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HYDROTHERMAL RESOURCES OF THE NORTHERN PART OF UNALASKA ISLAND, ALASKA

By
J.W. Reeder

STATE OF ALASKA
Department of Natural Resources
DIVISION OF GEOLOGICAL & GEOPHYSICAL SURVEYS

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INTRODUCTION

During DGGS geologic investigations of Unalaska Island in the summer of 1980, previously unreported active fumaroles and hot springs were located in the Makushin Volcano region. To date, eight fumarole fields are known to exist there. Large vapor-dominated hydrothermal reservoirs are suspected to exist in the area of the fumarole fields located on the southeast flank of Makushin Volcano.

BACKGROUND

The Makushin Volcano of Unalaska Island is one of at least 36 volcanoes on the Aleutian Islands arc that have been reported active since 1760 (Coats, 1950). Volcanic regions such as this, with shallow magma bodies and deep tectonic fracture systems, represent a setting favorable for the existence of large hydrothermal reservoirs.

Active hydrothermal surface manifestations have been known to exist on Unalaska Island for some time. Dall (1897, p. 472) stated, "In Unalaska, near Captain's Harbor, a thermal spring exists, with a temperature of 94° Fahrenheit, containing sulphur in solution." This is believed to be the warm spring located near Summer Bay (Reeder, 1981a), 5 km east of the community of Unalaska (fig. 1).

On rare clear days, a plume from an impressive fumarole field can be seen near the top of Makushin Volcano. This field has received attention in the past because of its known sulfur deposits (Maddren, 1919). Early investigations of sulfur deposits throughout this region resulted in the discovery of other hot springs and fumarole fields on the lower flanks of Makushin Volcano. Some of these discoveries are still known (Henry Swanson, R.G. Schaff, and W.E. Long, pers. commun., 1980), even though no written documentation of these early observations have been found. Exploration pits and cairns (p. 14) can still be seen at some of the fumarole fields.

Drewes and others (1961) observed fumaroles and hot springs on the southern flank of Makushin Volcano. Later, Miller and Smith (1977) suggested that a high-level magma chamber exists under the 3-km-dia summit caldera of the volcano.

Warm springs were also reported to exist in the northeastern part of Makushin Valley near Broad Bay (Swanson, pers. commun., 1980). Several large ponds in this region were checked during 1980, but no anomalously warm waters were found. Air reconnaissance in February 1982 showed ponds and swamps devoid of ice and snow in the northeastern part and along the southern edge of Makushin Valley. These unfrozen areas might be due to ground-water seeps at normal ground-water temperatures.

