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DIVISION OF GEOLOGICAL AND GEOPHYSICAL SURVEYS

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LITHOLOGIC LOG AND HYDROTHERMAL ALTERATION OF CORE FROM THE MAKUSHIN GEOTHERMAL AREA, UNALASKA ISLAND, ALASKA

By

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To convert centimeters (cm) to inches (in.), multiply by 0.39.
To convert meters (m) to feet (ft), multiply by 3.28.
To convert kilometers (km) to miles (mi), multiply by 0.62.

LITHOLOGIC LOG AND HYDROTHERMAL ALTERATION OF CORE FROM THE MAKUSHIN GEOTHERMAL AREA, UNALASKA ISLAND, ALASKA

By L.D. Queen[1]

INTRODUCTION

The Makushin geothermal area is located on the eastern flanks of Makushin Volcano, about 25 km west of the village of Unalaska on Unalaska Island, Alaska (fig. 1).

The area's thermal manifestations are described in Motyka and others (1983); geology of the Makushin geothermal area is discussed in Nye and others (1984); and surface hydrothermal alteration is described in Parmentier and others (1983). Logs shown on plate 1 are based on core recovered during drilling of three temperature-gradient holes (D1, E1, I1) in 1982 and one test well (ST-1) in 1983 (fig. 1). Additional descriptions of the core and thermal gradients measured in 1983 can be found in Isselhardt and others (1983). The state-funded Unalaska geothermal drilling program was administered by the Alaska Power Authority. Republic Geothermal, Inc., of California was the prime drilling contractor.

The upper parts of all cores are Nx size (54.8 mm diam) and the lower part are Bx (42.1 mm diam). Core from ST-1 above +150 m mean sea level (MSL) is HQ core (64 mm diameter) and the rest is Nx (54.8 mm diam). Coring began once consolidated material was encountered. Core recovery was between 90 and 100 percent for all wells except for the interval +240 to +170 m MSL in D1. The core from these drill holes is permanently stored at the DGGS core-storage facility in Eagle River, Alaska (P.O. Box 772116, zip 99577, ph 907-688-3555).

METHODS

Most of both the lithology and alteration discussed in this report is based on hand-sample logging of the core. Selected samples were removed for additional study by X-ray diffraction and petrography. The location of these samples is shown on the logs.

All minerals that could not be identified in hand sample either because of their fine-grained nature (clays) or the uncertainty of identification were identified by X-ray diffraction. No special preparation techniques other than crushing to about 100 mesh were used. Thin sections of representative core samples were examined to assist in the description of the lithological units. Surface samples of similar rocks were also examined in thin section.

The uppermost parts of the logs of wells from which core was not recovered are blank. The brief discussion of surface units in each log is based on observations at and around the drill site.

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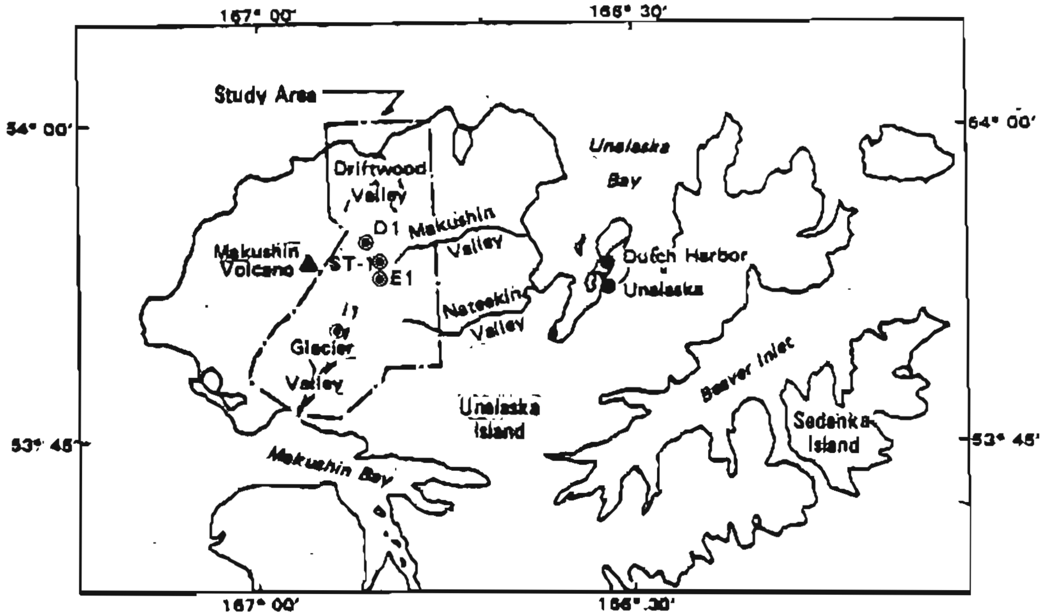

Figure 1. Well locations, Makushin geothermal area.

