

Hydrothermal alteration of basalts from Hawaii Geothermal Project Well-A, Kilauea, Hawaii

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ABSTRACT

Mineralogical examination of basaltic rocks obtained during drilling of a successful 1,962-m-deep geothermal well (HGP-A) in the east rift zone of Kilauea Volcano, Hawaii, reveals three zones of hydrothermal alteration beneath a zone of unaltered lavas. Each alteration zone is characterized by the dominance of a particular mineral: zone 1, montmorillonite; zone 2, chlorite; zone 3, actinolite. Three zones of relative permeability can be tentatively identified on the basis of filled versus partly filled vesicles and fractures. Because the well has not returned to thermal equilibrium as of this writing, stability relations between

secondary minerals and temperatures cannot be calculated with accuracy. However, the latest downhole temperatures measured at the boundaries of alteration zones, compared with similar data from high-temperature geothermal areas in Iceland, indicate that HGP-A temperatures are considerably higher than those encountered for the same alteration-zone boundaries in Icelandic wells. This indicates that the present-day thermal regime in HGP-A is relatively young and that the hydrothermal minerals probably have not reached equilibrium with existing conditions.

INTRODUCTION

A successful 1,962-m-deep geothermal test well, designated Hawaii Geothermal Project Well-A (HGP-A), was drilled in the east rift zone of Kilauea Volcano in the island of Hawaii (Fig. 1) in early 1976. The drill site is about 182 m above sea level, which means that the well penetrated a 1,780-m sequence of volcanic rocks below sea level, making it the deepest well yet drilled in the Hawaiian Islands. The success of the well is unusual in that most active geothermal fields are confined to or associated with rocks of a more silicic nature (Berman, 1975). Even in Iceland, silicic volcanism occurs at or near all geothermal fields except the 30-km zone from Reykjanes to Krysuvik (Koenig, 1973).

Above the 207-m level in the well (all references to depth are measured from the surface elevation at the drill site), poor circulation of drilling mud prevented systematic sampling of cutting chips; below that level, 780 cutting samples were recovered at 1.5- to 3-m intervals to the bottom of the well. Ten cores totaling 28 m (92% recovery) were taken at intervals of 125 to 275 m.

Macroscopic examination of cutting chips for percentages of vesicularity, black glass, and alteration products indicates that the well penetrated a sequence of thin subaerial pahoehoe and aa

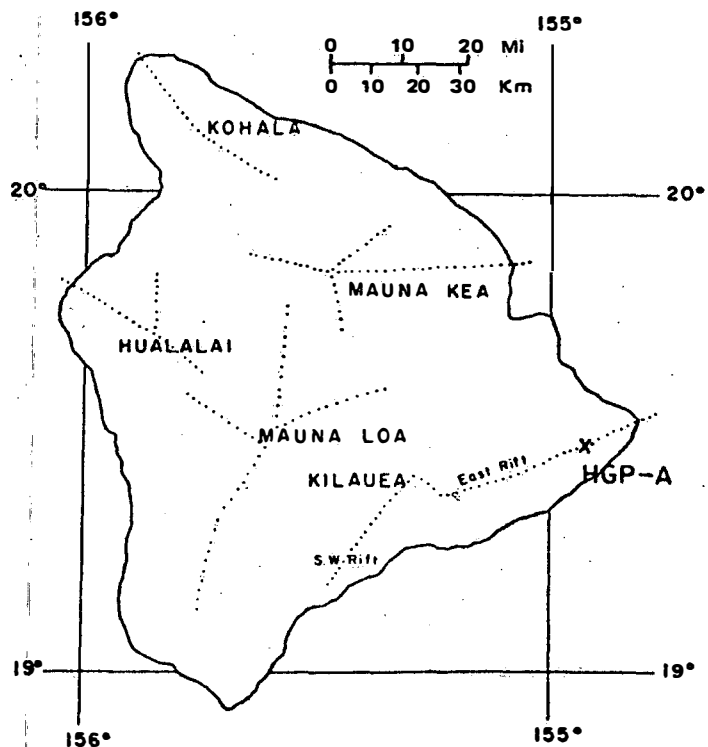


Figure 1. Map of island of Hawaii showing location of Hawaii Geothermal Project Well-A (HGP-A).

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basalt flows and submarine pillow basalts. (D. Palmiter, 1976, personal commun.). Chemical analyses (Stone, 1977) show that the rocks are quartz-normative tholeiitic basalts.

