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STRATIGRAPHY AND HYDROTHERMAL ALTERATION IN WELL BACA-8, SULPHUR SPRINGS AREA, VALLES CALDERA, NEW MEXICO

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ABSTRACT

Union Oil Company borehole Baca-8 (B-8) is a 1336 m geothermal well in the Sulphur Springs area, near the western "hinge" of the trapdoor Valles-Toledo caldera complex. B-8 penetrates essentially the same Pleistocene intracaldera rhyolite ash-flow tuff sequence as the wells along Redondo Creek, on the Valles caldera's resurgent dome; the sequence in B-8, however, is only about half as thick. Alteration zoning in B-8 is characterized by a mixed-layer illite/smectite cap above an illite zone in turn overlying a K-feldspar + epidote zone. Comparison of these assemblages with contemporary temperatures in the well suggests that the rocks of Sulphur Springs have undergone a more complex thermal history than those of Redondo Creek, and that fluids responsible for alteration in the two areas were of different compositions.

INTRODUCTION

Well B-8, completed in 1972 by Union Oil Company of California, is one of five intermediate-depth geothermal wells in the Sulphur Springs area of the Valles caldera (Fig. 1). Sulphur Springs is the locus for the caldera's most vigorous surface thermal activity and strongest surficial alteration. It is also one of two areas of highest heat flow within the caldera (Swanberg, 1983). Alteration at Sulphur Springs is typical of that produced by acid-sulfate springs and is believed to overlie a small vapor-dominated geothermal reservoir (Goff and Grigsby, 1982; Goff et al., 1985). This reservoir has been targeted for the second Continental Scientific Drilling Program corehole, VC-2a (Fig. 1; Nielson and Goff, 1985), as a followup to the successful completion of VC-1, near the caldera's southwestern ring fracture (Goff et al., 1986).

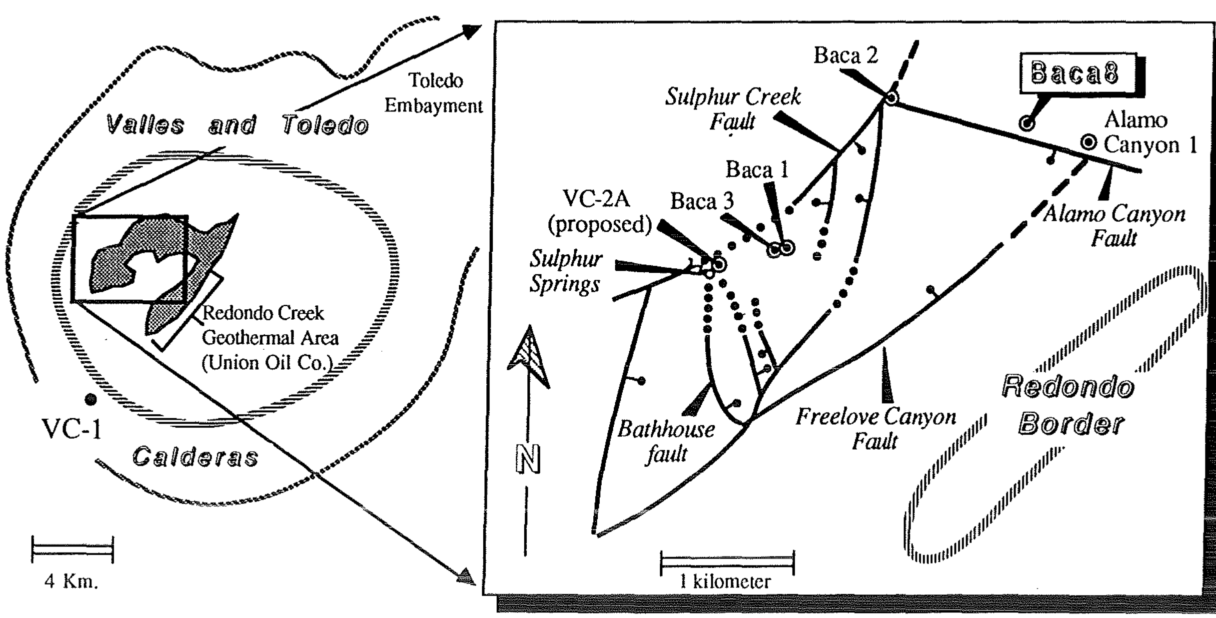

Figure 1. Index map (modified from Goff et al., 1985). Heavy hatched line at left is structural margin of Valles caldera. Stippled area denotes extent of active or recent surficial alteration (from Dondanville, 1978).

