The Geology of North America
Vol. G-1, The Geology of Alaska
The Geological Society of America, 1994

Chapter 32

Geothermal resources of Alaska

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INTRODUCTION

Most of the major known geothermal systems of the world are associated in some manner with recent volcanism and thermal springs. Both phenomena occur in sufficient numbers in Alaska as to indicate potentially large geothermal resources. The volcanic areas of principal geothermal interest are (1) the Aleutian arc (Fig. 1), a seismically active volcanic arc-trench system extending some 2,500 km across the North Pacific and Alaska mainland; and (2) the Wrangell Mountains volcanic pile in east-central Alaska, which underlies an area of some 10,000 km^2 and ranges in age from Miocene to Holocene. Volcanism in these two areas is both tholeiitic and calc-alkaline in character and is related to the convergence of the North American and Pacific Plates. Both regions contain evidence of silicic and explosive volcanism, indicating high-level near-surface magma chambers with attendant large heat reservoirs. The distribution of volcanic rocks is shown on Plate 12 (Plafker and others, this volume).

Although other volcanic provinces occur in the state, they appear to be less important from a geothermal standpoint. The western Alaska volcanic province, consisting of Pliocene to Holocene olivine tholeiite and alkali basalt, underlies scattered areas totaling about 25,000 km^2 chiefly on the Seward Peninsula, the Norton Sound area (including St. Lawrence Island), the Yukon River delta, and the Pribilof Islands. Similar, widely scattered Quaternary volcanic rocks occur in the central and eastern interior of Alaska. These basaltic volcanic provinces appear to be related to an extensional tectonic regime because of their composition and mode of occurrence. Near-surface heat reservoirs of possible geothermal interest appear to be lacking. Quaternary volcanic rocks are also found in a few localities in southeastern Alaska, chiefly at Mount Edgecumbe near Sitka and on Kupreanof Island.

Of the more than 100 thermal springs known to occur in the state, approximately half are associated with the Aleutian volcanic arc. The remaining half are concentrated in interior and southeastern Alaska and have no apparent spatial or temporal association with recent volcanism. Many of these thermal springs have been sites of sporadic direct use as spas or small agriculture areas since the turn of the century. Thermal spring areas are shown on Plate 12 (Plafker and others, this volume).

PREVIOUS WORK

The first systematic description of geothermal areas in Alaska was a remarkably comprehensive report by Waring (1917), who at this early date, listed 75 of the presently known 108 hot springs in the state (Alaska Division of Geological and Geophysical Surveys, 1983). Little further study on either the thermal springs or igneous-related geothermal systems took place until the early 1970s when the U.S. Geological Survey began regional geothermal studies in Alaska as part of its Geothermal Resource Program. Miller (1973) compiled an updated summary of 94 known or suspected thermal springs, including a total of 34 chemical analyses of the thermal waters. Studies of igneous-related geothermal systems, principally in the Aleutian volcanic arc and the Wrangell Mountains were begun in 1973 (Miller and Barnes, 1976). Data gathered from this study formed the basis for the calculations of estimated thermal energy remaining in a particular volcanic system (Smith and Shaw, 1975, 1979). Miller and others (1975) conducted a study of the geologic setting and chemical characteristics of the thermal springs across 200,000 km^2 of interior Alaska. Their study confirmed the close association of thermal springs with the margins of granitic plutons and proposed a model for their origin whereby deeply circulating meteoric water gained access to the surface along the fractured contacts of massive plutonic and hornfelsic wall rocks.

The Geophysical Institute at the University of Alaska began studies of individual geothermal areas in the 1970s and subsequently was joined by the Alaska Division of Geological and Geophysical Surveys, with most of the studies supported by the U.S. Department of Energy. These studies were followed by regional and statewide summaries of available resources in the mid-1970s and 1980s. A partial listing of studies by these organizations, which included geological, geophysical (gravity, magnetics, electrical, He and Hg surveys, seismic refraction, and heat-flow investigations), and geochemical investigations, include reports by Motyka and others (1980b), Turner and Forbes (1980), Turner and others (1980), Motyka and others (1981), Wescott and Turner (1983), Turner and Wescott (1982), and East (1982).

