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GEOLOGIC AND GEOCHEMICAL INVESTIGATIONS OF THE MEAGER CREEK GEOTHERMAL SYSTEM, BRITISH COLUMBIA, CANADA

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ABSTRACT

Meager Creek is perhaps the most intensely explored geothermal system occurring in the Cascade and Garibaldi Volcanic Belts. This paper describes the results of new lithologic, petrographic, X-ray, isotopic, and geochemical investigations of core and cuttings from the Meager Creek wells. The data demonstrate that alteration related to the present geothermal system is superimposed on basement rocks which were metamorphosed and intruded by dioritic stocks prior to the onset of volcanism. The geothermal alteration developed mainly after emplacement of hypabyssal dikes associated with Meager Mountain volcanism and is characterized by mineral assemblages consisting primarily of sheet silicates, quartz, carbonate, hematite, iron oxides, pyrite, and minor epidote, potassium feldspar, actinolite and biotite.

Permeabilities within the upper portions of the reservoir are low, reflecting filling of the fracture systems by carbonate. Petrographic observations suggest that sealing of the fractures accompanied hydrothermal brecciation and boiling of the fluids.

INTRODUCTION

The Meager Creek geothermal field is located approximately 200 km north of Vancouver in the rugged Coast Mountains of southwest B.C., Canada (Fig. 1). Geothermal investigations at Meager Creek have been in progress since late 1973. B.C. Hydro and Power Authority became involved in 1974 with a small-scale diamond drilling project designed to evaluate the thermal characteristics of Meager Creek Hot Springs and the surrounding area (Fig. 1). Subsequent investigations identified and localized a potential resource area on the southern flank of Meager Mountain, some 8 km upstream from the main vent of the springs.

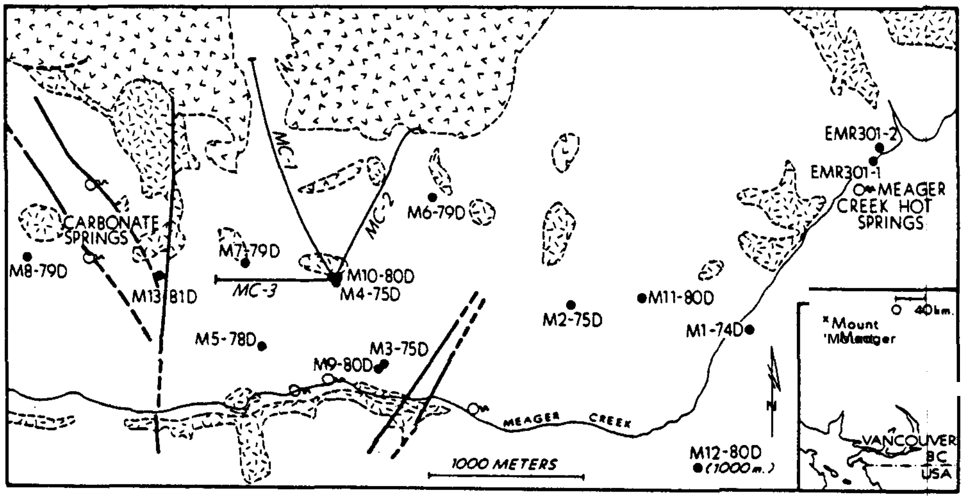
Exploration culminated with the drilling of three, large-diameter, rotary holes during 1980 to 1982 (Fig. 1). These 3000-3500 m holes, were directionally drilled to assess various targets identified in earlier studies. The program resulted in one well, MC-1, capable of long-term, sustained steam production. The other two wells, although unable to produce steam spontaneously in their present state, have been invaluable in the development of interpretive models for the geothermal reservoir. The deep wells encountered temperatures ranging from 233°C in MC-3 to 264°C in MC-2.

