# ANALYSIS OF VOLCANIC HAZARD$ FROM MAKUSHIN VOLCANO, UNALASKA ISLAND

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## ABSTRACT

*An* analysis of volcanic hazards in the Makushin region, Unalaska Island, is presented in this paper. Since a major geothermal energy development is now underway on the site, the significance of these volcanic hazards as they pertain to future activities and the design of facilities for geothermal utilizations is enhanced.

A historic analysis of local volcanism is followed by structural analysis. Recommendations for the positioning of facilities and distribution systems are offered. Finally, the impact of this analysis on the plant design is presented.

## INTRODUCTION

An awareness of the growth of energy consumption and the simultaneous natural resource depletion, coupled with a demand for environmental protection, has led to a diversification in power development. Present research and development is now aimed at exploiting energy sources which in the past were largely unknown or ignored; these include oil shale, coal gasification, hydroelectric power, and geothermal power (Otte and Kruger, **1973**). Although the physical characteristics and municipal demands of a specific area place constraints on the type of power and energy source which can be utilized, several regions exist where the future of geothermal energy appears attractive. One such area is Unalaska Island, in the Aleutian volcanic arc of Alaska (Economides and others, **1981**; Reeder, **1981**).

Drilling is currently underway to ascertain the vital characteristics (such as temperature, depth and extent) of the reservoir. If the geothermal resource is such that it can be profitably exploited, the community of Unalaska/Dutch Harbor is likely to provide a ready market in the form of public and industrial consumers.

However, many of the thermal areas on the island are located near Makushin Volcano. This broad domical cone has erupted at least fourteen times since **1760** and is still active today (Drewes and other, **1961**). This paper attempts to identify hazardous areas in the vicinity of Makushin Volcano, and also to recommend various sites where geothermal power facilities may be placed.

## BACKGROUND ON UNALASKA ISLAND

Unalaska Island is the second largest island west of the Alaska Peninsula, comprising an area of approximately 1200 square miles (Figure **1**). The geothermal resource on the island is probably associated with the two oldest lithologies: the Unalaska Formation and a series of granodioritic plutons. The interbedded igneous and sedimentary rocks of the Unalaska Formation are postulated to contain a shallow perched reservoir supplied by meteoric waters which are heated by steam and volcanic gases rising through a vapor-dominated zone from a much deeper reservoir. Fault and fracture systems, generated by the convergence of two major lithospheric plates and also by the forceful intrusion of calc-alkaline plutons, likely act as avenues for the circulation of heated fluids (Motyka and others, **1981**).

The geothermal potential on Unalaska Island is attractive for two reasons. First, the reservoir appears to be a high-temperature system. Initial geologic mapping by Reeder (1981) and geochemical work by Motyka and others (1981) has shown that water temperatures in the shallow perched reservoir approach 150°C, based on silica geothermometry. Drilling of three temperature gradient wells, just completed at press time of this paper, has revealed a maximum bottomhole temperature of 210°C at 400 meters depth of the plutonic rock. Second, the towns of Unalaska and Dutch Harbor support a permanent population of over 1,000 people, and these communities are close enough to the geothermal fields to provide a market for the resource (Figure 2).

## BACKGROUND ON VOLCANIC HAZARDS

The underlying premise of a volcanic hazards study is to predict how an eruption would most likely occur, and how large an area would be affected. This is based on the geologic record preserved in volcanic strata, the tectonic environment involved, and so on. In order to arrive at a conclusion, one must first assume that the volcano will behave in the future as it has in the past. This means that tomorrow's volcanism will be roughly of the same frequency, type and scale as yesterday's eruptive episodes (Crandell and Mullineaux, 1978).

The end-product of such studies is a report which identifies and describes the various risks in the vicinity of a given volcano, and a map which delineates hazardous zones. It must be remembered, however, that the risks may be quite variable throughout any hazard area and are influenced by such factors as local topography, elevation and proximity to source vents. Risks can change either abruptly or gradually across zone boundaries, depending on the nature of the boundary. Abrupt changes in risk are associated with topography features, such as valleys which may funnel and concnntrate lava flows (Peterson and Mullineaux, 1977). An example of a gradational boundary would be the designation of the outer line of a volcanic bomb fallout zone.