Miller, T. P., 1994, Geothermal resources of Alaska, *in* Plafker, G., and Berg, H. C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-1.

A multidisciplinary geological, geochemical, and geophysical study of igneous-related systems on northern Adak Island, with particular emphasis on Mt. Adagdak volcano, was done by the U.S. Geological Survey at the request of the U.S. Navy (Miller and others, 1978). Detailed geological mapping, coupled with geochronological and major-element geochemical studies, was done on Mt. Drum volcano in the western Wrangell Mountains (Richter and others, 1978).

The most detailed geothermal exploration program in Alaska was conducted on the flanks of Makushin volcano on Unalaska Island (Fig. 1) as part of a cooperative study begun in 1981 by the Alaska Power Authority and the Alaska Division of Geological and Geophysical Surveys. The study included detailed geological mapping, geochemical and isotopic studies, and self-potential investigations, which were followed by the drilling of three 460-m-deep geothermal gradient holes and a 1,220-m-deep exploration well (Parmentier and others, 1983; Motyka, 1983; Matlick and Parmentier, 1983; Isselhardt and others, 1983).

GEOTHERMAL SITES

Aleutian volcanic arc

The area of Alaska with the greatest geothermal resource is the Aleutian volcanic arc, which extends some 2,500 km from Hayes volcano 130 km west of Anchorage to Buldir Island in the western Aleutians (Fig. 1). Over 60 major volcanic centers of Quaternary age, ranging in volume from 5 to more than 400 km^3, are included in this island-arc and continental margin system, which spans both ocean and continent; these centers include at least 37 volcanoes that have been active within the past 200 years (Kay and Kay, this volume; Miller and Richter, this volume). Of particular interest from a geothermal standpoint is the occurrence of more than 20 major calderas (indicative of near-surface magma chambers and heat reservoirs) associated with these centers (Table 1). Most of the calderas are Holocene in age (Miller and Smith, 1987) and range in diameter from less than 2 km (Great Sitkin) to over 18 km (Fisher). Calderas east of 159°W on the Alaska Peninsula (Fig. 1) are characterized by silicic post-caldera volcanism, suggesting the continued presence of high-level magma chambers and reservoirs (Miller and Smith, 1987). Calderas west of 159°W are generally characterized by more mafic post-caldera activity, suggesting a return to a more primitive system. Numerous other volcanoes (Augustine, Spurr, Dana, Kialagvik, Chiginagak, Yantarni, Frosty, Adagdak) exhibit young silicic domes, which along with the calderas, attest to the existence of high-level magma chambers and therefore probable associated near-surface heat sources.

Associated with these volcanic centers are many thermal areas consisting of fumaroles, mud pots, and more than 30 thermal springs. Unlike thermal springs elsewhere in Alaska, these

Figure 1. Map showing distribution of calderas, igneous-related geothermal systems, and thermal springs in Alaska. Pattern indicates areas of abundant thermal springs in interior Alaska. Triangle, thermal spring site; circle, volcano; circle with x, caldera; numbers refer to Table 1.

