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GEOLOGIC SETTING AND CHEMICAL CHARACTERISITICS OF HOT SPRINGS IN CENTRAL AND WESTERN ALASKA

By

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ABSTRACT

Numerous hot springs occur in a variety of geologic provinces in central and western Alaska. Granitic plutons are common to all the provinces and the hot springs are spatially associated with the contacts of these plutons. Of 23 hot springs whose bedrock geology is known, all occur within 3 miles of a granitic pluton. The occurrence of hot springs, however, appears to be independent of the age, composition, or magmatic history of the pluton.

Preliminary chemical and isotopic analyses suggest the hot springs waters belong to two groups. Most of the analyzed hot springs appear to have chemical and isotopic compositions indicating they were derived from deeply circulating meteoric water. About 25 percent of the analyzed hot springs show a distinct saline character with high concentrations of chloride, sodium, potassium, and calcium indicating either much more complex water-rock reactions than occurred in the other hot springs or the addition of another type of water. The present chemical and isotopic data are insufficient to determine the source of the constituents of the saline hot springs.

Chemical geothermometers suggest subsurface temperatures in the general range of 100°C to 160°C. If the hot spring waters have derived their heat solely from deep circulation, the waters must have reached depths of 9,000 to 15,000 feet, assuming geothermal gradients of 30°C to 50°C/km. If hot magmatic water has been added to the geothermal systems or if dilution or mixing has occurred, temperatures of 100°C to 160°C may be reached at shallower depths.

The geologic and chemical data are too preliminary to make an estimate of the potential of the hot springs as a geothermal resource. The data suggest, however, that most of the hot springs of central and western Alaska have relatively low subsurface temperatures and limited reservoir capacities in comparison with geothermal areas presently being utilized for electrical power generation.

INTRODUCTION

Hot springs have long been known to occur in western and central Alaska but have received little study since they were discussed by Waring (1917) who visited 6 of the 15 hot springs known in 1915. At least 27 hot springs are now known in this region (fig. 1) and these springs constitute about 30 percent of the presently known hot springs in Alaska (Miller, 1973). Because the occurrence of hot springs is suggestive of geothermal resources and because of the increasing interest in such resources as possible sources of energy, an updated report on these springs is warranted. Studies elsewhere (Muffler, 1973; Combs and Muffler, 1973; White and others, 1971; White, 1973; Mahon, 1966; Fournier and Rowe, 1966; Fournier and Truesdell, 1973) have indicated that knowledge of the geologic setting of hot springs and the composition of their waters can give clues to conditions at depth such as subsurface temperatures, source of heat, and type of hot spring system. The purpose of this report, therefore, is to discuss the geologic setting and chemical composition of known hot springs in western and central Alaska with regard to their potential as a geothermal resource.

This study should be regarded as preliminary since only 19 of 27 presently known hot springs within the study area have been visited by us and chemical analyses are available for only 16 of the hot springs; indeed, reasonably complete analyses are available from only 5 springs. Measured temperatures are available on only 13 hot springs and no information of temperatures are available from 5 of the remaining 14 hot springs. In a few cases, geologic mapping of the general spring site is not complete and none of the hot springs has been studied in detail. It should be emphasized, also, that the area is sparsely populated and that the geologic mapping is chiefly of a small scale reconnaissance nature; additional unreported hot springs probably occur in the area.

White (1957) has classified springs as hot, or thermal, if their temperature is more than 6°C (15°F) above mean annual temperature of the area. Problems arise in applying White's definition to this part of Alaska because the mean annual temperature for much of the region is -4° to -7°C (Johnson and Hartman, 1969) which would result in springs with temperatures barely above freezing being considered as thermal. We have therefore restricted this report to springs with temperatures of at least 15°C (59°F).[1/]

We are indebted to our Geological Survey colleagues Raymond L. Elliott, Donald G. Grybeck, and Henry L. Heyward who assisted us in the sampling of hot springs and James B. O'Neil for oxygen and hydrogen isotopic analysis. R. B. Barnes, J. B. Rapp, T. S. Presser, and L. M. Willey provided chemical analyses of water samples. Travis B. Hudson graciously provided water samples and temperatures from Serpentine Hot Springs and Martin L. Olson of Golovin, Alaska supplied information on the location of several hot springs in southeastern Seward Peninsula. R. M. Chapman provided data on several hot springs in the Yukon-Tanana and Kokrines-Hodzana Highlands in the eastern part of the area.

[1/] Waring (1917) mentioned a possible warm spring on the headwaters of the Inmachuk River in the north-central Seward Peninsula; a later report by Gordon Herreid (oral comm., 1973) stated that the waters of the spring were not noticeably warm to the touch and the spring has not been included in this report.

GENERAL DESCRIPTION

The hot springs of central and western Alaska generally occur in valleys, and low on mountain slopes. A few localities show considerable differences in elevation of individual springs; at Clear Creek hot springs (fig. 1, no. 6) for example, there is as much as 200 feet difference in elevation between hot springs 1/4 mi apart. Only Pilgrim Hot Springs (no. 1, fig. 1) in the Seward Peninsula occurs in the middle of a "major" alluvium-filled valley more than a mile wide; all others occur either in smaller valleys or on the fronts of mountain ranges.

