HYDROTHERMAL ALTERATION MINERALS OF THE GEYSERS STEAM FIELD, CALIFORNIA AND THEIR POTENTIAL USE IN EXPLORATION

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INTRODUCTION

Little information has been published on the hydrothermal alteration minerals occurring at depth in the Geysers steam field, California. Steiner (1958) reported the occurrence of wairakite from a well; McNitt (1964) identified pyrite, sericite, calcite, quartz, siderite, apatite and chlorite in cores of Franciscan graywacke and greenstone. Recently, Union Oil Geothermal Division furnished a set of well cores from the cap rock overlying thesteam reservoir for geophysical studies (Lockner et al., 1980); sample localities are shown in Figure 1. Cores of metagraywacke and greenstone from 4 wells---Thermal 10 (TH10), Lakoma Fame 6 (LF6), D & V 1 (DV1) and Horner State (HS1)---were compared to unaltered Franciscan metagraywacke (GP5) from surface exposures(Table 1). Several previously unreported alteration minerals were found in the cored rocks, including epidote, tremolite-actinolite, prehnite and tourmaline. This note describes the observed alteration minerals and some of the factors that controlled their growth.

SAMPLE DESCRIPTIONS

GP5 -- Outcrops of Franciscan rock in the Geysers area consistof massive, fine-grained metagraywacke with the mineral assemblage quartz + albite + chlorite + phengite + pumpellyite + sphene ± calcite. GP5 contains some relict detrital epidote, that occurs as rounded grains or as part of schistose metamorphic rock fragments. These partly altered relics are readily distinguishedfrom the hydrothermal epidote of some cores.

HS1 -- The Horner State well is located near the northern limit of drilling operations in the Geysers steam field (Fig. 1). Metagraywacke at 1478 m depth is nearly identical to GP5, except for thepresence in HS1 of narrow veins of calcite + pyrite. Although calcite is associated with both the initial, Franciscan metamorphism and later hydrothermal activity, pyrite is exclusively a hydrothermal mineral. Therefore, these veins are correlated with events related to the steam field.

DV1 -- In contrast to the texturally unmodified GP5 and HS1 metagraywackes, the DV1 core is a semischist with partial segregation of quartzofeldspathic and chlorite-rich layers. Some of the quartzose layers have been fragmented and the pieces randomly oriented in the chloritic bands. This fragmented, schistose texture probably originated during Franciscan metamorphism and deformation;the veins associated with the hydrothermal events in DV1 cut across all the deformation features.

A large number of hydrothermal vein minerals occur in DV1 (Table 1); calcite alone is notably absent. One set of veins contains the assemblage epidote + calcic amphibole + chlorite + adularia + pyrite. Chlorite generally lines the walls of such veins, and euhedral epidote and adularia extend into the veins from the margins. The pale green calcic amphibole is probably tremolite or actinolite in composition. Wider veins in DV1, that cross-cut the epidote and actinolite-bearing veins, consist ofcoarse-grained adularia + quartz + pyrite + prehnite + chlorite. The prehnite in the large veins is an interstitial mineraland the quartz occurs as euhedral crystals that are enveloped by coarse-grained, anhedral adularia.

Other than vein development, the DV1 metagraywacke exhibits few effects of hydrothermal alteration. Minor amounts of epidote and actinolite are found in the wall rock adjacent to the epidote-bearingveins. DV1 also contains a considerable amount of green, blue-green, or brown tourmaline that has apparently crystallized in response to the hydrothermal activity. The tourmaline occurs as aggregates of irregularly shaped to tabular crystals in the chlorite-rich bands.

<u>TH10</u> -- This metagraywacke also shows a high degree of textural reconstitution, in this case owing to recrystallization during hydrothermal alteration rather than to deformation accompanying Franciscan metamorphism. In places this alteration has destroyed the sedimentary fabric, producing a fine-grained, nonfoliated mosaic of quartz + feldspar + chlorite + white mica. The alteration is characterized by the introduction of potassium and sulfur, and the loss of sodium. All feldspars in TH10, that previously had been albitized during Franciscan metamorphism, have been replaced by adularia with a tile-like texture identical to that of the adularia at Wairakei, New Zealand (Steiner, 1970). Extensive pyrite mineralization also has taken place, with sulfides concentrated in some shale and volcanic rock fragments and in the metagraywacke matrix.

