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CLAY MINERALOGY AND ZONING IN CSDP COREHOLE VC-2A: FURTHER EVIDENCE FOR COLLAPSE OF ISOTHERMS IN THE VALLES CALDERA

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ABSTRACT

Phyllic alteration in CSDP corehole VC-2A shows that a relatively cool, vapor-dominated zone above a depth of 240 m evolved from a high-temperature, liquid-dominated precursor. Sericite geothermometry indicates that temperatures near 200°C once prevailed near the present surface where temperatures are now below 80°C. Measured temperatures gradually approach but never reach paleotemperatures (212°C vs. approx. 230°C) in a deeper chlorite/sericite zone (163-528 m/TD). Alteration in other Valles boreholes indicates a caldera-wide cooling trend similar to that documented for VC-2A. Textural evidence from the VC-2A core shows that phyllic alteration post-dated or accompanied the waning stages of resurgent doming (at about 1.12 - app. 1 Ma). Collapse of isotherms was probably initiated by draining of a contemporaneous caldera lake after resurgence was complete.

INTRODUCTION

Acid springs, boiling mud pots, and fumaroles at Sulphur Springs, in the Valles caldera of New Mexico (Fig. 1) are the most active and intense surface expressions of intracaldera geothermal activity. Because of these thermal phenomena and associated surficial alteration, Sulphur Springs was chosen as the site of the caldera's second Continental Scientific Drilling Program (CSDP) corehole, VC-2A (Goff et al., 1987). The principal objective in drilling VC-2A was penetration and sampling of the high-level vapor cap beneath Sulphur Springs. Secondary goals included: obtaining hitherto unavailable continuous core through the Valles caldera-fill sequence; gathering critical structural information at the interface of the caldera's structural margin and resurgent dome; and characterization and interpretation of subsurface hydrothermal alteration.

Completed late in 1986, VC-2A not only fulfilled these objectives but encountered unusual and surprisingly intense hydrothermal alteration and mineralization. Instead of the widespread high-level, acid-sulfate (kaolin-alunite-opal-sulphur) alteration which occurs at the surface in the Sulphur Spring area, (Charles et al., 1986), VC-2A encountered intense phyllic (quartz-sericite-pyrite) alteration and associated molybdenum mineralization (Hulen et al., 1987) within 25 m of the present ground surface. This assemblage implies deposition at much higher temperatures than those currently prevailing at these shallow levels. Sulphur Springs clearly has undergone a more complex hydrothermal history than surface thermal features and alteration at first would indicate. In this paper, we use clay mineralogy and zoning in VC-2A to help reconstruct that history for Sulphur Springs and the entire Valles caldera complex.

GEOLOGIC SETTING

The Valles caldera complex, at the crest of the Jemez Mountains volcanic field in north-central New Mexico, encompasses the nested Valles (1.12 Ma) and Toledo (1.45 Ma) calderas, giant structures which collapsed simultaneously with eruption and emplacement of at least 300 km^3 of rhyolite ash-flow tuff (Doell et al., 1968; Smith and Bailey, 1968, Self et al., 1986; Heiken et al., 1986). Similar but much smaller eruptions prior to the Toledo event probably led to formation of a small, now totally concealed caldera (or calderas) at the same site between 3.6 and 1.8 Ma (Nielson and Hulen, 1984; Self et al., 1986). Soon after collapse, the subsided Valles caldera block was affected by resurgent doming and by rhyolitic volcanism which persisted intermittently until about 0.13 Ma.

Hydrothermal activity in the Valles caldera complex is focused both at Sulphur Springs and along Redondo Creek (Fig. 1), within the apical graben of the