TABLE 1. CALDERAS AND RELATED IGNEOUS SYSTEMS OF THE ALEUTIAN ARC AND THEIR CONTAINED THERMAL ENERGY*

Name	Location	Approximate diameter (km)	Thermal energy remaining in system (10^{18} joules)
1. Kaguyak	Alaska Peninsula; 58°37'N,154°05'W	2.8	38
2. Katmai	Alaska Peninsula; 58°16'N,154°59'W	2.1 x 3.2	50
3. Novarupta	Alaska Peninsula; 58°16'N,155°09'W	3	120
4. Ugashik	Alaska Peninsula; 57°45'N,156°21'W	5	71
5. Aniakchak	Alaska Peninsula; 56°53'N,158°10'W	9.7 x 8.4	540
6. Black Peak	Alaska Peninsula; 56°32'N,158°37'W	2.7 x 2.6	50
7. Veniaminof	Alaska Peninsula; 56°10'N,159°23'W	8.4	481
8. Emmons	Alaska Peninsula; 55°20'N,162°01'W	18 x 10	1,440
9. Fisher	Unimak Island 54°38'N,164°25'W	10 x 11	1,440
10. Akutan	Akutan Island 54°08'N,166°00'W	2	25
11. Makushin	Unalaska Island 53°52'N,168°56'W	2.4 x 3.2	25
12. Okmok I, II	Umnak Island 53°39'N,168°03'W	10; 11	603
13. Yunaska	Yunaska Island 52°39'N,170°39'W	2.9 x 3.4	96
14. Sequam I, II	Sequam Island 52°19'N,172°29'W	8; 5.5	480
15. Kliuchef	Atka Island 53°19'N,174°09'W	4.5	?
16. Great Sitkin	Great Sitkin Island 52°04'N,176°07'W	1.6	>13
17. Adagdak†	Adak Island 51°59'N,176°35'W	....	50
18. Kanaton	Kanaga Island 51°55'N,177°10'W	4	180
19. Takawangha	Tanaga Island 51°52'N,178°00'W	3.2	54
20. Tanaga	Tanaga Island 51°53'N,178°07'W	11	960
21. Semispochnoi	Semispochnoi Island 51°56'N,179°35'W	6.1 x 7.5	360
22. Little Sitkin	Little Sitkin Island 51°57'N,178°32'W	4.5	180
23. Davidof	Davidof Island 51°58'N,178°20'W	2.4	29

*After Smith and Shaw, 1979.
†Not a caldera.

springs are closely associated with the areas of active volcanism, and this association is reflected in both the high surface temperatures (in some cases at or near boiling temperature) of the spring waters and in the high reservoir temperatures (commonly in excess of 200°C as estimated from geochemical thermometers). The Geyser Bight area on the north-central side of Umnak Island has the most impressive surface manifestation of high heat flux of any hot-water convection system in Alaska. Numerous thermal springs and pools over a 4-km^2 area are at, or in some cases above, boiling and are superheated with temperatures to 104°C; small geysers erupting to heights of 25 cm are not uncommon. Similar superheating and geyser activity has been noted at a thermal spring on the east side of Kanaga Island on the southeast flank of Kanaga volcano.

Smith and Shaw (1975, 1979) have evaluated the heat content of young igneous-related systems in the United States to a depth of 10 km. They estimated thermal energy in these systems on the basis of assumed high-level silicic magma chambers (i.e., calderas, silicic domes, etc.), chamber volume, and the time of their latest eruptions. Smith and Shaw's thermal energy calculations assume that a fixed volume of magma cooled from an initial temperature of 850°C to its present temperature solely by conduction in surrounding rocks, starting from a fixed time.

Smith and Shaw (1979) calculated that the fixed-volume estimate of thermal energy remaining in 58 igneous systems in the United States is approximately $101{,}000 \times 10^{18}$ joules. These 58 systems include 22 of the Aleutian volcanic arc systems and are the ones judged by Smith and Shaw to have sufficient age and volume data to make meaningful calculations. Smith and Shaw (1979) caution that their estimate of $101{,}000 \times 10^{18}$ joules is conservative and that the total igneous-related energy is at least an order of magnitude greater. The lack of sufficient geochronologic data, and the likelihood that very young systems with relatively small single-chamber volumes have subchamber support systems much greater in size and longevity than are inferred from the age and extent of volcanic products, make it impossible at present to give more quantitative estimates of undiscovered thermal energy.

The 22 volcanic centers in the Aleutian arc for which Smith and Shaw (1979) calculated remaining thermal energy (Table 1) total more than $7{,}000 \times 10^{18}$ joules. Although this figure is only about 7 percent of the total U.S. estimate of $101{,}000 \times 10^{18}$ joules, it should be realized that 75 percent of the entire U.S. estimate comes from five large intracontinental caldera systems: Yellowstone, Island Park, Valles, Rexburg, and Long Valley. Also, at least a dozen Aleutian volcanoes whose volcanic products and age suggest high-level magma chambers have not been included in the calculations, chiefly because of the relatively small size of their erupted products or because age and volume data are still too tentative.

Brook and others (1979), in an assessment of hydrothermal convection systems with reservoir temperatures of 90°C or more, estimated that the identified resource base for the Aleutian arc was a relatively low 10×10^{18} joules, whereas the undiscovered accessible resource base was estimated at as much as 580×10^{18} joules.