This paper focuses primarily on the hydrothermal alteration in the upper portions of the thermal system. Three of the wells, M-7 (max. temperature = 202°C; Fig. 2a), M-10 (max. temperature = 161°C; Fig. 2b), and M-12 (max. temperature = 48°C), have been studied in detail and provide an illustrative cross section of the field. Because the wells were continuously cored, the paragenetic relationships among the alteration assemblages can be accurately defined. In contrast, the deep exploration wells were cored only infrequently. Petrographic examination of the cuttings and core from the deep wells has now been conducted. These observations provide additional insight into the geology and evolution of the thermal system. Detailed X-ray and electron microprobe analyses of the cuttings have been performed, and interpretation of these analyses is in progress.

GEOLOGY AND ROCK DESCRIPTIONS

Meager Mountain is the northernmost volcano in the Cascade and Garibaldi Volcanic Belts (Souther, 1976). This Pliocene to Recent volcanic edifice rests mainly on metamorphic and intrusive rocks of the Coast Range Plutonic Complex, which also hosts the geothermal reservoir (Fig. 1). Locally, the basement rocks are intruded by dikes of the Mount Meager Volcanic Complex and by quartz-monzonite which may be as young as late Miocene (Fairbank et al., 1981). The most recent volcanic activity produced the Bridge River Ash 2440 ± 10 years B.P. from a vent on the north side of Meager Mountain (Nasmith et al., 1967).

The basement rocks consist primarily of regionally metamorphosed quartz diorite characterized by the mineral assemblage quartz + hornblende + epidote + biotite + andesine + opaques. Propylitic alteration, accompanied in places by base-metal sulfides, preceded development of the present hydrothermal system and is superimposed on the metamorphic assemblage. This alteration assemblage consists of chlorite + illite +



▨ = Meager Creek Volcanic Complex (Quaternary); ▨ = Coast Range Plutonic Complex; ⌒ = fault; ● = drill hole; ○ = spring

Figure 1. Generalized map of the Meager Creek geothermal field.

epidote + Fe-Ti oxides. Veins containing quartz, epidote, potassium feldspar and minor calcite are sporadically present and also appear to be related to this event. The metamorphic rocks also locally carry andalusite, garnet and tourmaline adjacent to the quartz monzonite intrusions.

Quartz diorite intrusive rocks, intersected below about 2500 m (vertical depth) in MC-3 and at depths greater than 1600 m (vertical depth) in MC-1, consist of a porphyritic phase containing phenocrysts of plagioclase and biotite and an equigranular phase characterized by hornblende. Both phases contain minor amounts of potassium feldspar and sphene.

Dikes of the Mount Meager Volcanic Complex range from silicic to basic in composition, but intermediate compositions predominate. The dikes typically contain sparse phenocrysts of plagioclase, and less commonly biotite, hornblende, pyroxene, or quartz. Although there are wide compositional variations among the dikes even within individual wells, spatially associated dikes display similar alteration assemblages. Locally intense alteration suggests that fractures associated with the dikes have been important conduits for the movement of thermal fluids.

HYDROTHERMAL ALTERATION

As in most geothermal systems, the distribution of hydrothermal minerals at Meager Creek mainly reflects variations in temperature, permeability and fluid chemistry (Browne, 1978). However, in complex geologic terrains characterized by multiple thermal events it is often difficult to assign any individual mineral to a particular thermal regime. At Meager Creek, hydrothermal minerals occurring in the dikes of the Mount Meager Volcanic Complex can most clearly be related to the present geothermal system.

Hydrothermal minerals in the dikes include clays, illite, chlorite, pyrite, carbonate, quartz, iron oxides, and in the deep parts of the system, potassium feldspar, epidote, actinolite, and biotite. These alteration phases replace the primary minerals and the matrix of the dikes and also occur in veins. Similar alteration assemblages are also widely distributed throughout the pre-volcanic country rocks. Petrographic relationships, however, suggest that some of these minerals must have formed prior to the development of the present geothermal system.

