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GEOLOGIC SETTING AND CHEMICAL CHARACTERISTICS OF HOT SPRINGS IN WEST-CENTRAL ALASKA

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Abstract.—Numerous hot springs occur in a variety of geologic provinces in west-central 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 are within 4.8 km (3 mi) of a granitic pluton. The occurrence of hot springs, however, appears to be independent of the age, composition, or magmatic history of the pluton. Most of the analyzed hot springs appear to have chemical and isotopic compositions indicating that 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 in the other hot springs or the addition of another type of water. Chemical geothermometers suggest subsurface temperatures in the general range of 70° to 160°C. If the hot spring waters have derived their heat solely from deep circulation, they must have reached depths of 2 to 5 km (6,000–15,000 ft), assuming geothermal gradients of 30° to 50°C/km. If a shallow igneous heat source exists in the area or if dilution or mixing has occurred, these depths may be shallower. The geologic and chemical data, although preliminary, suggest that most of the hot springs of west-central Alaska have relatively low subsurface temperatures and limited reservoir capacities in comparison with geothermal areas presently being utilized for electrical power generation. The springs may, however, have some potential for limited power generation locally, if and when heat-exchange technology becomes available, as well as for space heating and agricultural uses.

Hot springs have long been known to occur in west-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 area (fig. 1), and these springs constitute about 30 percent of the presently known hot springs in Alaska (Miller, 1973). Because the occur-

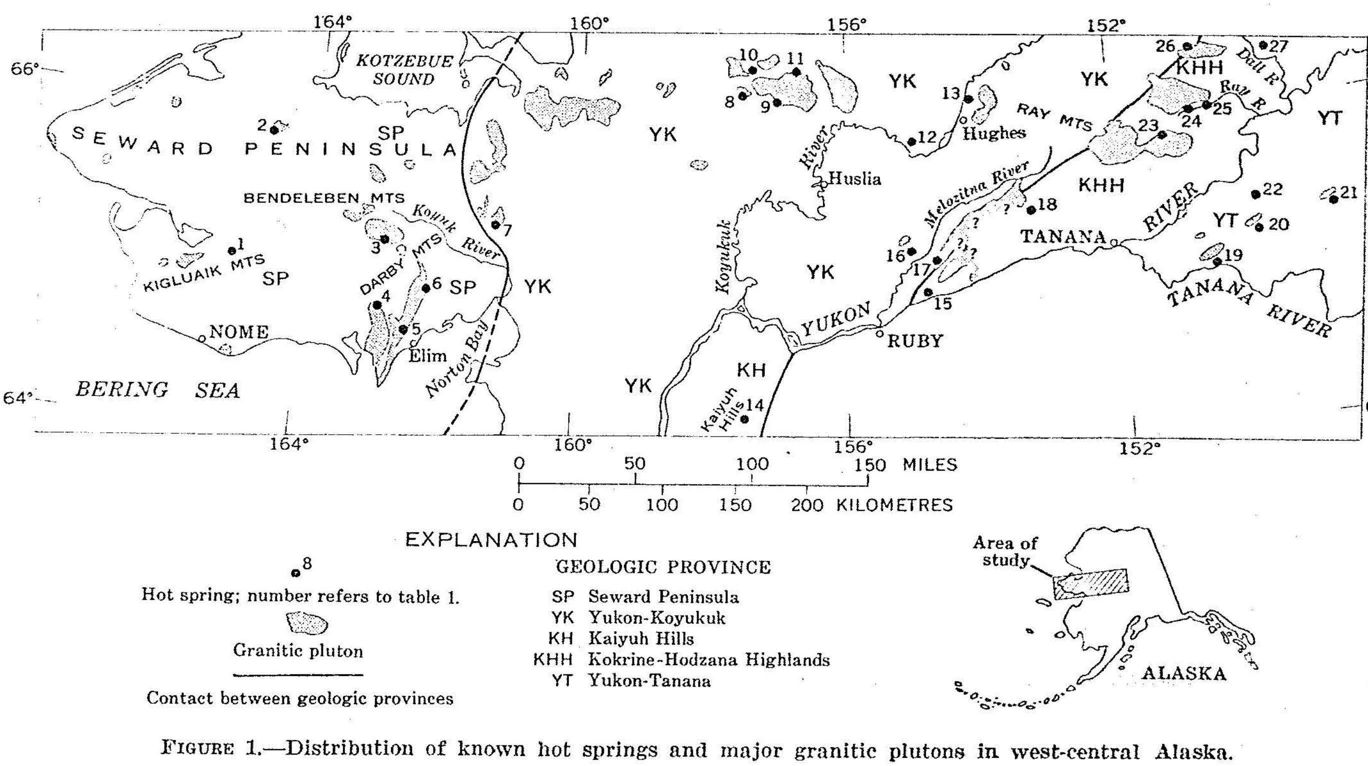

FIGURE 1.—Distribution of known hot springs and major granitic plutons in west-central Alaska.

rence of hot springs suggests possible geothermal resources and because interest in such resources as sources of energy is increasing, an updated report on these springs is warranted. Recent studies (Muffler, 1973; Combs and Muffler, 1973; White, 1973; Mahon, 1966; Fournier and Rowe, 1966; Fournier and Truesdell, 1973) have shown 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. This report, therefore, discusses the geologic setting and chemical composition of known hot springs in west-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 data are available for only 16; indeed, fairly complete analyses are available from only 5 springs. Measured temperatures are available on 13 hot springs, and no information of temperatures is available from 5 of the remaining 14. In a few places, geologic mapping of the general spring site is not complete, and none of the hot springs has been studied in detail. Additional hot springs probably occur in the area but are unreported because it is sparsely populated and geologic mapping has been chiefly small-scale reconnaissance.

White (1957a) has classified springs as hot, or thermal, if their temperature is more than 6°C (15°F) above the 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 means that springs with temperatures barely above freezing would be considered thermal. We have therefore restricted this report to springs with temperatures of at least 15°C (59°F).[1]

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GENERAL DESCRIPTION

The part of Alaska considered in this report includes the area between lat 64° and 66° N. and from the Bering Straits east almost to Fairbanks (fig. 1). This area is part of the Intermontane Plateaus physiographic division (Wahrhaftig, 1965) and includes parts of the Northern Plateaus, Western Alaska, and Seward Peninsula physiographic provinces. It consists of low mountain ranges, uplands, and alluvium-filled lowlands; altitudes of the mountains and uplands range from over 1,500 m (5,000 ft) in the east to generally less than 1,200 m (4,000 ft) in the west. Much of the region lies within the zone of continuous permafrost (Ferrians, 1965).