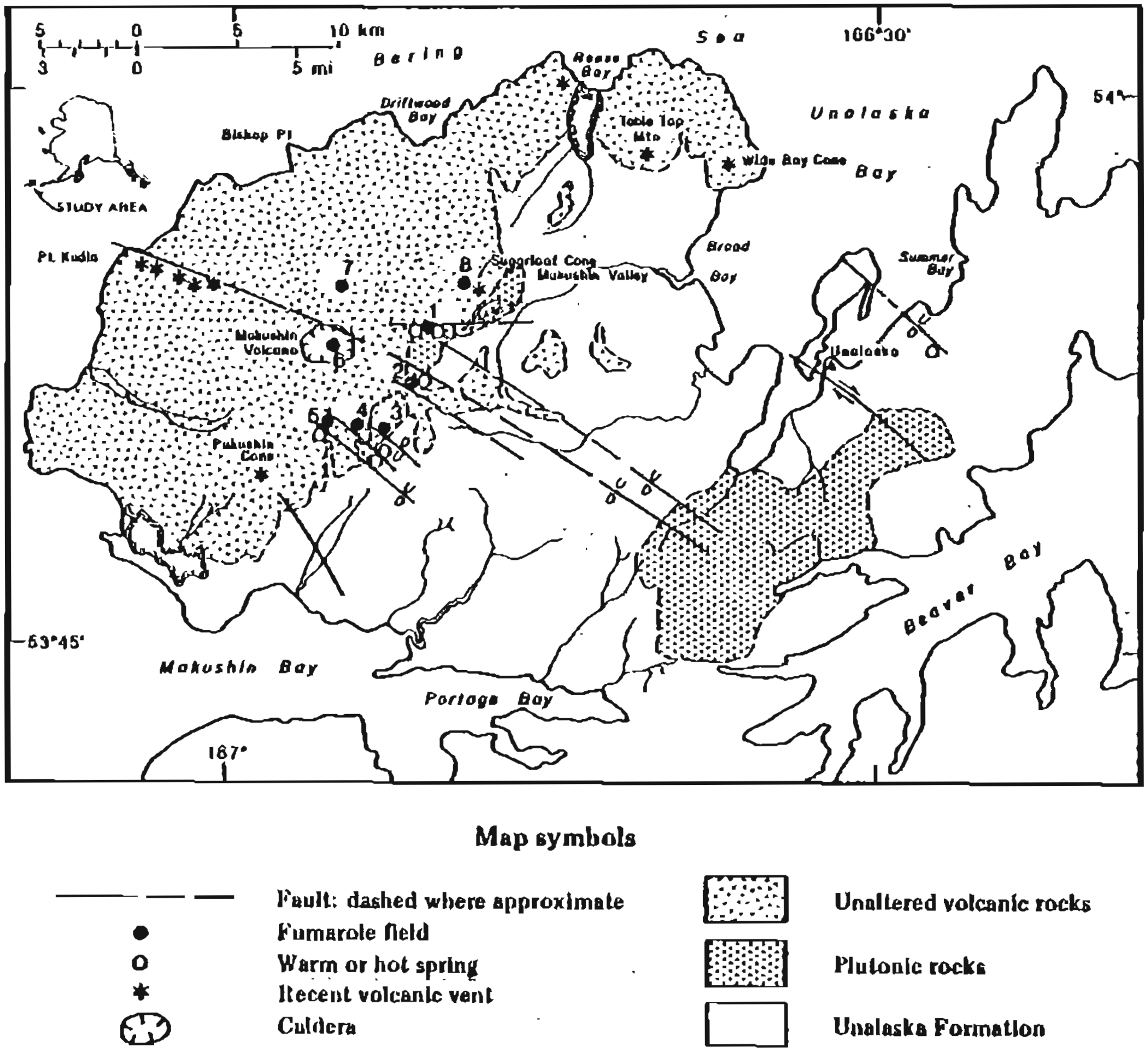

Figure 1. Simplified geologic reconnaissance map of the northern part of Unalaska Island.

The DGGS field party (Reeder, 1981b) discovered more active fumarole fields on the flanks of Makushin Volcano, bringing the total fields to eight (numbered clockwise in fig. 1).

APPLICATION

The Unalaska community serves the largest American fishing fleet for the Bering and North Pacific region and it could play a major role in the development of a bottomfish industry. In addition, there is a nearby potential for Outer Continental Shelf oil, gas, and mineral production. Present peak electric utility demands for Unalaska is 15 MW, including both the publicly owned diesel generators and those operated by the private fish processors. Projections for future energy demands are very uncertain, but peak demands by the year 2000 could reach 50 MW. Such energy demands and the previously mentioned observations of fumaroles and hot springs prompted the state (Markle, 1979; Reeder and others, 1980a,b) to develop a geothermal exploration plan for Unalaska Island.

FUMAROLE FIELDS

The Makushin fumarole fields vary in character and size (table 1). Fumarole fields 1-3 consist of fumarolic (boiling-point) activity, of warm ground, and of outcrops of highly hydrothermally altered plutonic and metavolcanic rocks (figs. 2-4). Field 4 consists of fumarolic activity in lateral moraine deposits along a stream (fig. 5). Pressurized fumarolic activity and warm ground occur in unaltered agglomerates at field 5 (fig. 6). A fairly large steam vent and corresponding fumarole field occur near the summit of Makushin Volcano. Part of this field occurs on a small volcanic dome of unknown composition and within the remains of a cinder cone partly covered with sulfur deposits (fig. 7). This field (no. 6) is located near the center of the 3-km-dia summit caldera of Makushin Volcano. Field 7 consists of fumarolic activity located in andesites covered by pyroclastics and tills (fig. 8). Field 8 consists of minor fumarolic activity, and of hot rock positioned on top of a small knob (fig. 9a); the field is located just west of Sugarloaf Cone in a region of unaltered basaltic andesites as based on the classification scheme of Jakes and White (1972).

Some warm and hot springs were found near the fumarole fields at lower elevations (fig. 1, table 1). Initial water analyses of some of these hot and warm springs (Motyka and others, 1981) indicated near-neutral sodium-bicarbonate-sulfate waters similar to hydrothermal waters described by Mahon and others (1980), which consisted predominantly of meteoric waters that had been heated by vapor-dominated hydrothermal systems generated from greater than 150°C alkali-chloride waters at greater depth. The term 'vapor-dominated hydrothermal systems' was originally coined by White and others (1971) for those systems in which the reservoir fluids are mainly vapor, not liquid; i.e., wet, dry-saturated, or superheated steam. The hot springs in the Makushin Volcano region probably derive most of their water from near surface-water or shallow ground-water sources, and most of their heat from the vapor-dominated hydrothermal systems that are the source of the fumaroles throughout the region.

Table 1. Some of the characteristics of the fumaroles and hot springs of Unalaska Island.