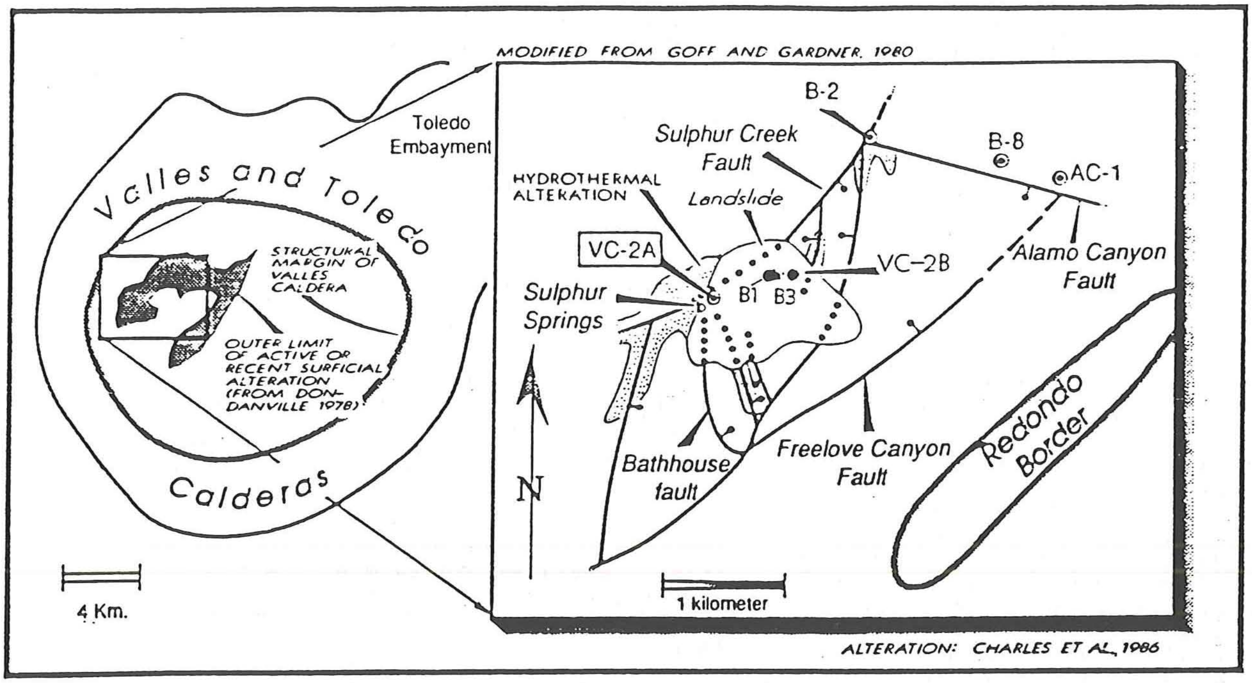

Figure 1. Location map of the Valles caldera complex. Detailed inset at right shows the Sulphur springs area, with positions of geothermal wells (prefix "B") and CSDP scientific corehole VC-2A and VC-2B.

caldera's resurgent Redondo dome. Exploration and development drilling in both areas by Union Oil Company of California (UOC) revealed a liquid-dominated, neutral-chloride, high-temperature (up to 300^{o}C) geothermal reservoir (Truesdell and Janik, 1986), with a vapor cap averaging about 500 m in thickness.

Previous hydrothermal alteration studies based on cuttings from UOC geothermal wells (Hulen and Nielson, 1986a, 1986b) revealed that alteration mineralogy, zoning and intensity in the Redondo Creek area are somewhat different than at Sulphur Springs. At Redondo Creek, a high-level, moderate-intensity, argillic cap is dominated by smectite with minor mixed-layer illite/smectite. This cap occurs above a weak- to moderate-intensity but pervasive propylitic alteration zone that is locally punctuated by intense phyllic alteration, tightly confined to widely-spaced structural and stratigraphic aquifers.

By contrast, in the northern Sulphur Springs area, exemplified by borehole B-8, alteration is more intense overall, and mixed-layer illite/smectite is much more abundant at high levels. Unusually intense, illite-adularia-epidote alteration occurs in the deepest available samples between 823 and 945 m (Hulen and Nielson, 1986b). Alteration in VC-2A is the most pervasive and intense yet encountered in any Valles borehole. Sericite accounts for an average 15-20 wt. % of all rocks penetrated by the corehole; restricted debris-flow intervals exceed 50 wt. % sericite. This intense alteration shows that, although now relatively impermeable (Goff et al., 1987), the Sulphur Springs rocks once allowed easy access for hot hydrothermal fluids.

