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THE OCCURRENCE OF ACID-LEACHED GRAYWACKE AT THE GEYSERS, SONOMA COUNTY, CALIFORNIA

Jeffrey Sternfeld and Mark Walters

GEO Operator Corporation
1330 North Dutton Avenue, Suite A
Santa Rosa, CA 95401

ABSTRACT

Acid-leached[1] graywacke has been identified in 15 of 19 GEO wells in the Northwest Geysers. The altered graywacke is characterized by a bleached appearance and a high degree of secondary dissolution porosity/permeability. Minerals deposited in vugs and veins include large (up to 30mm) doubly terminated quartz crystals, bladed calcite, pyrite, pseudohexagonal pyrrhotite, albite, potassium feldspar and kaolinite. Alunite, trace amounts of iron oxides, opaline silica and possibly sulfur are also observed. The dissolution features and the morphologies of the replacement minerals suggest that these rocks were subject to a complex history of boiling and low pH dissolution. The dissolution features include the leaching and replacement of detrital albite and selected matrix phyllosilicates. The acid-leached zones are generally encountered above the steam-bearing reservoir rocks and may represent the shallowest levels of the geothermal system. Examination of older GEO mudlogs and publically available data indicate that similar zones are present throughout The Geysers field.

INTRODUCTION

An abundant number of doubly terminated quartz crystals, approximately 2 mm. long, were encountered in mud drilled samples over several 3-9 m. intervals in GEO Operator's Prati 1 well in 1981. Because these crystals were unattached to any rock matrix, their origin was unknown at that time. In subsequently drilled GEO wells, various combinations of: large clear euhedral quartz crystals

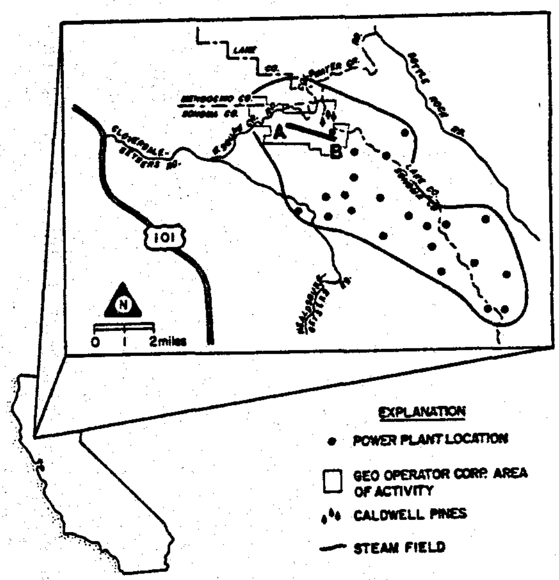

Figure 1: Map of The Geysers with location of cross section (A-B) of Figure 2.

(up to 30 mm. in length); pseudohexagonal pyrrhotite and euhedral calcite and quartz; bleached graywacke and quartz; and clear calcite and euhedral quartz, were observed in drill samples from many of GEO's steam wells in the Northwest Geysers. Because the samples of these materials were small fragments and constituted only a relatively small percentage of rotary drill cuttings, a hypothesis for a common origin was not made. Then in 1988, GEO blew a partially bridged well to the atmosphere to clean it out. Among the ejecta from the well were about 8 kgs. of white, bleached graywacke fragments up to 5 cm. across, composed primarily of euhedral quartz, white clay, bladed calcite, sulfides including pyrite and pyrrhotite and bleached graywacke with dissolution cavities. Because the location of the bridge was known

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[1] Used here to describe observed dissolution textures. Term is not analogous to acid-sulfate alteration.

approximately, the position of the bleached graywacke in the wellbore was determined to be at a depth of approximately 1,260 m. and correlated with an increase in drilling penetration rate. We have identified similarly altered rocks in other wells using the following criteria:

- abundant euhedral quartz, sometimes doubly terminated
- a bleached appearance to the graywacke
- clear, euhedral calcite
- lost circulation zones
- increased drilling penetration rates
- occurrence near or above the top of the steam reservoir.

It was determined that 15 of GEO's 19 wells encountered acid-leached graywacke. Laboratory studies were subsequently made to determine the characteristics of this rock. This paper reports the preliminary results of that work.