B-8, which was drilled to a depth of 1336 m, is the only Sulphur Springs area well for which cuttings remain available for study. The well thus provides a unique preview of the subsurface volcanic stratigraphy and hydrothermal alteration to be sampled by VC-2a. In this paper, we briefly describe the sequence of volcanic and volcaniclastic rocks penetrated by B-8, characterize the style and intensity of hydrothermal alteration affecting these rocks, and compare the altered rocks to those of the Redondo Creek area. Finally, we will show how the active Sulphur Springs hydrothermal system parallels those responsible for depositing epithermal silver-base metal ores even more closely than does the silver-bearing system beneath Redondo Creek (Hulen and Nielson, 1986). Such fossil hydrothermal systems can be of great benefit to the geothermal community as observable analogues of presently active systems.

LITHOLOGY AND STRUCTURE

Deep drilling and gravity signatures indicate that the Valles-Toledo caldera complex is a trapdoor structure, with its "hinge" on the west and deepest subsidence along the eastern margin (Nielson and Hulen, 1984; Heiken et al., 1986). Accordingly, the intracaldera volcanic and volcaniclastic sequence in the Sulphur Springs area is only about half as thick (1000 m) as the equivalent accumulation at Redondo Creek (Table 1 of Nielson and Hulen, 1984). Although all the major pyroclastic units recognized at Redondo Creek are also present in well B-8, their reduced thicknesses have resulted in differences in the degree of welding and devitrification. Pre-caldera stratigraphy at Sulphur Springs is also different; the Miocene Paliza Canyon Formation, an intermediate-composition volcanic sequence up to 377 m thick at Redondo Creek (Nielson and Hulen, 1984) is absent in B-8 and the other Sulphur Springs wells (Goff et al., 1985).

Well B-8 penetrates caldera-fill sediments, including a probable debris flow, to a depth of 177 m (Fig. 2). The sediments are dominantly immature, tuffaceous, lithic arkoses and arkosic conglomerates derived from intracaldera pyroclastic and flow rocks with minor contributions from Tertiary to Paleozoic clastic and carbonate strata as well as the Precambrian granitic basement. The debris flow, between 73 and 104 m, consists of angular to subangular fragments of andesite and minor felsic volcanic and carbonate rock as well as broken crystals of quartz, alkali feldspar and plagioclase in an altered, tuffaceous matrix.

Beneath the caldera fill sequence, between 177 and 500 m, B-8 encountered moderately to densely welded, rhyolite ash-flow tuff which we believe to be the "Upper Tuffs" and the Tshirege Member of the Bandelier Tuff. In B-8, as in Redondo Creek wells, these tuffs consist of subhedral to euhedral or broken phenocrysts of quartz, microperthite and minor plagioclase, along with sparse lithic fragments and pumice lapilli, embedded in welded, totally devitrified matrix. Former mafic phenocrysts are present in trace amounts only as pseudomorphs. A zone of granophyric crystallization, texturally identical to the Bandelier Tuff granophyres of Redondo Creek (Nielson and Hulen, 1984), occurs between 427 and 488 m. A 14.3 m zone of moderate welding separates this granophyre from an 8.2 m tuffaceous lithic arkose we have correlated with the S_3 sandstone of Redondo Creek (Nielson and Hulen, 1984).

Scattered throughout the "Upper Tuffs" and the Tshirege Member in borehole B-8, but concentrated below 427 m, are abundant vugs lined or filled with relatively coarse-crystalline quartz, alkali feldspar and rare albite. These vugs, also common in the Redondo Creek Tshirege, are similar to those described by Keith and Muffler (1978) in the Lava Creek Tuff of Yellowstone drill hole Y-5, and are similar to the miarolitic cavities of plutonic rocks.