### Flowage Hazards

#### Pyroclastic Flows

Pyroclastic flows are defined as air-cushioned avalanches of hot, dry, debris (Kienle and Swanson, 1980). Pyroclastic flows may be associated with volcanic domes (gravitational collapse as in the Merapi type or laterally directed blasts as in the Pelee type), or with the collapse of an eruptive column (Soufriere type). Large volumes of hot air and other gases are liberated within pyroclastic flows. These gases, combined with the cushion of trapped air beneath the flow and the force of the volcanic blast, account for the great speed and mobility of pyroclastic flows. Speeds up to 160 km/h have been reported. Miller and Smith, (1977) have studied several flows on the Alaska Peninsula which surmounted formidable topographic barriers (over 250m) at distances of tens of kilometers from their source.

Pyroclastic flows may also travel for significant distances over and under water. Sparks and others (1980) postulate that pyroclastic flows can move underwater for distances as great as thirteen kilometers without losing their fundamental characteristics.

#### Debris Flows

This category includes landslides and rockfalls, mudflows and lahars, and outburst floods (jokulhlaups). These phenomena, combined with pyroclasitc flows, constitute some of the most destructive and far-reaching effects of volcanism.

Rockfalls, lahars, and mudflows travel in much the same manner as dry debris flows, and present many of the same hazards. Because of their fluid nature they generally follow channels and valleys (Crandell and Mullineaux, 1978; Miller, 1980).

The distance and speed may be sizeable - some have been estimated to travel up to 85 km/h. The velocity is mainly dependent on the viscosity of the fluid and the angle of the slope over which it travels. The Osceola Mudflow from Mt. Rainier covered an area of over 250 square kilometers in the Cascade Range and Puget Sound lowland, and its volume has been estimated at over 2 billion cubic meters (Crandell, 1971).

Water reservoirs which may lead to jokulhlaups are formed at the ice-rock interface beneath depressions in the glacier surface. The initial depression is commonly caused by local areas of high heat flow, which subsequently lead to considerable subglacial melting, causing water to accumulate. Sudden release of this reservoir creates jokulhlaups (Bjornsson, 1975).

#### Lava Flows

Lava flows are coherent streams of molten material which commonly issue in a nonexplosive manner from a volcano and move slowly downslope. Lava rarely moves rapidly unless it is following a well-established channel down a steep slope. The fronts of lava flows usually advance at rates ranging from those which are barely perceptible (0.05 km/h) to about the speed of walking (3.25 km/h) (Miller, 1980).

Lava flows usually do not threaten people directly because their direction of movement can be roughly predicted once they begin. However, such flows are difficult or impossible to control or stop, and considerable property damage may result (Miller, 1980).

## Tephra Hazards

Tephra in this paper refers to molten or solid material of any size (from fine ash to course blocks) which is ejected into the atmosphere above a volcano. Tephra eruptions may be extrememly serious since they can occur suddenly and may be one of the first events in an eruptive episode. Thus there may be little, if any, time to warn those near the volcano (Miller, 1980).

If winds are present during an eruption, the falling particles will form a progressively thinning blanket which stretches from the volcanic vent downwind for hundreds of kilometers (Miller, 1980). The effects of ash fallout are therefore most pronounced near the volcano and along the axis where the ash is thickest.

If the wind direction were to change during an eruption, tephra would be spread over a large area. Consequently the amount deposited at a given location would be reduced. Strong winds during a tephra eruption have a similar effect in that they disperse the same quantity of material over a greater distance downwind. The risks would also be lessened if tephra were to extruded in small increments over a long period of time (Mullineaux, 1974).