Although the Aleutian arc has significant potential for large geothermal resources, the remoteness of the area had resulted in little interest in development until 1976, when the U.S. Navy collaborated with the U.S. Geological Survey in an investigation of the geothermal potential, particularly for direct-use space heating purposes, of Adak Island. Three Quaternary volcanoes—Mt. Moffett, Andrew Bay, and Mt. Adagdak—occur on the north side of the island. As a result of a multidisciplinary study of the area that included geological mapping, geophysical studies, and isotopic age-dating, Miller and others (1978) concluded that a high-level thermal anomaly probably existed beneath Mt. Adagdak volcano. This volcano is the youngest of the three—its most recent dated eruption having been dated at 140 ka. Geophysical studies indicated a low-density, very conductive, northeast-trending mass under the south and east side of Adagdak; low resistivity measurements suggested this rock might be hot. In 1977, the U.S. Navy drilled three holes in Adagdak in search of a heat source for space heating purposes. Unfortunately, because of access problems, the holes were not located on the geophysical anomaly. The closest hole to the anomaly, however, yielded a bottom-hole (600 m) temperature of about 66°C.

Unalaska Island is located approximately 1,500 km southwest of Anchorage in the eastern Aleutian Islands. The northern part of the island is dominated by Makushin volcano, a large (200 km^3 in volume), historically active andesitic stratocone reaching an altitude of 2,037 m and having a summit caldera about 3 km in diameter. Although not one of the larger volcanic centers in the Aleutian arc in terms of present heat content (Smith and Shaw estimate 25×10^{18} joules thermal energy still remaining in the system as compared to more than $1{,}400 \times 10^{18}$ joules for such large volcanic centers as Fisher caldera), the volcanic center is attractive as a geothermal resource because it is only 19 km from the major fishing port and population center of Dutch Harbor.

Detailed geological mapping, geochemical studies, and a self-potential geophysical survey conducted by the Alaska Division of Geological and Geophysical Surveys, and by private consultants in 1982 under contract to the state, led to the drilling of three primary temperature gradient holes to depths of about 440 m (Isselhardt and others, 1983). Subsurface temperatures as high as 195°C were obtained from these holes, and a water-dominated geothermal system was thought to exist on the eastern flank of the volcano.

A small-diameter resource-confirmation well was drilled in the area in 1983 to a depth of 594 m and yielded a bottom-hole static temperature of 193°C. Three potential geothermal resource zones were encountered in the hole. A long-term 34-day test of the well in 1984 suggested a shallow steam zone overlying a liquid-dominated reservoir in the fractured diorite basement rock (Economides and others, 1985). The reservoir (unflashed) fluid is a NaCl-type water with a total dissolved solid content of about 600 mg/l. A flowing temperature of 193°C was found at a depth of 594 m. The test suggested the reservoir could be highly productive. Sustained flow through a 3-in-diameter well bore of 63,000 lb/hr was achieved with less than 2 psi of pressure drawdown from an initial pressure of 494 psi. Economides and others (1985) calculated that a theoretical electricity reserve exists that would be sufficient for the needs of the local island populace for several hundred years at current consumption rates.

It seems clear that a large geothermal resource base exists beneath Makushin volcano. Whether it wil be exploited—given the remoteness of the region, the large initial costs of geothermal development, and the relatively small local population—is problematical.

Motyka and others (1981) have described large thermal areas on Atka and Akutan Islands in the central and eastern Aleutian Islands. On northeastern Atka Island, two large (50,000 m^2) thermal areas occur on the flanks of Mt. Kliuchef volcano (Kliuchef thermal area) and in a valley southeast of Korovin volcano (Korovin thermal area). These thermal areas consist of fumaroles, mud pots, boiling springs, warm ground, and hydrothermally altered zones. Thermal spring waters are of an acidic, low-chloride, high-sulfate variety. A combination of chemical and gas geothermometry using the techniques described by Fournier (1977) and Ellis and Mahon (1978) indicates reservoir temperatures of 239°C and >150°C for the two areas. Motyka and others (1981) suggest the possibility of a shallow vapor-dominated system associated with the Kliuchef thermal area.

The thermal area on Akutan Island occurs along a northeast-trending stream valley approximately 6 km east of Akutan volcano—a small andesitic stratocone with a small summit caldera. Hot-spring temperatures as high as 85°C, associated sinter deposits, and indicated reservoir temperatures of 180°C (Motyka and others, 1981) attest to the high heat flux of the area.