Fumarole Field	Elevation (meters above sea level)	Types of exposed rock	Approx. area of fumarole activity incl. warm ground & assoc. altered bedrock	Max. recorded surface temp. within the fumarole field	Hot Spring locations	Max. recorded temp. and corresponding ph for hot springs immediately outside of fumarole field
No. 1	350 - 370	Plutonics and some metavolcanics	3,000 m^2	98°C	W/in fumarole field, immed downslope from field along stream, & upstream from field up to 0.6 km	68°C/5±
No. 2	650 - 910	Plutonics and metavolcanics (solifluction & landsliding is occurring in field)	0.30 km^2	97°C	W/in fumarole field & immed. east of field in canyon at 600 m elevation	90°C/5.5±
No. 3	520 - 580	Plutonics and metavolcanic	0.20 km^2	98°C	W/in fumarole field & at several locations downstream up to a distance of 1.0 km	96°C/6±
No. 4	560 - 590	Lateral moraine, volcanics & metavolcanics	4,000 m^2	97°C	W/in fumarole field (canyon to south was not explored & might contain hot springs and/or fumaroles)	-
No. 5	800 - 820	Volcanic breccias (agglomerate)	4,000 m^2	97°C	W/in fumarole field & to southwest by about 0.2 km	71°C/Unknown
No. 6	1650 - 1710	Volcanic dome of unknown composition, pyroclastics & sulphur	0.1 km^2 (plus 0.2 km^2 region shows some signs of icefield thaw)	94°C	none found	-
No. 7	820 and at 860	Andesites covered by pyroclastics and tills	1000 m^2	96°C	On the eastern margin of the lower fumarole field	67°C
No. 8	520	Basaltic andesite	1000 m^2	86°C (at 0.25 m depth)	None found	-
Summer Bay Warm Springs (No fumaroles)	3	Metavolcanics and alluvium	Main warm spring about 2m^2, 2nd spring @ 0.25 m^2 & warm ground to 40 m of springs	-	Two closely located springs occur at edge of a marsh just SE of Summer Bay lake. Max. temp. of springs 35°C at pH of 7.0	-

Figure 2. The main part of fumarole field 1, looking northeast (July 24, 1980).

Geochemistry indicates that the fumaroles in the Makushin Volcano region are from more than one large vapor-dominated hydrothermal system. In 1980, two shallow exploration wells drilled into unconsolidated deposits near the Summer Bay warm springs encountered an artesian aquifer with a temperature of 50°C and a natural flow rate of 190 lpm (Reeder, 1981a). The waters from these wells and the main Summer Bay warm spring have similar ratios of major ions (fig. 10), which indicates a common thermal fluid ('parent'). By contrast, the waters from the hot springs of the Makushin Volcano region all have different ratios of major ions (fig. 10), which indicates the existence of chemically different vapor-dominated systems. It is also possible (but less likely) that rising vapors are mixing with chemically different shallow ground waters or surface waters to cause different ratios of major ions at the different hot springs.

GEOLOGIC SETTING

The rocks of Unalaska Island include an older group of altered sedimentary and volcanic rocks designated the Unalaska Formation by Drewes and others (1961), a group of intermediate-age plutonic rocks, and a younger group of unaltered volcanic rocks. The three groups can be correlated with those found throughout the eastern and central Aleutian Islands, namely, an early series of a marine volcanic and sedimentary sequence that has been metamorphosed to a greenschist grade, a middle series of plutonic rocks, and a late series of an

Figure 3a. Makushin Volcano, looking west-northwest (Feb. 27, 1982). Fumarole field 2 dominates the foreground, as outlined by thaw region (photograph taken 3 days after a fresh snow). Steam cloud near the summit of volcano marks the location of fumarole field 6.

unaltered sequence of Tertiary subaerial volcanic and sedimentary rocks (Marlow and others 1973). The early series is believed by Marlow and others (1973), Scholl and others (1975), and DeLong and others (1978) to be Eocene to middle Miocene, 53 to 15 m.y. old. The sedimentary and volcanic rocks of the Unalaska Formation found in the Makushin Volcano region have been altered by albitization, chloritization, epidotization, silicification, and zeolitization. The middle series or middle unit consists of plutons mainly of granodiorite that have intruded the early series. These rocks have radiometric dates of 10 to 15 m.y. before present (Marlow and others, 1973; DeLong and others, 1978). Perfit and Lawrence (1979) argued that the rocks of the Unalaska Formation were altered mainly during the emplacement of these plutonic bodies. The late series, which consists of basaltic and andesitic rocks that unconformably overlie the early and middle series, is up to at least 3 m.y. in age, based on radiometric ages from andesitic magmas (Cameron and Stone, 1970).

The region southeast of Makushin Volcano consists mainly of rock exposures belonging to the Unalaska Formation, whereas unaltered volcanics make up the Makushin Volcano and most of the rock exposures to the northwest of a line extending from Pakushin Cone to Table Top Mountain (fig. 1). Except for Pakushin Cone, the cones contained in the area have been subjected to intense