Another rhyolite ash-flow tuff, densely welded throughout and texturally identical to the Tshirege of well B-8, occurs beneath the S_3 sandstone between 510 and 817 m (Fig. 2), and probably represents the Otowi Member of the Bandelier Tuff. Microperthite phenocrysts in this tuff contain less albite and correspondingly more alkali feldspar than those in the overlying Tshirege. Alkali feldspar-quartz filled vugs remain a common feature. Granophyric crystallization is confined to the upper portion of the B-8 Otowi, between 510 and 640 m, and to a thin basal zone between about 777 and 817 m.

A pronounced cooling break at 817 m separates the lower Otowi granophyre in B-8 from a distinctive 134 m interval of poorly to densely welded, rhyolite ash-flow tuff, which we have correlated with the Lower Tuffs of Redondo Creek (Nielson and Hulen, 1984) and the pre-Bandelier ignimbrite of Self et al. (1986). This tuff is similar to the overlying Bandelier, but contains no obvious microperthite phenocrysts. Feldspar phenocrysts instead are essentially pure alkali feldspar; only scattered traces of albite are present. Vugs texturally similar to those in the overlying Bandelier are common throughout this tuff. Quartz and alkali feldspar crystals lining or filling these vugs, however, may be of both vapor-phase and hydrothermal origin.

Beneath the Lower Tuffs in borehole B-8, between 951 m and 1091 m, is an arkose identified by Lambert and Epstein (1980) as the Tertiary Santa Fe Formation. The Santa Fe, in turn, overlies hematitic siltstones and sandstones of the Permian Abo Formation to the total depth of the borehole at 1336 m.

B-8 is situated just 100 m north of the west-northwest-trending Alamo Canyon fault zone (Fig. 1). Not surprisingly, then, cuttings from several intervals in the well, for example 610-640 m, show evidence of strong fracturing and