As Figure 2 shows, the acid-leached graywacke is discontinuously encountered above steam-bearing rocks in geothermal wells in the Northwest Geysers. Although the geothermal system vents at the surface in the central and southeast portions of The Geysers steam field, there are few surficial hydrothermal manifestations in the Northwest Geysers (Walters et al, 1988). It is worthwhile to note that the shallowest occurrences of acid-leached graywacke shown in Figure 2 also are in close proximity to the few weak surficial manifestations in the Northwest Geysers.

Mineralogy

The acid-leached graywacke ejected from the well has a light gray to bleached white appearance with a highly porous sponge-like texture. Relict sedimentary textures and structures are poorly preserved or absent. Veinlets and veins up to 4 mm. across and irregular cavities up

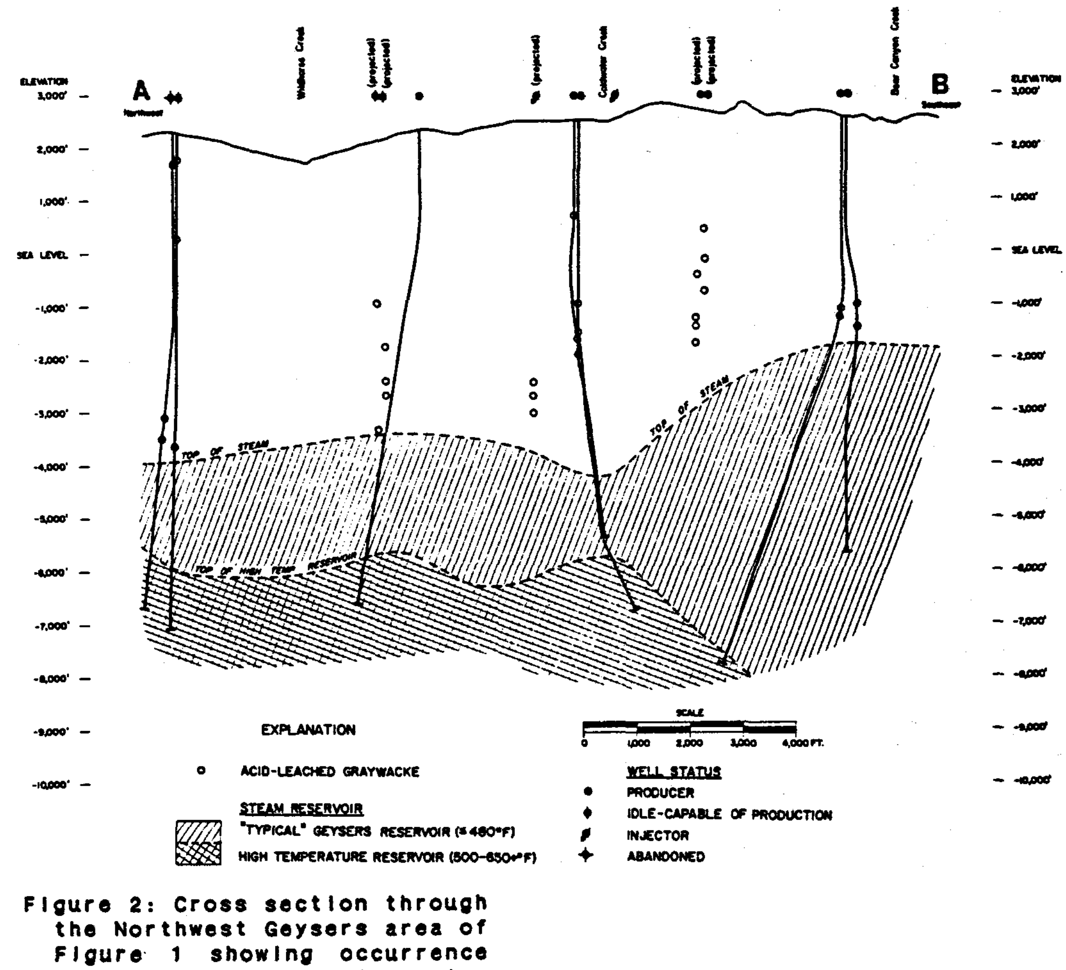

Figure 2: Cross section through the Northwest Geysers area of Figure 1 showing occurrence of acid-leached rocks relative to the steam reservoir.

to 5 mm. are common. The cavities and open fractures are ubiquitously lined with very fine to millimeter-sized quartz crystals and often infilled with other minerals including calcite, pyrite and pyrrhotite. There is also evidence for brecciation and cementation of rotated graywacke fragments.