The temperature logs for wells D1, E1, and I1 are static-temperature gradients measured by Republic Geothermal, Inc., in the summer of 1983, except for the lower part of E1, which was measured in 1982. The temperature log for ST-1 was measured by Republic Geothermal, Inc., in 1984.

LITHOLOGIC UNITS

Andesite flows (Nye and others, 1984): Plagioclase-orthopyroxene-clinopyroxene-olivine phyric andesites. Orthopyroxenes are reversely zoned and olivines are normally zoned (C.J. Nye, unpublished data). Six flows can be distinguished in the core. Flow boundaries are characterized by oxidized and vesiculated layers. Color ranges from medium gray to black. The volcanic rocks lack megascopic alteration.

Cinders: Black to red, 1-2 cm, cinders. Unconsolidated and unaltered. Recovery of material by drilling was poor (<10 percent).

Gravel: Moderately well-sorted, 1-2 cm, angular, unconsolidated gravel. Mixed lithologies. Overlies the basal lahar in D1.

Lahars: Poorly sorted, moderately to well-indurated debris flows. Brown to greenish brown. Angular to subangular clasts. Locally has lenses of brown laminated clay and silt. Matrix consists of sand and clay.

Andesitic dikes: Gray to gray-green porphyritic dikes. Similar in appearance to andesite flows. Green color is due to secondary chlorite and epidote. Randomly distributed throughout the gabbronorite as 2- to 30-cm-wide dikes. Only shown in D1 where a 4-m-wide dike occurs.

Hornfels: Contact metamorphosed volcaniclastic rocks, sediments, flows, and dikes of the Unalaska Formation. Hornfels seen in core is mainly of the pyroxene or hornblende hornfels facies, although some albite-epidote hornfels is present.

Hornfels is light green to black and aphanitic to fine grained. In hand specimen, small plagioclase laths can be seen in some samples. Alteration is not as common in the hornfels as in the gabbronorite, possibly because of limited occurrence of hornfels in core.

Gabbronorite: Medium grained (1 to 2 mm), equigranular to slightly porphyritic. Dark to light gray. Primary mineralogy is 50 to 70 percent plagioclase (An_{50-70}), with approximately subequal amounts of orthopyroxene, clinopyroxene, and accessory magnetite and apatite. Intergranular quartz may locally compose a few percent of the mode. Alkali feldspars and albite are restricted to late-stage pegmatitic veins (1 to 3 cm wide), which are scattered randomly throughout the stock.

STRUCTURE

The density of veining or fracturing, the approximate dip of the fractures, and the presence and relative age of breccia zones were determined during logging. The density of the veining or fracturing (indicated on the logs as the number of veins or fractures per 3-m interval) varies from 0 to 25. Generally, the most fractured zones are the most intensely altered.

The dip of most fractures and veins is greater than 50°. Often the veins are almost vertical. Exact values for the dips were not determined.

The core has comagmatic and postmagmatic breccia zones. The comagmatic breccias, which consist of hornfels clasts surrounded by gabbro, are most common near contacts between the Unalaska Formation and gabbro. Some breccias are associated with large amounts of deuteric alteration, which produces secondary biotite and hornblende. These are considered late-stage comagmatic breccias.

Postmagmatic breccias are always associated with intense hydrothermal alteration. The thickest section of breccia occurs in ST-1. From about +290 m to +130 m MSL, the core consists of clasts of gabbro surrounded by a matrix of quartz, calcite, magnetite, and sparry anhydrite. The clasts are angular, are 2 to 4 cm in diameter, and almost always have a chloritic alteration rim. A smaller breccia section occurs in D1, where hornfels is brecciated and the matrix is sparry calcite rather than anhydrite. However, the alteration rim is chloritic as in ST-1, and the clasts are of similar size and shape. The origin of these postmagmatic breccias is not known.

ALTERATION MINERALS

For this report, alteration is divided into vein and disseminated alteration. 'Vein alteration' consists of those minerals that occur in veins or breccias and their immediate alteration envelopes. 'Disseminated alteration' consists of those minerals outside the zone of plagioclase alteration, where such zones are associated with an alteration envelope around a vein.

Quartz: Quartz is present throughout the core. It varies from gray cryptocrystalline veins to clear, doubly terminated crystals in anhydrite-montmorillonite zones. Quartz veins range from 0.5 mm to 2.0 cm in width.

Anhydrite: Two distinct types of anhydrite veins are present in the core. The more common is white, finely crystalline, parallel-sided, and through-going. These veins may also contain calcite, quartz, pyrite, and occasional zeolites. Some veins contain open space and are lined with terminated crystals. The alteration envelopes around these veins are usually about the same thickness as the veins. Typically, the plagioclase in the envelope has been altered to montmorillonite.