STRATIGRAPHY AND STRUCTURE

VC-2A, completed at a depth of 528 m, penetrated a rhyolitic ash-flow tuff sequence which has been correlated with the intracaldera Bandelier Tuff and associated ignimbrites (Nielson and Hulen, 1984; Self et al., 1986; Fig. 2). Beneath a veneer of landslide debris and young volcaniclastic sediments, the sequence is as follows: 21.6-64.8 m-- the Upper Tuffs (UT; <1.12 Ma); 64.8-79.9 m -- the S_2 sandstone (and debris flow); 79.9-354.3 m -- the Tshirege Member of the Bandelier Tuff (Ts; 1.12 Ma); 354.3-

361.5 m -- the S_3 sandstone; 361.5-477 m -- the Otowi Member of the Bandelier Tuff (Ot; 1.45 Ma); 477-528 m -- the Lower Tuffs (LT; 3.6-1.45 Ma).

Structural disruption of this tuff sequence is concentrated above a depth of 163 m. In this interval, densely welded ash-flow tuffs are strongly fractured and locally cut by prominent gouge and breccia zones. Below this zone, fracturing is weak and widely-spaced, a difference reflected by decreased alteration intensity. Fracturing is both tectonic and hydrothermal in origin. Hydrothermal breccias (Nielson and Hulen, 1987) are distinct in showing well-developed "jigsaw puzzle" textures (e.g Hedenquist and Henley, 1985) and no evidence of crushing or shearing.

HYDROTHERMAL ALTERATION AND MINERALIZATION

Alteration in VC-2A is separable into two distinct zones. Above a depth of 163 m, and corresponding to the most intense fracturing, the rocks are thoroughly converted to quartz-sericite-pyrite aggregates (Hulen et al., 1987). Below 163 m, moderate-intensity chlorite-sericite alteration prevails, but quartz-sericite alteration zones are locally present. Rocks of the high-level phyllic zone are laced with hydrothermal veinlets consisting of various combinations of quartz, sercite, fluorite, pyrite and molybdenite, locally with minor sphalerite, rhodochrosite, and chalcopyrite. The richest sampled molybdenite veins assayed nearly 0.6 wt. % MoS_2 (Hulen et al., 1987). These veinlets are clearly epithermal in character. Open spaces are common, and many of these are delicately lined or filled with one or all of the secondary phases listed above. Veinlets in the chlorite-sericite zone are more sparsely distributed and generally consist of calcite and chlorite, with or without quartz, illite and phengite (a green, iron-rich illite analogue), adularia, fluorite, and pyrite.

LAYER SILICATE MINERALOGY AND ZONING

Figure 2 shows the downhole distributions of various layer silicate phases in the <5 micron fractions extracted from 71 VC-2A core samples. The clay-fractions are dominated by sericite, which accounts for 50-100 wt. %. Chlorite is the only other common clay, but generally occurs in amounts less than 10%. Smectite and kaolin (<5%) were identified in only two samples each.

For this study, sericite, a useful exploration term, encompasses illite, phengite, and illite-rich, mixed-layer illite/smectite (I/S). The term illite is restricted to varieties of sericite with <5% expandable (smectite) interlayers, since this is the lowest amount generally detectable by routine XRD (Reynolds, 1980); I/S, then, is defined as sericite with >5% expandandable interlayers.

As thus defined, I/S is largely confined to the phyllic zone above 163 m (Fig. 2). Figures 3A and 3C illustrate representative clay-fraction I/S X-ray diffractograms for phyllic zone core samples. The patterns show broad, basal reflections which shift dramatically and change shape upon vapor glycolation. Using the methods of Srodon (1980) and Srodon and Eberl (1984), these I/S clays are shown to be R3-ordered (or Kalkberg-ordered; Hoffman, 1981) and to contain approximately 5-14% smectite interlayers (Fig. 2). Corresponding crystallinity indices (width, in $^{\circ}2\theta$, at 1/2 height) range from $0.6\text{-}1.0^{\circ}2\theta$.

A deep I/S zone occurs in densely welded ash-flow tuff and fallout tuff just below the S_3 sandstone and in the upper Otowi Member of the Bandelier Tuff (Fig. 2). Three clay-fractions from this zone are dominated by I/S which generates an X-ray response virtually identical to those occurring at higher levels. Unlike those at higher levels, however, these deeper I/S clays occur intergrown with hydrothermal chlorite.