The characteristic fracture-fill mineral assemblages consist of colorless euhedral and traces of doubly terminated quartz crystals ranging in size from <.1 mm. to 25 mm. in length; subordinant amounts of massive white quartz; bladed to rhombohedral white to colorless calcite crystals (up to 1.5 mm.) and crystal aggregates; disseminated pyrite cubes (<.05 mm.) and pyrite aggregates up to 3 mm. in length; and pseudohexagonal crystals of pyrrhotite up to 1.0 mm. in size. There are also minor amounts of soft, powdery, white to bluish white, very finely granular mineral(s). This material lacks crystalline geometries under the binocular stereoscope and locally forms botryoidal masses. XRD analyses of the powdery material indicate the presence of albite, potassium feldspar and kaolinite. Trace amounts of reddish brown iron oxides and a yellowish granular material, possibly sulfur or jarosite, are also observed.

In order to study the alteration characteristics of acid-leached graywacke, several pieces of the well ejecta, as well as graywacke cuttings ("GW" of Table I) originating approximately 75 m. above the estimated depth of the ejected material, were studied using whole rock geochemical analysis, X-ray diffraction analysis and petrographic analysis.

The samples of altered graywacke referenced in Table I are: A-1, altered material with no visible veining or dissolution features but with recognizable sedimentary textures; A-2, altered graywacke with abundant quartz crystals; A-3, altered graywacke with abundant calcite and quartz crystals; and A-4, altered graywacke with significant amounts of the white granular material.

Sample "GW" is typical of the graywackes from the Northwest Geysers. It is a medium dark greenish gray, weakly metamorphosed, textural type 1.0 graywacke. It is composed (see Table 1) of quartz, plagioclase, chlorite, illite (with a broad 100% peak indicative of some mixed montmorillonite layers) and traces of montmorillonite. In thin section, framework grains of quartz, twinned albite and lithic fragments (argillite, chert, greenstone) with trace amounts of detrital epidote, muscovite, biotite and sphene are observed in a heterogeneous matrix of phyllosilicate cements, chlorite, phengite and incompetent deformed grains of claystone. Grain boundaries in the graywacke are sharp and well defined. The Franciscan metamorphic minerals consist of minor pumpellyite after plagioclase and incipient lawsonite in the matrix.

Petrographic observations of the altered graywacke reveal a pervasive silicic replacement and recrystallization of the original graywacke. The altered material is composed of microcrystalline to subhedral prismatic quartz grains surrounded by a relatively homogeneous fine-grained matrix of sericite and chlorite, with sporadic disseminated cubic pyrite. Relict quartz grains, when present, display embayed or corroded, pitted boundaries and lithic grains are typically rounded and partially replaced. Plagioclase grains are totally absent.

The bulk of the altered graywacke has a web texture of small (<0.1 mm. to 0.5 mm.) irregular quartz blebs in a matrix of fibrous to scaly, fine-grained sericite and chlorite. Near large mineralized veins, open fractures and cavities, the material develops a coarser (0.1 to 1.0 mm.) decussate texture of subidioblastic prismatic quartz crystals with minor amounts of interstitial fibrous sericite and trace amounts of chlorite. Less commonly, irregular patches of calcite are also observed intergrown with, or replacing, the sericitic matrix.

XRD-derived mineralogies (see Table 1) support the thin section observations. The altered material is composed chiefly of quartz and sericite (micaceous illite with an extremely strong 8.8° 2θ peak) with trace to minor amounts of chlorite and pyrite. Plagioclase and smectite are absent and the relative percentage of chlorite is lower compared to the unaltered graywacke. It should be noted that in sample A-4, the observed white granular material proved to be authigenic albite and alkali feldspar. However, in samples A-2 and A-3 kaolinite and alunite were identified.