Sheet Silicates

Sheet silicates are the most abundant alteration phases present in the dikes (Fig. 2). Smectite is widespread; it occurs as the only secondary sheet silicate in the dikes in M-12 and is abundant in dikes and crystalline rocks above about 250 m in M-7 and at depths shallower than 360 m in M-10. In M-7 and M-10 it is associated with chlorite and illite. Small amounts persist, however, to the bottom of both M-7 and M-10.

Interstratified illite-smectite is associated with smectite. X-ray diffradtograms show that both alleverdite and kalkberg ordering are present.

Chlorite and illite tend to display similar distributions. Chlorite occurs as a replacement of biotite and amphibole in the crystalline and dike rocks, in veins, and as an alteration product of both plagioclase phenocrysts and the groundmass of the dikes.

Illite occurs as a fine- to medium-grained replacement of plagioclase and as a fine-grained alteration product in the groundmass of the dikes. Its association in M-12 with chlorite in samples of the crystalline basement rocks, where dikes carry only low-temperature alteration minerals, argues that

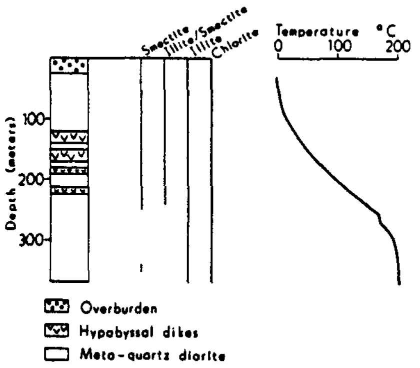


Figure 2a. Distribution of alteration minerals, rock types and temperatures in drill hole M-7.

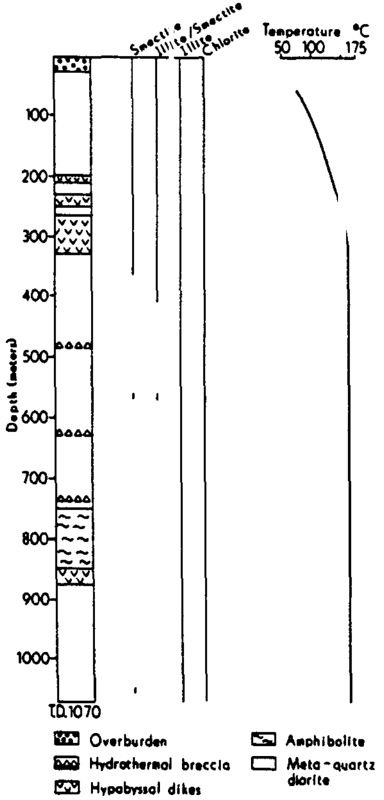


Figure 2b. Distribution of alteration minerals, rock types and temperatures in drill hole M-10.

much of the illite and chlorite in the basement rocks is pre-geothermal.

Veins containing biotite cut the metamorphic rocks at a vertical depth of approximately 1950 m in MC-2. The biotite occurs as small brown flakes associated with quartz, pyrite, calc-silicates, potassium feldspar and chlorite.

Carbonate and Sulfate Minerals

Carbonates are found throughout the altered rocks. The dominant carbonate is calcite, locally iron-rich, although minor amounts of dolomite are also present. the carbonates occur as vesicle fillings in the dikes, in veins, and as a replacement of plagioclase and mafic minerals in the dikes and crystalline rocks.

Anhydrite and barite are found in trace amounts in M-10 and MC-2. Anhydrite is associated with carbonate + quartz veins in amphibolite in M-10 and in cavities with actinolite in MC-2 (KRTA; unpublished report, 1983). Traces of barite have been found in M-10 (620 m) where it occurs in veins containing carbonate and minor quartz.

Quartz

Quartz is a common vein mineral, occurring primarily with calcite, chlorite and pyrite, although potassium feldspar, actinolite, barite and epidote may also be present. The age relationships between the various veins are discussed more fully below.