PREVIOUS INVESTIGATIONS

Chemical alteration of Kilauea basalts was described by Macdonald (1944) and Stearns and Macdonald (1946). The present-day formation of palagonite in Kilauea caldera was described by Hay and others (1969). Fujishima and Fan (1977) studied hydrothermally altered basalts of the Kailua Volcanic Series, Oahu, and described both vertical and horizontal zones of zeolite and clay-mineral alteration. Druecker and Fan (1976) and McMurtry and others (1976) described the hydrology and chemistry of ground water in the Puna district on the east rift zone of Kilauea. Macdonald (1973) reviewed the occurrence of hot water and steam in Hawaii. Hydrothermal alteration of Icelandic basalts in high- and low-temperature geothermal fields has been summarized by Kristmannsdóttir (1975).

In the first of two attempts to locate geothermal energy in Hawaii, the Hawaii Geothermal Power Company drilled four wells in the Puna area in 1961 (Macdonald, 1973). In 1973 the first deep bore hole, 1,262 m, was drilled at the summit of Kilauea Volcano; the maximum temperature for that well, 137 °C, was measured at the hole bottom (Zablocki and others, 1974). Temperatures encountered in all wells are insufficient to warrant commercial interest at present.

GEOLOGIC SETTING

The Hawaiian Islands extend nearly 2,600 km across the north-central Pacific Ocean, decreasing in age from northwest to southeast. The youngest and southeasternmost island of Hawaii is composed of five volcanoes, two of which, Mauna Loa and Kilauea, constitute the center of present-day volcanic activity in the Hawaiian Islands. Lavas of the two volcanoes interfinger near the surface, but Kilauea rests on the flank of Mauna Loa and is, therefore, the younger edifice.

Kilauea has two principal rift zones extending outward from the summit caldera and lying at an obtuse angle to each other. These are the southwest and east rift zones, characterized by open cracks, lines of pit craters, smaller parasitic shields, and spatter cones. In addition, steam vents and warm-water springs and wells exist at several points along the east rift zone (Macdonald, 1973). Eruptions occur at frequent intervals at the summit of Kilauea and along the rift zones.

HYDROTHERMAL ALTERATION MINERALS

Alteration products were identified by whole-rock X-ray diffraction and thin-section examination of cores and cutting chips. A few mineral separates were X-rayed, heated, and X-rayed again. The occurrence of secondary minerals observed in HGP-A is shown in Figure 2.

Montmorillonite. Traces of montmorillonite that rim a few olivine phenocrysts are first noted at a depth of about 318 m. By 675 m the montmorillonite is present interstitially and as pseudomorphs after olivine. It increases in abundance with depth to about 1,350 m in this same mode and then decreases as chlorite becomes the dominant alteration mineral. Montmorillonite is not observed below 1,894 m.

Chlorite. Chlorite is found locally at a depth of 675 m and occurs sporadically down to 1,350 m where it supersedes montmorillonite as the dominant alteration mineral. On the basis of the X-ray intensity ratio of [(002)/(004)] 7A/14A peaks (Carroll, 1969), both Mg-chlorite and Fe-chlorite are identified in the altered rocks. At the 1,350-m depth both varieties occur. With increasing depth, magnesium decreases and iron increases. By 1,960 m the chlorite is very Fe-rich. All chlorites are 11b polytypes. Chlorite occurs interstitially and fills vesicles and fractures in the basalt. At 1,962 m chlorite occurs as pseudomorphs, and it replaces actinolite in the centers of actinolite pseudomorphs after augite and olivine. Chlorite is superseded by actinolite as the principal alteration product at 1,894 m; at 1,959 m it is a minor constituent only.

Actinolite. Actinolite is sporadic from depths of 1,350 to 1,894 m. From this depth to the bottom it is the dominant alteration mineral. It occurs as pseudomorphs after augite and olivine and as a groundmass replacement along with quartz, magnetite, and hematite.

Calcite and Anhydrite. Between depths of 675 and 875 m, calcite is found in thin section as a minor constituent that partly fills some vesicles. Anhydrite is observed lining fractures in hand specimens of cores 8 (1,642 m), 9 (1,835 m), and 10 (1,962 m). Euhedral crystals in fractures in core 10 indicate that the rock is not completely sealed at that depth. Calcite and anhydrite are nowhere abundant enough to be detected by whole-rock X-ray diffraction.

Zeolite. Zeolite is found between depths of 675 and 875 m. X-ray analysis of mineral separates indicates that the species is heulandite; it appears along a flow margin at 675 m and lines vesicles there and in other samples. Zeolite does not occur deeper in the well where higher temperatures prevail. Like calcite and anhydrite, it was not detected by whole-rock X-ray analysis.