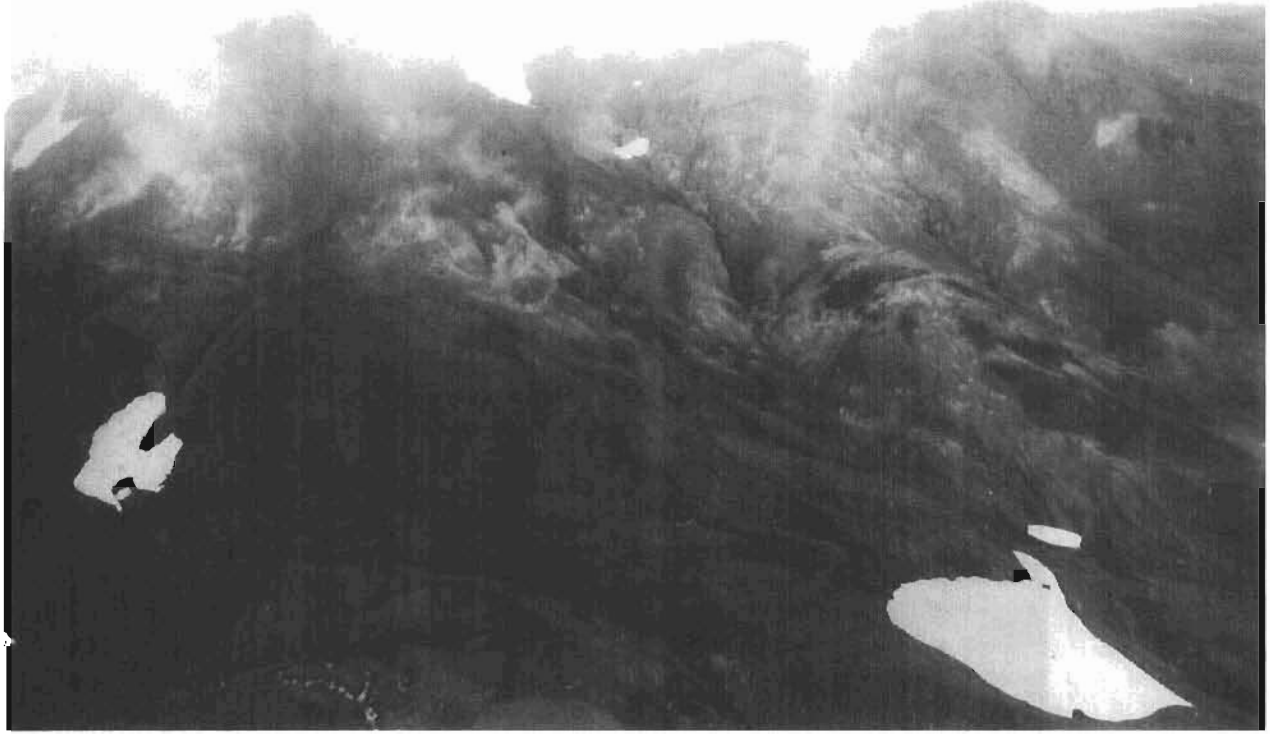

Figure 3b. The main part of fumarole field 2, looking northwest (Aug. 8, 1980)

glacial erosion. Both the Pakushin and Wide Bay Cones, which lack intense glacial erosion, are suspected to have formed since the last glacial maximum which ended about 11,000 yr ago (Black, 1976). The line of cones trending toward Point Kadin (fig. 1) and the corresponding extruded lavas are believed by Drewes and others (1961) to have formed within the last several thousand years; they based their claim on the lack of glacial erosion on the cones and flows, and on the degree of development of a submarine bench at Point Kadin. On the basis of the large lichens on the surfaces of some of the scoriaceous andesites exposed on the largest of these explosions craters, these craters are at least several hundred years in age.

A fairly thick sequence of pyroclastic deposits, which are similar to the flow type described by Sheridan (1979), occur in three valleys located in the region roughly outlined by fumarole fields 2 and 7, Bishop Point, Driftwood Bay, and Sugarloaf Cone. These tephras collectively represent a volume of about 0.21 km^3, about half of which occupies the upper reaches of Makushin Valley just below fumarole field 2 and near fumarole field 1. In the second largest deposit, 0.08 km^3 of material occupies the valley leading from field 7 to Bishop Point. The remainder, 0.03 km^3, occurs in a valley located between fields 7 and 8, and Driftwood Bay. There are other pyroclastic flow deposits in the Makushin Volcano region, such as a deposit between fields 3 and 4, but none approach a volume of more than 0.001 km^3.

