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HYDROTHERMAL FACTORS IN POROSITY EVOLUTION AND CAPROCK FORMATION AT THE GEYSERS STEAM FIELD, CALIFORNIA — INSIGHT FROM THE GEYSERS CORING PROJECT

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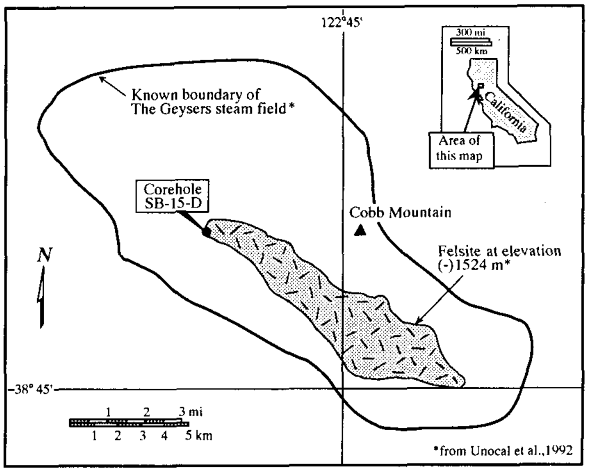
ABSTRACT

The Department of Energy (DOE)/geothermal industry-sponsored Geysers Coring Project (GCP) has yielded 236.8 m of continuous core apparently spanning the transition between the uppermost Geysers steam reservoir and its caprock. Both zones in the corehole are developed in superficially similar, fractured, complexly veined and locally sericitized, Franciscan (late Mesozoic) graywacke-argillite sequences. However, whereas the reservoir rocks host two major fluid conduits (potential steam entries), the caprock is only sparingly permeable. This discrepancy appears to reflect principally vein texture and mineralogy. Two types of veins are common in the core — randomly-oriented, Franciscan metamorphic quartz-calcite veins; and high-angle, late Cenozoic veins deposited by The Geysers hydrothermal system. The older veins locally contain hydrothermal carbonate-dissolution vugs, which, although concentrated at the larger fluid conduit, are scattered throughout the core. The younger veins, commonly with intercrystalline vugs, consist dominantly of euhedral quartz, calcite, K-feldspar, wairakite, and pyrite — those in the reservoir rock also contain minor epidote and illite. The corresponding caprock veins are devoid of epidote but contain abundant, late-stage, mixed-layer illite/smectite (5-18% smectite interlayers) with minor chlorite/smectite (40-45% smectite interlayers). We suggest that clots of these two expandable clays in the caprock clog otherwise permeable veins and carbonate-dissolution networks at strategic sites to produce or enhance the seal on the underlying steam reservoir. Illite/smectite geothermometry indicates that the SB-15-D caprock clays were precipitated in the approximate temperature range 180-218°C, and those in the reservoir at about 218-238°C. These temperatures, along with occurrence of the clays on commonly etched calcite, K-feldspar, or wairakite, suggest that the clays were precipitated from mildly acidic steam condensate under conditions similar to those now prevailing.

INTRODUCTION

The GCP is a geothermal industry/DOE collaboration aimed at improving understanding of porosity, permeability, and remaining fluid saturation in The Geysers vapor-dominated geothermal system (Fig. 1; Hulen et al., 1995).



*from Unocal et al.,1992

Figure 1. Location map

Gaining that understanding requires core, which, prior to the GCP, was a scarce commodity here. At the time the project was initiated, only 24 short (<8 m) cores <90 m in combined length had been collected from the field. The drilling phase of the GCP, completed late in 1994, yielded 236.8 m of additional continuous core, spanning the depth interval 251.4-488.3 m, from a newly-created sidetrack (SB-15-D) to an existing Unocal Corporation production well (Fig. 1).

Detailed characterization and precise quantification of porosity, permeability, and fluid saturation in this new core must await the results of focused investigations now in progress by the GCP's collaborating investigators (e.g. Bonner et al., 1995). However, our own baseline geologic studies in support of these efforts have begun to reveal significant differences between core from the relatively impermeable upper 70% of SB-15-D (above a depth of 417.3m) and the lower 30%, in which two prominent fluid conduits (potential steam entries) were penetrated (Hulen et al., 1995). Chief among these differences are the types, distributions, and abundances of vein-hosted hydrothermal clays. This paper discusses the implications of these differences — with emphasis on the clays — for evolution of reservoir porosity and formation of the caprock above the modern Geysers steam field.