Silicate Minerals

Dike rocks containing epidote, potassium feldspar, and actinolite, associated with quartz and chlorite, occur in a hydrothermal breccia near the "top" of an altered zone extending from 1600 to 2500 m (vertical depth) in MC-2. These minerals occur as alteration products of the primary phases in the dike fragments and in the matrix of the breccia. Within the dike fragments epidote and potassium feldspar replace plagioclase, whereas fine, acicular crystals of actinolite replace hornblende. The breccia is cut by veins containing epidote and potassium feldspar. In places actinolite is altered to carbonate and chlorite. At greater depths, actinolite-bearing veins in the metamorphic rocks also contain minor secondary biotite and pyrite.

Oxide and Sulfide Minerals

Hematite, magnetite and pyrite have been found in both the altered dikes and crystalline country rock. Hematite sppears to be most abundant in the upper portions of the wells. It occurs primarily as disseminated flakes throughout the rocks and in carbonate and carbonate + chlorite veins, where it is associated with magnetite or pyrite as an alteration product. Fractures filled with hematite and calcite are common in M-7 and M-10.

Magnetite occurs as a primary mineral in the dikes, as porphyroblasts, as an alteration product with chlorite after biotite and as small crystals in veins.

Pyrite is the only sulfide mineral identified by us in the hypabyssal dikes, although P. Read (pers. comm.) has also reported the occurrence of sphalerite in one of the dikes from M-7. Quartz, chlorite, and carbonate are typically associated with pyrite in the veins. Chalcopyrite, sphalerite, galena and molybdenite locally accompany pyrite in the metamorphic rocks, but their distribution bears no apparent relationship to alteration of geothermal age or to the present temperature distributions in the field (Moore et al., 1983).

VEIN DISTRIBUTIONS AND RELATIONSHIPS

Four different vein sets related to the geothermal system can be differentiated: 1) carbonate and carbonate + quartz veins; 2) carbonate + chlorite veins; 3) hydrothermal breccias; and 4) veins containing potassium feldspar ± calc-silicate minerals ± biotite.

In general, carbonate veins appear to be the youngest veins in the field. Crosscutting relationships with all other vein types have not been found. However, carbonate veins typically crosscut carbonate + chlorite veins, and along with rare quartz and quartz + carbonate veins, are the only vein types occurring in the dikes in M-7 and M-10. Similar veins occur in the metamorphic basement rocks, particularly in the upper portions of these wells, and fragments of carbonate veins were found to occur widely in chips at least throughout the upper 1600 m (vertical depth) of the deep wells. In contrast, carbonate veins are not found in dikes from M-12.

Carbonate veins characterized by chlorite ± quartz, iron oxides, and pyrite occur at depths as shallow as 40 m in M-7. Although these veins have only been found in samples of the metamorphic basement rocks, the vein minerals are very similar to the alteration assemblages of the dikes, suggesting a genetic link between the two. Despite their simple mineralogy, many of the veins in this group appear to have undergone a complex evolution involving deposition of chlorite + carbonate veins, brecciation of the vein and adjacent country rock, deposition of carbonate ± chlorite, quartz, iron oxides and pyrite, or more rarely, illite in the matrix of the breccia, and finally, deposition of simple carbonate veins.

Individual veins and breccias typically display complex crosscutting relationships with each other and often a marked assymetry with the vein axis. In some, brecciation has been repetitive. These relationships suggest that vein development proceeded through repeated fracturing of sealed rock.

Breccias up to several meters thick are locally associated with porphyritic dikes of the Mount Meager volcanic complex. The breccias contain variably rounded fragments of dike and metamorphic rocks in a groundmass that consists mainly of commuted country rocks. In M-10, the breccia at 620 m is intruded by a dike.

"Pipe-like" breccias (hydrothermal breccias) have been recognized in many active and fossil geothermal systems and their formation is now generally ascribed to explosive boiling triggered by hydraulic or tectonic fracturing of sealed fractures (see, for example, Fournier, 1983). At Meager Creek, the close association between the dikes and breccias suggests that these dikes may have contributed both heat and volatiles to fluids trapped beneath the sealed zones, allowing pore pressures to become large enough to fracture the enclosing rock. The resulting rubbilized zones (pipes) may have been important channels connecting the shallow parts of the thermal field to high-temperature zones at depth.