The hot springs of west-central Alaska generally are found along valley margins and at low altitudes on mountain and hill slopes. Only Pilgrim Hot Springs (No. 1, fig. 1) in the Seward Peninsula is in the middle of a large alluvium-filled valley more than 2 km wide; all others are either in smaller valleys or along the fronts of mountain ranges. A few localities show considerable differences in altitudes of individual springs; at Clear Creek (fig. 1, No. 6), for example, there is as much as 62 m (200 ft) difference in altitude between hot springs 400 m (¼ mi) apart.

Most of the hot springs are 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. Although the immediate area around the springs is commonly marked by open grass-covered meadows and bare ground, the margins of hot-spring areas support a variety of lush vegetation. The lush vegetation aids in locating 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 (Brock and Brock, 1971).

Measured temperatures are available from 12 hot springs and range from 17° to 77°C with only one spring below 40°C; estimated temperatures are available from another 7 localities and range from 15° to 60°C. Data on the daily temperature fluctuation are almost nonexistent. T. B. Hudson (written commun.,

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

1969) kept daily temperature records over a 6-week period in the summer of 1969 at Serpentine Hot Springs and reported a range of only 3°C from 74° to 77°C. Seasonal data are not available. Temperatures measured in recent years are generally similar to those reported by Waring (1917) over 50 yr ago from the same springs.

The amount of warm ground (insofar as indicated by vegetation patterns) at individual hot springs ranges from a few tens of square metres to as much as tens of thousands of square metres at 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 springs appears to be relatively stable.

Information regarding discharge rates is also sparse. Waring (1917) reported discharges ranging from a few gallons per minute to as much as a few hundred. Estimates made by us at springs not visited by Waring are in the same range. These are minimum estimates since it is not known 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 west-central Alaska has been for bathing and limited agricultural purposes; cultivated areas have not exceeded 0.24 km² (60 acres) at any hot-spring locality.

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. Regional aeromagnetic surveys have been made of parts of the area but at flightpath spacings too large (greater than 1 km) to provide much information on the relatively small hot-spring areas. Gravity maps are not available at a scale larger than 1:1,000,000.

The hot springs of west-central Alaska occur in several geologic provinces (table 1, fig. 1). From west to east, these are the Seward Peninsula, the Yukon–Koyukuk, the Kokrine–Hodzana Highlands, the Yukon–Tanana Upland, and the Kaiyuh Hills.

The Seward Peninsula is underlain chiefly by a thrust-faulted sequence of 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 by Cretaceous granitic rocks along the east-west Hogatza plutonic belt. Quaternary basalt covers several hundred square kilometres in the western part of the province. The province is bounded by narrow belts of mafic volcanic and intrusive rocks that probably belong to an ophiolite sequence.

The igneous and metamorphic complex of the Kokrine–Hodzana Highlands lies east of the Yukon–Koyukuk province and consists of a thick sequence of pelitic schists, quartzites, and carbonate rocks of Paleozoic and perhaps Precambrian age intruded by late Mesozoic granitic plutons. The metamorphic grade is chiefly greenschist facies with high-temperature thermal aureoles around the plutons.

The Yukon-Tanana Upland and Kaiyuh Hills areas 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). Ultramafic and mafic volcanic rocks of probable Devonian age and Permian-Triassic age are also present, and the entire sequence is intruded by granitic plutons of Cretaceous and Tertiary age.

Within this large area of about 155,000 km² (60,000 mi²), a variety of geologic features and structural trends is found; some are confined to a single province, whereas others are 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 bedrock geology is known are within 4.8 km (3 mi) of the contact of a granitic pluton. Of these 23 hot springs, 11 are inside the pluton within 2.5 km (1.5 mi) of the contact, 2 are approximately on the contact, and 10 are outside the pluton within 4.8 km (3 mi) of the contact. The local geologic setting of each hot spring, insofar as it is known, is given in table 1.

There appears to be no relation between the absolute age or composition of the plutonic rocks and the occurrence of hot springs. Plutons with associated hot