GEOLOGIC AND HYDROTHERMAL SETTING

The Geysers geothermal system occurs principally in subduction-trench-related Franciscan (Late Mesozoic) metagraywacke, metashale, and metasiltstone, hereinafter referred to as "graywacke" and "argillite" (McLaughlin, 1978, 1981; Sternfeld, 1981, 1989). These rocks are intruded by a large (>100 km^3), composite, late Cenozoic felsic pluton (the felsite; Fig. 1) which has produced a thick, contact-metamorphic aureole in the enveloping older lithologies (Schriener and Suemnicht, 1982; Thompson, 1992; Dalrymple, 1992; Hulen and Nielson, 1993). The intrusive and contact-metamorphic rocks also host a significant portion of the steam field. Mapped faults at The Geysers include high-angle, northwest-trending, dextral strike-slip faults related to the San Andreas system, and low- to high-angle, also commonly northwest-trending thrust faults of probable Franciscan age (McLaughlin, 1978, 1981; Oppenheimer, 1986; Thompson and Gunderson, 1992). Faults and fractures controlling major steam conduits tend to be high-angle in the felsite (Thompson and Gunderson, 1992) and low- to moderate-angle in the Franciscan rocks (Beall and Box, 1992; Thompson and Gunderson, 1992).

The Geysers steam field is divisible into a so-called "normal" reservoir, with a pre-exploitation temperature of about 235°C at a pressure of about 3.3 MPa (White et al., 1971) and, principally in the northwest Geysers, a deeper, "high-temperature" reservoir (Walters et al., 1992) with rock temperatures locally exceeding 300°C. Although now vapor-dominated, The Geysers hydrothermal system was initially hot-water dominated, with deeper temperatures probably as high as 400°C (Moore, 1992; Gunderson and Moore, 1994). While in this earlier stage, the system created significant secondary porosity by dissolving calcite from Franciscan metamorphic quartz-calcite veins (Hulen et al., 1991, 1992; Thompson and Gunderson, 1992; Gunderson, 1992). The system also precipitated a well-zoned suite of hydrothermal vein minerals including tourmaline at deeper levels, epidote throughout most of the future steam reservoir, and commonly bladed calcite at higher elevations (McLaughlin et al., 1983; Hulen et al., 1991, 1992; Moore, 1992). The bladed calcite has been cited as an important porosity-sealing phase in The Geysers' caprock (Hulen et al., 1991, 1992; Moore, 1992).

The existence of such a caprock is necessary to "...inhibit the free escape of rising vapor" from the underlying steam reservoir (White et al., 1971). As we will argue, corehole SB-15-D apparently penetrates the transition zone between the basal portion of this caprock and the upper portion of the subjacent reservoir. This penetration provides an opportunity to investigate the means by which this essential seal was formed.

LITHOLOGY, FRACTURING, ALTERATION, VEIN MINERALIZATION, AND THE NATURE OF POROSITY

The GCP corehole encountered a sequence of interbedded Franciscan graywackes and argillites, with the graywackes strongly predominant (Fig. 2). These rocks were deposited as turbidites. The generally fine- to medium-grained graywackes show graded bedding and load casts, and the argillites, prominent flame structures (see also Sternfeld, 1989). Prevailing dip angles in these strata (relative to a plane normal to the core axis, itself inclined 83° from horizontal) range from 40-65°. The argillites at deeper levels, below a depth of about 375 m, appear slightly more indurated and competent than their higher-level counterparts (Hulen et al., 1995).

Although the SB-15-D core was highly fractured throughout (Hulen et al., 1995), losses of the water- and polymer-based drilling fluid to the formation were only 10-25% to a depth of 417.3 m. At this depth, a total loss of circulation occurred (Fig. 2), and the remainder of the hole was cored without drilling-fluid returns. A second major fluid conduit, somewhere between 472.4 m and 488.3 m (Fig. 2), was detected by a post-drilling Sandia National Laboratories temperature survey conducted immediately following injection of cool water into the partially thermally reequilibrated corehole (Brian Koenig, pers. communication, 1994). Both this deeper conduit and the one at 417.3 m almost certainly would have been steam entries had SB-15-D been air-drilled.