Geothermal resources on Atka and Akutan Islands are of some interest in that, unlike many other geothermal areas in the Aleutian arc, they occur relatively close to small fishing villages. Local use is therefore possible, particularly as (and if) the fishing industry expands.

Wrangell Mountains volcanic pile

A thick calc-alkaline pile of Neogene volcanic rocks underlies about 10,000 km^2 of the Wrangell Mountains in east-central Alaska. The rocks range in composition from basalt to rhyolite and in age from Miocene to Holocene (Miller and Richter, this volume). The Wrangell volcanic pile appears to be related to a northwest-trending, northeast-dipping subduction zone resulting from underthrusting of the Pacific Plate beneath the North American Plate (Stephens and others, 1984). The Wrangell volcanic pile is separated from the Aleutian arc by a gap of some 400 km; the relation between the two arcs, if any, is uncertain.

Few thermal springs are associated with the Wrangell volcanic rocks, and only Mt. Wrangell itself, a 4,320-m-high shield volcano with a summit caldera, has an active thermal area. Historic eruptions have been rare in the Wrangell volcanic pile. The presence of several large Quaternary stratovolcanoes, however, attests to the extent and nature of recent volcanism. These include Mount Drum (3,622 m), Mount Sanford (4,950 m), Mount Blackburn (5,037 m), Regal Mountain (4,210 m), and large shield volcanoes such as Tanada Peak and Capitol Mountain, which cover areas of 400 and 200 km^2, respectively (Richter and others, 1984). K-Ar ages of 200 to 2,000 ka have been obtained from these volcanoes; a volcanic center now largely under the Klutlan Glacier about 10 km from the Canadian border erupted explosively about 1,900 and 1,250 ^{14}C B.P. (Lerbekmo and others, 1975), depositing the White River ash over 300,000 km^2 of eastern Alaska and northwest Canada.

Mount Drum, the westernmost stratovolcanic complex in the Wrangell Mountains, has received a considerable amount of study as a possible geothermal resource (Richter and others, 1978). This volcanic center consists of a deeply dissected stratocone ringed by peripheral silicic domes. The presence of young silicic rocks initially suggested the possibility of a high-level magma chamber (Miller and Barnes, 1976) that might have geothermal potential. Subsequent mapping and petrologic and geochronologic studies showed at least two principal cycles of volcanism, each cycle consisting of andesitic and dacitic cone-building followed by peripheral emplacement of dacite, rhyodacite, and rhyolite domes. The younger cycle culminated in an explosive eruption resulting in destruction of part of the central stratocone and emplacement of volcanic avalanche deposits. K-Ar ages indicate that the volcano began to form about 800 ka and that the youngest dated event occurred about 240 ka; field relations indicate one or more still younger events.

The two complete cycles of volcanism consisted of similar episodes of cone building and dome emplacement. After the eruption of the first-cycle rhyolite domes, the magma chamber beneath Mount Drum was either depleted of much of its silicic differentiate or received an influx of more mafic magma, because the second-cycle cone-building lavas were predominantly dacite and andesite. The larger area outlined by the distribution of the ring domes suggests that the size of the magma chamber had increased considerably by the end of the second cycle. Stratocone rocks range from basaltic andesite (54.5 percent SiO_2) to dacite (63 percent SiO_2), whereas the silicic domes are composed of dacite, rhyodacite, and rhyolite (SiO_2 content as much as 72 percent).

The distribution and composition of the silicic-ring domes peripheral to the Mount Drum cone suggest the presence of a high-level magma chamber. Calculations based on the probable size, age, and composition of this magma chamber indicate the existence of a thermal anomaly of considerable magnitude, 26.5 to 114×10^{19} cal, one of the largest estimates for any volcanic system in Alaska.

Thermal spring areas, central and northern Alaska

More than 60 thermal springs are scattered throughout Alaska, and most of them occur in settings seemingly unrelated to Quaternary volcanism. In the vast area north of the Alaska Range

($\sim$1,000,000 km^2), 36 thermal springs have been reported, 32 of which are located in a 200-km-wide east-west band extending across interior Alaska from the Seward Peninsula to within 160 km of the Canadian border (Fig. 1). More thermal springs may occur in this area, but geological studies detailed enough to reveal them have been completed for less than 10 percent of the area.