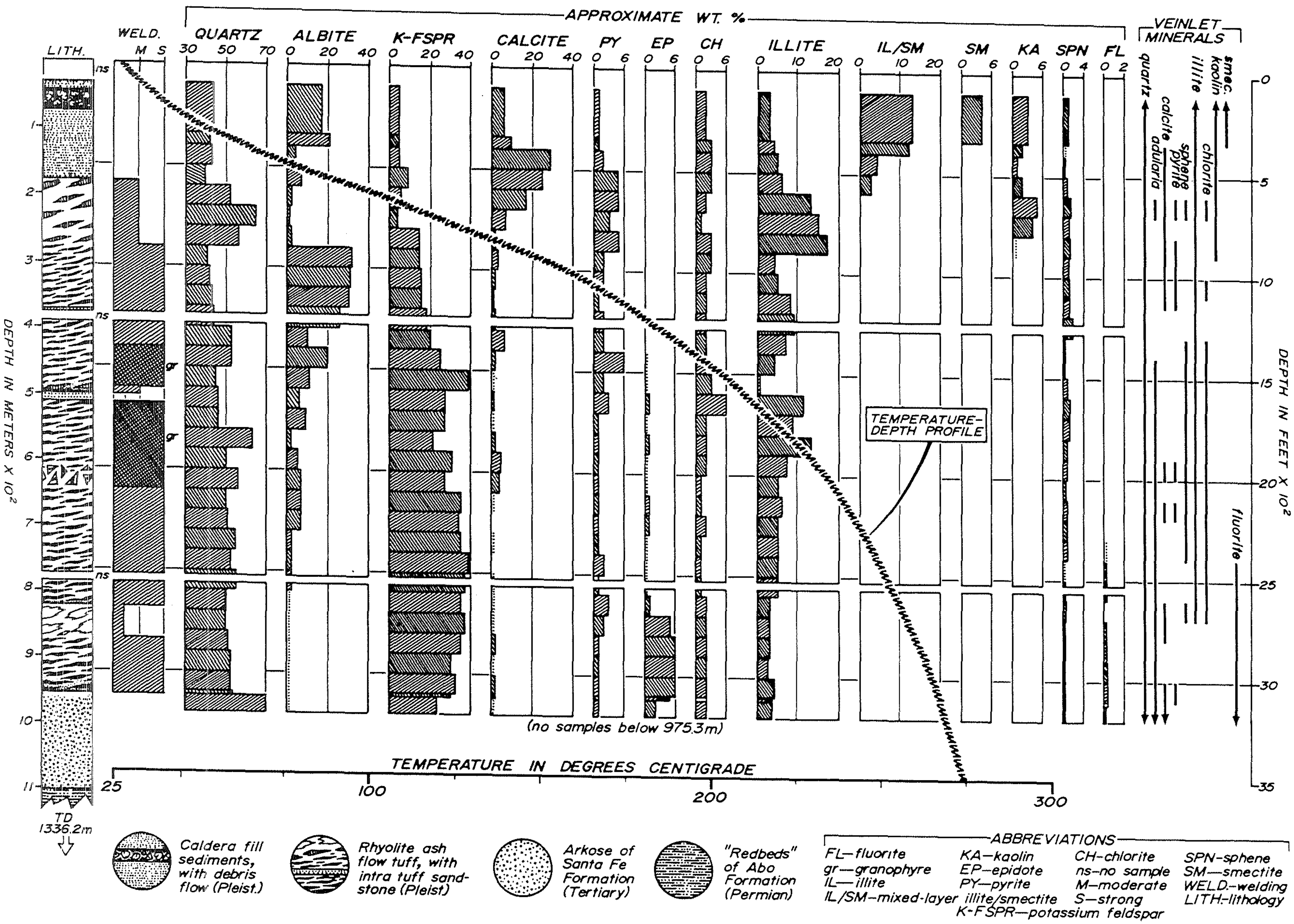

Figure 2. Lithology and distribution of rock-forming and hydrothermal alteration minerals, borehole B-8.

brecciation. Proximity to the Alamo Canyon fault no doubt is largely responsible for the pervasive and locally intense hydrothermal alteration observed in well B-8.

HYDROTHERMAL ALTERATION AND MINERALIZATION

The rocks penetrated by borehole B-8 have been pervasively altered and mineralized by circulating hydrothermal fluids. Alteration assemblages are distinctly zoned but some of the B-8 assemblages are much different than those of Redondo Creek (Hulen and Nielson, 1986), suggesting different physical and chemical characteristics of the fluids responsible for the alteration.

We have divided the hydrothermal assemblages of B-8 into three zones: illite/smectite, illite, and K-feldspar + epidote. The high-level smectite-rich argillic zone so prevalent in the Redondo Creek wells (Hulen and Nielson, 1986) is absent in B-8. In its place, to a depth of 183 m, is an illite/smectite zone dominated by ordered, mixed-layer illite/smectite and illite with calcite and pyrite as well as minor sphene, chlorite, kaolin and, confined to 30-104 m, calcium smectite. The illite/smectite is Kalkberg-ordered (Hower, 1981) with 10-15% smectite interlayers, a type common in the argillic cap above epithermal silver/base-metal deposits such as Creede, Colorado (Horton, 1983). All layer silicates in the illite/smectite zone of B-8 occur both as massive replacements and subordinately as veinlets. Kaolin and smectite veinlets post-date all others, and are thus probably related to a late retrograde episode perhaps associated with a drop in the water table and the initiation of acid-sulfate alteration, as was described in the immediate vicinity of Sulphur Springs by Charles et al. (1986). Secondary calcite is common as a veinlet constituent, and also forms cement in caldera-fill sandstones, as well as replacing plagioclase and pumice lapilli. Pyrite is principally disseminated.

The deepest occurrence of mixed-layer illite/ smectite and an increase in illite abundance marks the upper boundary of the illite zone at 183 m, corresponding to a present temperature of about 100°C (Fig. 2). Illite, accounting for up to 20 wt.% in this zone, typically replaces plagioclase and pumice lapilli but also occurs as microveinlets and sparse disseminations throughout tuff or sandstone matrix. Hydrothermal phases occurring with illite in this zone include quartz and calcite with minor chlorite, kaolin (above 274 m), and sphene. A dramatic decrease in the volume of illite at 274 m coincides with the onset of dense welding in the Tshirege member.