In addition to illite-rich I/S, the phyllic zone above 163 m in VC-2A hosts abundant illite relatively free of expandable interlayers; Figure 3B shows a typical X-ray diffractogram. Unlike the I/S described above, this illite is characterized by sharp, well-defined basal reflections which shift only slightly upon vapor glycolation. Corresponding crystallinity indices are generally $0.5^{\circ}2\theta$ or less, although locally up to $0.75^{\circ}2\theta$.

Figures 4 and 5 are scanning electron photomicrographs of representative sericites from the phyllic zone penetrated by corehole VC-2A. Figure 4 (see also figure 3B) shows delicate, flower-like, illite aggregates intergrown with euhedral quartz in the molybdenite zone. Figure 5, at much lower magnification, shows co-precipitated I/S and quartz.

With local exceptions, such as the I/S interval just below 361.5 m (Fig. 2), the chlorite-sericite zone is mineralogically monotonous. Figure 3D illustrates a typical <5-micron-fraction X-ray diffrac-

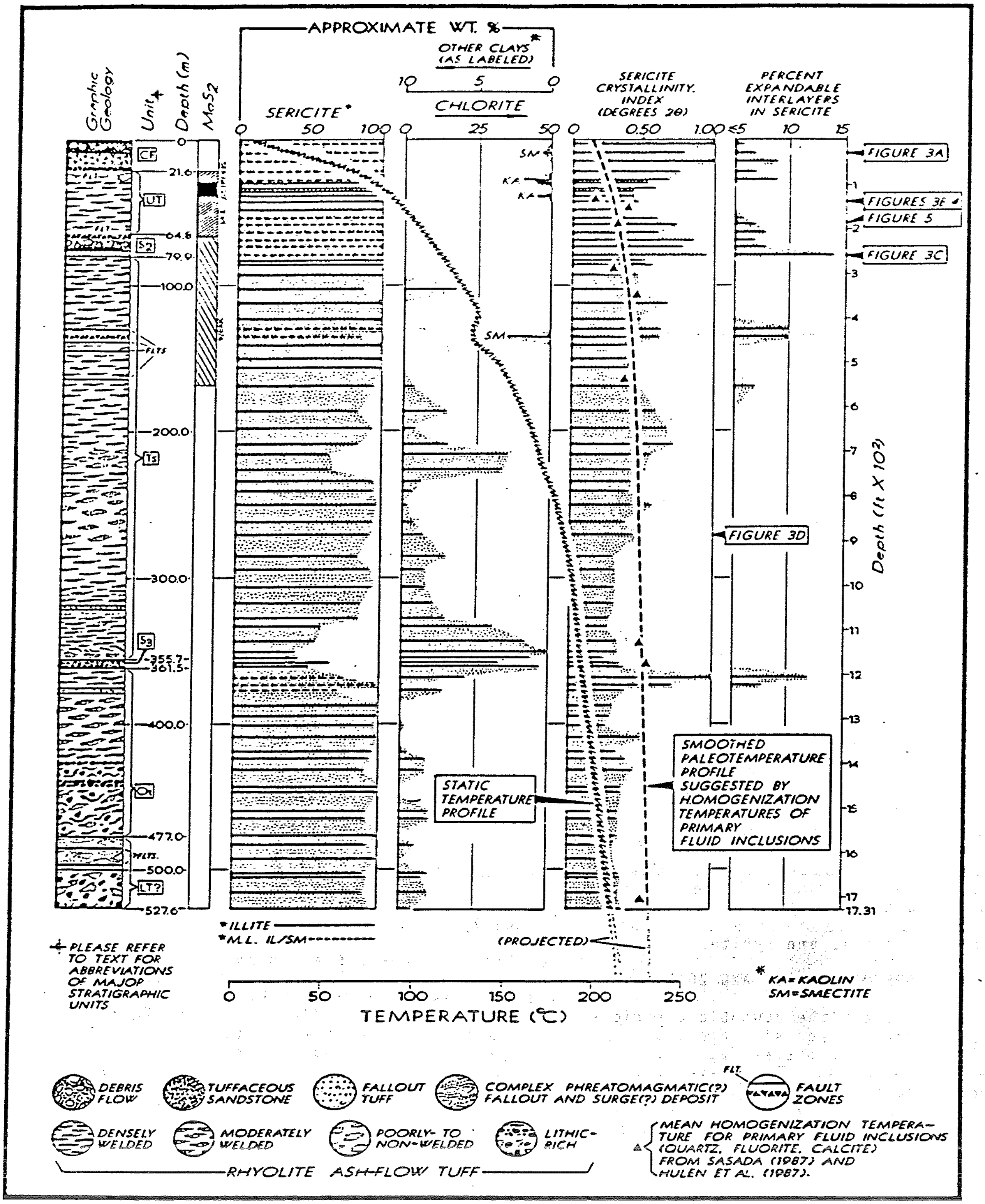

Figure 2 Downhole distribution of clay minerals in the clay fractions extracted from 71 core samples from CSDP corehole VC-2A. Shown for comparison are a static temperature profile and a paleotemperature profile based on mean homogenization temperatures for primary fluid inclusions in quartz, fluorite and calcite.