## Miscellaneous Hazards

### Earthquakes

The common mode of seismicity in areas of recent volcanism is in the form of earthquake swarms, which are commonly quite shallow in depth. The mean magnitude of the earthquakes comprising the swarm tend to increase with time. Major earthquakes associated with swarms are not known to exceed magnitude $M = 6.5$. This is apparently due to the fact that the strain accumulation in this type of shallow activity is not large enough to produce a major shock (Lomnitz and Singh, 1976).

It must be remembered, however, that even though the quakes themselves are not of exceptional magnitude, they may still be large enough to trigger hazardous events. This is the situation which occured prior to the May 18, 1980 eruption of Mount St. Helens. The actual eruption (lateral blast) was caused by a catastrophic landslide, which in turn was initiated by a magnitude $M = 5.1$ earthquake (Decker and Decker, 1981).

### Tsunamis

Tsunamis are the longer water waves (with periods in the 5 to 60 minute range) generated impulsively by mechanisms such as underwater tectonic displacements, high-speed subaqueous slides, volcanic explosions, and debris flows which enter the ocean. These giant waves spread outward in all directions from their source, and can travel across the deep ocean floor at speeds approaching 800 km/h (Wiegel, 1976). On encountering shallow water they decrease in speed. Some waves have been recorded at heights of over thirty meters (Lambert, 1980).

### Gas Emmission

Active volcanoes may emit large quantities of gas either during an eruptive episode (due to the great decompression which occurs when the melt approaches and reaches the surface), or by quiet degassing from the vent. The most abundant constituent of this gaseous mixture is $H_2O$, followed by $CO_2$, $SO_2$, $H_2S$, CO, $NH_3$ $Cl_2$, and $F_2$ (Kienle and Swanson, 1980).

### Acid Rain

The reaction of volcanogenic material (chlorine and sulfur gases) with atmospheric water can lead to the formation of acid rain. The effects from acid rain may be far reaching. Kienle and Swanson (1980, p. 106), summarizing work by Griggs (1922), state that acid rains from the 1912 Katmai eruption were experienced as far away as Vancouver and Chicago.

### Lightning and Whirlwinds

Lightning flashes are very common during volcanic eruptions, especially volcanian eruptions involving abundant ash. Lambert (1980, p. 32) states that the cause of lightning is believed to be a result of either contact of seawater with magma (or lava), or the generation of static electricity by frictional interaction of colliding particles.

Also common during volcanic eruptions are whirlwinds. Workers in Iceland (Thorarinsson and Vonnegut, 1964) have postulated that the energy for the whirlwinds may come from high-velocity gas jets, heat released into the atmosphere during tephra fallout, or phreatic explosions between lava and seawater.

## HAZARDS FROM MAKUSHIN VOLCANO

Pyroclastic flows, debris flows and tephra fallout present the most serious hazards to life and property in the vicinity of Makushin Volcano. Although other types of risk may arise during a given eruption, they are not as serious.

Several large pyroclasitc flows have originated from Makushin in the recent past. These deposits may be found in Jasper, Bishop, and upper Makushin valleys (Figure 3). The flow in Makushin Valley is the most critical, since this is the present area of sxploratory drilling and the likely area of future power facilities.

The Makushin Valley flow consists of vesicular basalt, andesite, and obsidian clasts up to two meters in diameter within a sand-sized matrix of scoria and glass. The flow is over fifty meters thick, and is at least three kilometers in length.

The three major thermal areas in the vicinity of Makushin Valley are located 4 to 6 kilometers from the summit caldera. These areas offer little or no topographic protection and would be extremely vulnerable to any future flows on the volcano's eastern flank. The location of the drilling camp, directly on the pyroclastic flow, also represents a high risk zone. This is based on the assumption that future flows will follow old patterns.

From a safety standpoint, this assumption dictates that power generating facilities should be located as far from the volcano as is technologically possible. Since, though, heat dissipates to the atmosphere, geothermal fluids cannot be transported far from their point of recovery without suffering substantial heat losses.

