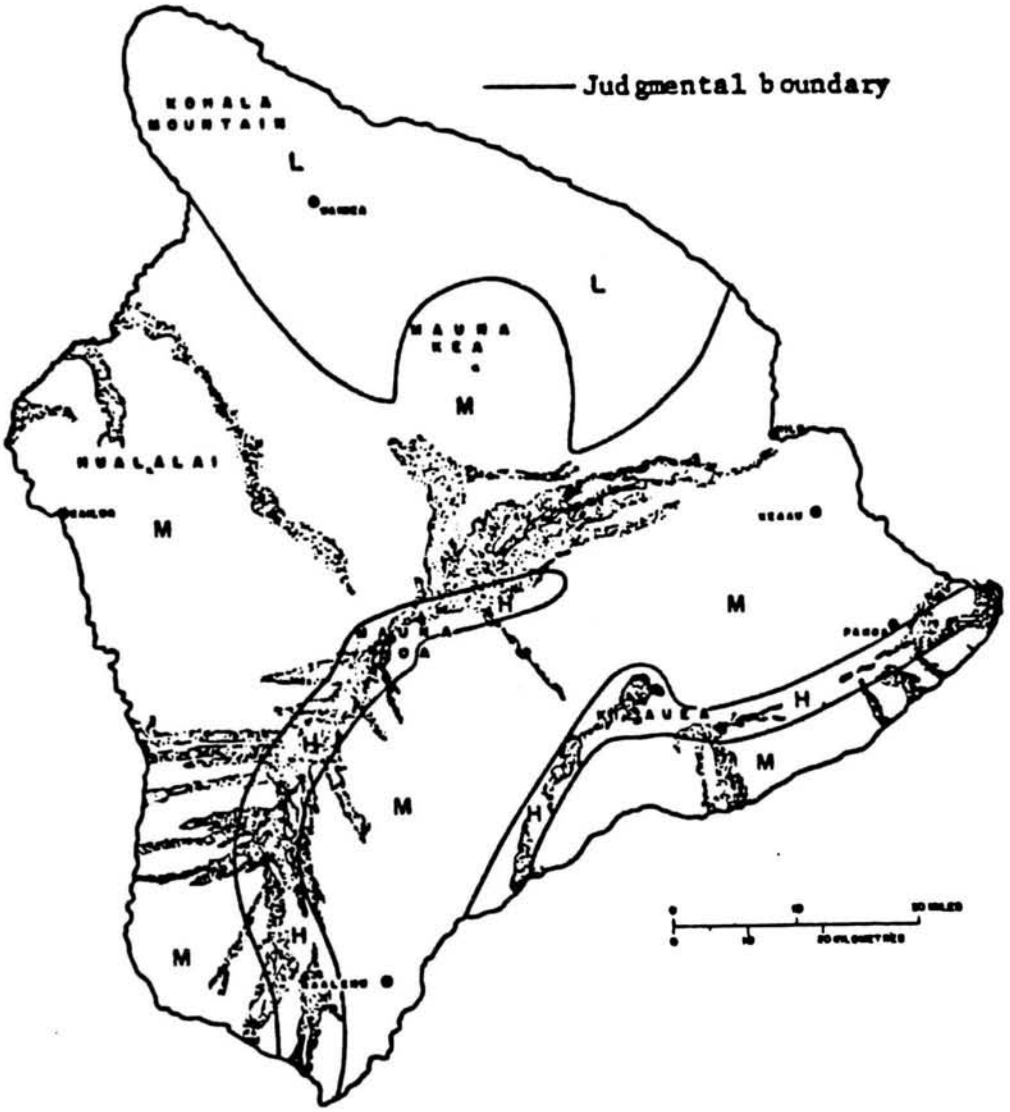


Figure 13. Zones of relative risk from falling volcanic fragments: H, high; M, medium; L, low. (Mullineaux and Peterson, 1974)