The less common anhydrite veins are sparry and coarsely crystalline; they occur as irregular veins or breccia fillings and are associated with magnetite, quartz, and calcite. Vugs with crystals of quartz, calcite, and anhydrite are locally present. The veins are typically 0.5 to 2.0 cm wide. Chlorite is the principal mineral of the alteration envelope. The fine-grained anhydrite veins always cut the sparry veins. The sparry veins are most common above +130 m MSL in ST-1.

Calcite: Calcite is present as veins and as fine-grained mixtures with clay alteration. Most clay zones contain at least a trace of calcite. Calcite occurs as the principal mineral in some thin (1 to 2 mm) veins and as scalenohedrons in larger open-space veins.

Pyrite: Pyrite is principally an accessory mineral in veins, although some short (<2.0 cm), thin (<0.5 mm) veins of massive pyrite have been observed. In other veins, it is present as small, euhedral crystals (0.5 to 1.0 mm).

Pyrite is also present as small, disseminated grains. In this habit, it commonly replaces magnetite grains in relatively unaltered gabbro. Pyrite also replace pyroxenes or their alteration products. It is a common phase in vein-alteration envelopes.

Epidote: Epidote, like pyrite and chlorite-actinolite, occurs both in veins and as disseminated anhedral grains in the rock. In veins, it is never the dominant mineral. Typically, the epidote is associated with quartz and (less commonly) with calcite veins. It is also found with the sparry anhydrite, although rarely with the fine-grained anhydrite. Epidote occurs as euhedral crystals in irregularly shaped, miarolitic, albite-quartz-epidote veins. It may make up to 1 to 2 percent of the mode in the albite-quartz-epidote veins. In disseminated form, it occurs as 0.5- to 1.0-mm-diam grains scattered throughout altered zones, especially near contacts between hornfels and gabbro.

Chlorite-actinolite: These minerals were grouped together because of their intimate association and the difficulty in distinguishing them in hand specimen. Most disseminated occurrences of these minerals result from deuteric alteration of the pyroxenes and are associated with anthophyllite-cummingtonite.

The chlorite-actinolite veins are usually thin (0.5 to 3.0 mm), regular in shape, and light to dark green. They typically exhibit shallower dips than other veins and may also contain a small amount of quartz. The high-temperature stability of these minerals suggests that a deuteric origin is possible.

Chlorite also forms dark-green, 3- to 4-mm-thick alteration envelopes around sparry anhydrite veins. Chlorite is a common phase in the montmorillonite zones.

Montmorillonite: Montmorillonite is most abundant in the clay zones that dominate the alteration in the upper parts of the cores. Generally the clay zones do not extend much deeper than 40 m below surface, but in I1 (the coldest well), the zones occur down to 450 m below surface. The clay zones are gray to gray-green and from 2 to 20 cm wide. Calcite is usually present. Mixed-layer clays found in the montmorillonite clays from the surface are not seen in clay zones of the core.

Montmorillonite also replaces plagioclase in alteration envelopes around anhydrite veins. Here, the montmorillonite forms soft, white pseudomorphs after the plagioclase laths.

Illite: Illite is found in a clay zone in well I1. The zone is similar in appearance to the montmorillonite clay zones.

Mordenite: Mordenite occurs as white acicular crystals in an open-space calcite-quartz vein in I1.

Laumontite: Laumontite occurs as stubby euhedral crystals in open-space calcite veins throughout the core. Generally, it is found closer to the surface than wairakite.

Yugawaralite: Yugawaralite is present as euhedral crystals in vuggy altered gabbro and with quartz veins.

Wairakite: Wairakite occurs as euhedral white crystals in an open-space quartz vein and in ST-1 as a massive alteration of the gabbro. The altered gabbro is light gray; aphanitic and euhedral pyrites compose about 1 to 2 percent of the altered zone. The alteration surrounds a fracture zone that produced steam (205 m depth).

Magnetite: Magnetite occurs as an accessory mineral disseminated throughout the gabbronorite. Most magnetite appears to be primary and is not shown on the logs. The magnetite that is indicated on the logs occurs as large (2 to 3 mm), sooty, anhedral grains associated with sparry anhydrite veins. Magnetite also occurs as large isolated grains that are apparently removed from any other alteration.

ALTERATION ASSEMBLAGES

Although not explicitly indicated on the logs, the alteration minerals do have distinctive associations and occurrences and can thus be grouped into five assemblages. The assemblages are determined from consistent mineral associations, habit, and relative age relationships of the alteration. While not based on assumptions of origin, the assemblages can be interpreted genetically. The genetic interpretations are documented by direct association with hydrothermal fluids, by correlation with other geothermal fields, and by theoretical mineral stabilities.