The 36 known thermal springs (Miller, 1973) show no temporal or spatial association with Tertiary or Quaternary volcanism (Moll-Stalcup and others, this volume; Plafker and others, this volume, Plate 12) but rather (Miller and Barnes, 1976) are closely associated with the margins of granitic plutons. Of the 36 thermal springs, 33 occur within 5 km of the margin of a granitic pluton. One of the few apparent exceptions to this empirical observation is Pilgrim Hot Springs on the Seward Peninsula (Fig. 1) where the springs appear to be related to a faulted margin of a Tertiary basin.

The occurrence of thermal springs in this large area is independent of the absolute age or composition of the associated plutonic rocks. Plutons with associated thermal springs range in age from 315 to 380 Ma in the Brooks Range (Dillon, 1980) to 60 Ma in the Yukon-Tanana Upland (DuBois and others, 1986). Most of the plutons, however, are Cretaceous, ranging in age from 110 to 66 Ma. The plutons include biotite granite, two-mica granite, granodiorite, monzonite, syenite, and nepheline syenite.

The distribution of thermal springs is independent of the age and lithology of the country rock enclosing the pluton. The country rocks, for example, range in age from Paleozoic and perhaps Precambrian(?) to Late Cretaceous, and include limestone, graywacke, andesite, mafic volcanic rocks, and regionally metamorphosed rocks of low and high grade. The hot springs occur in a number of different geologic provinces (Seward, Koyukuk, Ruby, Arctic Alaska, Angayucham, Yukon-Tanana, etc.) and tectonostratigraphic terranes that have a large variety of geologic and structural features; some of these features are confined to a single province or terrane, while others are found in two or more provinces and terranes. The only feature common to thermal springs and the terrane in which they occur is the existence of granitic plutons.

A prerequisite for the occurrence of a thermal spring throughout this large area appears to be a mass of competent, well-fractured rock near the margins of a massive, nonfoliated granitic body. All known thermal springs that occur outside the boundary of a pluton occur in nonfoliated rocks such as graywacke, mudstone, basalt, and andesite that may have been affected to some extent by contact metamorphism but not by regional metamorphism. Fracture systems apparently were not developed or are not sufficiently open in crystalline regionally metamorphosed rocks with a well-developed planar fabric to allow deeply circulating hot water to gain access to the surface. Where the wall rock surrounding a pluton consists of well-foliated, regionally metamorphosed rock, the thermal spring invariably occurs within the pluton.

Oxygen and hydrogen isotopic analysis of waters collected from ten thermal springs scattered across an area extending from the western Seward Peninsula to the Hodzana Highlands (Fig. 1) are similar to isotopic analyses of locally derived meteoric waters (Miller and others, 1975). The thermal spring waters are weakly alkaline and somewhat high in chloride. They appear to be deeply circulating meteoric water whose increased solvent action due to the increase in temperature and long flow path brought about leaching of the country rock. Six of 34 analyzed thermal springs contain dissolved solids in excess of 1,000 mg/l, ranging from 1,150 to more than 6,000 mg/l. These springs are also more saline than the other 28 springs and are characterized by higher concentrations of chloride, sodium, calcium, potassium, fluorine, lithium, bromine, and boron. Saline thermal springs occur in the same geologic provinces as nonsaline thermal springs and are found as far west as Serpentine Hot Springs on the Seward Peninsula and as far east as Tolovana and Big Windy Hot Springs near Fairbanks in central Alaska. The chemical and isotopic data indicate that both types of hot springs originate from deeply circulating meteoric water; their compositions probably result from a difference in the extent of leaching or in water-rock reactions from one locality to another (Miller and others, 1975).