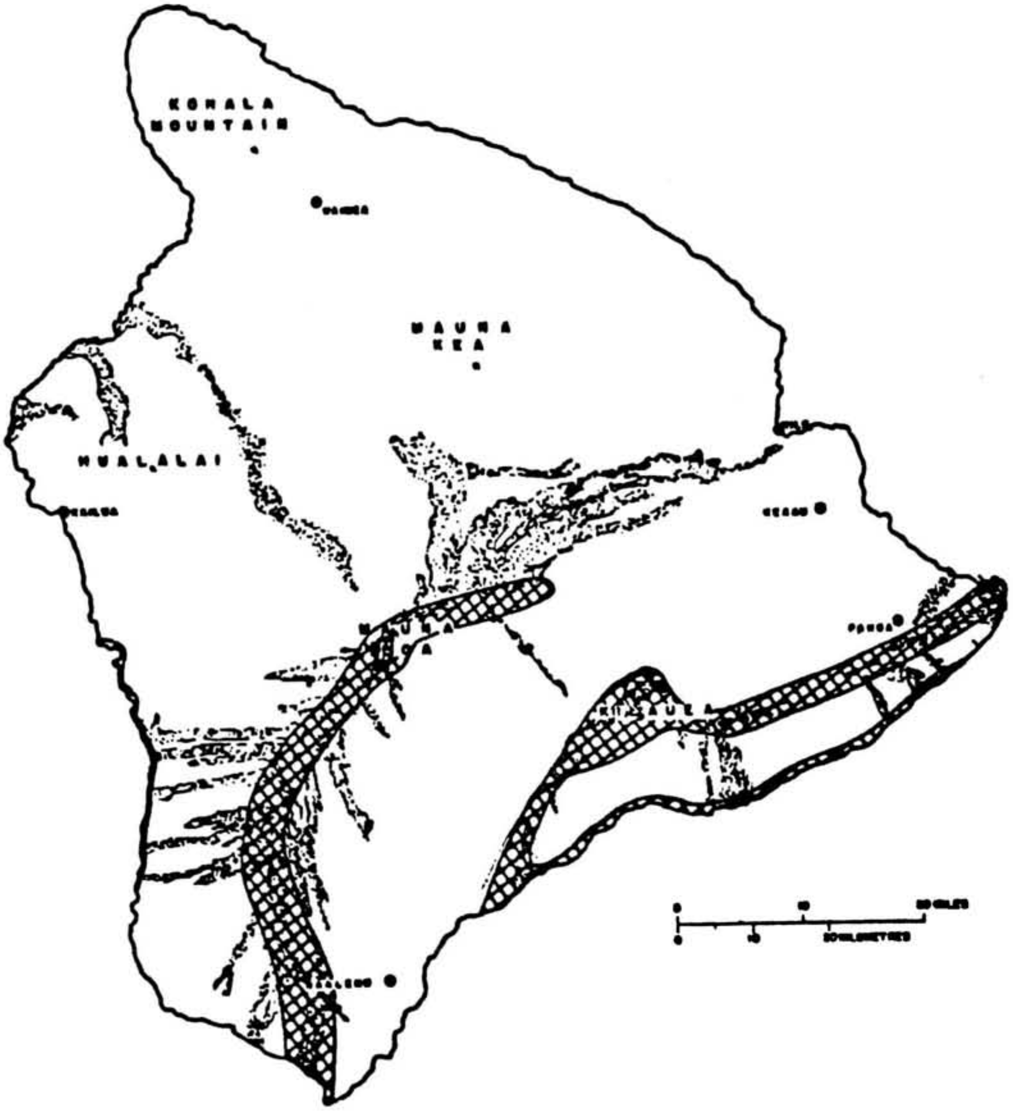


Figure 14. Volcano rift and shoreline zones subject to relatively high risk from subsidence (cross hachured). (Mullineaux and Peterson, 1974)