The part of Alaska considered in this report generally includes the area between 64°N. and 66°N. lat, and from the Bering Straits east almost to Fairbanks (fig. 1). This region is part of the Intermontane Plateaus physiographic division (Wahrhaftig, 1965) and includes parts of the Northern Plateaus, Western Alaska, and Seward Peninsula physiographic provinces. The region consists of low mountain ranges, uplands, and alluvium-filled lowlands; elevations of the mountains and uplands range from over 5,000 feet in the east to generally less than 4,000 feet in the west. Most of the region lies within the zone of continuous permafrost (Ferrians, 1965).

Most of the hot springs occur in forested areas; the exceptions are Pilgrim, Serpentine, Lava Creek, and Granite Mountain hot springs (nos. 1, 2, 3, and 7, fig. 1) on the Seward Peninsula which are beyond tree line. The hot spring areas support a variety of lush vegetation, although the immediate area around the spring is commonly marked by open grass-covered meadows. The lush vegetation aids in the locating of hot springs, particularly in late spring or fall when the green coloring is most conspicuous against the gray and brown of the surrounding area. On cooler days in the summer, low clouds of vapor commonly form over many springs.

Thick growths of algae including red, white, and green varieties are common on the bottom of hot springs and their runoff channels, as are long "streamers" of white bacteria (?).

Measured temperatures are available from 12 hot spring localities and range from 17°C to a maximum of 77°C for Serpentine Hot Springs in the Seward Peninsula (no. 2, fig. 1) with only one below 40°C; estimated temperatures are available from another 7 localities and range from 15°C to 60°C. Data on the temperature fluctuation on a daily basis is almost nonexistent. Travis B. Hudson (written comm., 1969) kept daily temperature records over a six-week period in the summer of 1969 at Serpentine Hot Springs and reported a range of only 3°C from 74°C to 77°C. Seasonal data are not available. Temperatures measured in recent years are in general similar to those reported by Waring (1917) over 50 years ago from the same springs.

The area of hot spring development and/or thawed ground (insofar as can be deduced from vegetation patterns) at individual hot spring localities range from as small as a few hundred square feet to as much as 40 to 50 acres in the case of Division hot springs (no. 11, table 1, fig. 1). Judging from the lack of change in vegetation patterns, the area of high heat flow at individual hot spring localities appears to be relatively stable.

Information regarding discharge rates is also sparse. Waring (1917) reported discharges ranging from a few gal/min to as much as a few hundred gal/min. Estimates made by us at springs not visited by Waring are in the same range. These are minimum estimates since it is unknown how much hot water seeps undetected into the unconsolidated material overlying bedrock at many of the springs.

Current and historical use of hot spring waters in western and central Alaska has been for bathing and limited agricultural purposes; cultivated areas have not exceeded 60 acres at any hot spring locality. No large scale development of the hot springs other than for recreational use is currently taking place.

REGIONAL GEOLOGIC SETTING

About 80 percent of the area discussed in this report is covered by modern geologic mapping at a scale 1:250,000 or larger. Topical studies on many of the plutonic rocks and mineral deposits of the region have been carried out in recent years. Geophysical information, however, on hot springs in western and central Alaska is nonexistent. Regional aeromagnetic surveys have been made of parts of the region but at flight-line spacings too large (3/4 mi or more) to provide meaningful information of the relatively small hot spring areas. Gravity maps are not available at a scale larger than 1:1,000,000.

The hot springs of central and western Alaska occur in several different geologic provinces (table 1). From west to east, these are the Seward Peninsula, the Yukon-Koyukuk, the Kokrines-Hodzana Highlands, the Yukon-Tanana, and the Kaiyuh Hills. The locations of these provinces is shown in figure 1 and a brief description of them is given below.

The Seward Peninsula is underlain chiefly by regionally metamorphosed pelitic and carbonate rocks of probable Precambrian age and by lesser amounts of Paleozoic carbonate rocks. Numerous stocks and plutons of granitic rocks of Cretaceous and possibly Tertiary age intruded this assemblage, particularly along the arcuate trend defined by the Kigluaik, Bendeleben, and Darby Mountains (fig. 1). Basalt of Quaternary age covers large parts of the north-central part of the Peninsula.

East of the Seward Peninsula is the Yukon-Koyukuk province, a large wedge-shaped tract of volcanogenic sedimentary and andesitic volcanic rocks of Early and late Early Cretaceous age (Patton, 1973). Locally this assemblage is overlain by Late Cretaceous and Tertiary subaerial volcanic rocks and intruded along an east-west belt by Cretaceous granitic rocks. Quaternary basalt covers several hundred square miles in the western part of the province. The province is bounded by narrow belts of mafic volcanic and intrusive rocks which probably belong to an ophiolite sequence.

The igneous and metamorphic complex of the Kokrines-Hodzana Highlands lies east of the Yukon-Koyukuk province and consists of a thick sequence of pelitic schists, quartzite, and carbonate rocks of Paleozoic and perhaps Precambrian age intruded by late Mesozoic granitic plutons. The metamorphic grade ranges from greenschist facies in the western part of the province to almandine amphibolite facies in the eastern part.