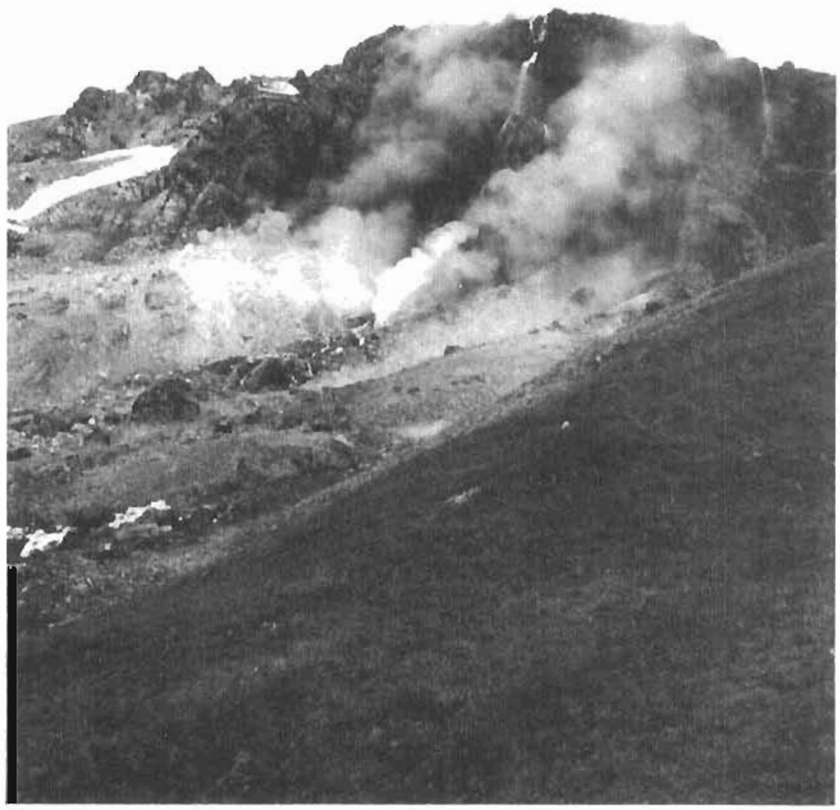

Figure 4. Part of fumarole field 3, looking northwest (Aug. 11, 1980). (Photograph courtesy K.E. Swanson).

A 60-m-thick section of these pyroclastics is exposed across the creek from fumarole field 1. At the base of this section is a pyroclastic surge deposit at least 6 m thick with antidune bed forms. Glacial tills are exposed between pyroclastics and bedrock just upstream from this exposure, and tills probably underlie this unit at shallow depths. Atop the unit is a 1-m-thick ungraded mixture of ash, lapilli, blocks, rounded boulders, and assorted debris. This lahar contains a few plutonic rock fragments. The next unit is a welded tuffaceous agglomerate of up to 3 m thick. The dark-gray color and hardness of this unit distinguish it from the other units; andesitic glass blocks are plentiful here. Atop this unit are about six normally sorted ash-lapilli flows, each up to 12 m thick. Similar ash-lapilli flow units were recognized at the other two large pyroclastic deposits.

Figure 5. Part of fumarole field 4, looking east (Aug. 8, 1980).

The surfaces of the large pyroclastic deposits, which are thought to be related to a large eruption of Makushin Volcano that occurred since the last glacial maximum ending about 11,000 yr ago, slope away from the volcano. The volume of pyroclastic material involved indicates that the eruption was related to the formation of the 3-km-dia Makushin summit caldera. On the basis of the sequence of pyroclastic deposits at fumarole field 1, the eruption probably began as a large vertical eruption cloud which collapsed to form large pyroclastic surges. Following this, enough time elapsed for debris to flow along some the drainages of the volcano. Explosions then destroyed the summit by ejecting large quantities of material into the atmosphere, the caldera collapsed, and large amounts of magma and debris flowed north and east. The lack of soil horizons within this sequence indicates that the deposits were probably formed over a fairly short period of time, certainly no longer than several years.

The Unalaska Formation in the region of fumarole fields 1-3 has been extensively intruded by bodies of intermediate plutonic rocks and some gabbro. The bodies and the surrounding Unalaska Formation are extensively fractured, especially along contact boundaries. A common joint system that strikes between N. 30°-35° E. with an 80°-90° S. dip in this contact region aligns roughly with fumarole fields 1, 2, 3, and 8 and with the orientation of many of the valleys. The fractures probably serve as conduits for hydrothermal convection. The hydrothermal surface manifestations of fumarole fields 1 and 2

Figure 6. Fumarole field 5, looking west (Aug. 12, 1980).

(fig. 1) are oriented east to northeast along respective northern and southern boundaries of an intervening plutonic body. One prominent near-vertical fracture on the northern boundary of this pluton strikes east-west directly through fumarole field 1.

Other near-vertical fractures, striking N. 40°-70° W. and appearing to be normal faults, were found near the fumarole fields (fig. 1). One fault, which strikes N. 60° W. at field 2, extends nearly the entire length of the northern part of Unalaska Island, a distance of over 36 km.

The Aleutian arc is part of a ridge-trench system associated with active volcanism and seismicity. The Aleutian Trench is located about 180 km south of Unalaska Island. Global tectonics has the floor of the Pacific Ocean (the Pacific Plate) approaching the Aleutian arc (the North American Plate) in a northwesternly direction at a rate of about 7 cm/yr (Minster and others, 1974). On the basis of seismic models, the Pacific Plate dips about 30° under the Aleutian arc until it reaches a depth of about 40 km, where its dip increases abruptly to about 70° (Jacob and Hamada, 1972); thus, the Pacific Plate at the Aleutian Trench is being thrusted under the North American Plate.