The most studied geothermal area north of the Alaska Range is Pilgrim Springs in the west-central Seward Peninsula (Fig. 1). Unlike the other thermal springs in the region, its geologic setting is unclear because it lies in the center of the 2-km-wide, alluvium-filled Pilgrim River valley, a fault-bounded, graben-like structure where the basement rocks are not exposed. The valley is flanked by amphibolite-facies metamorphic rocks of probable Precambrian and Paleozoic age cut by Cretaceous plutons. The thermal springs are located in an oval-shaped 1.5-km^2 area of thawed ground surrounded by permafrost. Chemical geothermometry (Miller and others, 1975; Motyka and others, 1980a) indicates possible reservoir temperatures of 146 to 154°C. Seismic, gravity, and resistivity surveys (Turner and Forbes, 1980) suggest that the crystalline basement rocks that floor the Pilgrim River valley are at least 200 m deep beneath the thermal area and that the springs lie in a fault-bounded zone.

A total of six holes were drilled to depths of 45 to 305 m at Pilgrim Springs between 1979 and 1982. Siting of these holes was based on geophysical studies and a helium survey. The results of this drilling (Kunze and Lofgren, 1983) indicate that a perched hot-water reservoir (maximum temperature of 88°C) exists at a depth of 15 to 37 m and its underlain by a cold-water reservoir. Kunze and Lofgren (1983) noted that this reservoir represented less than 10 percent of the resource to be expected in the area and that a much larger and deeper source of hot water must exist.

The origin of Pilgrim Hot Springs is uncertain. Turner and Forbes (1980) have postulated that the Pilgrim River valley is part of a rift system extending in a general east-west direction across the Seward Peninsula and that the thermal springs may be related to active rifting. Motyka and others (1980b) suggest that because of the highly saline, alkali-chloride character of the thermal spring waters, and because the large Quaternary basalt field of the Imuruk Lake area is only 60 km away, a volcanic association cannot entirely be discounted.

Perhaps of greater significance, however, is the fact that Pilgrim Springs is only one of more than 30 thermal springs that occur in the 200-km-wide band that crosses several geologic provinces and terranes almost to the Canadian border. These springs show no relation to recent volcanism (i.e., no recent volcanic rocks exist within about 100 km of most of these springs). The saline character of Pilgrim Springs water is not unique; saline water is found both at Serpentine and Kwiniuk Hot Springs on the Seward Peninsula (both of which are unequivocally associated with margins of granitic plutons) as well as at Tolovana and Big Windy Creek (Keith and Foster, 1979; Keith and others, 1981) thermal springs in east-central Alaska. These characteristics suggest to me that Pilgrim Hot Springs has an origin similar to the other thermal springs in interior Alaska, that a granite body exists at depth beneath the Tertiary and surficial cover, and that the faulted margin of the Tertiary basin only controls the actual site of upwelling.

Southeastern Alaska thermal springs

Thermal springs in southeastern Alaska also appear to be related to the fractured margins of granitic masses (Waring, 1917; Miller and others, 1975; Motyka and others, 1980b). Of 18 known or reported thermal springs in southeastern Alaska, at least 12 occur within, or very close to, granitic plutons. In addition, Twenhofel and Sainsbury (1958) found that 14 of these hot springs are located on prominent lineaments. These springs appear to have no spatial association with Pleistocene-Holocene volcanic rocks at Mount Edgecumbe volcano near Sitka, nor with rocks in the Kuiu-Etolin volcanic belt (Fig. 1) on Kupreanof Island (Brew and others, 1985). Motyka and others (1980b), in a study of thermal spring sites in southeastern Alaska, concluded that the thermal waters are alkali-sulfate to alkali-chloride in character and are probably derived from the interaction of deeply circulating meteoric waters with granitic wall rock. Assuming a geothermal gradient of 30 to 50 °C/km, chemical geothermometers suggest subsurface temperatures of 55 to 151°C, indicating circulation to depths of 1.5 to 5 km.

Other geothermal sites

Turner and Wescott (1982) have speculated that zones of discontinuous hot water may exist at depth in the Susitna Basin in south-central Alaska some 60 km north of Anchorage (Fig. 1). Although no surface manifestations of anomalous heat flux have been found, four dry wildcat wells drilled for petroleum in the area encountered anomalously high temperatures with gradients of 44 to 123 °C/km in the underlying Tertiary sedimentary rocks. The source of the heat is unknown, but a helium survey of soil gas, and water, encountered elongate anomalies possibly controlled by Tertiary faults, along which hydrothermal convection could have occurred (Turner and Wescott, 1982). No hot water has been found, and only preliminary work has been done in searching for possible reservoirs. An obvious attraction for any geothermal resource development in this area is its proximity to over 60 percent of Alaska's population.