The K-feldspar + epidote zone is defined by the distribution of K-feldspar veinlets and disseminated epidote and is continuous between 427 m and the deepest available sample at 975 m (Fig. 2). Within this zone, hydrothermal K-feldspar (adularia) typically occurs as small euhedral crystals intergrown with quartz in veinlets and possibly in vugs; it may also replace albite, which gradually diminishes downhole in this interval from about 30 to 2 wt %. In many cases, hydrothermal adularia and quartz in cavities may be petrographically indistinguishable from primary miarolitic alkali feldspar and quartz deposited late in the cooling history of the host ash-flow tuff. Minor hydrothermal pyrite, sphene (leucoxene), chlorite and illite invariably accompany quartz and adularia throughout this interval. Between 640 and 670 m, immediately beneath a major breccia zone (Fig. 2), illite prominently floods open spaces in veinlets and miarolitic cavities. Calcite occurs in scattered trace to minor amounts in the K-feldspar + epidote zone; fluorite appears in traces below 701 m, above a present temperature of 245°C.

The Lower Tuffs (817-951 m) and at least the upper 24 m of the underlying Santa Fe Formation sandstone (our deepest sample) in B-8 are especially enriched in adularia and epidote. Epidote, increasing in this interval to an average 6 wt %, is a bright yellow to yellow green variety which commonly forms spectacular, acicular crystal clusters in vugs with quartz and alkali feldspar. Adularia and quartz are texturally similar to their occurrence in the overlying Bandelier. Fluorite is present as sparse disseminations and as a veinlet constituent with quartz, alkali feldspar and calcite in various combinations. Epidote appears to be one of the latest hydrothermal phase in this lower part of the hole. It replaces all other minerals except fluorite (which, however, was probably deposited with adularia), including vein calcite, in which it forms large euhedral fans and rosettes.

Although pyrite is the dominant hydrothermal metallic phase in borehole B-8, unidentified, dark gray, metallic minerals occur locally in traces with quartz and adularia in veinlets. Energy dispersive SEM analysis of one such dark crystal, from 945-975 m, yielded strong peaks corresponding with silver and bromine. This would certainly be an unusual occurrence, since the silver bromide, bromyrite, is typically found in the oxide zone. Electron microprobe and single-crystal X-ray studies are scheduled to further characterize this intriguing silver-bearing mineral.

DISCUSSION

A generalized mineral stability diagram (Fig. 3) prepared using compositions of fluids from the Redondo Creek area (White, 1986) can be used to draw some preliminary conclusions concerning the composition of the geothermal fluids in the Sulphur Springs area. The coexistence of epidote and K-feldspar suggests that compositions are approximated by the zoisite-K feldspar reaction line in Figure 3. Compositions of Redondo Creek fluids are plotted on Figure 3 for reference, and we can see that the Sulphur Springs fluids should have higher relative activities of potassium and calcium than do fluids in the Redondo Creek area. In addition, it can be seen that a simple decrease in temperature is not sufficient to result in the deposition of the late-stage illite which we observe. It is necessary to change the fluid composition, most likely by decreasing the pH. This would bring the fluid compositions more in line with those presently circulating beneath the Redondo Creek area.

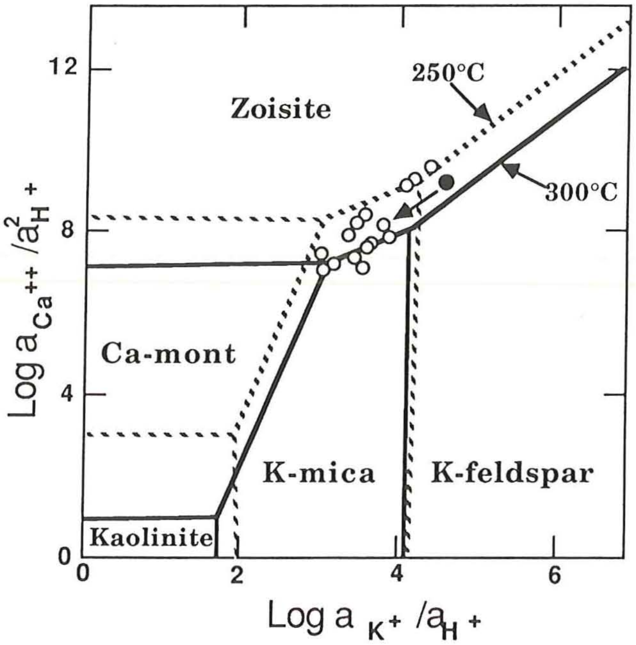

Figure 3. Activity-activity diagram showing compositions (open circles) of reservoir fluids from the Redondo Creek area (White, 1986) and suggested composition and chemical change of fluids from Sulphur Springs (solid dot and arrow).