This underthrusting causes compressional stresses in the direction of plate convergence in the arc region (Nakamura, 1977). Therefore, because the Pacific and North American Plates converge at about N. 45° W. at Unalaska

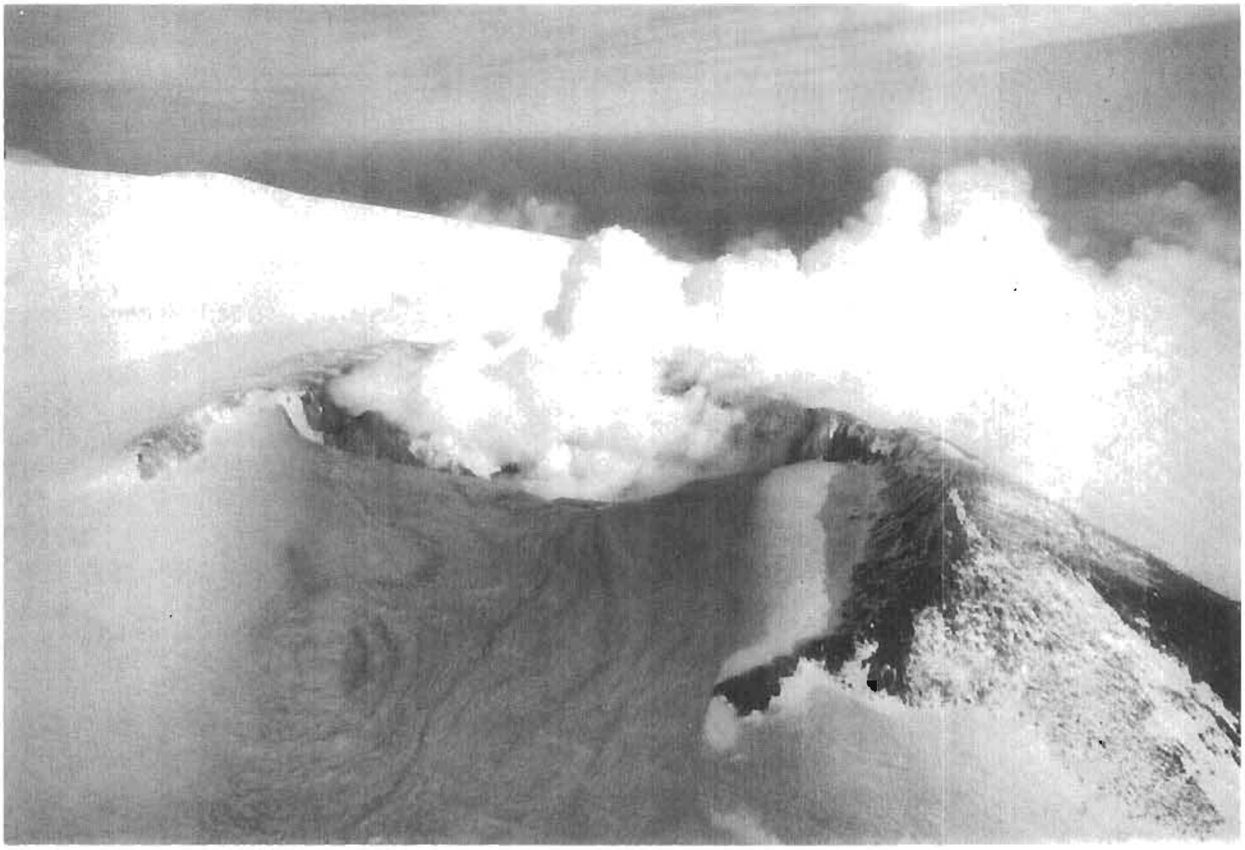

Figure 7. Fumarole field 6, looking northwest (Aug. 11, 1980).

Island, these near-vertical northwest-striking fractures are suspected to have been caused by compressional tectonic stresses. The fractures, even though they correlate with most of the fumarole fields, do not appear to influence the actual surface configuration of the hydrothermal manifestations. Moreover, they do not appear to serve as conduits for hydrothermal convection, at least not near the ground surface.

For Makushin Volcano, Nakamura (1977) determined, on the basis of orientation of flank eruptions, a maximum stress orientation of N. 60° W. where the expected azimuth should be about N. 45° W. If the expected azimuth is the actual one, the recognized fractures striking about N. 60° W. should contain a strike-slip component. As shown in figure 1, one N. 60° W. fault near the community of Unalaska has such a strike-slip component (based on observed slickensides).