The Yukon-Tanana and Kaiyuh Hills regions consist chiefly of sedimentary and low-grade metamorphic rocks ranging in age from Precambrian to Mississippian and overlain by Cretaceous and Tertiary sedimentary rocks (Foster and others, 1970; Mertie, 1937a,b). Ultramafite and mafic volcanic rock of probable Devonian age and Permo-Triassic age are also present and the entire sequence is intruded by granitic plutons of Cretaceous and Tertiary age.

Within this large area, covering about 60,000 sq mi, a variety of geologic features and structural trends are found, some of which are confined to a single province while others occur in two or more provinces. A feature that is common to all the provinces, however, regardless of geologic or structural setting, is the occurrence of granitic plutons of late Mesozoic and early Cenozoic age and it is with these plutons that the hot springs are spatially associated (fig. 1). This association, first noted by Waring (1917), is a close one; all 23 hot spring localities where the general bedrock geology is known occur within 3 mi of the contact of a granitic pluton. Of these 23 hot springs, 11 are inside the pluton within 1 1/2 mi of the contact, 2 are approximately on the contact, and 10 are outside the pluton within 3 mi of the contact. The local geologic setting of each hot spring, insofar as it is known, is given in table 1.

Although the hot springs are spatially related to the plutons, or more specifically to the pluton-country rock contact, there appears to be no relationship to the absolute age or composition of the plutonic rocks. Plutons with associated hot springs have yielded K-Ar age dates ranging from 106 m.y. (Early Cretaceous) for the Granite Mountain pluton in the western Yukon-Koyukuk province (Miller, 1972) to 63 m.y. (early Tertiary) for the Hot Springs Dome pluton in the Yukon-Tanana region (Chapman, Weber, and Taber, 1971), a range of over 40 m.y. These plutons are composed of such rock types as biotite granite, quartz monzonite, granodiorite, monzonite, syenite, nephelene syenite, and quartz latite; thus included are calc-alkaline, subalkaline, and alkaline rocks. Preliminary analysis (Carl M. Bunker, written comm., 1971) suggest that the plutons with which the hot springs are associated show a considerable difference in radioactivity and radiogenic heat production. Uranium, thorium, and heat production vary from 2-4 ppm, 17-22 ppm, and 5.7-8.1 µcal/g yr respectively in the Bendeleben pluton with which the Lava Creek hot springs (no. 3, fig. 1) is associated, to 9-15 ppm, 49-65 ppm, and 17.4-22.3 µcal/g yr for the Darby pluton with which the Kwiniuk and Clear Creek hot springs (nos. 5 and 6, fig. 1) are associated. The radioactivity and radiogenic heat of the Bendeleben pluton are similar to granitic rocks elsewhere (Rodgers and Adams, 1969; Wollenberg and Smith,1968) while the Darby pluton is anomalously high in both quantities.

Plutons with hot springs are composed of rocks that are typically massive and well-jointed with little or no foliation or lineation. The jointing may increase the fracture permeability sufficiently to promote deep circulation of meteoric water (local snowmelt and rainwater). Plutons composed of rocks with a well-developed foliation, such as the large (350 sq mi) Selawik Hills pluton (Miller, 1970) in the western Yukon-Koyukuk province do not appear to have hot springs, possibly due to a low fracture permeability.

The occurrence of hot springs also appears independent of the size of the pluton as plutons with associated hot springs range from 15 sq mi to over 300 sq mi in outcrop area.

A strong correlation obviously exists between the distribution of Cretaceous and early Tertiary plutons and hot springs in western and central Alaska. This association is present elsewhere in Alaska outside the region covered in this report, for example at Circle and Chena hot springs in east-central Alaska (Waring, 1917) and in eastern Chukotka Peninsula, U. S. S. R., opposite the Seward Peninsula where most of the reported hot springs are spatially associated with granitic rocks (Golovachev, 1937; Nikolski, 1937, Rabkin, 1937). The association of hot springs with the pluton contacts and in some cases with known faults and lineaments suggest that well-developed "open fracture systems" exist near the pluton margins which allow hot water to rise to the surface. A necessary prerequisite for the occurrence of a hot spring in this part of Alaska appears to be the presence of a mass of competent, well-fractured rock such as the massive granitic plutons. It is of interest that all 10 of the hot springs that lie near but outside plutons occur in such rocks as graywacke, mudstone, basalt, and andesite that may have been affected to some extent by thermal metamorphism but not by regional metamorphism. Apparently fracture systems were not developed or are not sufficiently "open" in the well-foliated regionally metamorphosed rocks to allow deeply circulating hot water to gain access to the surface. Massive contact metamorphic rocks on the other hand may have a higher fracture permeability resulting in a more favorable setting for hot springs.

Some of the hot spring localities occur near mapped or inferred faults and lineaments; for example, Pilgrim, Serpentine, Kwiniuk, Clear Creek, Hawk River, South, Division, and Horner hot springs (nos. 1, 2, 5, 6, 8, 9, 11, and 15, fig. 1). These faults and lineaments range in length from a few miles to over 275 miles in the case of the Kaltag fault (Patton and Hoare, 1968). Hot springs, however, only occur where the faults and lineaments are near the plutons; i.e., those parts of the faults away from plutons seemingly have no hot springs associated with them. The hot springs as a group are not spatially associated with faults along which recent movement has occurred although a few do occur near such faults (i.e., Horner, Little Minook Creek hot springs).