The relative ages of the assemblages are determined by crosscutting relationships seen in the cores. The five assemblages are discussed below (from youngest to oldest).

Montmorillonite ± Chlorite ± Calcite ± Pyrite

The assemblage montmorillonite ± chlorite ± calcite ± pyrite, common in the upper parts of the cores, accounts for most of the montmorillonite occurrences in the cores. The clay zones in which this assemblage occurs are described on p. 5.

The depth at which the assemblage occurs, the lack of mixed-layer clays, and the consistent ratio of chlorite to montmorillonite indicate the assemblage is of hydrothermal origin. The presence of the assemblage in the Makushin geothermal-area fumarole fields and its restriction to shallow depths indicate that the assemblage is formed by the cooler or more oxidized part (or both) of the current hydrothermal system. The assemblage is found in the cooler portions of other geothermal systems (Ellis, 1979).

Anhydrite ± Quartz ± Calcite ± Ca zeolites ± Epidote ± Pyrite

The veins are locally open-space and have euhedral crystals of anhydrite, quartz, calcite, and calcium zeolites growing along the edges. Minor amounts of sphalerite are also present. The assemblage occurs in regular, steeply dipping (>70°) veins throughout the cores. The assemblage anhydrite ± quartz ± calcite ± Ca zeolites ± epidote ± pyrite constitutes most alteration observed in veins. Sealed veins are much more abundant than open veins.

The veins range in width from 0.5 mm to 2.0 cm. The assemblage is restricted to depths greater than 120 m from the surface. This assemblage is found in fracture zones in well ST-1, which yielded steam and hot water (193°C). These minerals are generally indicative of 'water-dominated' geothermal systems. Estimated fluid composition of hot water obtained from the 593-m-deep fracture zone of ST-1 is in equilibrium with this assemblage.

The age relationship between this assemblage and the montmorillonite assemblage cannot be conclusively determined, although they appear to be contemporaneous.

Anhydrite ± Quartz ± Calcite ± Magnetite ± Chlorite ± Pyrite ± Epidote

The assemblage anhydrite ± quartz ± calcite ± magnetite ± chlorite ± pyrite ± epidote is mineralogically similar to the above assemblage, although details of mineral habit indicate they are not the same. This assemblage, characterized by sparry rather than massive or fine-grained anhydrite, occurs as a breccia filling (as opposed to regular veins). Furthermore, the vein assemblage cuts the breccia assemblage, which shows that the vein assemblage is younger. This breccia assemblage is described in the anhydrite section (p. 4).

The fact that the assemblages are not the same and are of different ages implies that the breccia assemblage is not directly related to the current system (that is, present thermal waters at the depths that the assemblage occurs are not in equilibrium with the assemblage). The similarity between this assemblage and the preceding one suggests that this breccia assemblage may represent an earlier stage of the present system.

Albite ± Biotite ± Epidote ± Hornblende ± Actinolite ± Quartz

The assemblage albite ± biotite ± epidote ± hornblende ± actinolite ± quartz occurs as dikelike veins and as pervasive alteration in comagmatic breccias. The veins range from 1 to 10 cm in width and may contain miarolitic cavities. The biotite typically occurs along the borders of the veins. Trace amounts of alkali feldspars are found in the veins.

In the comagmatic breccias, the assemblage is not restricted to veins. The breccia is dark gray with angular 2 to 5 cm clasts of gabbro in an aphanitic matrix. The matrix is composed of albite ± biotite ± hornblende ± quartz ± epidote with accessory rutile and hematite. Few (if any) primary minerals are present in the matrix. The clasts retain the original plagioclase laths, but the pyroxenes have been replaced. The replacement does not retain the original shape of the pyroxenes. The biotite and hornblende are frequently euhedral in both the clasts and the matrix. They are, however, always found with the fine-grained albite and quartz, which indicates they are not primary.

This assemblage, like the one below, is indicative of high temperatures and, in this case, high fO_2. This assemblage is interpreted to be a late-stage magmatic alteration product and appears to be the same age as the chlorite ± actinolite ± anthophyllite ± cummingtonite ± magnetite ± pyrite assemblage.

Chlorite ± Actinolite ± Anthophyllite ± Cummingtonite ± Magnetite ± Pyrite

The assemblage chlorite ± actinolite ± anthophyllite ± cummingtonite ± magnetite ± pyrite replaces mafic phases in the gabbronorite and hornfels. This assemblage and the preceding one are the oldest alteration products in the core. It is also the most widespread alteration assemblage---it is present throughout the core and on the surface. Rocks that have been altered to this assemblage are frequently greenish with cloudy plagioclase. The characteristics of this alteration product are consistent with those described by Taylor (1979) for intrusive rocks that have interacted with surface-derived waters.

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