A 10" insulated hot water pipeline carrying fluid of initial temperature of 150°C loses approximately 375 kcal/hr per linear foot. A 12" insulated steam pipeline carrying vapor of initial temperature of 200°C loses approximately 500 kcal/hr per linear foot. Table 1 represents the temperature loss of a flow rate of 500,000 kgr/hr of hot water at various distances.

Table 1

Example Output Temperature of Geothermal Water Pipeline. Flow rate 500,000 kg/hr.

$T_{ambient}$ = 5°C $T_{initial}$ = 150°C

| L (meters) | T output |
|---|---|
| 1,000 | 147.5°C |
| 2,000 | 145°C |
| 10,000 | 125°C |
| 20,000 | 100°C |

Table 2 represents the quality loss (i.e., degree of condensation) in a steam pipeline carrying 200 tons/hr of saturated steam of initial temperature of 200°C. The site of temperature gradient well D-2 is approximately 2,000 meters away from Sugarloaf.

Table 2

Example Quality Loss of Geothermal Steam Pipeline. Flow rate 200 tons/hr, $T_{initial}$=200°C $T_{ambient}$ = 5°C

| L (meters) | Steam Quality |
|---|---|
| 0 | 100% |
| 200 | 99.6% |
| 500 | 99.1% |
| 1,000 | 98.2 |
| 4,000 | 92.8% |

During a future volcanic event it is likely that debris flows will be generated. Because of the abundant hydrothermal activity on upland slopes and the 40 $km^2$ ice cap on the summit, debris flows may originate from virtually any location on the mountain. Areas of especially high risk include the broad northern flank of the volcano, along with Scorpio, Glacier, and Makushin valleys (Figure 4). As with pyroclastic flows, the risk from debris flows would be lessened on ridges and elevated plateus away from the volcano (such as the Sugarloaf Plateau).

Damage by tephra fallout comprises another category of major hazards from Makushin Volcano. A large tephra eruption may occur in the future because such eruptions have occured in the past. Individual ash layers over 23 kilometers from the vent are almost one meter thick. The immediate vicinity around the volcano therfore constitutes a high risk zone. Since the prevailing wind direction is from the west, those areas east of the summit are likely to sustain the worst damage (Figure 5).

Although not as serious as the above hazards, potential damage from lava flows is also possible. Quaternary lava flows have occured at several locations around Makushin Volcano. These include Point Kadin, Koriga Point, Table Top Mountain, and Sugarloaf Plateau (Drewes and others, 1961). The movement of lava along a unique structural conduit is thus absent. As with other types of flows, lavas may follow valleys. But since lava flows can inundate level areas and since a well-established flow course from Makushin is not seen, no areas have been designated as lava flow hazard zones. (The Point Kadin rift is discussed separately.)

. Even though earthquakes related to magma movement are not excessively dangerous, tremors related to tectonics present a serious risk in the Aleutian Islands. Recent work by Davies and others (1981) has drawn attention to the Shumagin Gap and the resulting high earthquake potential of this region. Subductive interaction between the Pacific and North American lithospheric plates has in the past produced earthquakes of magnitude M = 8. These workers state that a great earthquake with resultant magnitude up to [illegible] = 9.0 is probable within the next one or two decades.

Since faults and joints may provide avenues for both the escape of lava and the explosive (phreatic) mixing of lava and water, their location and orientation is important. Reeder (1981) has recognized several faults striking between N 40° W to N 70° W in the vicinity of the fumarole fields. Two of these faults (which trend about N 60° W) extend nearly the entire length of northern Unalaska Island, a distance of over 36 km. These two active faults bound the largest fumarole field in the area (Figure 2). Reeder states that such faults probably penetrate deep into the crust, where they may contain magma. Extensive flows and vents of recent age at the Point Kadin rift indicate that this magma reached the surface. Therefore, the Point Kadin rift, and its southeast extension, represents a proven crustal weakness which could again be the site of volcanism in the future.