TABLE 1.—*Description and geologic setting*

Locality No. and name	Location	General description
1. Pilgrim (formerly Kruzgamepa).	Bendeleben A–6 quadrangle; 65°06′ N., 164°55′ W.; 65 km (40 mi) north of Nome, 0.8 km (0.5 mi) south of Pilgrim River.	Several springs are found within a distance of a few hundred feet in middle of 8-km(5-mi)-wide alluvium-filled valley of Pilgrim River. An area 100 by 800 m appears to be underlain by warm ground. Discharge is small, less than 0.6 l/s (10 gal/min) according to Waring (1917). Recorded temperatures range from 69° (1915) to 60°C (1972). Chemical analysis available. Classified as "Known Geothermal Resource Area" (Godwin and others, 1971).
2. Serpentine (Arctic)	65°51′ N., 164°42′ W.; Bendeleben D–6 quadrangle; 150 km (95 mi) north of Nome on Hot Springs Creek.	Springs in two main areas about 800 m (0.5 mi) apart on Hot Springs Creek. Discharge at eastern spring estimated at about 2.2 l/s (35 gal/min) and temperature measured as 77°C. (T. B. Hudson, written commun., 1970). Chemical analysis available.
3. Lava Creek	65°13′ N., 162°54′ W.; Bendeleben A–2 quadrangle; 80 km (50 mi) north of Golovin on south side of Bendeleben Mountains.	One principal spring on east side of Lava Creek about 30 m (100 ft) above valley floor. Strong flow; temperature estimated at 60°–65°C. Noticeable H_2S odor. Chemical analysis available.
4. Battleship Mountain	64°48′ N., 162°55′ W.; Solomon D–2 quadrangle; 30 km (20 mi) north of Golovin.	One spring on east side of east fork of Cliff Creek on small bedrock terrace about 25 m (75 ft) above creek. H_2S odor; temperature of 17°C. measured in 1970. Chemical analysis available.
5. Kwiniuk	64°42′ N., 162°28′ W.; Solomon C–1 quadrangle; 14 km (9 mi) northwest of Elim.	One principal spring about 100 m (100 yd) north of Kwiniuk River. Temperature estimated at 40°–50°C in 1971. Chemical analysis available.
6. Clear Creek	64°51′ N., 162°18′ W.; Solomon D–1 quadrangle; 26 km (16 mi) north of Elim.	Hot springs are on both sides of east-flowing tributary of Clear Creek. Spring south of tributary has large flow estimated at several tens of litres per second and is about 120 m (400 ft) above Clear Creek valley floor. Temperature of 63°C measured in 1970. Two hot springs occur north of tributary. The upper spring is inaccessible by helicopter; the lower one has a smaller flow than the spring to the south and a temperature of 67°C. Chemical analysis available.
7. Granite Mountain (Sweepstakes).	65°22′ N., 161°15′ W.; Candle B–5 quadrangle; 65 km (40 mi) southeast of Candle on south side of Granite Mountain.	Several hot springs are found within a distance of about 30 m (100 ft) on the west side of Spring Creek about 15 m (50 ft) above valley bottom. Temperature: 49°C (1972). Chemical analysis available.
8. Hawk River	66°14′ N., 157°35′ W.; Shungnak 1:250,000 quadrangle; 80 km (50 mi) south-southwest of Kobuk.	At least one hot spring is in east bank of Hawk River on south side of Purcell Mountains. Spring is at south end of clearing 25 m by 60 m (75 ft by 200 ft) in tall timber and flows directly into Hawk River. Temperature estimated at +50°C. No chemical analysis available.
9. South	66°09′ N., 157°07′ W.; Shungnak 1:250,000 quadrangle; 84 km (52 mi) south of Kobuk on south side of Purcell Mountains.	Several hot springs scattered about a west-facing timbered slope 60 to 120 m (200–400 ft) above south-flowing tributary to Hawk River. Only one hot spring visited. Temperatures estimated at +50°C. Chemical analysis available.
10. Purcell Mountain	66°23′ N., 157°32′ W.; Shungnak 1:250,000 quadrangle; 71 km (44 mi) south-southwest of Kobuk.	Spring is on north bank of unnamed north-flowing tributary to Shinilikrok Creek about 8 km (5 mi) northeast of Purcell Mountain. Small flow, temperature estimated at 15°–20°C. No chemical analysis available.
11. Division	66°22′ N., 156°44′ W.; Shungnak 1:250,000 quadrangle; 61 km (38 mi) south of Kobuk on north side of Purcell Mountain.	Numerous springs on both sides of a headwater stream of Selawik River. Large open meadows as much as 900 m (1,000 yd) long by 180 m (200 yd) wide; largest area of apparent thawed ground of any hot spring in western Alaska. Temperature estimated at 50°–60°C. No chemical analysis available.
12. Deniktow Ridge	65°54′ N., 155°00′ W.; Melozitna D–4 quadrangle	Melozitna D–4 topographic map (1:63,000 scale) shows hot-spring symbol on north side of Hot Springs Creek 8 km (5 mi) from Koyukuk River. Not visited by us and no information regarding temperature, flow, number of springs, or chemistry is available.
13. Tunalkten Lake	66°11′ N., 154°01′ W.; Hughes A–3 quadrangle; 19 km (12 mi) northeast of Hughes 2.4 km (1.5 mi) from Koyukuk River.	Hot-spring symbol shown on Hughes 1:250,000-scale quadrangle.
14. Reported hot spring	General location: east side of Kaiyuh Hills	Waring (1917) quotes prospector as reporting a hot spring on tributary of upper Innoko River. No other information available.
15. Horner	64°55′ N., 154°47′ W.; Ruby D–4 quadrangle; 40 km (25 mi) northeast of Ruby on north side of Yukon River.	Hot springs issue from several points along small spring on west side of creek (Waring, 1917). Temperatures range from 30°C to 49°C. Chemical analysis available. Not visited by us.
16. Dulbi	65°16′ N., 155°16′ W.; Melozitna B–5 quadrangle; 31 km (19.5 mi) N. 61° W. of Melozi Springs.	Several hot springs are found within a distance of about 100 m (100 yd) in small clearing along west side of south-flowing tributary to Dulbi River. Temperatures estimated at 50°–60°C. No chemical analysis available.
17. Melozi Hot Springs (Melozitna).	65°08′ N., 154°40′ W.; Melozitna B–1 quadrangle; on Hot Springs Creek 48 km (30 mi) northeast of Ruby.	From Waring (1917): One main hot spring flowing over 5-m (17-ft) bank into Hot Springs Creek. Temperature measured at 55°C. Total flow of 8.3 l/s (130 gal/min). H_2S odor. Chemical analysis available.
18. Little Melozitna Hot Springs.	65°28′ N., 153°20′ W.; Melozitna B–1 quadrangle; 64 km (40 mi) west of Tanana.	Hot springs on west bank of Hot Springs Creek. Temperature of 38°C (Waring, 1917). H_2S odor. Partial chemical analysis available.
19. Manley Hot Springs (Baker Hot Springs).	65°00′ N., 150°38′ W.; Tanana A–2 quadrangle; at north edge of Manley Hot Springs.	Principal hot springs are in valley of Karshner Creek, a tributary to Hot Springs Slough. Temperature of 50°C measured. In 1915 area had 0.25 km² (60 acres) under cultivation (Waring, 1917). Chemical analysis available.
20. Hutlinana	65°13′ N., 149°59′ W.; Livengood A–6 quadrangle; about 110 km (70 mi) west of Fairbanks.	Several hot springs are found within a distance of about 10 m (30 ft) on west side of Hutlinana Creek. Faint H_2S odor. Temperature of 43°C; discharge estimated at about 3 l/s (50 gal/min) (Waring, 1917). Chemical analysis available.
21. Tolovana	65°16′ N., 148°50 W.; Livengood B–4 quadrangle	From R. M. Chapman, written commun., 1972: Several hot springs are found along west side of creek draining east side of Hot Springs Dome. Temperatures of 60°C measured. Chemical analysis available.