The initial occurrence of epidote in B-8 is in the 427-457 m interval at a present temperature of 190°C. This compares with a first occurrence of epidote at 170°C in wells of the Redondo Creek area (Hulen and Nielson, 1986). The lower temperature Redondo Creek occurrence contributed to the conclusion that the area had cooled from a previous thermal maximum. The epidote in B-8 appears within microperthites growing along exsolution planes. This textural relationship suggests a reaction with the feldspar probably involving the anorthite component of the plagioclase in such a reaction as

$$CaAl_2Si_2O_8 + Ca^{++} + Fe^{+++} + SiO_2 + 3H_2O \rightarrow Ca_2FeAl_2Si_3O_{12}(OH) + 5H^+$$

(Bird and Helgeson, 1981). However, the greatest increase in epidote abundance in B-8 occurs in the depth range 823-853 m, associated with a present temperature of 257-259°C. Some of the epidote at this depth clearly replaces K-feldspar. However, much is growing in the matrix of the ash-flow tuff which, assuming the Lower Tuffs of B-8 are similar to those of the Redondo Creek area, initially consisted of both K-feldspar and albite.

Browne's (1978) compilation of hydrothermal minerals in active geothermal systems lists fluorite from only two studied systems, Yellowstone and Kawah Kamojang, Java. The mineral is common, however, in precious metal vein deposits associated with volcanic environments. Richardson and Holland (1979) suggest that a decrease in solubility associated with cooling may be the most likely cause for the deposition of fluorite. However, small changes in salinity, pH, or Ca^{++} may also bring about fluorite precipitation.

SUMMARY AND CONCLUSIONS

The intracaldera pyroclastic sequence penetrated in well B-8 contains all the major units recognized nearer the center of the Valles caldera's resurgent dome. Although the sequence is much thinner in B-8, the individual strata can be correlated readily with counterparts in the dome. This correlation should allow more detailed reconstruction of the geologic history of the Valles caldera complex.

The rocks penetrated by B-8 are more intensely altered than all but restricted intervals in the wells completed by Union Oil Company at Redondo Creek (Hulen and Nielson, 1986). Alteration mineralogy and zoning in B-8, although broadly similar to that documented for the Redondo Creek area, show significant differences. Most importantly, adularia, lacking at Redondo Creek, is an abundant alteration mineral in B-8. Also significant: the smectite-dominated argillic zone of Redondo Creek is replaced in B-8 by a mixed-layer illite/smectite cap which is practically devoid of discrete smectite. At Redondo Creek, most alteration phases are present at much lower than their typical formation temperatures (Hulen and Nielson, 1986), suggesting cooling of the host rocks since their deposition. In B-8, while some alteration phases (such as mixed-layer illite/smectite) show this relationship, others (such as epidote) are largely confined to their typical thermal stability ranges. A more complex thermal history has likely affected the rocks of the Sulphur Springs area.

The altered rocks of borehole B-8 resemble those of silver-base metal ore systems such as Creede, Colorado (Barton et al., 1982; Wetlaufer et al., 1978), even more than do those of Redondo Creek. Although the Redondo Creek rocks show an impressive array of parallels with Creede-type systems (Hulen and Nielson, 1986), the adularia typical of the ore-bearing portions of these systems has not been identified. By contrast, adularia is abundant in B-8. The well displays Creede-type alteration complete even to a cap rich in highly ordered mixed-layer illite/smectite (Horton, 1983). We have not identified in B-8 the silver-bearing sulfides or sulfosalts typical of silver-base metal systems, but silver-rich minerals yet to be fully characterized are present in the borehole. Evidence continues to accumulate that the geothermal system in the Valles caldera is an active analogue of those responsible for depositing epithermal silver-base metal ores.

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