The lack of an obvious correlation between fracture type or density (not illustrated on Figure 2) and the fluid conduits noted above suggests to us that many of the penetrated fractures were induced or enhanced during drilling and core recovery. Probable causes for this artificial fracturing include relief of overburden pressure (formation of hackly disk-like fractures) and core contraction accompanying cooling (enlargement of existing fractures; "pull-apart" of weakly cemented veins). There are, however, numerous, clearly natural, high-angle (typically >65°), slickensided fractures (principally in argillites) along the entire length of the core. The slickensides are commonly subhorizontal features, recording strike-slip to low-angle oblique-slip displacement.

Hydrothermal alteration of the core is typically minimal and confined to thin (less than a few mm) selvages on the Geysers hydrothermal veinlets described immediately below. However, scattered zones of intense alteration up to a meter or more in length occur locally (for example, around the major fluid conduit at 417.3 m). Sericitization, the principal alteration type, is characterized by replacement of susceptible original clastic components of the rock (especially albite and volcanic rock grains) by white to greenish-white illite (or phengite). The illite throughout the core generally contains <5% smectite interlayers, as determined by X-ray diffraction (XRD) analysis. Other alteration minerals occurring both

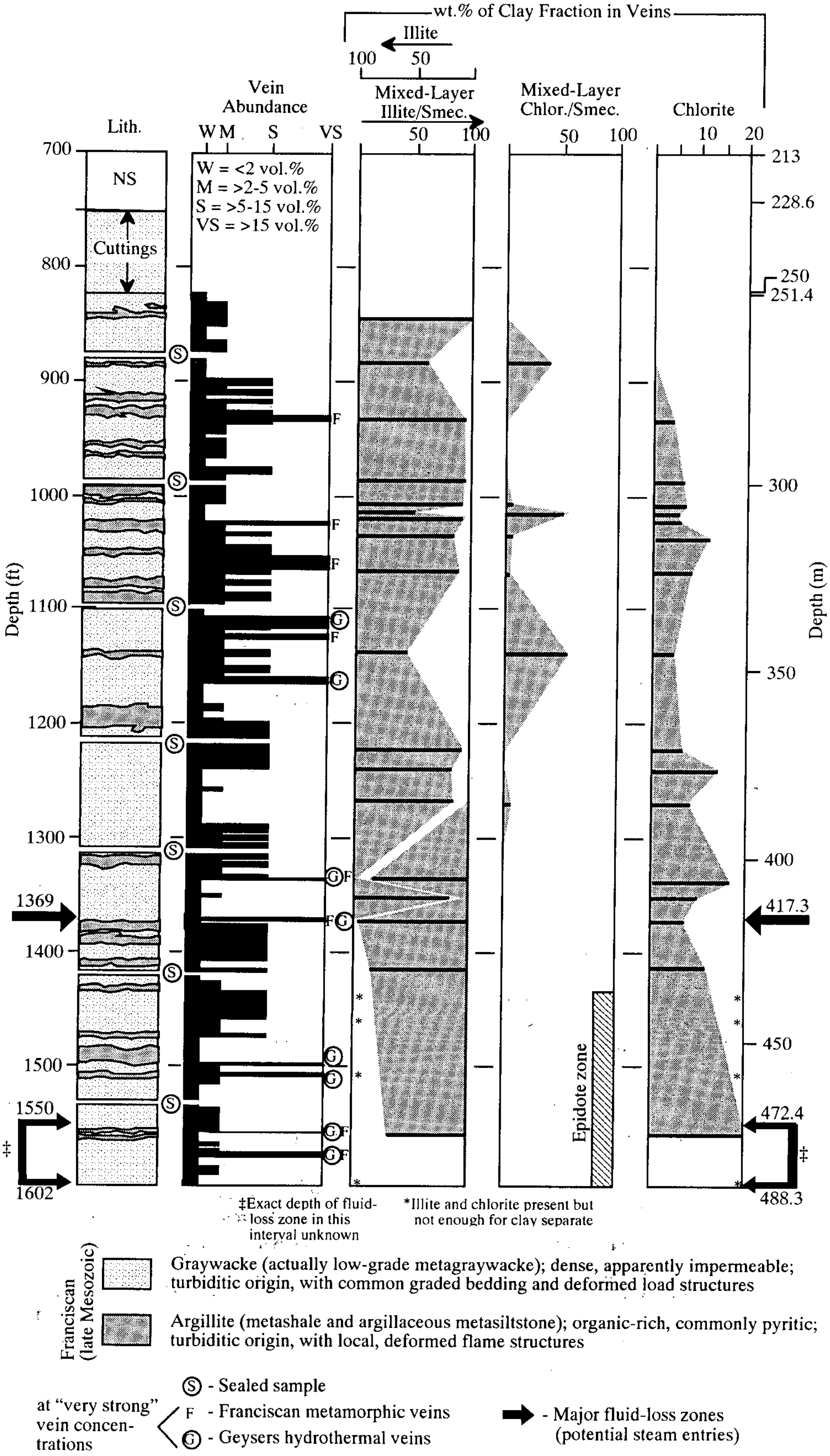


Figure 2. Corehole SB-15-D — Simplified log of lithology, vein distribution, and clay mineralogy of hydrothermal veins.

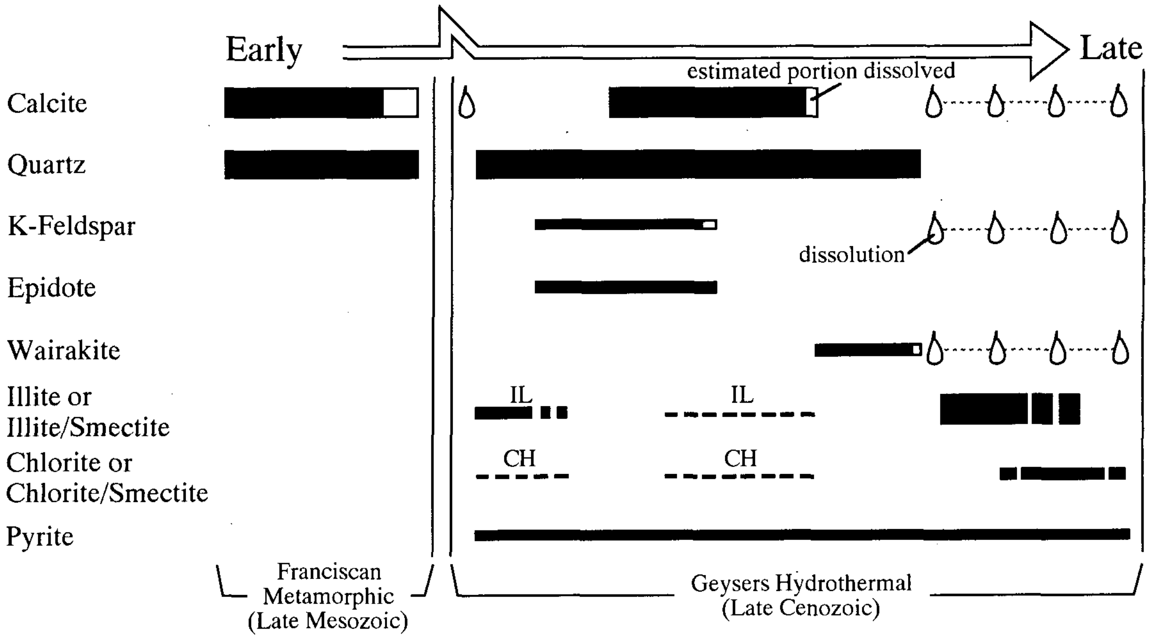


Figure 3. Corehole SB-15-D — Generalized vein–mineral paragenetic sequence. Bar widths denote relative abundances of minerals. IL = illite only. CH = chlorite only.

with the sericite and in separate selvages include K-feldspar, quartz, chlorite, and pyrite.

Metamorphic and hydrothermal veins are abundant in the SB-15-D core (Figs. 2 and 3). The metamorphic veins are Franciscan in age, randomly oriented, of variable shape, and consist exclusively of turbid white calcite and quartz. Hydrothermal veins, deposited during the hot-water-dominated stage of the Geysers geothermal system, are texturally distinctive from the Franciscan varieties. They tend to be high-angle (>65°), straight-sided, and uniform in width (typically 0.5-1.5 mm). Their fillings are also readily detachable from the veinlet walls, whereas the Franciscan veins are "frozen" to their wallrocks. The hydrothermal veinlets contain colorless to translucent white, euhedral prismatic quartz, bladed calcite, and (locally) K-feldspar, with minor pyrite, wairakite, illite, chlorite, mixed-layer clays, epidote (below a depth of 435.8 m), and scattered traces of sphalerite, galena, and chalcopyrite. The calcite is the bladed variety, indicating precipitation from a boiling hydrothermal solution (Tulloch, 1982).