of hot springs in west-central Alaska

Geologic setting		
Geologic province	Host rock	Remarks
Seward Peninsula ___	Concealed ____________	Bedrock concealed; springs are 4 km (2.5 mi) north of plutonic and high-grade metamorphic rocks of Kigluaik Mountains and 4 km (2.5 mi) south of low-grade metamorphic rocks of Hen-and-Chicken Mountain. Springs are 2½ km (1.5 mi) west of inferred fault (Sainsbury and others, 1969). Aeromagnetic survey (State of Alaska aeromagnetic survey, 1972, Bendeleben A–4, A–5, A–6 quadrangles) suggests springs may lie along possible east-west fault that may be an extension, or branch, of range-front fault bounding south side of central and eastern Bendeleben Mountains (Miller and others, 1972).
-----do ____________	Biotite granite ________	Springs occur in Serpentine Hot Springs pluton about 1.6 km (1.0 mi) from faulted contact. Pluton composed of biotite granite of Cretaceous or Tertiary age; country rock is Precambrian metasiltite and related rocks. (Sainsbury and others, 1969).
-----do ____________	Quartz monzonite _____	Spring almost on contact between Late Cretaceous quartz monzonite of Bendeleben pluton and migmatite zone of Precambrian age. Biotite sample from Bendeleben pluton has yielded K:Ar age of 79.8±2.4 m.y. (Miller and others, 1972). Parts of floor of Lava Creek underlain by basalt of Quaternary age.
-----do ____________	Granodiorite __________	Spring is in granodiorite of Kachauik pluton near contact with Precambrian schistose marble. Granodiorite is of probable Cretaceous age (Miller and others, 1972).
-----do ____________	Quartz monzonite _____	Spring is in Darby pluton about 3.2 km (2 mi) from country rock and on or near conspicuous lineaments in pluton contacts. Darby pluton is Late Cretaceous in age (Miller and others, 1972).
-----do ____________	-----do ______________	Springs are in quartz monzonite of Darby pluton less than 400 m (0.25 mi) from contact with Devonian limestone. Pluton and limestone contact is inferred to be major fault (Miller and others, 1972) trending N. 18° E.
Yukon-Koyukuk _____	Nepheline syenite _____	Springs are in small satellitic stock of mafic nepheline syenite about 1.5 km (1 mi) south of Granite Mountain pluton of mid-Cretaceous age (Miller, 1972). Country rock is Lower Cretaceous andesite (Patton, 1967).
-----do ____________	Concealed ____________	Spring is in alluvial valley of Hawk River, and bedrock is concealed. On basis of map position (Patton and others, 1698), bedrock is probably hornfelsic andesite of Early Cretaceous age. Spring lies about 400 m (0.25 mi) south of mid-Cretaceous monzonite of Hawk River pluton and very close to east-west fault that cuts pluton (Miller, 1970).
-----do ____________	Quartz monzonite _____	Springs are in Late Cretaceous quartz monzonite of Wheeler Creek pluton within 400 m (0.25 mi) of contact with Lower Cretaceous andesite (Miller, 1970). Springs are approximately on conspicuous lineament trending N. 80° W. (Patton and others, 1968).
-----do ____________	Quartz latite __________	Spring is in Late Cretaceous hypabyssal volcanic complex composed of tuffs, flows, and intrusive rocks (Patton and others, 1968). Spring is about 400 m (0.25 mi) from contact with Lower Cretaceous andesite and near contact with granitic pluton (Miller, 1970).
-----do ____________	Andesite _____________	Springs are in Lower Cretaceous andesite near conspicuous N. 70° W.-trending lineament and about 2.5 km (1.5 mi) north of quartz monzonite of Wheeler Creek pluton (Patton and others, 1968; Miller, 1970).
-----do ____________	Andesite(?) ___________	Spring locality is in area of generally hornfelsic andesite cut by numerous quartz latite porphyry dikes. The numerous dikes and widespread thermal metamorphism suggests an unexposed pluton at shallow depth (Miller and Ferrians, 1968).
-----do ____________	Graywacke-mudstone ___	Hot springs is in alluvial deposits but probably underlain by Cretaceous graywacke and mudstone. Spring locality about 4 km (2.5 mi) west of granodiorite of Indian Mountain pluton near inferred synclinal axis (Patton and Miller, 1966).
Kaiyuh Hills _______	Unknown _____________	Unknown.
Kokrine-Hodzana Highlands.	Granite ______________	According to Waring (1917), springs are in fractured granite of small pluton. Country rock is probably schist of Precambrian(?) to Paleozoic age. Springs are near Kaltag fault (Patton and Hoare, 1968).
Yukon-Koyukuk _____	Graywacke-mudstone ___	This report: spring is in hornfelsic graywacke and mudstone of Cretaceous age about 3.2 km (2 mi) from a possible pluton inferred from aerial photographs.
Kokrine-Hodzana Highlands.	Quartz monzonite ______	This report: spring is in quartz monzonite pluton about 3.2 km (2 mi) from contact with hornfelsic mafic and ultramafic rocks and 2.5 km (1.5 mi) from pelitic schist.
-----do ____________	Granite ______________	From Waring (1917); Springs are in small granitic pluton intruded into schist.
Yukon-Tanana Upland.	Concealed ____________	Bedrock at springs locality is concealed: black hornfels crops out 800 km (0.5 mi) up Karshner Creek from hot springs and presence of abundant large blocks of biotite granite float suggests contact is very close. Hornfels probably represents metamorphosed sedimentary rocks of Jurassic and (or) Cretaceous age; biotite granite is of Cretaceous and (or) Tertiary age (Mertie, 1937; Chapman and others, 1971).
-----do ____________	Quartzite-hornfelsic graywacke.	Spring is at base of sheared quartzite of Jurassic and(or) Cretaceous age (Chapman and others, 1971) about 5 km (3 mi) east of granitic pluton of Cretaceous and(or) Tertiary age.
-----do ____________	Mudstone ____________	Springs are in mudstone of Jurassic and(or) Cretaceous age about 1.5 km from granitic rocks of Cretaceous and(or) Tertiary age exposed in the Tolovana Hot Springs Dome (R. M. Chapman, written commun., 1972).