SUMMARY

Alaska, perhaps more than any other single region in North America, probably has the greatest number of potential geothermal energy sites. Regional and reconnaissance geological studies indicate that more than 25 igneous-related systems and thermal areas in the state have thermal anomalies of sufficient magnitude to be of interest for large-scale geothermal energy development. Exploration and research into Alaska's geothermal resources began about 1972 and is still in an early phase. Few of the large volcanic centers likely to have geothermal resources have been studied in sufficient detail to document their potential. Geophysical studies have been done only on Makushin and Adagdak volcanoes in the eastern and central Aleutian Islands and at Pilgrim Hot Springs on the Seward Peninsula, and those are the only sites in the state where extensive drilling has been conducted.

The remoteness of many of the geothermal areas with the greatest potential, the sparse population base, the difficulty in delivering the energy to distant markets, and the high front-end development costs are factors that affect the utilization of the resource. An additional complicating factor is that virtually all of the potentially large geothermal systems in the Aleutian volcanic arc and the Wrangell Mountains are located within the boundaries of national parks and monuments and wildlife refuges.

The Makushin geothermal site is probably typical of a volcanic system in the Aleutian volcanic arc that might constitute a geothermal resource. An exploration well drilled to about 600 m encountered a shallow steam zone at a temperature of 163°C overlying a liquid-dominated reservoir at a temperature of 193°C. It was estimated that a single production well from this site could supply about 9 MW of electrical power. The potential seems high elsewhere in the Aleutian arc and Wrangell volcanic pile for more such vapor- and hot-water-dominated convection systems to exist associated with volcanoes that have a high-level magma chamber and heat reservoir.

Geological, geophysical, and drilling information from Adagdak volcano on Adak Island in the Aleutians suggests that it might be typical of a high-level heat source relatively close to the surface large enough to provide direct use energy for space heating.

A prerequisite to development of any geothermal resource is the existence of a potential user. In addition to Makushin and Adagdak volcanoes with their nearby population centers of Unalaska and Adak, Mount Spurr (130 km west of Anchorage), Mount Drum in east-central Alaska (55 km from the main highway networks), and possibly Mount Edgecumbe in southeastern Alaska (25 km west of Sitka) all have potential since they are close to major population areas.

Thermal springs in Alaska outside of the Aleutian volcanic arc are characterized by relatively low surface temperatures (generally less than 60°C) and by low reservoir temperatures as indicated by geothermometry (usually less than 150°C). They appear to be associated with the fractured margins of granitic plutons and have low porosity. Indicated reservoir temperatures are typically below the 150 to 180°C thought necessary to generate electricity. The low porosity makes most of the thermal spring localities relatively poor candidates for large-scale direct-heat sources. Only Pilgrim Hot Springs on the Seward Peninsula may have sufficient porosity and volume to be a viable geothermal resource for development as a direct heat source.

All of the thermal springs represent hydrothermal convection systems, and, based on their high chloride and alkaline pH levels, are water- rather than vapor-dominated. There has been little detailed study of these thermal springs, and fewer than half a dozen such systems in Alaska have been drilled. Of this group, only Bailey Bay in southeastern Alaska, with a calculated reservoir temperature of 151°C, qualifies as a high-temperature hot-water system as defined by White and Williams (1975): that is, a system with a reservoir temperature >150°C. Of the remaining thermal springs, approximately 25 percent are intermediate-temperature systems with estimated reservoir temperatures of 90 to 150°C, and about 75 percent are low-temperature systems with estimated reservoir temperatures below 90°C (Miller, 1973; Turner and others, 1980).

The thermal springs appear to have little potential for large-scale production of electricity or for space heating. Their geologic setting and chemical geothermometry suggest limited reservoirs and fracture porosity, and relatively low reservoir temperatures. Many of them, however, have a long history of use for local recreational and agricultural purposes, and those uses, together with space heating for small numbers of houses in isolated villages and resorts, seem likely to continue indefinitely.

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MANUSCRIPT ACCEPTED BY THE SOCIETY MAY 21, 1990

Printed in U.S.A.