TH10 is extensively cut by veins whose mineral assemblages differ from DV1 in the absence of epidote and actinolite and the presence of calcite (Table 1). An early generation of narrow, laminar veins consists of alternating layers of fine-grained quartz and chlorite. Later, wider veins composed principally of quartz + adularia + pyrite are similar to veins in DV1. Minor, interstitial prehnite in these younger veins is partly replaced by calcite; in places the vein walls are lined with chlorite.

<u>LF6</u> -- Greenstone samples from 2 depths were examined from the Lakoma Fame well. At the deeper, 969 m level, the rock was originally an aphanitic metabasalt with scattered small plagioclase laths and scarce relict pyroxene phenocrysts. The igneous

minerals were replaced by the assemblage albite + chlorite + sphene + white mica during Franciscan metamorphism. Narrow veins of albite + chlorite may also be correlated with the early Franciscan metamorphism, for the following reasons: 1) the albite-bearing veins are cut by veins clearly associated with the steam field; and 2) the characteristic feldspar of the hydrothermal veins is adularia rather than albite. Later veins consist principally of coarse-grained chlorite + adularia + pyrite. Neither calcite, quartz, nor epidote was positively identified in this rock. Other than vein formation, this greenstone shows no evidence of hydrothermal alteration.

Greenstone at the 922-927 m level in LF6 is considerably coarser-grained and contains many more pyroxene phenocrysts than the greenstone at greater depth. The 922 m rock also has larger veins that contain calcite, epidote, and actinolite in addition to pyrite, adularia, and chlorite (Table 1). The calcite is a late vein mineral that fills the centers of some veins and cuts across minerals such as epidote and adularia. Minor amounts of epidote have also crystallized within the greenstone wall rock.

CONTROLS ON MINERAL DISTRIBUTION

Because of the limited number of cores examined here, generalizations about mineral distribution and the controls of mineral occurrence cannot be made. However, variations in mineral assemblages have been observed at different depths and locations within the Geysers steam field. The observed distributions may have been influenced by the following factors:

1) Temperature. The crystallization of epidote and actinolite in the cores may be most strongly controlled by temperature. In other geothermal fields, epidote and actinolite occur at temperatures above about 220°C. According to White *et al.* (1971), temperatures within the steam reservoir at the Geysers are relatively uniform at 240°C. The epidote- and actinolite-bearing core DV1 was located just above the steam reservoir, where temperatures near 240°C may also have prevailed. Similar temperatures may have existed at depth in the Lakoma Fame well. Reduced temperatures at the shallow depths (100 m) of the TH10 core may explain the absence of epidote and actinolite from that thoroughly recrystallized metagraywacke.

Cored metagraywacke from the Horner State well was obtained at the greatest depth of all examined cores, yet HS1 displays the least development of veining and no wall rock alteration. This well may have been drilled into low-temperature rock lying outside the influence of the steam reservoir.

2) Pressure. According to Browne (1978), pressure has little direct effect on hydrothermal alteration. However, changes in fluid pressure, such as those produced by boiling, may alter the fluid composition and thus promote crystallization of certain

vein minerals. Boiling and subsequent loss of CO_2 may have resulted in the deposition of calcite, quartz and adularia in some cores. In contrast, non-boiling of the hydrothermal fluid at DV1 is a possible explanation for the absence of calcite from that core.

3) Permeability. Permeability is an important factor in the amount of rock alteration attained within a geothermal field. In rocks of low permeability, interaction between the rock and a hydrothermal fluid is slight and equilibrium is certainly not attained. At the Ohaki-Broadlands geothermal area in New Zealand, the replacement of plagioclase by adularia in the reservoir rocks is roughly correlated with an increase in the measured well permeability (Browne, 1970). Of the Geysers cores studied, TH10 may have been the most permeable; the abundance of pyrite and adularia indicate that a significant amount of chemical exchange has taken place. In contrast, LF6 and DV1 show little rock alteration, most of which is concentrated near veins.