TABLE 1.—*Description and geologic setting of*

Locality No. and name	Location	General description
22. Reported hot spring near little Minook Creek.	General location: 66°25′ N., 150°00′ W.; Livengood B–6 or Tanana B–1 quadrangles.	Waring (1917) gives prospectors report of a hot spring near divide between Little Minook Creek and a tributary of Hess (Hoosier?) Creek. No other information available.
23. Kilo Hot Springs	65°49′ N., 151°12 W.; Tanana D–3 quadrangle; 177 km (110 mi) northwest of Fairbanks on Kanuti Kilolitna River.	From R. M. Chapman, written comm., 1973: Several hot springs are in an open grassy area of about 100 m² (1,000 ft²). Temperature estimated at 50°C. No chemical analysis available.
24. Ray Hot Springs	65°58′ N., 150°55′ W.; Tanana D–2 quadrangle; about 170 km (105 mi) northwest of Fairbanks on north side of Ray River.	Hot spring is at base of hill in flood plain on north side of Ray River. Slight H_2S odor. Temperature measured at 47°C. Chemical analysis available.
25. Lower Ray River	65°59′ N., 150°35′ W.; Tanana D–2 quadrangle	Several hot springs are found within a distance of 60 m (200 ft) in gravel bar on north side of Ray River. H_2S odor. Temperature measured at 61°C. Chemical analysis available.
26. Kanuti	66°20′ N., 150°48′ W.; Bettles 1:250,000 quadrangle; 8 km (5 mi) southwest of Caribou Mountain.	Several hot springs are on east side of Kanuti River in large open grassy area 100 m (100 yd) in diameter underlain by alluvium. Strong H_2S odor. Temperature measured at 66°C. Chemical analysis available.
27. Dall Creek	General location near Dall River in southwest Beaver 1:250,000 quadrangle.	Brosgé, Brabb, and King (1970) show a possible hot spring near Dall River.

springs have yielded potassium-argon 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 Upland area (Chapman and others, 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 calc-alkaline, subalkaline, and alkaline rocks are included. Preliminary analysis (C. M. Bunker, written commun., 1971) suggests that the plutons with which the hot springs are associated have a considerable range in radioactivity and in radiogenic heat production. Uranium and thorium content and the heat production range 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), but the Darby pluton is anomalously high.

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 Selawik Hills pluton (Miller, 1970) in the western Yukon-Koyukuk province, do not appear to have hot springs, possibly owing to a low fracture permeability.

The occurrence of hot springs also appears to be independent of the size of the pluton because plutons with associated hot springs range from 39 km² (15 mi²) to over 780 km² (300 mi²) in outcrop area.

The strong correlation that exists between the distribution of Cretaceous and early Tertiary plutons and hot springs in western and central Alaska is present in nearby areas in Alaska, for example at Circle and Chena hot springs in east-central Alaska (Waring, 1917). It is also found in the adjacent eastern Chukotka Peninsula, U.S.S.R. 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 places with known faults and lineaments suggests that well-developed open fracture systems exist near the pluton margins and 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. Significantly all 10 hot springs that lie near but outside a pluton occur in rocks such 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 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 springs are 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 km to over 440 km (275 mi) for the Kaltag fault (Patton and Hoare, 1968). Hot springs, however, occur only where the faults and *hot springs in west-central Alaska*—Continued

Geologic setting		
Geologic province	Host rock	Remarks
Yukon-Tanana Upland.	Unknown	General area is underlain by Paleozoic conglomerate and shale and Jurassic and (or) Cretaceous mudstone intruded by small granitic stocks of Cretaceous and(or) Tertiary age (Waring, 1917; Chapman and others, 1971).
Kokrine-Hodzana Highlands.	Quartz monzonite	Springs issue from pluton of porphyritic quartz monzonite of tentative Cretaceous age on, or very close to, contact with schist and hornfels of Precambrian(?) and Paleozoic age (R. M. Chapman, written commun., 1973).
do	Concealed	Bedrock concealed but spring probably occurs on contact between Early Cretaceous quartz monzonite of the Sithylemenkat pluton (Patton and Miller, 1973) and pelitic schist of Precambrian(?) and Paleozoic age. (Chapman and Yeend, 1972).
do	do	Bedrock concealed but springs are approximately on contact between quartz monzonite of probable Cretaceous age and pelitic schist of Precambrian(?) and Paleozoic age (Chapman and Yeend, 1972).
do	do	Bedrock concealed but springs are in area underlain by mafic volcanic rocks of Permian, Triassic, and Jurassic age within 400 m (0.25 mi) of contact with Cretaceous granitic rocks of Hot Springs pluton (Patton and Miller, 1973).
do	Unknown	General area is underlain by pelitic schist of Precambrian or Paleozoic age intruded by granitic pluton of probable Cretaceous age.

lineaments are near the plutons; that is, 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 taken place, although a few do occur near such faults (for example, Horner and Little Minook Creek hot springs, Nos. 15 and 22).

A local structural control is suggested at several localities where hot springs are not in the bottoms of valleys but issue from different 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 in the world are commonly related to recent volcanic activity. Late Cenozoic basalts are found in several areas of west-central Alaska, particularly in the western part where they cover about 9,100 km^2 (3,500 mi^2). Potassium-argon 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 yr. Hopkins (1963) stated 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 yr 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, however, 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 4.8 km (3 mi) from the probable source area for basalt that 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 area described in this report. A discontinuous belt of felsic volcanic rocks of Late Cretaceous and Tertiary age are found near the east margin of the Yukon-Koyukuk province (Patton and Miller, 1970). Although only a single potassium-argon 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 lithology of country rock around the pluton because the country rock ranges from Precambrian to Late Cretaceous and includes limestone, graywacke, andesite, mafic volcanic rocks, and regionally metamorphosed rocks of low and high grade.