TABLE I

XRD MINERALOGY

Semi-quantitative Analyses in Weight Percent

	GW	A-1	A-2	A-3	A-4
Quartz	55.0	77.0	85.9	87.4	73.7
Plagioclase[1]	29.0				3.4
Chlorite	6.2	7.1	4.0	1.7	4.0
Illite	4.3				
Sericite[2]		12.8	7.5	2.3	6.9
Calcite	4.3			5.3	1.3
Pyrite		1.3	1.7	2.7	3.7
Alkali Feldspar		1.9			2.0
Kaolinite			1.0	0.8	
Alunite (?)			Tr.		
Pyrrhotite				Tr.	

1 Albite
2 Micaceous illite

GW Typical Graywacke
A-1 Altered Graywacke
A-2 Altered Graywacke with drusy quartz
A-3 Altered Graywacke with drusy calcite
A-4 Altered Graywacke with white material

Albite, alkali-feldspar and kaolinite could not be petrographically identified. There were localized concentrations of a fine-grained, mosaic silicate mineral but it was not possible to identify it as feldspar or quartz. Trace amounts of a colorless to pale green, fibrous to scaly, very fine-grained phyllosilicate mineral were observed coating some quartz crystals and infilling the interstitial spaces between quartz and calcite crystals, but it was not possible to optically identify this material as kaolinite, sericite or chlorite.

Geochemistry

Comparisons between the whole rock geochemical values for unaltered and altered graywackes are presented in Figure 3. The plots clearly illustrate the selective leaching of plagioclase, smectite clays and clorite, and the introduction of silica and sulfur. Sodium (Na) found primarily in plagioclase is virtually absent in the altered material. Calcium (Ca) and strontium (Sr) are also severely depleted, probably as a result of the dissolution of pre-existing calcite veins and secondarily due to the destruction of pre-existing smectite clays. Additional evidence for the dissolution of the matrix chlorites and clays is exhibited by the depletion of iron (Fe), magnesium (Mg), manganese (Mn) and titanium (Ti).

The differences in the degree of alteration and recrystallization between samples A-1 and A-2 are reflected in their chemical characteristics. Sample A-1, which is only moderately altered and contains less secondary quartz and more secondary sericite than A-2, exhibits increased values of potassium (K), aluminum (Al) and titanium (Ti), and small decreases in Fe, Mg and Mn. Silica (Si) remains unchanged. Sample A-2, which is predominated by drusy quartz and contains smaller volumes of sericite and chlorite than A-1, exhibits a strong increase in Si, unchanged K, and strong depletions of Al, Fe, Mg, Mn and Ti.