Both types of veins in the GCP core are locally vuggy, especially in the vicinity of the upper major fluid conduit at 417.3 m. Here, the vugs are clearly an important element of porosity and permeability, but such cavities are present to a lesser extent even in the tight overlying strata. The vugs are of two origins. Some Franciscan veins contain amoeboid to irregular voids believed on textural evidence to represent hydrothermal dissolution of metamorphic calcite. These dissolution voids are commonly lined by the same assemblage of secondary minerals found in the younger veins. Larger vugs in these Geysers hydrothermal veins are intercrystalline, the result of incomplete filling of the initially available open space. Both types of vugs are generally <1 cm in diameter but a few (for example in the fluid-conduit zone at 417.3 m) reach diameters or lengths of up to 5 cm. In addition to these major vug types, there are also small-scale (<1-50 micron), surficial dissolution pits and scours locally present on hydrothermal calcite, K-feldspar, and wairakite crystals.

CLAY MINERALOGY OF HYDROTHERMAL VEINS

The vein-hosted clays in the SB-15-D core are principally late-stage minerals (Fig. 3), commonly precipitated on weakly etched wairakite, K-feldspar, and (especially) bladed calcite. Some illite and chlorite also occur both in early bands precipitated on vein walls and in multiple zones of solid inclusions in euhedral quartz crystals. The late-stage clay minerals show a distinct vertical zonation (Fig. 2). Illite occurs in veins below a depth of 406 m, and mixed-layer clays are found in those above 410 m, with minor amounts of chlorite nearly ubiquitous (Fig. 2). (We define discrete illite and chlorite for this study arbitrarily as having <5% expandable interlayers as determined by XRD). Clays are also much more abundant in veins at and above the major fluid-loss zone at 417.3 m than in those below this depth. The higher-level veins commonly contain up to 10% late-stage clay, whereas most of their deeper counterparts are essentially clay-free.

Mixed-layer illite/smectite (IL/SM) occurring in these veins (Figs. 3-5) is a brilliant white to greenish-white, pearlescent variety. As determined from XRD scans of

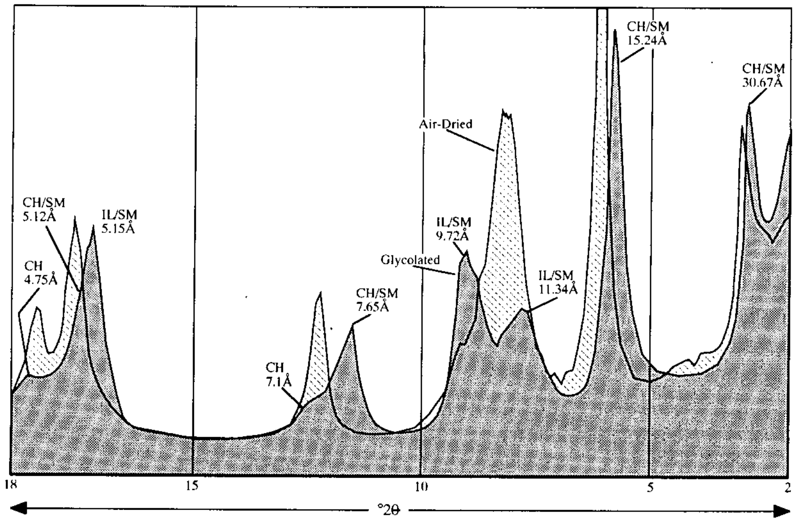


Figure 4. Corehole SB-15-D — X–ray diffractogram of clay (<5 micron) fraction extracted from hydrothermal vein at depth of 346.2 m. IL/SM = mixed-layer illite/smectite. CH/SM = mixed-layer chlorite/smectite. CH = chlorite.