GEOCHEMISTRY

Chemical analyses of water samples from west-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, Skougstad, and Fishman (1970). The analytical results given under L. M. Willey and T. S. Presser, analysts, are the most reliable because the samples were filtered in the field through a 0.2-μm-effective filter paper. In addition, samples for calcium, magnesium, aluminum and iron analyses were acidified in the field to a pH $\leqq 2$ with sulfuric acid. Bicarbonate 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

TABLE 2.—*Chemical analyses of water from thermal springs in west-central Alaska*

[All data in milligrams per litre except temperature (in degrees Celsius) and pH]

Name	Pilgrim		Serpentine			Lava Creek	Battleship Mountain	Kwiniuk	Creek Clear	Granite Mountain		South
Locality No. (fig. 1, table 1)	1	1	2	2	2	3	4	5	6	7	7	9
Analyst	L.M. Willey, T.S. Presser [1]	(2)	L.M. Willey, T.S. Presser [1]	J.B. Rapp [1]	J.B. Rapp [1]	L.M. Willey, T.S. Presser [1]	L.M. Willey, T.S. Presser [1]	L.M. Willey [1]	L.M. Willey, T.S. Presser [1]	L.M. Willey, T.S. Presser [1]	J.B. Rapp [1]	R.B. Barnes [1]
SiO_2	100	87	100	90	89	84	56	45	83	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	2.0	4.8	130	2.0	2	1.8	5.9
Mg	1.4	7.4	.48	.35	.34	<0.1	<0.1	.1	<0.1	.04	.05	.01
Na	1,450	1,587	730	800	800	79	120	500	55	51	67	83
K	61	61	40	41	41	1.8	1.2	9	1.6	1.3	1.9	2.1
Li	4.0	----	4.7	----	----	0.13	0.2	----	0.05	.04	----	----
NH_3	----	----	----	----	----	<1	<1	----	<1	----	----	----
HCO_3	30.1	21	64.5	57	56.8	120.9	53.8	10.2	95	45.7	90	----
CO_3	----	----	----	1.3	.7	5	----	----	8	----	----	----
SO_4	24	25	29	1	1	53	16	----	27	62	50.3	122
Cl	3,346	3,450	1,480	1,450	1,420	5.9	120	912	4.2	9.3	6.4	6
F	4.7	----	6.4	6	6	10	9	5.8	3.9	8.2	----	----
Br	----	----	----	4.9	4.8	----	----	4	----	----	----	----
B	2.4	----	3.4	2.9	2.8	0.08	0.66	1	0.16	.13	.22	----
pH	6.75	----	7.91	----	7.94	8.6	9.20	7.3	8.33	10.14	9.55	
Temperature	55	69	60	77	71	50	17	[3]+50	60	49	49	[3]+50

Name	Horner	Melozi	Manley			Hutlinana		Tolovana	Ray River	Lower Ray River	Kanuti	Maximum value found in surface waters of Alaska [5]
Locality No. (fig. 1, table 1)	15	17	19	19	19	20	20	21	24	25	26	
Analyst	(2)	(2)	L.M. Willey, T.S. Presser [1]	L.M. Willey, T.S. Presser [1]	(2)	L.M. Willey, T.S. Presser [1]	(2)	(4)	R.B. Barnes [1]	R.B. Barnes [1]	R.B. Barnes [1]	
SiO_2	29	78	65	65	59	40	44	75	----	----	----	41
Al	.2	----	.016	.046	.8 (Al + Fe)	.014	----	----	----	----	----	----
Fe	2.7	.75	----	----		----	.09	.02	----	----	----	89
Ca	10	11	4	6.8	9.1	20.2	22	82	5.6	11	2.7	280
Mg	3	2.8	1	.29	.9	6.6	6.0	1.2	.7	.1	.3	74
Na	58 (Na + K)	107 (Na + K)	130	130	121	180	208 (Na + K)	321	71	95	111	67
K			4.5	4.8	8.2	7.9		23	1.4	2.0	3.7	9.5
Li	----	----	.28	.28	----	.16	----	----	----	----	----	----
NH_3	----	----	4.9	.5	----	.4	----	----	----	----	----	----
HCO_3	22	32	89.6	90.7	86	488	494	49	74	93	169	1,040
CO_3	32	31	----	----	0.0	----	0.0	----	22	21	----	----
SO_4	45	61	54	51	48	55	67	40	19	23	21	184
Cl	39	92	134	132	120	40	38	615	9.1	25	28	100
F	----	----	8.5	8.2	----	.8	----	.2	----	----	----	1
Br	----	----	----	----	----	----	----	----	----	----	----	----
B	----	----	1.3	1.2	----	.3	----	----	.6	1.6	1.3	----
pH	----	----	7.7	7.72	----	7.66	----	7.7	9.16	9.04	8.01	----
Temperature	47	56	59	56	52	43	45	52	45	66	66	----

[1] Analysis from U.S. Geological Survey files. [2] Analysis from Waring (1917). [3] Estimated. [4] Analysis from Anderson (1970). [5] Analysis from U.S. Geological Survey (1959).

analyses of surface waters of Alaska unaffected by seawater (U.S. Geol. Survey, 1969); most of the recorded values are far below the analyses of hot-springs maxima reported in west-central Alaska.

Chemical composition

General agreement (White and others, 1963) is that most of the water discharged at the surface in thermal areas is meteoric in origin but that a small part might be magmatic, metamorphic, or connate. When the composition of hot springs in west-central Alaska is compared with the composition of 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 Alaska springs do indeed appear to be derived from local meteoric water. Their composition can be explained by deeply circulated meteoric water whose increased solvent action due to the increase in temperature and long flow path brought about leaching of the country rock (White and others, 1963). The high discharge rates and the generally high chloride content relative to nearby ground water indicate that the hot springs of west-central Alaska belong to the hot-water type of geothermal system and not to the vapor-dominated type (White, 1970).

Four of the 16 hot springs for which chemical analyses are available are saline in nature, however, and are characterized by concentrations of chloride, sodium, calcium, potassium and perhaps lithium, bromide, and boron 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 three are in the Seward Peninsula, and Tolovana is over 480 km (300 mi) to the east (fig. 1).

The composition of these springs compared with that of the more dilute springs appears to demand either increased leaching or the 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 in some ways from the water-rock reactions typically seen elsewhere in granitic rocks. The composition of meteoric waters issuing from granitic rocks has been published by Feth, Roberson, and Polzer (1964) and Miller (1961); the Na^+/Cl^- ratios calculated from their data all exceed a value of 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 four saline springs, however (table 3),

TABLE 3.—*Na^+/Cl^- and Cl^-/Br^- ratios from available data on the hot-spring waters*

Locality No. and name (fig. 1, table 2)	Na^{+1}/Cl^{-1}	Cl^{-1}/Br^{-1}	Locality No. and name (fig. 1, table 2)	Na^{+1}/Cl^{-1}	Cl^{-1}/Br^{-1}
1. Pilgrim	.46	---	15. Horner	1.5	---
2. Serpentine	.55	296	17. Melozi	1.2	---
3. Lava Creek	13.3	---	19. Manley	1.0	---
4. Battleship Mountain.	1.0	---	20. Hutlinana	4.5	---
			21. Tolovana	.52	---
5. Kwiniuk	.55	228	24. Ray River	7.8	---
6. Clear Creek	13.1	---	25. Lower Ray River.	3.8	---
7. Granite Mountain.	10	---	26. Kanuti	4.0	---
9. South	14	---	Seawater	.55	292

are all less than 1 and indeed are similar to seawater, 0.55.