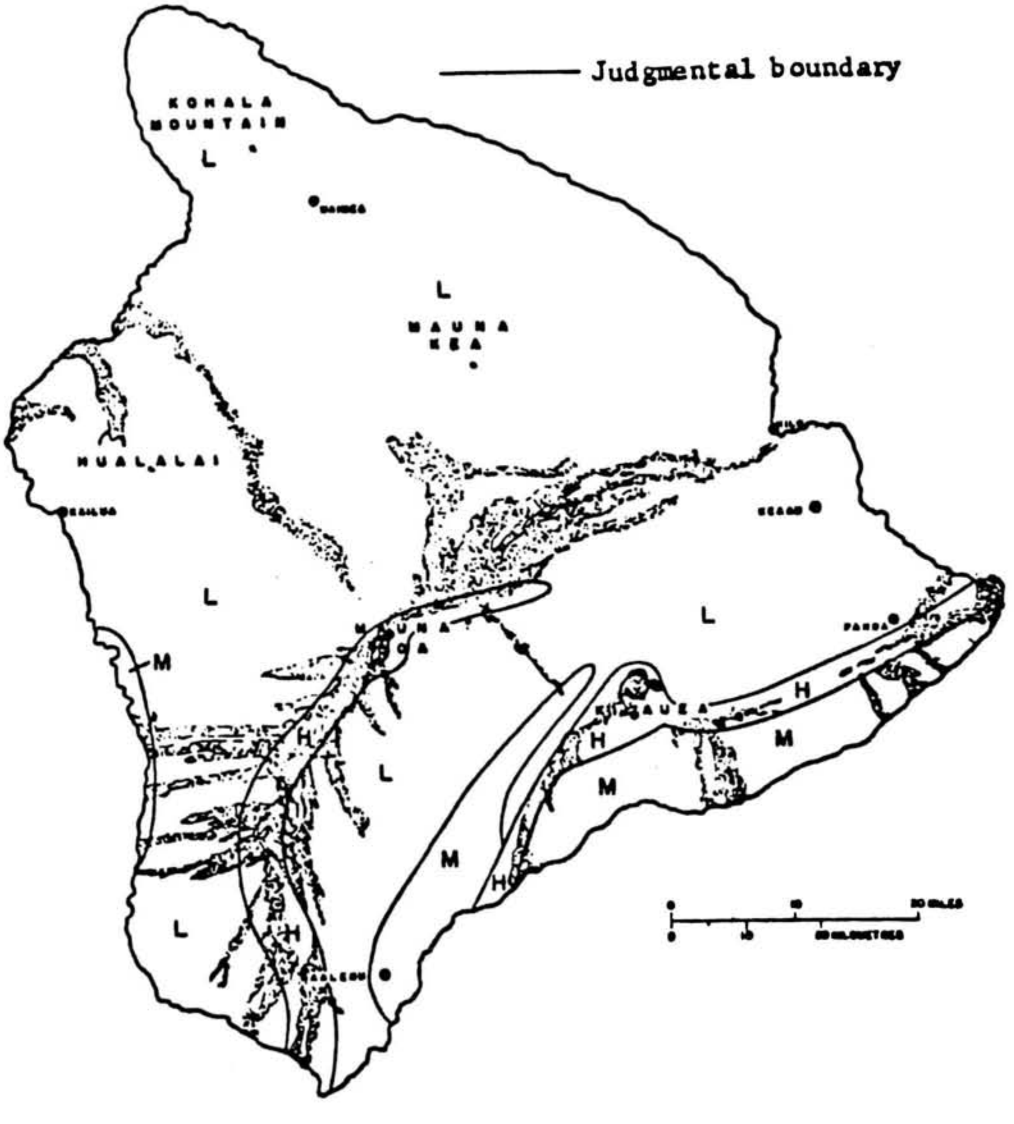
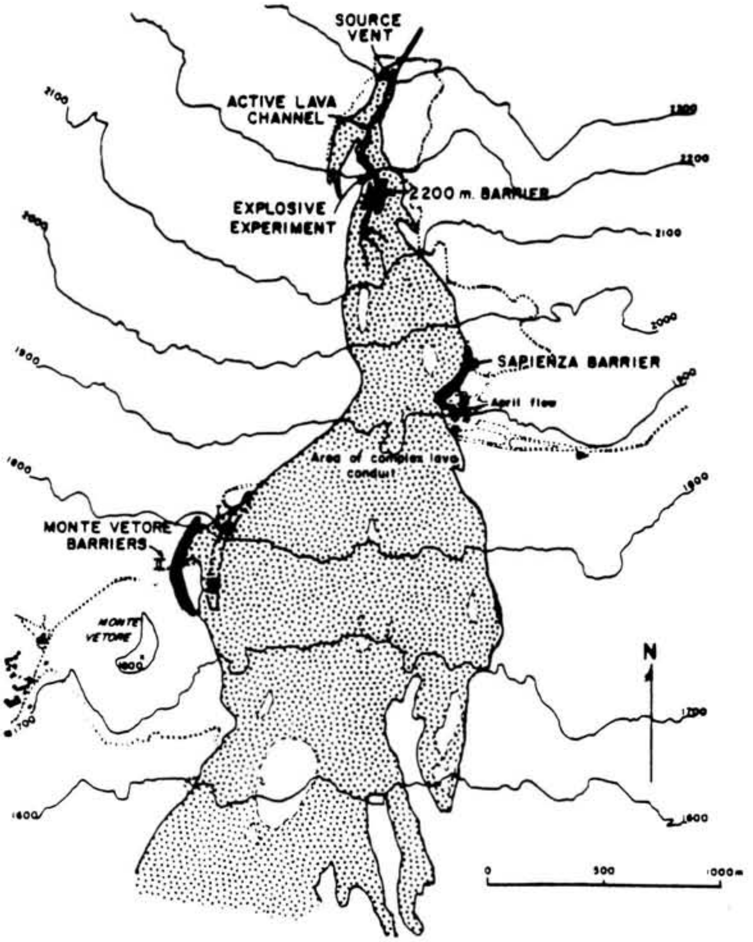