A local structural control is suggested at several localities where hot springs are not in the bottoms of valleys but issue from varying altitudes (Clear Creek, South, nos. 6 and 9, fig. 1). White (1968) has suggested that differences in altitude of individual hot springs from the same locality may indicate that no single structure is permeable enough to discharge all the water in the system.

Hot springs elsewhere are commonly but not exclusively related to recent volcanic activity. Late Cenozoic basalts occur in several areas of west-central Alaska and particularly in the western part of the region where they cover an area of about 3500 sq mi. K-Ar age dates on these basalts and correlative basalts on the islands of the Bering Sea (Hoare and others, 1968) range from about 6 m.y. to 30,000 years. Hopkins (1963) states that Lost Jim lava flow near Imuruk Lake in the central Seward Peninsula, which appears to be one of the youngest flows in western Alaska is at least several hundred and possibly several thousand years old. The existence of volcanic rocks ranging in age from 6 m.y. to 30,000 years or younger certainly suggests that parts of western Alaska may still be a volcanically "active" region. No hot springs, fumaroles, or other manifestations of current volcanic activity occur within areas underlain by these basalt flows and the known hot springs show no spatial association with these young basalts; the closest hot spring to basalt is the Lava Creek spring (no. 3, fig. 1) which is about 3 mi from the probable source area for basalt which flowed down Lava Creek in the Bendeleben Mountains (Miller and others, 1972).

The late Cenozoic volcanic rocks described above are all basalts or basaltic andesite (Hopkins, 1963; Miller and others, 1972); no Pliocene or younger volcanic rocks of intermediate or silicic composition are known within the region described in this report. A discontinuous belt of felsic volcanic rocks of late Cretaceous and Tertiary age occurs near the eastern margin of the Yukon-Koyukuk province (Patton and Miller, 1970). Although only a single K-Ar age of 58± 1.7 m.y. (Eocene) has been obtained from these rocks (Patton and Miller, 1973), it is unlikely that they are younger than mid-Tertiary in age and no hot springs, fumaroles, or other signs of recent volcanic activity have been found associated with these rocks.

The distribution of hot springs is independent of the age and type of country rock around the pluton as the country rock ranges from Precambrian to Late Cretaceous and includes limestone, graywacke, andesite, regionally metamorphosed rocks of low and high grade, and mafic volcanic rocks.

GEOCHEMISTRY

Chemical analyses of water samples from western and central Alaska are given in table 2. All the analyses listed as being from the U. S. Geological Survey files were done by the methods described in Brown and others (1970). The analytical results given under Willey and Presser, analysts, are the most reliable because the samples were filtered in the field through a 0.2 micron effective filter paper. In addition, samples for Ca, Mg, Al, and Fe analyses were acidified in the field to a pH $\leqslant$ 2 with sulfuric acid. HCO_3 and pH were also determined in the field using methods described by Barnes (1964). The analyses reported from analysts other than Willey and Presser were on unfiltered samples with no treatment in the field. Also given in table 2 are the highest values of constituents found in analyses of surface waters of Alaska unaffected by sea water (U.S. Geol. Survey, 1969); most of the recorded values are far below the maxima given here.

Geothermal systems are commonly classified into two types, hot-water and vapor-dominated systems whose criteria are defined in White (1970). The high discharge rate and the generally high contents of SiO_2, Cl, Na, K, and B relative to nearby ground water indicates that the hot springs of central and western Alaska belong to the hot-water type.

It is generally agreed (White and others, 1963) that most of the water discharged at the surface in thermal areas is meteoric in origin but that a part might be magmatic, metamorphic, or connate. When the composition of hot springs in western and central Alaska is compared to hot springs that are probably entirely meteoric in origin (White and others, 1963, table 25; Feth and others, 1964), and with the known composition of surface waters in Alaska (table 2), most of the Alaskan springs do indeed appear to be composed of locally derived meteoric water. Their composition can be explained by deeply circulated meteoric water whose long flow path and increased solvent action, due to the increase in temperature, brought about leaching of the country rock (White and others, 1963).

Four of the sixteen hot springs for which chemical analyses are available are saline in nature and characterized by concentrations of Cl, Na, Ca, K, and perhaps Li, Br, and B that are considerably greater than the other 12 analyzed springs. These four springs are Pilgrim (no. 1, table 2), Serpentine (no. 2, table 2), Kwiniuk (no. 5, table 2), and Tolovana (no. 21, table 2); the first 3 are in the Seward Peninsula while Tolovana is over 300 miles to the east (fig. 1).

The composition of these springs appears to demand either greatly increased leaching or addition of another type of water. If the anomalous composition of these springs is the result of an increased amount of leaching, then this leaching differed from the water-rock reactions typically seen in granitic rocks. Composition of thermal meteoric waters issuing from granitic rocks have been published by Feth and others (1964), and Miller (1961); the Na/Cl ratios calculated from their data all exceed 1 as do similar ratios for 11 of the other 12 analyzed hot springs in western and central Alaska. The Na/Cl ratios for the 4 saline springs, however (table 4), are all less than 1 and indeed are similar to sea water, 0.55. Reactions more complex than mere leaching would be required to provide the proportions of ions given in table 2.