Fluid Inclusions Geothermometry

Quartz and calcite crystals from the altered ejecta graywacke as well as

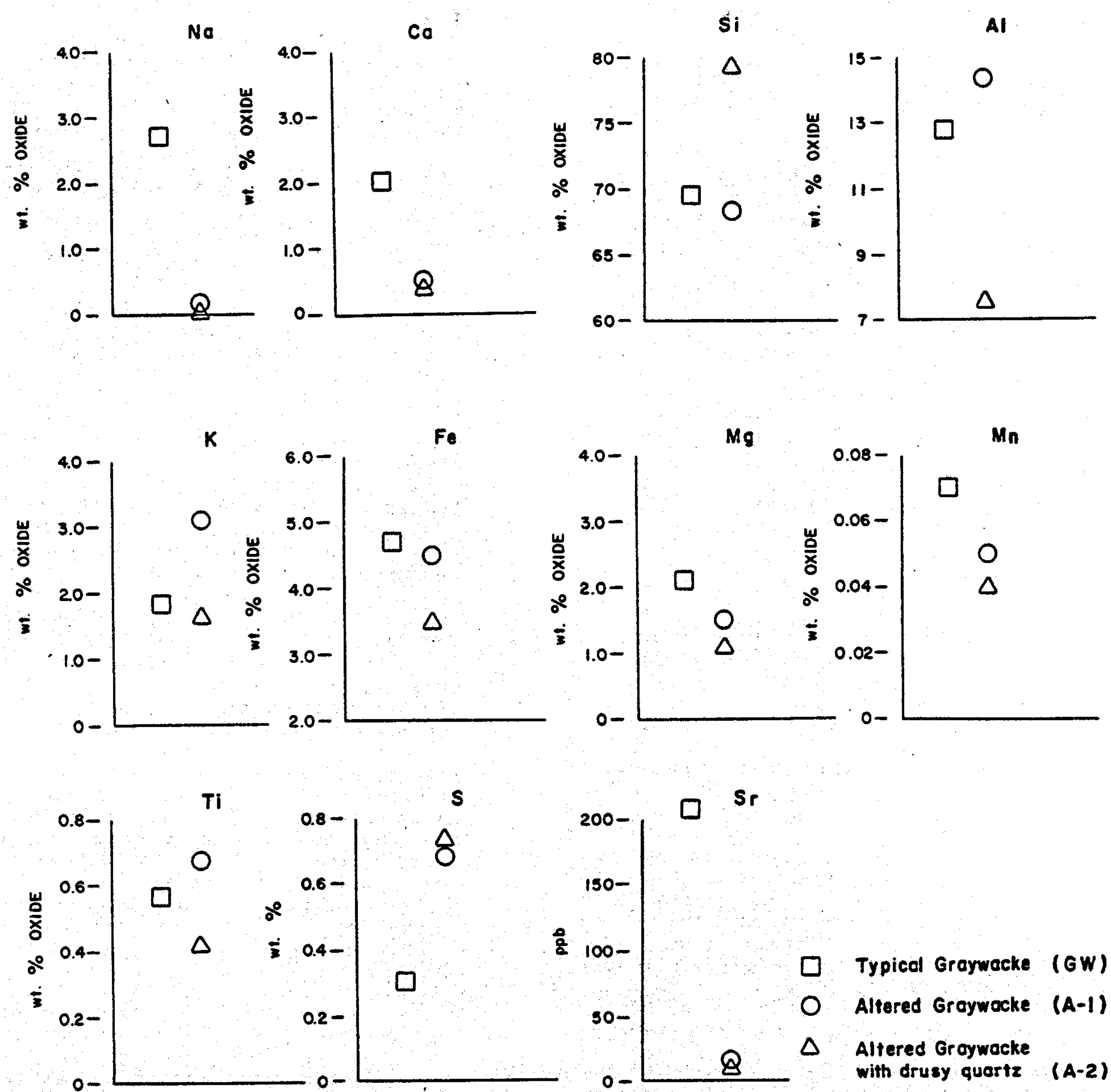

Figure 3: Whole rock geochemical compositions of altered graywacke and unaltered graywacke.

crystals from acid-leached graywacke zones in two other wells were analyzed. However, only preliminary results are available at this time. Vapor-filled inclusions associated with both primary and secondary liquid-rich inclusions were identified in some of the euhedral quartz crystals. Although no data on vapor-rich inclusions were obtained, petrographic relationships suggest that the vapor and liquid-rich inclusions were deposited as a result of boiling.

The homogenization and ice melting temperatures of liquid-rich inclusions vary widely but tend to plot into two distinctive groupings. One group, composed of primary and secondary inclusions from quartz and calcite, has homogenization temperatures that range between 280° to 320°C but have highly variable ice melting temperatures. These ice melting temperatures range from -2.4°C to -0.2°C which correspond to apparent salinities of 2.7 to 0.4 wt.% NaCl equivalent. The second group, composed of secondary inclusions from quartz, are tightly clustered with homogenization temperatures of 230 to 240°C and ice melting temperatures of -0.1 to -0.4°C.

The fluid inclusions may represent different generations of fluids in the reservoir. Another possibility is that these inclusions are related to subsurface boiling. The 280-320°C temperatures approach the boiling point curve for low saline waters at the depths that these crystals originated (Haas, 1971) and the 230-240°C correspond to the predicted temperatures at depth in a 2-phase vapor-dominated reservoir (White et al., 1971). The variation in the apparent salinities of the high temperature group could be a function of fluctuating CO_2 levels in a boiling environment (Moore, J., verbal communication).

Conclusions

The acid-leached graywacke encountered in the GEO Northwest Geysers steamfield is a product of complex alteration processes. The graywacke displays a unique bleached appearance, and a cellular texture with abundant dissolution features. It is composed of a unique silica+sericite+chlorite matrix which has replaced pre-existing plagioclase grains and matrix illites and chlorites. Infilling the open spaces in the bleached graywacke is an assemblage of quartz+sericite+calcite+pyrite+pyrrhotite with trace amounts of authigenic albite, alkali feldspar, kaolinite and alunite.