Figure 15. General areas of high (H), medium (M); and low (L) risk from surface ruptures. (Mullineaux and Peterson, 1974)



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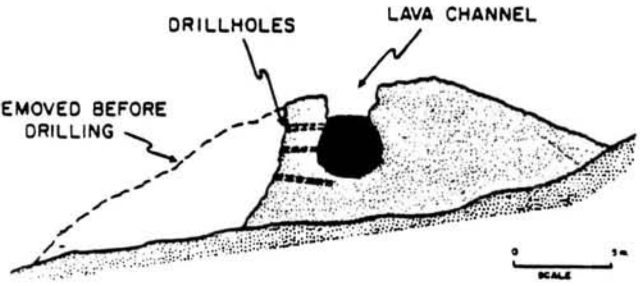

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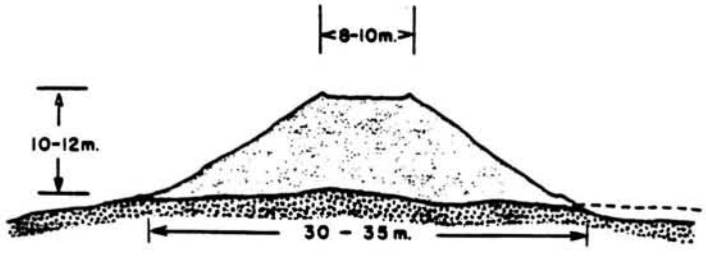

16c

Figure 16A. 1983 lava flow on Mt. Etna in Italy.
Figure 16B. Cross-section of explosives placement area.
Figure 16C. Typical barrier cross-section
(Figures from Lockwood, 1983)

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