It is possible that the composition of these four saline springs may be due to the addition of magmatic, metamorphic, or connate waters to local meteoric water. The interpretation of the histories of mineralized thermal waters from their chemical composition, however, is difficult, as has been discussed by White (1969, 1973, 1957a, b). Of the constituents given in the analyses in table 2, few may be used to determine the origin of the solutions. SiO_2 may only reflect the solution of quartz in the thermal waters (Fournier and Rowe, 1966, Mahon, 1966). Aluminum (Al) may be involved in reactions of too many aluminosilicates to reflect the earlier history of the solution. Iron (Fe) is largely controlled by the local oxidation potential (Barnes and Back, 1964; Barnes, Stuart and Fisher, 1964). Calcium (Ca) data may only reflect local solution and deposition of calcite, thus the bicarbonate (HCO_3) and Ca data may give information on present processes rather than the earlier history of the water. Magnesium (Mg) concentrations may be controlled by reactions of not only Mg-carbonates but also chlorite in geothermal systems (Muffler and White, 1969). Potassium (K) and lithium (Li) are both sufficiently low in concentration that additions or subtractions of small amounts will obscure the earlier history. Sodium (Na) alone of the cations is present in sufficient concentrations and sufficiently nonreactive that small additions or losses will not obscure the earlier Na concentrations.

As far as the anions are concerned, sulfate (SO_4) may be affected to a large extent by reduction of sulfide or oxidation of sulfide minerals to sulfate. Fluoride (F) may be in part controlled by the solubility of fluorite (CaF_2), and boron (B), although leached from some rocks at moderate temperatures (White, 1957b), is difficult to use since its mineralogic source is not always known. The chloride (Cl) and bromide (Br) concentrations, in contrast to the other anions, may be more significant in interpreting the history of the water. Although the Cl in most rocks is easily leached by water at high temperatures (Ellis and Mahon, 1964), host rocks of the hot springs in the study area are not likely to be rich in Cl judging from their known composition. No obvious mineralogic source or sink for either Cl or Br has been found in the rocks of the study area.

The high Cl and Na content suggests the possibility of the addition of magmatic water since hot spring waters found in areas of active volcanism often contain large amounts of these elements (White and others, 1963). Such springs, however, also commonly contain large amounts of HCO_3, SO_4, and SiO_2 which the saline hot springs of central and western Alaska do not. Further, the salinity of the hot springs appears unrelated to the most direct evidence of magma, the Quaternary volcanic rocks.

Metamorphic waters are defined by White (1957) as water that is or has been associated with rocks during their metamorphism and is probably derived drom the reconstitution of hydrous minerals to anhydrous minerals. Such waters are thought to be high in Na, HCO_3, and B (Barnes, 1970) in contrast to the saline hot springs of this report that do not have large concentrations of HCO_3 and B.

The saline nature of the hot springs suggests the admixture of connate sea water or of present sea water. The Na^+/Cl^- and Cl^-/Br^- ratios from available data on the hot spring waters are given in table 4. The Na^{+1}/Cl^{-1} data fall in two groups—a group with the ratio 1 or greater, similar to the results of Feth and others (1964) and Miller (1961), and a group with the ratio near the 0.55 ratio of sea water. The Br^{-1}/Cl^{-1} seems to give the same result, a separation of locally derived meteoric water from the more saline waters of a more complex history; the data, however, are too few to warrant extensive interpretation. A simple, although not necessarily correct interpretation, is that the saline waters contain some old sea water or waters derived from sea water, with little change in the Na^{+1}/Cl^{-1} or Cl^{-1}/Br^{-1}. Although the Cl/Br ratios may be interpreted as dilution of sea water, the geologic evidence is against submergence of the rocks of the region since the Cretaceous. If leaching is to account for the Cl/Br ratios, the leaching fortuitously results in ratios the same as present day sea water.

Waring (1917) recognized the saline character of Pilgrim Hot Springs and although noting that the spring was not far above the tide level, suggested that the high salinity was not due to admixture of sea water since the ratios of SO_4/Cl and Ca/Na were not similar to sea water. In view of the possible water-wallrock reactions involving Ca and SO_4 mentioned above, however, Waring's objection may not be valid. A more serious objection to the admixture of either old or present sea water is the geologic and geographic distribution of the saline hot springs. Three of the four saline springs occur in a region of igneous and regionally metamorphosed rocks where connate water is unlikely. While two of the saline springs (Pilgrim and

Kwiniuk) occur relatively near sea water and along structural trends that may directly connect with the ocean, the other two are either far removed from the ocean (Tolovana) or do not lie on such structures (Serpentine).

A final discrepant point in regard to the four saline springs is their lack of a geologic pattern to their distribution. Other hot springs in the Seward Peninsula where 3 of the 4 saline springs occur, are non-saline; this is particularly striking in regard to Kwiniuk (saline) and Clear Creek (non-saline) hot springs which are only 12 miles apart and in the same pluton (fig. 1). Whatever the process that has resulted in the saline hot springs, it appears to be a highly selective one. The low Cl springs may be older than the high Cl springs and most of the Cl may already have been leached along the permeable paths. The high Cl waters may be younger in the sense that the Cl has not yet been completely leached along the presently permeable paths.