Both the breccias in M-10 at 620 m and in MC-2 are cut by veins. The veins in M-10 consist dominantly of calcite with minor quartz and barite. In contrast, the veins in MC-2 contain epidote and potassium feldspar.

Veins containing variable quantities of quartz, epidote, actinolite, pyrite, potassium feldspar, biotite and chlorite occur sporadically in the metamorphic rocks beneath the breccia in MC-2. Their spatial association and similarity in hydrothermal mineralogy with the breccia suggest that the two were formed by the same thermal Yluids.

TEMPERATURES DURING HYDROTHERMAL ALTERATION

Temperatures during alteration were estimated from the distribution and occurrence of alteration minerals, and the isotopic compositions of the carbonate minerals in the altered rocks. Temperatures in M-1 and M-12 were also estimated by Kelley and Bldckwell (1984) using fission track techniques, Their data suggest that temperatures in the shallow portions of these wells may have exceeded 120' ± 25°C but were probably no hotter than 200' ± 25°C in the past.

Temperature Estimates from Mineralogical Data

Despite the generally spotty occurrences of hydrothermal minerals related to the present geothermal system, these minerals are strongly zoned with respect to the present temperature distribution in the field, Three distinct hydrothermal alteration zones can be recognized. These include: 1) a low-temperature zone characterized by smectite ± interlayered illite-smectite, 2) an intermediate-temperature zone characterized by illite and chlorite, and 3) a high-temperature zone containing epidote, actinolite, potassium feldspar, and locally biotite. As in many geothermal systems, the boundary between the low- and intermediate-temperature zones is gradational (Cole and Ravinsky, 1984). The overlap between these zones at Meager Creek is clearly illustirated by the distribution of sheet silicates in M-7 and M-10. Smectite, interlayered illite-smectite, illite and chlorite are all present in the altered dikes occurring at intermediate levels in these wells.

Mineral zoning patterns similar to Meager Creek have been mapped in many high temperature geothermal fields (Kristmannsdottir, 1975; Browne, 1978; Elders et al., 1979; McDowell and Elders, 1980; Cathelineau et al., 1983; Bird et al., 1984). Despite wide variations in rock and fluid chemistry in these systems, the sheet silicates appear to be stable only within a relatively narrow temperature range. In general, smectite and interstratified illite-smectite may persist to temperatures as high as 175 and 225°C, respectively. At temperatures above 220-225°C, illite and chlorite are the typical sheet silicates, although both may form at temperatures as low as about 150°C. The presence of illite and chlorite suggests that temperatures in the upper parts of M-10 and M-7 could have been at least 100°C higher than the present temperatures.

Actinolite and biotite are found only in geothermal systems where temperatures exceed 300°C. Fluid inclusion measurements on a quartz vein in volcanic rocks containing secondary biotite suggest that temperatures at Meager Creek were substantially higher (KRTA, unpublished data, 1983). These measurements indicate that temperatures exceeded 400°C during hydrothermal alteration.

Temperature Estimates from Isotopic Data

Oxygen isotope data were used to estimate the temperatures of calcite deposition in the upper portion of the thermal system. Calcites from wells M-7, M-10 and M-12 were isotopically analyzed. Equilibrium temperatures were calculated from these data using three isotopically different fluids. In the first model, the δO^{18} content of the fluid was taken as -8.73 per mil. This value is the composition calculated for the fluid discharged from MC-1. The composition of the fluid in the second model, -1.25 per mil, was estimated from fluid inclusion data on vein calcite taken from M-7 at a depth of 190 m. Homogenization temperatures obtained on 4 primary inclusions yielded an average temperature of 194°C (S. Morrison, unpublished data). A δO^{18} content of -15 per mil was used in the third model. This value is the composition of the thermal fluids discharged from Meager Creek Hot Springs and the shallow wells (Clark et al., 1982).