HYDROTHERMAL RESOURCE POTENTIAL

Large vapor-dominated hydrothermal systems probably exist in the northeast-oriented zone roughly marked by fields 1-4. Lava flows that still retain details of their constructional forms can be found to the a) northwest (flows from the upper reaches of Makushin Volcano and from the prominent rift zone near point Kadin), b) northeast (flows surrounding the Sugarloaf Cone), and c) southwest (the volcanic rocks of the Pakushin Cone). Yet, no such

Figure 8. Fumarole field 7, looking west (Aug. 1968). (Photograph courtesy W.E. Long)

deposits have been found within the northeast-oriented zone or in the region to the southeast. In fact, no unaltered volcanic rocks have been recognized as being extruded from this zone, which indicates that no magma extrusions have occurred in this region for the last 3 m.y.; this is corroborated by the known range of radiometric age dates for unaltered volcanics for the Aleutian arc (Cameron and Stone, 1970). A few basaltic and andesitic dikes of unknown age are exposed in the region, but again no corresponding extruded deposits have been found. There have been few, if any, extrusions because the magma probably has not existed at depth. However, there is also the possibility that the magma has been and may still be at depths of several kilometers where it could be more viscous than magmas to the northeast or southwest. If such deep magma bodies exist in the region, they might have a dikelike configuration oriented in a direction corresponding to the N. 60° W. fractures shown in figure 1; these bodies and any magma bodies located near the volcanic centers to the west, northwest, and north could be the heat sources for any large vapor-dominated hydrothermal systems.

In contrast, any hydrothermal convective systems linked to fumarole fields 5-8 are suspected to be limited to shallow zones, where any heat sources would also be at shallow depths. Such sources might be due to either recent surface

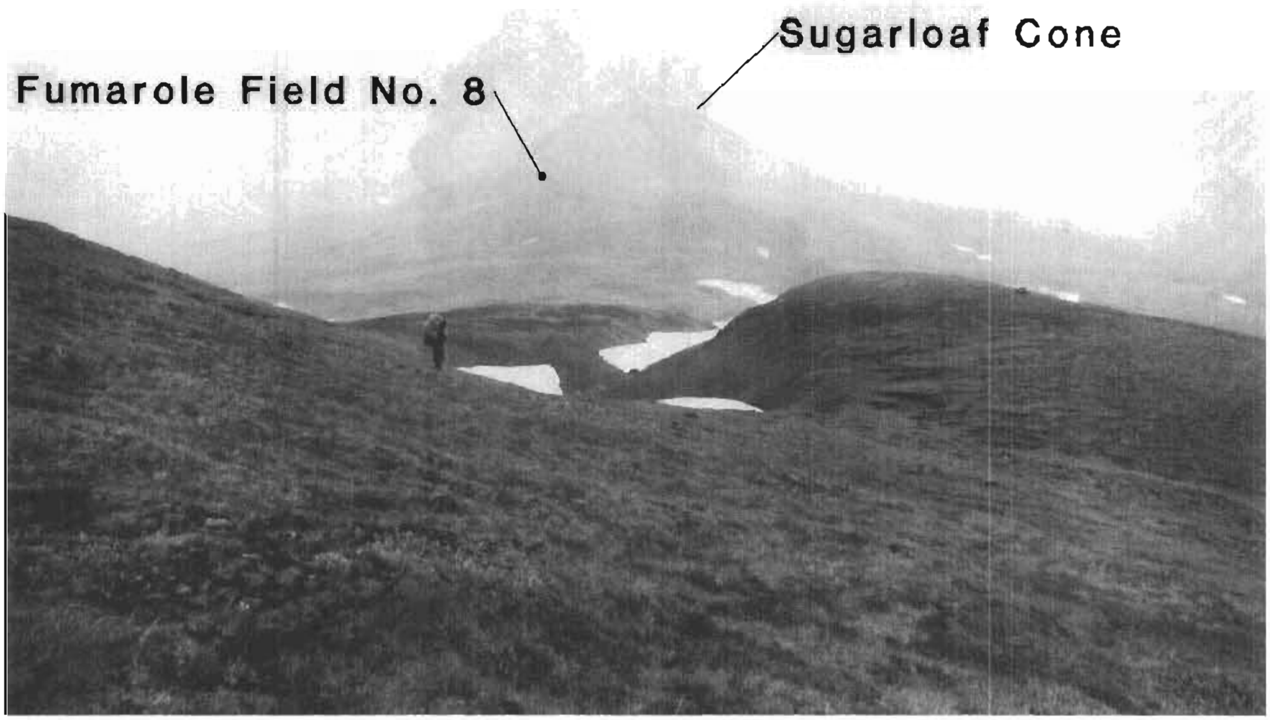

Figure 9a. Fumarole field 8 and Sugarloaf Cone, looking east-northeast (Aug. 12, 1981). (Photograph courtesy M.J. Larsen.)

volcanic flows that still contain heat, as suspected at fumarole field 8, or to the cooling of shallow magma bodies, as reflected by the dome in field 6.

Most of the recent extrusive rocks in the northern part of Unalaska Island are porous. Any heat in such rocks have been mostly removed, except for small isolated areas such as the one found at field 8. Hydrothermal convective systems might exist in the fractured Unalaska Formation and corresponding plutonic bodies that are suspected to underlie most of the unaltered volcanic rocks of the northern part of Unalaska Island. However, no real evidence has been found for the existence of such systems. In fact, except for the Summer Bay area near the community of Unalaska (Reeder, 1981a), no hydrothermal systems are known to exist in the Unalaska Formation beyond the immediate fumarole field regions ot Makushin Volcano.