The few isotopic analyses available are from the non-saline hot springs. Insufficient D data are available for a direct comparison of D enrichments of meteoric waters with the hot spring waters. Therefore the δO^{18} was calculated from the enrichment in D from Craig's (1961) equation:

$$\delta O^{18} = (\delta D - 10)/8,$$

which applies to meteoric water that has not exchanged oxygen with the rocks. The results, given in table 3, show a close agreement between δO^{18} of the hot spring waters and what would be expected of meteoric water. The hot spring waters show a slight (0.6 to 1.6 ^{o}/oo enrichment relative to that predicted for meteoric water which may be expected from oxygen exchange between water and rock. The close comparison holds even in two areas differing by nearly 6 ^{o}/oo in δO^{18} for the meteoric water. We conclude that the waters reported in table 3 are predominantly meteoric waters of local origin. Isotopic analyses from the saline hot springs, not yet available, may shed some light on the source of the constituents. For instance, Pilgrim Hot Spring contains 3,500 mg/l Cl. If the Cl is from mixing of sea water (19,000 ppm Cl) with locally derived meteoric water low in Cl, a change of some 2 to 3 ^{o}/oo in δO^{18} would be found assuming the same dilution in O^{18} and Cl.

Water chemistry has proven valuable in estimating subsurface temperatures and the various techniques and approaches are described by Mahon (1970), Fournier and Rowe (1966), White (1970), and Fournier and Truesdell (1970, 1973). The most quantitative temperature indicators have been shown to be (1) the variation in solubility of quartz as a function of temperature and (2) the temperature dependence of base exchange or partitioning of alkalies between solutions and solid phases with a correction applied for the calcium content of the water (the Na-K-Ca geothermometer). There is some ambiguity and uncertainty in both methods and in any particular region, subsurface information may be necessary to adequately calibrate, or choose between, the methods. Silica maybe precipitated rapidly enough from waters hotter than 180°C to give erroneously low values (White, 1970). The calculated subsurface temperatures (table 5) using the quartz conductive cooling geothermometer are 137°C as a maximum so silica precipitation may not affect the validity of the results. The Na-K-Ca geothermometer maybe in error either because of continued reaction of the water with the rocks at temperatures below the highest subsurface temperature calculated or because of calcite precipitation. Continued reaction may yield low calculated temperatures due to Ca concentration increases (Fournier and Truesdell, 1973). Calcite precipitation may yield erroneously high subsurface temperatures because of Ca concentrations decreases (Fournier and Truesdell, 1970).

Lacking knowledge of subsurface reactions we have calculated subsurface temperatures using both the quartz solubility and Na-Ca-K geothermometers. For the quartz conductive cooling geothermometer (Fournier and Rowe, 1966), the equation is (Fournier, oral comm., 1973):

$$\log_{10} C_{SiO_2(aq)} = (1.309X10^3/T) - 5.19$$

where

T = Temperature °K

and

C_{SiO_2} = concentration of silica in mg/l.

For calculations of subsurface temperatures from Na-K-Ca concentrations (Fournier and Truesdell, 1973), the equation is (for temperatures above 100°C):

$$\log_{10}(M_{Na^{+1}}/M_{K^{+1}}) + 1/3 \log_{10}(M_{Ca^{+2}})^{1/2}/M_{Na^{+1}}) =$$

$$1647/T - 2.240$$

where

$M_{Na}{}^{+1}$ = molality of sodium ion

$M_K{}^{+1}$ = molality of potassium ion

$M_{Ca}{}^{+2}$ = molality of calcium ion.

For temperatures below 100°C the equation is:

$$\log_{10}(M_{Na}{}^{+1}/M_{K}{}^{+1}) + 4/3 \log_{10}(M_{Ca}{}^{+2})^{1/2}/M_{Na}{}^{+1}) =$$

$$1647/T - 2.240.$$

The results of these calculations for individual hot springs are given in table 5. The quartz conductive cooling geothermometer shows a range of 78° to 137°C for the 10 springs for which it could be calculated. The Na-K-Ca geothermometer shows a range (based on 14 springs) of 40°C to 161°C although only one spring was below 100°C. The difference between temperatures measured by the two geothermometers for any one spring ranges from 8° to 59°. Perhaps the most important point that can be determined from these data is the maximum temperatures recorded by both geothermometers; these are 137°C for the quartz conductive method and 161°C for the Na-K-Ca method. Both of these maximum temperatures are below the minimum temperature (180°C) currently thought necessary to drive steam turbine generators (Muffler, 1973).

Another indication of relatively low subsurface temperatures is the lack of siliceous sinter and the presence of travertine in the hot spring deposits. Such characteristics imply (White, 1970) low subsurface temperatures.

DISCUSSION

A study of the geologic setting of hot springs in central and western Alaska shows a close correlation between the occurrence of hot springs and the contact zones of granitic plutons. Where the bedrock geology of the hot spring area is known, the hot springs are almost without exception within 3 miles of the contact of a pluton. Where the country rock is strongly foliated metamorphic rocks, the hot springs are restricted to the pluton proper; where sedimentary or volcanic rocks form the country rock, the hot springs occur both within and outside the pluton. The hot springs distribution is, however, independent of the age, composition, and magmatic events that formed the pluton. The occurrence of hot springs also appears to be related to fracture and fault zones near the margins of the pluton.