4) Rock Type. At low temperatures, the composition of the reservoir and cap rocks may influence the alteration minerals observed (Browne, 1978). The concentration of chlorite, calcic amphibole, and epidote along the vein walls suggest that some of the iron and magnesium required for their crystallization was provided by the host rock, through exchange reactions with the hydrothermal fluid. Had other rock types of different compositions been present, different vein minerals might have formed.

POTENTIAL USE OF ALTERATION MINERALS IN EXPLORATION

Unlike hot-water systems, the mineral relationships of vapor-dominated geothermal systems have not been investigated in any detail (White, 1970). However, of the above parameters, the relationships between temperature and mineral occurrence may prove useful in evaluating the steam-producing potential of different wells. In particular, the occurrence of epidote and actinolite in cap rocks of various compositions indicates that temperatures approaching those of the steam reservoir have been attained. Similarly, the borders of vapor-dominated systems may be identified by the absence of high-temperature mineral assemblages even at great depth. Knowledge of the permeability of the cap rock may prove important in evaluating the effectiveness of the seal that produces a vapor-dominated system.

REFERENCES

Browne, P. R. L., 1970, " Hydrothermal alteration as an aid in investigating geothermal fields", Geothermics Spec. Issue 2: 564-570.

Browne, P. R. L., 1978, "Hydrothermal alteration in active geothermal fields", Ann. Rev. Earth Planet. Sci. 6: 229-250.

Lockner, D. A., Summers, R., Moore, D., and Byerlee, J. D., 1980, "Laboratory measurements of reservoir rock from the Geysers geothermal field, California", in press.

McNitt, J. R., 1964, "Geology of the Geysers thermal area", Proc. U. N. Conf. New Sources Energy 1961 2: 292-301.

Steiner, A., 1958, "Occurrence of wairakite at the Geysers, California", Am. Mineral. 43: 781.

Steiner, A., 1970, "Genesis of hydrothermal K-feldspar (adularia) in an active geothermal environment at Wairakei, New Zealand", Mineral. Mag. 37: 916-922.

White, D. E., 1970, "Geochemistry applied to the discovery, evaluation and exploitation of geothermal energy resources", Geothermics Spec. Issue 2: 58-80.

White, D.E., Muffler, L. P. J., and Truesdell, A. H., 1971, Vapor-dominated hydrothermal systems compared with hot water systems", Econ. Geol. 66: 75-97.

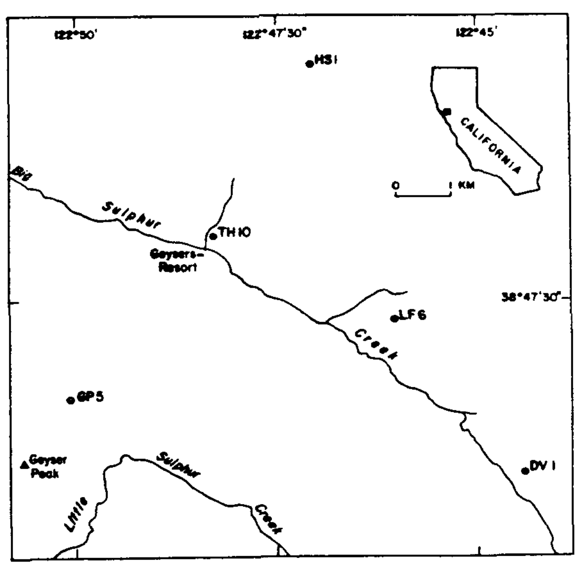

Figure 1.

Sites of wells and sampling areas at The Geysers

Mineral	GP5	HS1-1478M		TH10-100M		LF6 922-927M		LF6 969M		DV1-1260M	
		Rock	Vein	Rock	Vein	Rock	Vein	Rock	Vein	Rock	Vein
Quartz	X	X	X	X	X		X			X	X
Albite	X	X				X	X	X	X	X	
Chlorite	X	X		X	X	X	X	X	X	X	X
White mica	X	X		X	X	X		X	X	X	
Sphene	X	X		X		X		X		X	
Pumpellyite	X	?									
Adularia				X	X		X		X		X
Pyrite			X	X	X		X		X		X
Calcite	X	X	X		X		X				
Prehnite					X						X
Epidote						X	X			X	X
Amphibole							X			X	X
Tourmaline										X	

Table I

Alteration minerals in the various rocks