The calculated temperatures were compared with other geologic and mineralogic data to determine the most realistic values. Fluids with a δO^{18} content equal to water discharged from MC-1 (-8.73 per mil) provided the most reasonable estimates for samples with calcite veins containing iron oxides but lacking chlorite. The calculated temperatures ranged from 104° to 200°C and averaged 149°C. These temperatures are similar to the present-day temperatures in the wells.

Isotopically derived temperatures obtained using a δO^{18} value of -1.25 per mil yielded the most reasonable estimates for the formation of calcite + chlorite veins. The calculated temperatures generally ranged from 169° to 261°C, although one value of 144°C was calculated. These values are consistent with the 190°C temperatures determined by McDowell and Elders (1980) for the lower limit of the carbonate-chlorite zone in the Salton Sea geothermal field.

Dikes in M-12 are weakly altered and contain vesicle fillings of calcite. Temperatures based on the isotopic composition of MC-1 range from 68 to 84°C. The absence of sheet silicates other than montmorillonite in the dikes supports the conclusion that temperatures were below 150°C during carbonate deposition.

SUMMARY AND CONCLUSIONS

Hydrothermal alteration at Meager Creek is characterized by relatively simple mineral assemblages that belie a complex thermal history. At least two distinct periods of hydrothermal activity are represented by these mineral assemblages.

The earliest period of hydrothermal alteration preceded the volcanic activity and development of the modern-day geothermal system. Hydrothermal assemblages related to this phase of thermal activity are characterized by illite, chlorite, epidote and base metal sulfides.

Hydrothermal fluids related to the geothermal system have deposited sheet silicates, carbonate, quartz, pyrite and sparse potassium feldspar, calc-silicate minerals and biotite, in the altered country rocks and dikes of the Meager Mountain volcanic complex. The sheet silicates are strongly zoned with respect to present-day temperatures. Smectite and interlayered illite-smectite occur predominantly in the cooler portions of the field where temperatures are below 160°C. At higher temperatures, illite and chlorite predominate. Secondary biotite was found in altered crystalline rock penetrated at a depth of about 2200 m in the highest-temperature well drilled to date. Fluid inclusion measurements suggest that temperatures during alteration were greater than 400°C (KRTA; unpublished data).

Alteration related to the modern-day geothermal activity followed emplacement of hypabyssal dikes of widely varying composition. Explosive hydrothermal brecciation accompanied emplacement of some dikes. In the upper 1000 m of the thermal system, illite and chlorite formed in the dikes, whereas veins of carbonate + chlorite were deposited in the crystalline reservoir rocks by the circulating fluids. Locally, at depths below 1600 m hydrothermal veins containing biotite, calc-silicate minerals, potassium feldspar, quartz, pyrite and chlorite were deposited in the altered rocks, Boiling of the thermal fluids and brecciation of the reservoir rocks occurred repeatedly during deposition of the vein minerals.

Available fluid inclusion and isotope data from altered rocks at depths above 1000 m indicate that the fluids were weakly saline and that temperatures during this phase of activity typically ranged from 170 to 260°C. The relatively high temperatures that must have persisted during this phase of alteration suggest that fluid movement may have been driven by repeated influx of magma into shallow portions of the thermal system.

Subsequent geothermal activity resulted in the formation of carbonate veins in both the dikes and crystalline reservoir rocks. In contrast to the explosive activity that accompanied formation of carbonate + chlorite veins, deposition of the carbonate occurred under relatively quiescent conditions. Although the temperatures during this phase of alteration have not been determined directly, temperatures estimated from the δO^{18} content of present day fluids and calcite in the altered rocks suggest that the fluids were no hotter than 200°C.

Collectively, the isotopic and mineralogical data suggest that temperatures in the geothermal system at Meager Creek have declined since its formation, in part as a result of carbonate deposition in fracture zones that served as fluid channels. Temperatures during the peak of alteration may have been 50-150°C higher than the presently observed temperature.

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