The final variable which must be identified in order to predict the severity of an eruption and the location of hazardous zones is the chemical composition of the magma body. Kienle and Swanson (1980, p. 68) explain that silica forms a three dimensional molecular framework due to its polymerization with Oxygen. The higher the silica content of the magma, the larger the polymers. Since flowage of the magma (or lava) is related to the size and abundance of these polymers, silica-rich magmas ($SiO_2$ = 65%) will be much more viscous and flow slower than silica-poor magmas. Because of this high resistance to flow, silicic magmas cause violent explosions during volcanic eruptions (such as Tambora, Katmai, and Krakatoa).

In contrast to these violent eruptions are the relatively mild events associated with magma of basic compositions. These basalts have a significantly lower silica content (approximately 50%). This means that there are fewer polymers within the melt to retard flowage. As a result, volcanic eruptions are commonly characterized by fluid lava flows which emanate rather quietly from their source vents. Although tall lava foundations may be produced during the early stages of volcanism, these eruptions do not approach their silicic counterparts in violence.

This $SiO_2$ content of volcanic rocks from Unalaska Island (both the Makushin volcanics and the Eider Point basalts) range from 49.5 to 63.0 weight percent (Drewes and others, 1961). Most of the samples, however, are located closer to the basic end of the spectrum (49-53 wt.% $SiO_2$). An argument could thus be made that the most likely type of future activity would not be of the violent, silicic nature. A further point supporting this contention is that many soil-ash profiles near Makushin display an upward decrease in grain size of pyroclastics, and this may indicate a gradual decrease in violence and frequency of eruptions (Drewes and others, 1961). These two observations could therefore suggest that the volcanic hazards from Makushin Volcano are not extreme.

## CONCLUSIONS

In light of our study two locations are recommended for power facilities. These sites are interpreted as representing the most reasonable locations given the contrasting influences of fluid transport and safety.

The first location is on Sugarloaf Plateau, roughly eight kilometers northeast of Makushin summit (Figure 6). Of the two recommended sites, this is closest to both the volcano and the geothermal areas.

Sugarloaf Plateau is a gently rolling plateau of basaltic lava which dips northward. The best location for power facilities would be northeast of Sugarloaf Cone. This area would likely provide protection from the hot avalanche position of a pyroclastic flow since it lies over 300 meters above the valley bottom and is screened from the valley by Sugarloaf Cone. The same reasoning applies to debris flows, which should be deflected away from the Sugarloaf vicinity and into the drainage of the Makushin

River. Furthermore, this site is judged to be safe from tsunami hazard, for besides the fact that this location is 450 meters above sea level it is also seven kilometers inland from Driftwood Bay (on the north) and eleven kilometers inland from Broad Bay (on the east).

The main hazards to life and property at this location would be from tephra fallout and nuees ardentes. Since the Sugarloaf Plateu is extremely close to the source vent it could conceivably receive damage by volcanic bombs or fine ash particles. Also, those areas east of the summit would probably incur the heavient damage from tephra due to prevailing winds (Figure 5). Another possibility is that the glowing cloud portion of a pyroclastic flow cauld detach itself from the underlying avalanche and seriously damage generating structures (Figure 4). If such an event were to occur, the screening effect of Sugarloaf Cone could prove to be insignificant. A final consideration is that structures built here should be located away from local depressions. These depressions, a common feature on this undulating plateu, could be extremely dangerous since they may concentrate and confine noxious gases.

The second location is in Vista Canyon, approximately nine kilometers east of Makushin's summit (Figure 6). Although this site is also close to the summit caldera, it is protected from eastward balsts by the north-trending massif of Vista Ridge. This ridge provides a barrier over 300 meters high. Therefore, this canyon would likely be protected from both the basal avalanche and glowing cloud portions of pyroclastic flows, and from debris flows. Since this area is away from known points of lava extrusion, and since no major faults in the Unalaska Formation (which may provide lava pathways) have been mapped through here, this site should also be safe from lava flows. Tsunamis would not be a problem since this area is over 400 meters above sea level and ten kilometers inland. But as with the first location, this site would also be susceptible to tephra fallout.