The chemical and isotopic composition of analyzed hot springs within the region suggests that most of them are composed of locally derived meteoric water. Four of the sixteen analyzed hot springs however, have very saline compositions which appear to require either much increased leaching of country rock or addition of another type of water. The present data do not permit a unique solution to the problem.

The tentative model suggested by the available information on the geologic setting and geochemistry of the hot springs in central and western Alaska is as follows. Most of the hot springs are the result of deeply circulating locally derived meteoric water which has percolated through the fractured granitic plutons and the surrounding wallrock to depths of several thousand feet, become heated due to the geothermal gradient, and found access to the surface along the fractured and faulted margins of the pluton. In a few cases, another type of water, either sea water or magmatic water may have been added to the meteoric water. If no addition of magmatic water is considered, the subsurface temperatures indicated by the chemical geothermometers suggests the water must have reached depths of 9,000 to 15,000 feet based on assumed geothermal gradients of 30°C/km and 50°C/km and a maximum subsurface temperature of 160°C (table 3). If magmatic water, or heat from an underlying magma, has been added to the system, the calculated temperatures from the chemical geothermometers may be reached at shallower depths than those calculated from normal geothermal gradients.

The following point can be made concerning the potential of the hot springs for power generation. Muffler (1973) gives 180°C as the lowest reservoir temperature that can presently be utilized for the generation of electricity by steam turbine generators. The subsurface temperatures suggested by the present study are therefore too low for such uses. They are, however, within the ranges suggested for turbines utilizing a heat exchange system involving such working fluids as freon and iso-butane. An experimental plant of this type has been operating at Paratunka, Kamchatka (USSR) since 1970 utilizing 81.5°C water (Facca, 1970).

The hot springs appear to occur along fractured zones near the margins of granitic plutons and the reservoir of such a system may not be large. According to White (1965), the yield of stored heat may drop relatively quickly in crystalline rocks with low permeability where circulation of water is localized in faults and fractures. The total surface area of rocks in direct contact with migrating fluids is relatively small and the recoverable stored heat is transferred to the circulating fluids by conduction over long distances. These fault and fracture zones in the crystalline plutonic rocks are liable to be narrow or widely spaced and less numerous at greater depths.

Only preliminary data are available on the geologic setting and geochemistry of hot springs in central and western Alaska and therefore interpretations must also be considered preliminary. The data, however, do suggest that most, if not all, of the hot springs are characterized by reservoirs of limited extent and relatively low temperatures in comparison to hot spring systems presently being exploited for power generation. The springs may, however, have some potential for limited power generation for local use using heat exchanger technology if and when such becomes available, as well as for space heating and horticultural uses. If magmatic water or heat is being added to the geothermal system, the area would have more potential as a geothermal resource and in this regard studies of the geology and chemistry of the springs will continue.

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Table 2. Chemical analyses of water from thermal springs in western and central Alaska. Numbers refer to figure 1 and table 1--Cont'd

Name and map symbol (fig. 1)	Melozi 17	Horner 15	Ray River 24	Lower Ray River 25	Kanuti 26	Manley 19	Manley 19	Manley 19	Hutlinana 20	Hutlinana 20	Tolovana 21	Maximum value found in surface waters of Alaska
Source of analysis	Waring (1917)	Waring (1917)	USGS files	USGS files	USGS files	USGS files	USGS files	Waring (1917)	USGS files	Waring (1917)	Anderson (1970)	U.S. Geol. Survey (1969)
Analyst			R.B. Barnes	R.B. Barnes	R.B. Barnes	L.M.Willey T.S.Presser	L.M.Willey T.S.Presser		L.M.Willey T.S.Presser			
SiO_2 -----	78	29	-----	-----	-----	65	65	59	40	44	75	41
Al ------	-----	.2	-----	-----	-----	.016	.046	.8	.014	-----	-----	
Fe ------	.75	2.7	-----	-----	-----	-----	-----		-----	.09	.02	89
Ca ------	11	10	5.6	11	2.7	4	6.8	9.1	20.2	22	82	280
Mg ------	2.8	3	.7	.1	.3	1	.29	.9	6.6	6.0	1.2	74
Na ------	107	58	71	95	111	130	130	121	180	208	321	67
K -------			1.4	2.0	3.7	4.5	4.8	8.2	7.9		23	9.5
Li ------	-----	-----	-----	-----	-----	.28	.28	-----	.16	-----	-----	
NH_3 -----	-----	-----	-----	-----	-----	4.9	.5	-----	.4	-----	-----	
HCO_3 ----	32	22	74	93	169	89.6	90.7	86	488	494	49	1,040
CO_3 -----	31	32	22	21	-----	-----	-----	0.0	-----	0.0	-----	
SO_4 -----	61	45	19	23	21	54	51	48	55	67	40	184
Cl ------	92	39	9.1	25	28	134	132	120	40	38	615	100
F -------	-----	-----	-----	-----	-----	8.5	8.2	-----	.8	-----	.2	1
Br ------	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	
B.-------	-----	-----	.6	1.6	1.3	1.3	1.2	-----	.3	-----	-----	
pH ------	-----	-----	9.16	9.04	8.01	7.7	7.72	-----	7.66	-----	7.7	
Temp.°C	56	47	45	66	66	59	56	52	43	45	52	