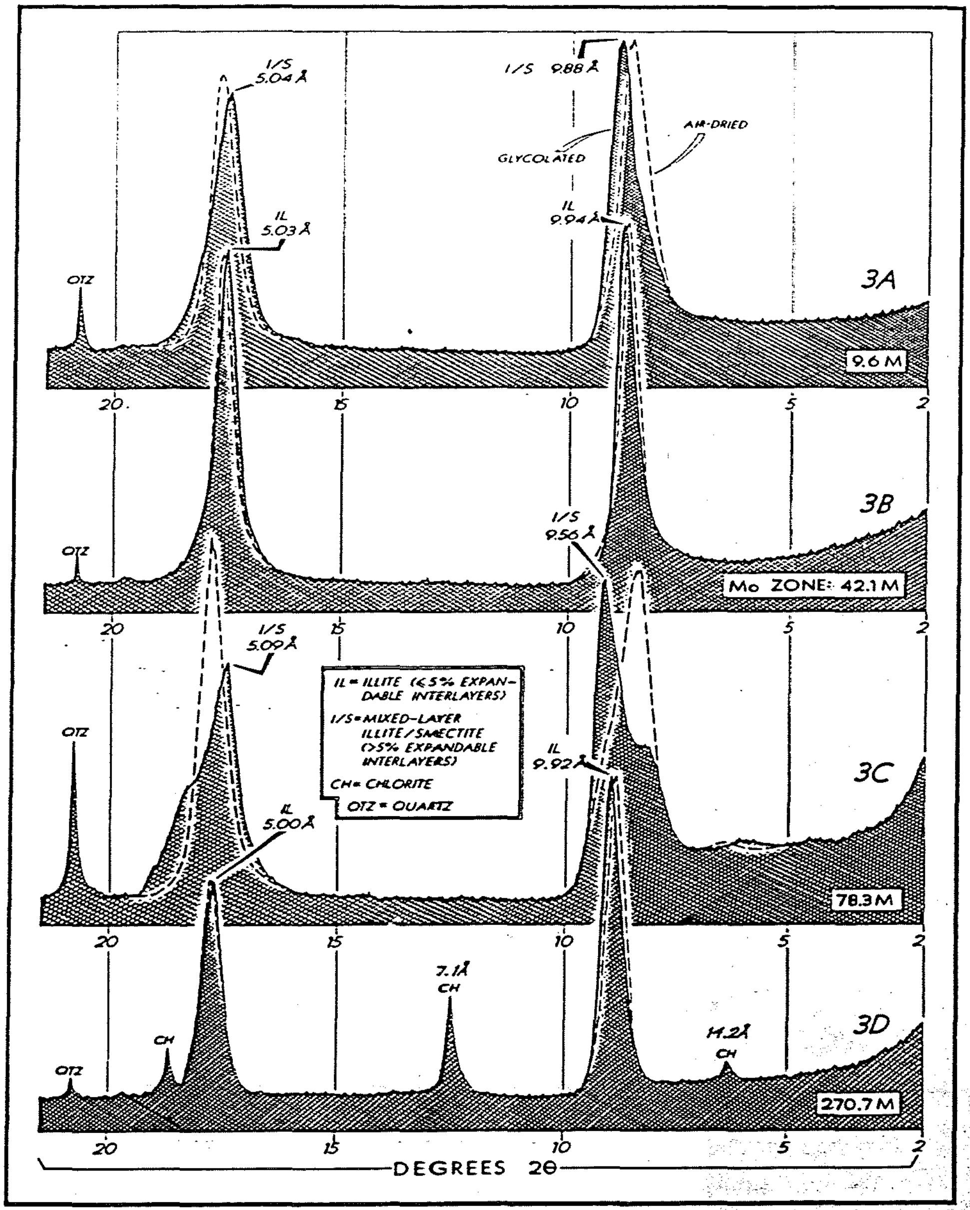

Figure 3. Representative VC-2A clay-fraction X-ray diffractograms. 3A and 3C -- R3 (or Kalkberg) - ordered, illite-rich, mixed-layer illite smectite. 3B -- illite. 3D --- illite plus phengite with minor chlorite.

togram for this zone, in this case from a depth of 270.7 m. The 10A clay dominating this pattern is actually a combination of iron-free illite, similar to that occurring in the overlying phyllic zone, and phengite (the relationship between these two sericites in the chlorite-sericite zone remains to be determined). Upon vapor glycolation, the basal peaks generated by illite plus phengite shift only slightly, indicating minimal interlayer smectite. Minor chlorite occurring in the chlorite-sericite zone

Figure 4. SEM photomicrograph of flower-like illite aggregates intergrown with euhedral quartz from a vug in quartz-sericitized tuff in the molybdenite zone (depth 42.1 m) in corehole VC-2A (see also Figures 2 and 3).

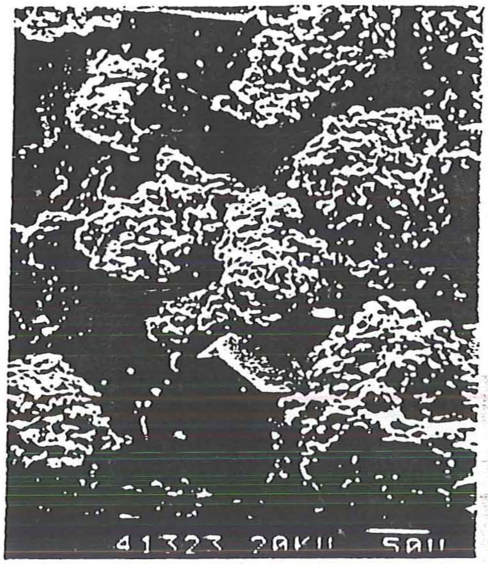

Figure 5. SEM photomicrograph of mixed-layer illite/smectite aggregates intergrown with quartz in a vein in quartz-sericitized tuff (depth 57.2 m) in corehole VC-2A (see also Figure 2).

predates coexisting illite but its age relationship to phengite is presently uncertain. The chlorite preferentially replaces pre-existing mafic minerals, but also partially replaces feldspar phenocrysts, pumice and matrix. Along with calcite, it is also one of the two most common vein-filling phases in this zone. The chlorite is an iron-rich variety, based on the relationship of its 14A peak intensity (weak) to its 7A peak intensity (strong; Warshaw and Roy, 1961).

CLAY MINERAL GEOTHERMOMETRY

In active geothermal fields worldwide, numerous investigators have shown a correlation between increasing temperature and decreasing expandable interlayer content in I/S (e.g. Steiner, 1968; Muffler and White, 1969; McDowell and Elders, 1980; Browne, 1978, 1984). In almost all cases, the appearance of illite (<5% expandable interlayers) coincides with temperatures in excess of 200°C (The range is 200-240°C, and the precise illite appearance temperature is field-specific). In corehole VC-2A, however, illite extends up to a present depth of at least 25 m, where the present temperature is only about 80°C. This relationship, along with other textural and mineralogical evidence to be discussed, shows that the upper levels of the Sulphur Springs hydrothermal system have dramatically cooled since illite was formed.