The assemblage of pore-filling minerals is similar to the adularia-sericite-type of epithermal ore deposits which are formed by the interaction of hot neutral pH chloride waters with meteoric waters (Heald et al., 1987). However, the observed bleached appearance, the dissolution textures, the leaching of plagioclase and the presence of alunite and kaolinite must have been caused by acidic conditions. The open cavities and pore spaces existed before the precipitation of the sericite-andularia-type minerals which are indicative of neutral pH waters. The logical source of the acidic fluids is the condensation of volatiles, primarily H_2S and CO_2, released through boiling at depth. Evidence for subsurface boiling can be found in the fluid inclusion homogenization temperatures and their variable ice melting temperatures.

Thus, we have the situation where low pH fluids, generated from boiling fluids at depth, altered the graywacke. Subsequently, the pore spaces were filled by boiling neutral pH fluids. Finally, the traces of kaolinite and alunite indicate that low pH conditions returned to the fracture network after the neutral waters had boiled away.

The altered graywackes with dissolution features and evidence for boiling represent the highest elevations reached by geothermal fluids. The fluids subsequently began to boil down toward present day reservoir levels. The distribution of altered graywacke lies above, or within the upper levels of the typical Geysers steam reservoir (see Figure 2). To date, no occurrences of bleached graywacke have been identified within the lower portions of the typical steam reservoir nor within the high temperature (650°F) reservoir (Walters et al., 1988). However, trace amounts of calcite with pyrrhotite inclusions have been observed in the typical reservoir especially where clusters of entries are separated by barren intervals hundreds of feet thick.

There is evidence in the public domain that indicates to us that rocks affected by dissolution and/or boiling may occur throughout The Geysers steamfield. Although we have not inspected the rocks, some or all of our criteria for acid-leached rocks appear to be met in the following Geysers wells outside of GEO Operator leases:

1. The drilling of the Ottoboni State 2, 6, and 13 wells in the Northwest Geysers produced notable occurrences of euhedral quartz crystals according to mudlogs on file with the California Division of Oil and Gas (D.O.G.). The quartz crystals for Ottoboni State 13 were described as being doubly terminated.

2. Moore (1980) describes a core from Thermal 10 in The Geysers Resort area which closely fits the mineralogical and chemical criteria for acid-leached rocks we have studied in the Northwest Geysers. Moore attributes "Boiling and subsequent loss of CO_2...in the deposition of calcite, quartz and adularia..."

3. A core report on open file with the D.O.G. for the Lakoma Fame - 6 well in the Central Geysers describes a very permeable and vugular greenstone with calcite veins and quartz crystals up to 25 mm. in length.

4. W.T. Box (Verbal Communication) reports that veins in graywacke with dissolution features are also present in wells in the Southeast Geysers.

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XRD patterns were made by Utah Research Institute (UURI). Fluid inclusion microthermometry was conducted by Dr. Joe Moore and Michele Lemieux of UURI.

References

Haas, J.L., 1971, The Effect of Salinity on Maximum Thermal Gradient of a Hydrothermal System at Hydrostatic Pressure. Econ. Geol., v.66, pp.940-946.

Heald, P., Foley, N.K., and Hayba, D.O., 1987, Comparative Anatomy of Volcanic-Hosted Epithermal Deposits: Acid-Sulfate and Adularia-Sericite Types. Econ. Geol., v.82, pp. 1-26.

Moore, D., 1980, Hydrothermal Minerals in The Geysers Steam Field, California and their Potential Use in Exploration. Proceedings of the Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, pp.361-366.

Walters, M.A., Sternfeld, J.N., Haizlip, J.R., Drenick, A.F., Combs, J., 1988, A Vapor-Dominated Reservoir Exceeding 600°F. at The Geysers, Sonoma County, CA. Proceedings of the Thirteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA., in press.

White, D.E., Muffler, L.J.P., Truesdell, A.H., 1971, Vapor-Dominated Hydrothermal Systems Compared to Hot-Water Systems. Econ. Geol., v.66, pp. 75-97.