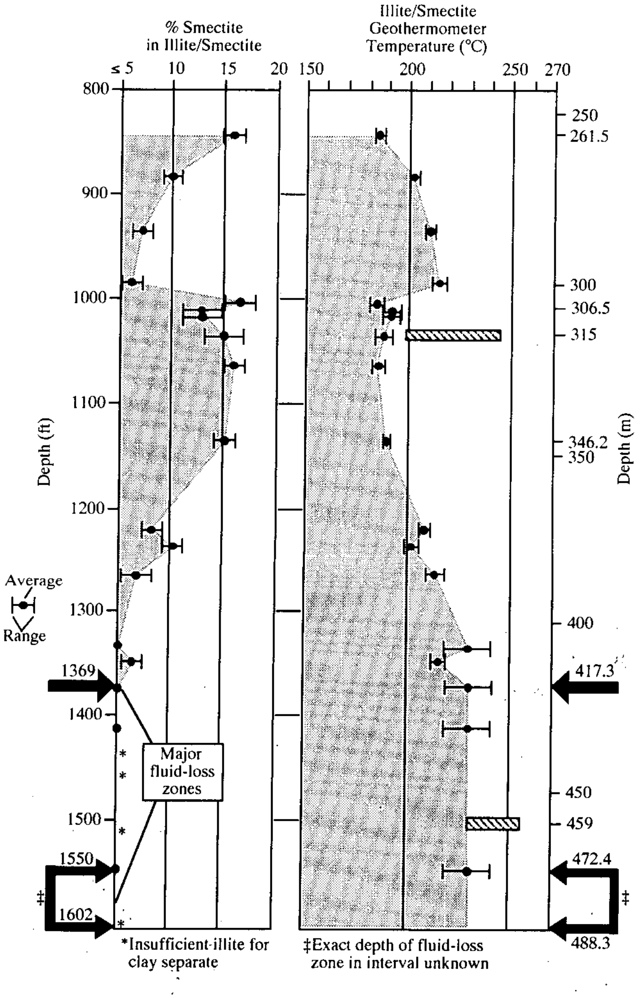


Figure 5. Corehole SB-15-D — Illite/smectite expandability and geothermometer temperatures for hydrothermal veins. Hachured horizontal bars denote ranges, in two selected hydrothermal veins, of primary and pseudosecondary fluid-inclusion homogenization temperatures for earlier-stage euhedral quartz (courtesy of Joseph Moore, pers. communication, 1995).

<5μ separates of the veins, using the methods of Środoń (1980), it is an R3-ordered variety containing 5-18% smectite interlayers (Fig. 5). There are two smectite-interlayer maxima, one at a depth of 261.5 m, the other at 306.5 m. Below each of these maxima, smectite percentage in general decreases with depth (Fig. 5). The upper major fluid conduit in SB-15-D occurs at about the point in the corehole where expandable interlayers in IL/SM diminish to <5% (Fig. 5).

The pale greenish-gray mixed-layer chlorite/smectite occurring with IL/SM in these veins (Figs. 3 and 4) is the variety corrensite, an R1-ordered clay with a distinct superlattice peak at about 30.7A. According to methods outlined in Moore and Reynolds (1989), the corrensite in the SB-15-D veins contains 40-45% smectite interlayers. At this stage of our investigation, we cannot explain the discrepancy in ordering and interlayer smectite content between the corrensite and coexisting IL/SM.

Vein-Mineral Illite/Smectite Geothermometry

The smectite-interlayer content of IL/SM (especially hydrothermal varieties) is a sensitive indicator of depositional temperature — in general, as this temperature rises, fewer smectite interlayers are formed, and those which do form attain a higher degree of ordering with illite interlayers (Steiner, 1968; Henley and Ellis, 1983; Browne, 1984; Hedenquist and Houghton, 1988; Moore and Reynolds, 1989; Pollastro, 1991). A widely used IL/SM geothermometer is the one calibrated for active New Zealand geothermal systems by C.P. Wood (personal communication reported in Hedenquist and Houghton, 1988). According to this geothermometer, an IL/SM precipitated at 187°C would have a smectite interlayer content of 15%, whereas one formed at 238°C would have no smectite interlayers (and by the definition given above would actually be an illite).