As it appears from Table 2, a substantial loss in quality will be experienced in transporting saturated steam. This loss will result in an unacceptable composition of the inlet fluid in power generating turbines. So while the distance between Sugarloaf and the reservoir site is necessary to alleviate volcanic hazards, an unavoidable by-product is the installation of large gas-liquid separating vessels at the entrance of the power plant. This would increase substantially the cost of construction.

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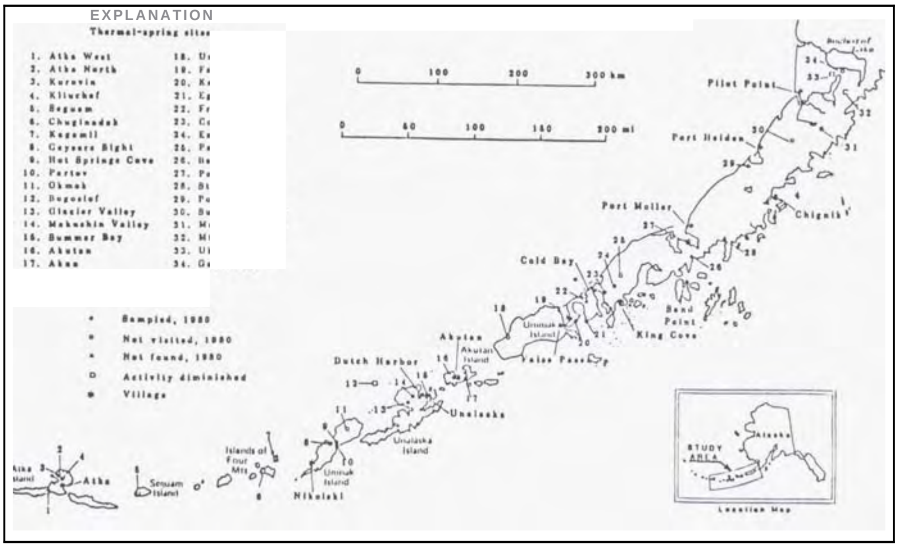


Figure **1**: .Reported thermal sites in the Aleutian arc, from Becharof Lake to Atka Island (From Motyka and others, **1981**).