A northeast-oriented zone roughly marked by fields 1-4 has been identified as possibly containing large vapor-dominated hydrothermal reservoirs. There are only a few places in the world, such as The Geysers, California, and Larderello, Italy, where hydrothermal systems consist mainly of vapor (White and others, 1971). These systems have been developed where they now represent the major source of electrical geothermal power. Further exploration may better define the nature of reservoirs in the Makushin Volcano region, but deep exploratory drilling and well testing such as described by Economides and others (1982) is required to determine their potential.

Figure 9b. Old cairn that marks location of fumarole field 8 (July 23, 1980).

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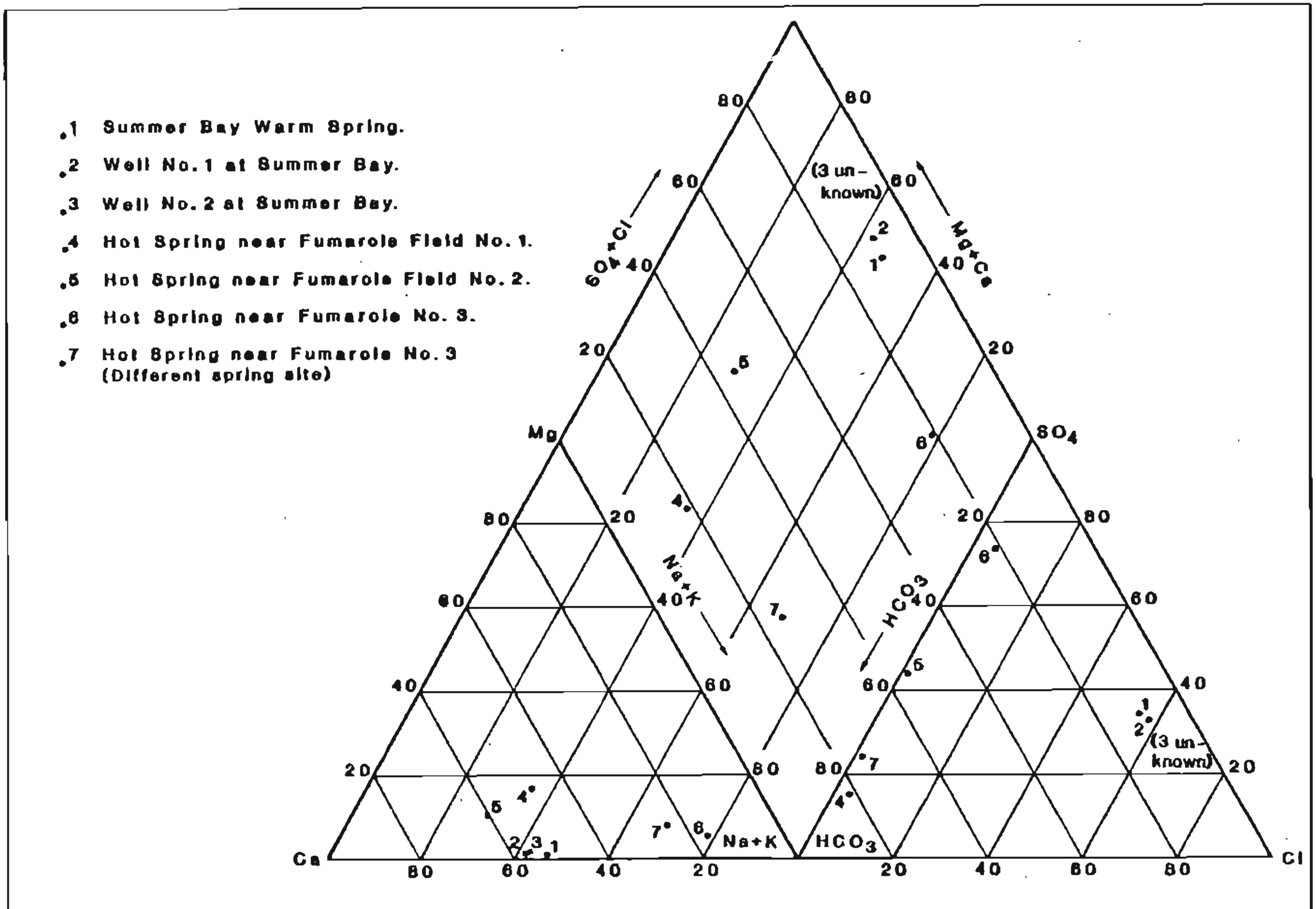

Figure 10. Diagram showing the ratios of major ions of hot-spring waters from Unalaska Island and of hot waters from two exploration wells near Summer Bay on Unalaska Island. (Data from Motyka and others, 1981, and from author.)

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