Opaque Minerals. Magnetite is found in varying amounts throughout the section. It occurs as primary euhedral crystals, secondary skeletal grains, and by-product dust. At a depth of 1,480 m, hematite is found by X-ray diffraction; it occurs sporadically to a depth of 1,894 m where it exceeds magnetite and becomes the dominant opaque mineral to the bottom of the well. The occurrence of hematite coincides with that of actinolite.

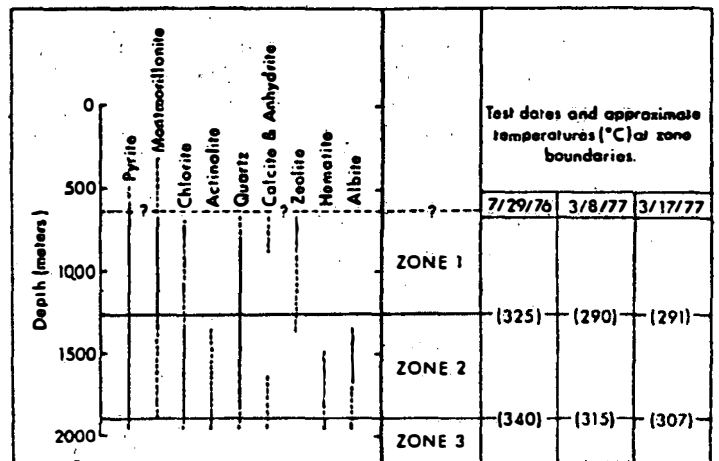


Figure 2. Occurrence of hydrothermal minerals in HGP-A well, zones of alteration, and temperatures measured on three occasions.

anhydrite, quartz, and zeolites are minor accessory minerals. Epidote is not observed.

Three zones of permeability can be identified on the basis of unfilled versus filled vesicles and fractures.

Thermal equilibrium that was disturbed during drilling has not been reestablished in the well. Comparison, however, of HGP-A hydrothermal mineral zone boundaries and the latest downhole temperature profiles with similar data from high-temperature geothermal areas in Iceland indicates that temperatures are higher in the Hawaiian well than in most Icelandic wells. It appears that the present-day thermal regime is relatively young and may be due to a recent injection of magma into the east rift zone from the shallow reservoir beneath the summit of Kilauea Volcano.

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ACKNOWLEDGMENTS

Reviewed by Gordon A. Macdonald and Ralph Moberly. Supported by Energy Research and Development Administration (ERDA) Grant EY-76-C-03-1093 (formerly ERDA E(04-3)-1093). Hawaii Institute of Geophysics Contribution No. 829.

MANUSCRIPT RECEIVED AUGUST 11, 1977

MANUSCRIPT ACCEPTED APRIL 21, 1978

Pyrite is first observed in cutting chips at 485 m and is present in varying amounts throughout the well, generally increasing in abundance with depth. Euhedral pyrite grains occur with quartz and clay minerals that fill vesicles and fractures in the bottom 500 m of the well. In shallow cores ilmenite is found in thin section, but with increasing depth and alteration it is not recognized.

Quartz. Quartz is first found in minor amounts that fill vesicles at about the 675-m depth; it becomes increasingly abundant with depth to about 1,835 m and then decreases somewhat. It occurs interstitially and fills vesicles and cracks. In one thin section at 1,642 m, quartz appears to be replacing plagioclase but this is not observed in other samples.

Albite. Albite is first noted to be replacing plagioclase at a depth of 1,350 m. Albitization increases with depth, and at 1,962 m the plagioclase phenocrysts are about 50% altered.

DISCUSSION

On the basis of a dominant mineral, three zones of alteration can be distinguished beneath a zone of unaltered lavas (Fig. 2). The uppermost altered zone, with a depth of 675 to 1,350 m, is characterized by montmorillonite, with minor calcite, quartz, zeolite, and chlorite. Vesicles in this zone are only partly filled with secondary minerals. The second zone, at a depth of 1,350 to 1,894 m, is characterized by extensive chlorite superseding montmorillonite as the principal alteration mineral, with quartz, actinolite, and montmorillonite as accessory products. All vesicles and fractures appear to be completely filled within this zone. The third zone of alteration becomes evident at a depth of about 1,835 m and is dominant at 1,959 m. Actinolite predominates; chlorite, quartz, and opaque grains, principally hematite and pyrite, are the accessory minerals. The degree and type of alteration throughout most of the third zone is distinct from and more extensive than that encountered in the lavas at shallower depths. The mineral assemblage resembles that found in greenschist facies metamorphism and reflects higher pressure and probably higher temperature. Because fractures and vesicles are not completely filled, it is probable that greater permeability also is significant in causing more intense alteration at this depth.