Table 2. Chemical analyses of water from thermal springs in western and central Alaska. Numbers refer to figure 1 and table 1

[Concentrations are in mg/l]

Name and map symbol (fig. 1)	Pilgrim		Serpentine			Lava Creek	Battleship Mountain	Kwiniuk	Clear Creek	Granite Mountain		South
	1	1	2	2	2A	3	4	5	6	7	7	9
Source of analysis	USGS files	Waring (1917)	USGS files	USGS files	USGS files	USGS files	USGS files	USGS files	USGS files	USGS files	USGS files	USGS files
Analyst	L.M.Willey T.S.Presser		L.M.Willey T.S.Presser	J.B.Rapp	J.B.Rapp	L.M.Willey	R.B. Barnes	L.M. Willey	R.B. Barnes	L.M.Willey T.S.Presser	J.B. Rapp	R.B. Barnes
SiO$_2$	100	87	100	90	89	70	-----	45	-----	75	69	65
Al	0.044	4.1	0.083	0.06	0.06	-----	-----	-----	-----	0.094	0.2	0.1
Fe	-----	.7	-----	<.01	<.01	-----	-----	-----	-----	-----	<.01	<.01
Ca	530	545	47	75	78	2	14	130	5.6	2	1.8	5.9
Mg	1.4	7.4	.48	.35	.34	<.025	.2	.1	.06	.04	.05	.01
Na	1,450	1,587	730	800	800	75	111	500	54	51	67	83
K	61	61	40	41	41	1.4	1.1	9	1.4	1.3	1.9	2.1
Li	4.0	-----	4.7	-----	-----	-----	-----	-----	-----	.04	-----	-----
NH$_3$	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
HCO$_3$	30.1	21	64.5	57	56.8	100	40	10.2	34	45.7	90	-----
CO$_3$	-----	-----	-----	1.3	.7	-----	10	-----	34	-----	-----	-----
SO$_4$	24	25	29	1	1	-----	16	-----	25	62	50.3	122
Cl	3,346	3,450	,480	1,450	1,420	8	122	912	4.9	9.3	6.4	6
F	4.7	-----	6.4	6	6	9	-----	5.8	-----	8.2	-----	-----
Br	-----	-----	-----	4.9	4.8	1	-----	4	-----	-----	-----	-----
B	2.4	-----	3.4	2.9	2.8	.8	.6	1	.2	.13	.22	-----
pH	6.75	-----	7.91	-----	7.94	9.1	8.97	7.3	9.43	10.14	9.55	
Temperature °C	55	69	60	77	71	+50(est)	17	+50(est)	67	49	49	+50(est)

Table 3. Measured values of δO^{18} and δD in per mil (‰) and the calculated value of δO^{18} for locally derived meteoric waters.

Locations, numbers refer to figure 1.		Measured δO^{18}	Measured δD	Calculated δO^{18}
4	Battleship Mountain hot spring---------------	-13.8	-106	-14.5
6	Clear Creek hot spring----------------------	-15.6	-119	-16.2
	Local water for above samples---------------	-14.2		
24	Ray River hot spring------------------------	-19.1	-150	-20.0
25	Lower Ray River hot spring------------------	-19.2	-157	-20.8
26	Kanuti hot spring --------------------------	-18.0	-146	-19.5
	Local meteoric water for above three samples	-19.9	-159	-21.1

Table 4. Na^{+1}/Cl^{-1} and Cl^{-1}/Br^{-1} ratios from available data on the hot spring waters

Sample, numbers refer to table 2	Na^{+1}/Cl^{-1}	Cl^{-1}/Br^{-1}
1 Pilgrim------------------	.46	
2 Serpentine---------------	.55	296
3 Lava Creek---------------	9.4	8
4 Battleship Mountain------	.9	
5 Kwiniuk------------------	.55	228
6 Clear Creek--------------	11	
7 Granite Mountain---------	10	
9 South--------------------	14	
17 Melozi------------------	1.2	
15 Horner------------------	1.5	
24 Ray River---------------	7.8	
25 Lower Ray River---------	3.8	
26 Kanuti------------------	4.0	
19 Manley------------------	1.0	
20 Hutlinana---------------	4.5	
21 Tolovana----------------	.52	
Sea water-----------------	.55	292

Table 5. Estimates of subsurface temperatures based on the quartz conductive cooling geothermometer and the appropriate Na^{+1}-K^{+1}-Ca^{+2} geothermometers

[Estimated temperatures are in degrees Celsius (°C)]

Sample, numbers refer to table 2 and to figure 1.	Quartz	Na^{+1}-K^{+1}-Ca^{+2}
1 Pilgrim-------------------	137	120
2 Serpentine----------------	137	160
3 Lava Creek----------------	118	107
4 Battleship Mountain-------	--	40
5 Kwiniuk-------------------	97	105
6 Clear Creek---------------	--	111
7 Granite Mountain----------	122	111
9 South---------------------	114	137
17 Melozi-------------------	123	--
24 Ray River----------------	--	103
25 Lower Ray River----------	--	105
26 Kanuti-------------------	--	136
19 Manley-------------------	78	137
20 Hutlinana----------------	114	130
21 Tolovana-----------------	122	161