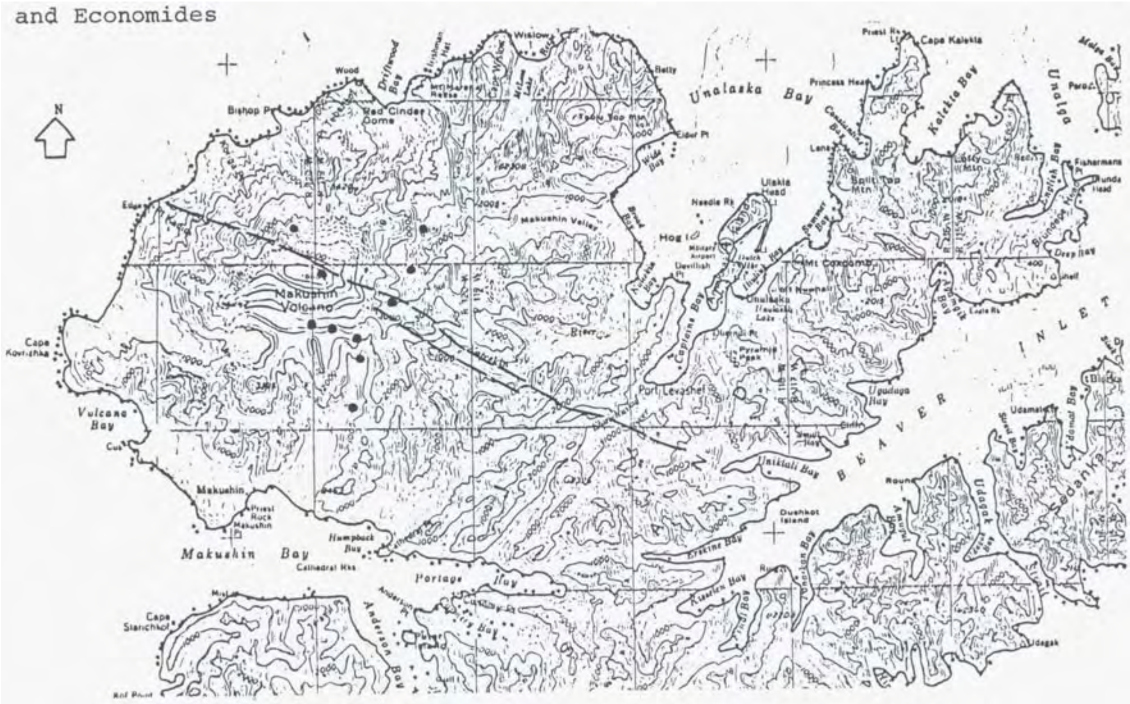


Figure 2: Locations of major thermal sites (dots) on northern Unalaska Island, and trend of faults (From Reeder, 1981).


Figure 3: Locations of known pyroclastic flows around Makushin Volcano (From Drewes and others, 1961; Reeder, 1981).


Figure 4: Zones of probable damage due to flowage hazards from future eruptions of Makushin Volcano. Dashed pattern indicates hazard zone from moderate eruption. Slanted pattern indicates hazard zone from large eruption.

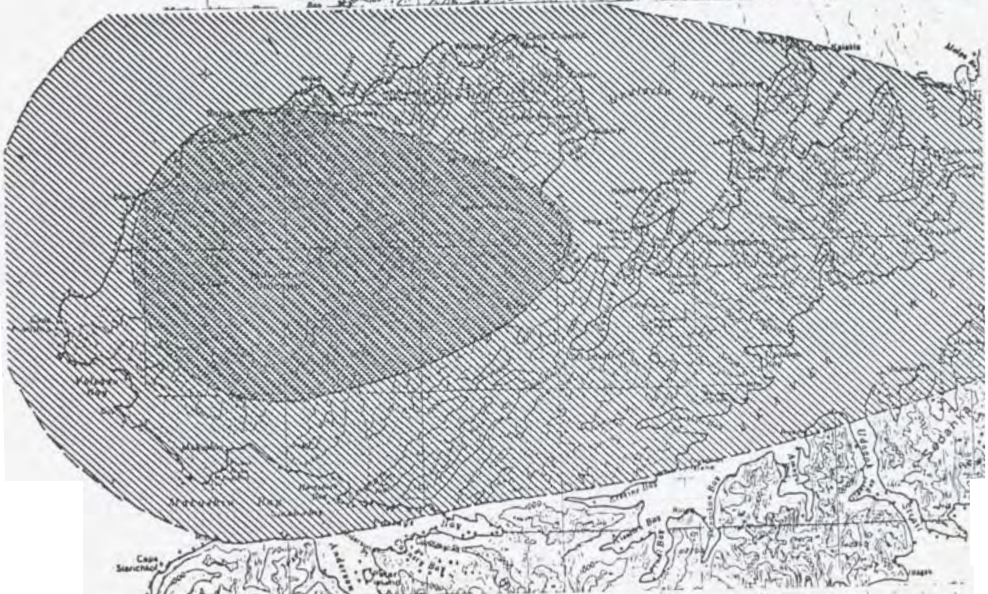

Figure 5: Zones of probable damage due to tephra fallout from future eruptions of Makushin Volcano. Dashed pattern indicates hazard zone from small to moderate eruption, with western radius of 10 km and elongate eastern lobe due to prevailing winds. Slanted pattern indicates hazard zone from moderate to large eruption, with western radius of 20 km.


Figure 6: Locations of recommended power plant sites (triangles) and major thermal sites. Dashed lines indicate possible powerline routes, and dotted lines indicate underwater routes.