Although 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 is difficult (White, 1957a, b, 1969, 1973). Of the constituents given in the analyses in table 2, few may be used to determine unequivocally the origin of the solutions. Silica may reflect only the solution of quartz in the thermal waters (Fournier and Rowe, 1966; Mahon, 1966), and aluminum may be involved in reactions of too many aluminosilicates to reflect the earlier history of the solution. Iron is largely controlled by the local oxidation potential (Barnes and Back, 1964; Barnes and others, 1964). Calcium data may only reflect local solution and deposition of calcite; thus the bicarbonate and calcium data may give information on present processes rather than the earlier history of the water. Magnesium concentrations may be controlled by reactions of not only magnesian carbonates but also chlorite in geothermal systems (Muffler and White, 1969). Potassium and lithium are both sufficiently low in concentration that additions or subtractions of small amounts would obscure the earlier history. Sodium alone of the cations is present in sufficient concentrations and sufficiently nonreactive that small additions or losses would not obscure the earlier sodium concentrations.

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

The high chloride and sodium content suggests that magmatic water may have been added because hot-spring waters found in areas of active volcanism often contain large amounts of these elements (White and others, 1963). Such springs, however, commonly contain larger amounts of bicarbonate, sulfate, and silica than the saline hot springs of west-central Alaska. Furthermore, the saline hot springs are unrelated geographically to the most direct evidence of young magma, the Quaternary volcanic rocks.

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

The saline nature of the hot springs suggests the mixture of connate seawater or of present-day seawater.[2] The Na^+/Cl^- and Cl^-/Br^- ratios from available data on the hot-spring waters are given in table 3. The Na^+/Cl^- data fall in two groups—a group with the ratio 1 or greater, similar to the results of Feth, Roberson, and Polzer (1964) and Miller (1961), and a group with the ratio near the 0.55 ratio of seawater. The Cl^-/Br^- seems to give the same result, a separation of locally derived meteoric water from the more saline waters with a more complex history; the data, however, are too few to warrant extensive interpretation. If leaching is to account for the Cl^-/Br^- ratios, the leaching fortuitously results in ratios the same as present-day seawater.

An objection to the mixture of either old or present seawater is the geologic and geographic distribution of the saline hot springs. Although the Na^+/Cl^- and Cl^-/Br^- ratios may be interpreted as dilution of seawater, the geologic evidence is against submergence of the rocks of the region probably since the Cretaceous. Also, 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 seawater 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). The four saline springs show no geologic pattern to their distribution. Other hot springs in the Seward Peninsula, where three of the four saline springs occur, are nonsaline; this is particularly striking in regard to Kwiniuk (saline) and Clear Creek (nonsaline) hot springs, which are only 7.5 km (12 mi) apart and in the same pluton (fig. 1).

The isotopic data (table 4) available from 10 of the hot springs in the study area, 2 saline and 8 nonsaline, give some indication of the source of the constituents in the saline springs. These data show that in terms of deuterium (D), the saline springs, Pilgrim and Serpentine, are almost identical to Serpentine LDMW (locally derived meteoric water) indicating that all are derived from the same source, namely local snowmelt and rainwater. The salts in these saline springs would therefore appear to be derived from the leaching of rocks, and the proportions of ions are indeed only fortuitously identical to those of seawater. The two saline springs also show an enrichment in O^{13}, as indicated by the difference in δO^{18} and δO^{18} calculated,[3] and thus suggest more extensive water-rock reactions than found in the nonsaline springs of which only three of eight springs show a similar enrichment in O^{18}. Of these three exceptions, at Manley Hot Spring (No. 19; table 4), either the LDMW sample is not representative or the recharge takes place at a higher altitude with greater depletion in D; at Lower Ray River and Kanuti springs (Nos. 25, 26; table 4) the LDMW shows a similar enrichment in O^{18}, suggesting perhaps that the relation between δD and δO^{18} is not linear in this area.

TABLE 4.—*Oxygen and hydrogen isotopic compositions, in parts per thousand, of hot-spring waters and locally derived meteoric waters*

[SMOW, standard mean ocean water; LDMW, locally derived meteoric water. Analyses kindly supplied by J. R. O'Neil]

Source of samples (locality No. and name refer to fig. 1 and table 2)	δD (SMOW)	δO^{13} (SMOW)	O^{13} (calc)
Seward Peninsula:			
1. Pilgrim	−122	−14.9	−16.6
2. Serpentine	−123	−15.2	−16.7
Serpentine LDMW	−124	−16.4	−16.7
4. Battleship Mountain	−106	−13.8	−14.5
6. Clear Creek	−119	−15.6	−16.2
LDMW for samples 4 and 6	-----	−14.2	-----
7. Granite Mountain	−116	−15.7	−15.8
Granite Mountain LDMW	−118	−16.0	−16.0
Interior Alaska:			
19. Manley	−142	−18.1	−19.0
Manley LDMW	−130.3	−15.7	−17.5
20. Hutlinana	−144.9	−19.2	−19.3
Hutlinana LMDW	−148.5	−19.7	−19.8
24. Ray River	−150	−19.1	−20.0
25. Lower Ray River	−157	−19.2	−20.8
26. Kanuti	−146	−18.0	−19.5
LDMW for samples 24–26	−159	−19.9	−21.1

The differences in δD and δO^{18} between the hot springs from the Seward Peninsula (Nos. 1, 2, 4, 6, and 7; table 4) and the hot springs from the interior (Nos. 19, 20, 24, 25, and 26; table 4) are probably the result of increasing distance from the ocean: the interior waters are isotopically lighter (lower in δD and δO^{18}), similar to trends noted elsewhere (White and others, 1973).