The smectite interlayer content of the SB-15-D IL/SM above a depth of 410 m varies from 5% to 18%, corresponding to a geothermometer temperature range of 180-218°C (Fig. 5). The illites below 406 m contain <5% expandable interlayers and indicate a depositional temperature range of 218-238°C. This reservoir paleotemperature range corresponds well with the reported pre-exploitation temperature of about 235°C for The Geysers steam reservoir as a whole (White et al., 1971), and with the estimated initial reservoir temperature (about 230°C) encountered in the upper reaches of production well SB-15 (Brian Koenig, pers. communication, 1994). It is interesting to note, however, that both the modern and clay-mineral geothermometer temperatures are slightly lower than those indicated by preliminary fluid-inclusion microthermometry of pre-clay hydrothermal quartz in veins at depths of 315 m and 459 m (Fig. 5; Joseph Moore, pers. communication, 1995). This relationship suggests that the clays were precipitated after The Geysers hydrothermal system at these depths had cooled slightly from its thermal maximum.

DISCUSSION AND CONCLUSIONS

The nature and distribution of late-stage clay minerals in hydrothermal veins in the SB-15-D core, when considered along with (1) the downhole locations of major fluid conduits (potential steam entries) and (2) the depth range of vein epidote, now suggest to us that the corehole penetrates the transition zone between the uppermost Geysers steam reservoir and its largely impermeable caprock. Below the upper fluid conduit at 417.3 m (Figs. 2 and 5), epidote is present, vein-hosted clay minerals are minor constituents, and mixed-layering in these clay minerals is minimal. By contrast, in veins above the 417.3 m fluid channel, epidote is absent, clay minerals are common, and mixed-layering is prevalent. In support of this caprock-reservoir zoning model is the subtle apparent textural difference between less competent argillites at upper levels in the corehole and brittler, more competent argillites at deeper levels.

The vein- (and vug-) hosted mixed-layer clays are the most distinguishing features of what we have interpreted as the caprock in SB-15-D. The reservoir and caprock lithologies (apart from the slightly different argillite textures) are very similar, and they are cut by similar types and abundances of fractures and veinlets. Carbonate-dissolution and intercrystalline vugs in the veins are locally present throughout the core, although the largest and most interconnected of these vugs are certainly found at the 417.3 m fluid conduit (Hulen et al., 1995).

Gunderson (1992) and Williamson (1992) have presented evidence that much of the matrix rock at The Geysers is only weakly porous and permeable, with fractures, breccias, and open veins in this matrix providing the reservoir's major steam-bearing conduits. The corollary to this suggestion is that a zone of such rock without these conduits, or with the conduits sealed at strategic sites, would be an effective hydrologic barrier — a caprock if positioned above the reservoir. We contend that the SB-15-D mixed-layer clays would function as effective vein seals, particularly the corrensite, with up to 45% smectite interlayers. Clots of these expandable clays, if kept moistened (most likely by steam condensate) would choke off otherwise open channels. Furthermore, unlike brittle vein minerals (for example calcite), the clays would tend to absorb tectonic stresses plastically rather than breaking to create new porosity.

It must be noted that steam entries were encountered in the original production well, SB-15, at depths as shallow as 330.7 m (Hulen et al., 1995), well within the zone in SB-15-D we have characterized as caprock. One possible explanation for this discrepancy is that the controlling conduits for these original steam entries are steeply-inclined, and either miss SB-15-D entirely or intersect the corehole below 417.3 m. This would imply that the caprock-reservoir interface is complex and irregular, with salients of each zone locally projecting deeply into the other.

The physical/chemical conditions prevailing during precipitation of these vein-hosted mixed-layer clays and illite remain to be fully understood. White et al. (1971) speculated that pore-clogging smectite and kaolin above the steam reservoir could form by reaction of (acidic) CO_2-saturated steam condensate with rock- (and by extension, vein-) forming silicates. Although these lower-temperature minerals (e.g. Browne, 1984) might be expected to develop at higher elevations than those tested by SB-15-D, the same mechanisms at deeper levels and higher temperatures might readily form the smectite-interlayered clays and illite encountered by the corehole.

The layer silicates in the SB-15-D veins commonly occur on slightly corroded calcite blades as well as etched K-feldpar and wairakite (Hulen et al., 1995). This relationship supports the concept of clay precipitation from a late-stage acidic condensate. Since (1) inferred modern temperatures and vein IL/SM geothermometer temperatures are comparable for the SB-15-D steam-reservoir interval (417.3-488.3 m); and (2) fluid-inclusion temperatures for pre-IL/SM quartz in selected reservoir and caprock veins are up to 26-53°C higher than the IL/SM temperatures (Fig. 5), we suggest that the clay-precipitating condensate developed under similar-to-modern vapor-dominated conditions rather than in the precursor hot-water-dominated hydrothermal system.

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