The 200°C minimum temperature required for illite formation presently occurs in VC-2A at a depth of about 400 m (Fig. 2). However, a paleotemperature profile based on mean homogenization temperatures for primary fluid inclusions in hydrothermal vein- and vug-filling minerals occurring with (and in part co-precipitated with) sericite (Fig. 2; data from Hulen et al., 1987, and Sasada, 1987) shows that the 200°C isotherm once occurred at least as high as about 20 m beneath the present surface.

DISCUSSION AND CONCLUSIONS

The distribution of hydrothermal sericite in CSDP corehole VC-2A shows that paleotemperatures in the Sulphur Springs hydrothermal system once reached at least 200°C near the present ground surface, even though present temperatures are much cooler at these shallow depths. Fluid-inclusion evidence from quartz and fluorite intergrown with the illite shows that all three minerals were deposited under liquid-dominated conditions. Water vapor, however, is now the pressure-controlling fluid to a depth of at least 240 m (Goff et al., 1987).

Other wells in the Valles caldera have shown similar cooling to that demonstrated by VC-2A. Alteration minerals in wells in the Redondo Creek area (Hulen and Nielson, 1986a) have shown cooling of between 50 and 100°C. Baca-8, north of VC-2A, has also demonstrated cooling and a drop in the water table of at least 250 m since maximum hydrothermal temperatures (Hulen and Nielson, 1986b). VC-1, located immediately outside the caldera, has shown a decline in temperature of as much as 100^{o}C although it is clear that this area experienced overpressures at its temperature maximum (Nielson and Hulen, 1987).

There are several alternatives to explain the caldera-wide cooling from a temperature maximum defined by hydrothermal alteration: 1. less heat input from the magma, 2. draining of a caldera lake whose hydrostatic head could have allowed the temperatures at the present surface to reach 200^{o}C, 3. erosion of an overlying rock column exposing the deeper levels of a hydrothermal system, 4. uplift due to resurgence, or a combination of the above factors.

The core from VC-2A shows that the volcanic units beneath the Upper Tuffs dip at 40^{o}, and that dips of 20 to 30^{o} are found in the Upper Tuffs and overlying caldera fill (Hulen et al., 1988). The phyllic alteration described above affects all of these rocks. It is clear from these relationships that the thermal maximum must have occurred after or in the waning stages of resurgence. Smith and Bailey (1968) proposed that resurgent doming was completed about 100,000 years following caldera collapse, or at about 1.02 Ma. They also state that the resurgent dome was uplifted through a caldera lake.

Goff and Shevenell (1987) have dated the travertine deposits at Soda Dam in San Diego Canon to the south of the caldera. These hot spring deposits are produced by leakage of the Valles hydrothermal system along the Jemez fault zone. Following formation of the Valles caldera and prior to the initial deposition of travertine at 1 Ma, Goff and Shevenell estimate that at least 400 m of Bandelier Tuff was eroded. The earliest travertine is deposited directly on Paleozoic and Precambrian rock. Studies of the travertine indicate that since 1 Ma, discharge volumes may have been higher, but fluid temperatures have been relatively constant, probably never more than 10^{o} hotter than at present. This implies that the temperature of the Valles hydrothermal system has remained essentially unchanged in the past 1 Ma.

From the above evidence, the following scenario is proposed. The hydrothermal alteration maximum took place in the 100,000 year interval following collapse of the Valles caldera and through the end of uplift of the resurgent dome. Three factors may have contributed to the high near-surface paleotemperatures documented throughout the caldera: 1. latent heat from the recently erupted Tshirege Member of the Bandelier Tuff, 2. high heat flow from the resurgent magma chamber, and 3. the hydrostatic head from a caldera lake. It is compelling to call upon draining a caldera lake as an explanation for both the collapse of isotherms and lowering of the water table. Draining the lake through San Diego Canon could produce the high erosion rates documented by Goff and Shevenell. A rapid lowering of the water table would not only reduce the convective heat flow, it is a logical cause for hydrothermal brecciation observed in both VC-1 and VC-2A.

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