These preliminary chemical and isotopic data thus suggest that both the saline and nonsaline springs are derived from deeply circulating meteoric water. The difference in chemistry between the two types of springs appears to result from a difference in the extent

[2] 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 seawater because the ratios of SO_4:Cl and Ca:Na were not similar to those of seawater. In view of the possible water-wallrock reactions involving calcium and sulfate. Waring's objection may not be valid.

[3] δO^{18} may be estimated by the following equation from Craig (1961): $\delta O^{13}\ (\text{calc}) = \frac{\delta D - 10}{8}$, assuming a linear relation between δO^{13} and δD.

of leaching, or water-rock reactions. It may be that the nonsaline springs have been subjected to a greater amount of leaching in the past, or for a longer period of time, than the saline springs, resulting in a smaller supply of solutes now available for leaching. Such a suggestion would be compatible with the oxygen isotope data in that the more extensive the oxygen isotope exchange has been between water and rock, the more depleted the rock is in O^{18} and the less the effect in the water (owing to isotopic exchange) with resulting lower δO^{18} at present for the nonsaline springs.

Chemical geothermometers

Water chemistry has proved 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 (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 calibrate adequately, or choose between, the methods. Silica, for example, may be 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

TABLE 5.—*Hot-spring subsurface temperatures, in degrees Celsius, calculated from quartz conductive-cooling geothermometer and appropriate* Na-K-Ca *geothermometer determinations*

Locality No. and name of hot spring (fig. 1, table 2)	Quartz	Na-K-Ca
1. Pilgrim	137	146
2. Serpentine	137	167
3. Lava Creek	128	91
4. Battleship Mountain	107	63
5. Kwiniuk	97	72
6. Clear Creek	127	83
7. Granite Mountain	122	75
9. South	115	72
17. Melozi	124	---
19. Manley	115	137
20. Hutlinana	92	98
21. Tolovana	122	162
24. Ray River	---	60
25. Lower Ray River	---	60
26. Kanuti	---	136

137°C as a maximum; therefore, silica precipitation may not affect the validity of the results. The Na-K-Ca geothermometer may be 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 owing to increases in calcium content (Fournier and Truesdell, 1973). Calcite precipitation may yield erroneously high subsurface temperatures because of decreases in calcium content of the water (Fournier and Truesdell, 1970).

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

$$-\log_{10} C_{SiO_{2(aq)}} = (1.309 \times 10^3/T) - 5.19,$$

where T = temperature in kelvins, and

C_{SiO_2} = concentration of silica in milligrams per litre.

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

$$\log_{10}(m_{Na^+}/m_{K^+}) + \tfrac{1}{3}\log_{10}(\sqrt{m_{Ca^{+2}}}/m_{Na^+}) = 1647/T - 2.240$$

where T = temperature in kelvins, and

m_{Na^+} = molality of sodium ion,

m_{K^+} = molality of potassium ion, and

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

For temperatures below 100°C the equation is

$$\log_{10}(m_{Na^+}/m_{K^+}) + \tfrac{4}{3}\log_{10}(\sqrt{m_{Ca^{+2}}}/m_{Na^+}) = 1647/T - 2.240.$$

The results of these calculations for individual hot springs are given in table 5. The quartz conductive-cooling geothermometer shows a range of 92° to 137°C for the 12 springs for which it could be calculated. The Na-K-Ca geothermometer shows a range (on the basis of 14 springs) of 63° to 167°C. The difference between temperatures measured by the two geothermometers for any one spring ranges from 6° to 47°C. Perhaps the most important point that can be determined from these data is the relatively low subsurface temperature suggested for the hot springs of west-central Alaska. The maximum temperatures recorded are 137°C for the quartz conductive method and 167°C for the Na-K-Ca method. These suggested subsurface temperatures are low compared with subsurface temperatures of geothermal fields presently being exploited. Both of these maximum temperatures, for example, are below the minimum temperature (180°C) currently thought necessary to drive steam-turbine generators (Muffler, 1973).

The lack of siliceous sinter and the common occurrence of travertine in the hot-springs deposits also imply low subsurface temperatures (White, 1970).

DISCUSSION

A study of the geologic setting of hot springs in west-central 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 4.8 km (3 mi) 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 occurrence of hot springs also appears to be related to fracture and fault zones near the margins of the pluton. The distribution of hot springs is, however, independent of the age, composition, and magmatic events that formed the pluton.

The chemical and isotopic compositions of analyzed hot springs within the region suggest that most of them are composed of locally derived meteoric water. Four of the 16 analyzed hot springs however, have very saline compositions that appear to require either increased leaching of country rock at the present time or addition of another type of water. The present data suggest that the leaching is more likely.

The tentative model suggested by the available information on the geologic setting and geochemistry of the hot springs in west-central Alaska is as follows. Most of the hot springs are the result of deeply circulating, locally derived meteoric water that has percolated through the fractured granitic plutons and the surrounding wallrock to depths of several thousand feet, become heated owing to the geothermal gradient, and found access to the surface along the fractured and faulted margins of the pluton. If no addition of magmatic water or heat is considered, the subsurface temperatures indicated by the chemical geothermometers suggest that the water must have reached depths of 3.3 to 5.3 km (9,000–15,000 ft) on the basis of assumed geothermal gradients of 30°C/km and 50°C/km and a maximum subsurface temperature of 167°C. If heat from an underlying magma has been added to the system, the water may have reached a shallower depth than that calculated from the above geothermal gradients.

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 likely to be narrow or widely spaced and less numerous at greater depths.

Although the data available on the geologic setting and chemistry of the hot springs of west-central Alaska are preliminary in nature, they suggest that most, if not all, of the hot springs are characterized by reservoirs of limited extent and relatively low temperatures in comparison with temperatures of geothermal systems presently being exploited for power generation. Muffler (1973) gave 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 lower than 180°C but are within ranges suggested for proposed turbines using a heat-exchange system involving such working fluids as Freon and isobutane. An experimental plant of this type, for example, operating at Paratunka, Kamchatka (USSR), since 1970 utilizes 81.5°C water (Facca, 1970). These springs may therefore have potential for limited power generation locally, if and when heat-exchange technology becomes available, as well as for space heating and agricultural uses.

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