On the basis of the degree of secondary mineralization that fills vesicles and fractures in HGP-A cores, three zones of permeability can be identified. From the surface down to about 875 m, the lavas appear to be highly permeable; between about 1,050 and 1,835 m, they are slightly permeable; and between 1,835 and 1,959 m, the lavas become moderately permeable. The exact boundary between permeable zones has not been established with certainty due to the distance between samples; probably permeability is gradational.

It is informative to compare temperature profiles and mineral assemblages from the Hawaiian well with similar data from high-temperature geothermal areas in Iceland, because both occur in predominantly basaltic lavas.

In Iceland the main alteration zones are characterized by a smectite-zeolite zone, a mixed-layer clay-mineral-prehnite zone, and a chlorite-epidote zone. The presence of an incipient fourth zone is suspected in one area because of the appearance there of amphibole at temperatures exceeding 280 °C (Kristmannsdóttir, 1975).

Kristmannsdóttir (1975) stated that the degree of alteration varies among the different areas and that the temperatures at which certain hydrothermal minerals occur also vary. However,

maximum and minimum temperatures for the occurrence of alteration minerals have been established through comparison of data from the different areas. Rock temperatures at zone borders are approximately 200 °C between the smectite-zeolite and mixed-layer clay-mineral-prehnite zones and 230 °C between the latter zone and the chlorite-epidote zone. The Nesjavellir high-temperature geothermal area is an exception in that the depth and temperature of occurrence of the same mineral assemblages are often significantly different from those found in the other high-temperature areas (Kristmannsdóttir and Tómasson, 1975). They cited the occurrence of the zeolite zone to temperatures up to 280 °C and to depths of 1,000 m, and the occurrence of nearly unaltered glass at 450-m depth and a rock temperature of about 200 °C. In addition they stated that, "The zone of dominant smectite minerals reaches to much higher temperatures than observed in other areas . . . [and the] epidote-chlorite zone is not clearly defined in the depth range of the holes. Epidote is only found in narrow veins in the deepest drillhole" (Kristmannsdóttir and Tómasson, 1974). They concluded that temperatures in the Nesjavellir area have increased too recently for the minerals to have reequilibrated to existing temperature conditions.

Figure 2 shows the zones of alteration observed in the HGP-A well and the temperatures measured on three occasions. By comparison, the hydrothermal mineral zones in the HGP-A well are similar to those found in the high-temperature geothermal areas of Iceland in general, and they most closely resemble the conditions found in the Nesjavellir area in particular. The one problem is that instrumental techniques were unable to resolve the presence of a mixed-layer clay-mineral zone between the montmorillonite and chlorite zones in the HGP-A assemblage. Other similarities between Nesjavellir and HGP-A include the presence of a 2.2-m thickness of intensely fractured glass at a depth of 878 m in HGP-A. The fractured surfaces have a thin coating of montmorillonite, but the interiors of the pieces are unaltered. In addition, the montmorillonite zone in HGP-A extends to temperatures in the range of 290 °C (Fig. 2), and epidote is not found in the HGP-A alteration assemblage at any depth. Assuming that the assessment of Nesjavellir by Kristmannsdóttir and Tómasson (1974) is correct, the HGP-A mineral assemblages likewise may not be in equilibrium with present temperature conditions encountered in the area. Contradictions to this conclusion are raised by P. Kroopnick (1977, personal commun.) who stated that the agreement between observed temperatures and calculated geochemical temperatures in HGP-A indicates that the waters are in equilibrium with the surrounding rock.

On the basis of chemistry of summit and east rift lavas erupted during historic times, Wright and Fiske (1971) proposed that "batches" of magma from the shallow reservoir beneath the summit of Kilauea are periodically injected into the east rift zone and that the more highly differentiated lavas may be held there for periods of more than a century. A recent magma injection of this sort could provide the apparent "new" heat source we are observing.

SUMMARY

Beneath a zone of fresh lavas three zones of alteration are observed in HGP-A, each characterized by a dominant hydrothermal mineral: (1) 675 to 1,350 m, montmorillonite; (2) 1,350 to 1,894 m, chlorite; and (3) 1,894 to 1,962 m, actinolite. Calcite,