THE GEYSERS CORING PROJECT, SONOMA COUNTY, CALIFORNIA, USA — SUMMARY AND INITIAL RESULTS

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ABSTRACT

The Geysers Coring Project (GCP), a US. Department of Energy (DOE) – geothermal industry joint venture, has yielded the first substantial length **(236.8** m) of continuous core from The Geysers vapor-dominated geothermal reservoir. The new corehole, a sidetrack from an existing steam–production well, penetrated a fractured and veined, weakly metamorphosed, Franciscan (late Mesozoic) graywacke/argillite sequence of turbiditic origin. This sequence is disrupted in the corehole by two throughgoing fluid conduits which likely would have been steam entries rather than fluid–loss zones had the corehole been air-drilled. The conduits coincide with superimposed concentrations of two types of veinlets common throughout the core: **(1)** randomly — riented, Franciscan metamorphic quartz-calcite veinlets; and **(2)** high-angle, late Cenozoic, Geysers hydrothermal veinlets consisting principally of euhedral quartz, bladed calcite, pyrite, and (below a depth of **435.8** m) epidote. This mineral assemblage and its texture indicate precipitation at a minimum temperature of **220°C** from at least intermittently boiling water. Locally corroded calcite blades coated with sericite (illite or mixed–layer illite/smectite) may record invasion of the veins by late–stage, acidic steam-condensate. Calcite–dissolution vugs in Franciscan veins and intercrystalline vugs in hydrothermal veins are locally prominent, particularly in and around the larger of the two fluid–loss zones. The hydrothermal veins are fragile and commonly refractured along strike. However, many of these vein–controlled fractures and others which are unmineralized appear to be artifacts related to mechanical or thermal stresses induced or relieved by the drilling process. Detailed studies underway on the core, including two intervals retrieved and frozen under pressure to preserve contained fluids, will provide Geysers steam–field operators with new information for refined reservoir modeling. The GCP has demonstrated the value of wireline coring as an exploration tool in high–temperature vapor-dominated geothermal regimes.

1. INTRODUCTION

The GCP is a cooperative endeavor involving the DOE's Geothermal Division (GD), Unocal Corporation and other steam–field operators, and a team of collaborating investigators representing national laboratories, universities, and various governmental agencies (Hulen et al., **1994).** The project is designed to improve knowledge of critical reservoir controls in the world's largest vapor–dominated geothermal field, The Geysers (Fig. 1). The principal impetus for the GCP was the recent onset of serious reservoir–pressure declines, largely responsible for a drop in modern power production to about **70%** of the field's **2043** MW installed electrical–generation capacity (Barker et al., **1992).** In order to help mitigate this depressurization, Geysers steam–field operators required detailed new information about in situ reservoir porosity, permeability, and fluid saturation. Much of this information can only be obtained from a considerable length of continuous reservoir core. However, prior to **1994,** only **24** short **(<8** m) cores less than **90** m in aggregate length had been retrieved from the resource and its relatively impermeable caprock.

The coring phase of the GCP was completed late in September **1994.** Continuous core **236.8** m in length was retrieved for the GCP by Tonto Drilling Services (Salt Lake City, Utah) from a new sidetrack (SB–15–D) to an existing Unocal steam–production well, **SB–15**

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(Fig. 1). The new core nearly quadruples the total amount now available from The Geysers. Detailed, multidisciplinary studies of this core being carried out by the GCP research team (Hulen and Nielson, **1994)** should provide steam–field operators with valuable new information for improved, long–term reservoir modeling and management. This paper summarizes the GCP drilling operations, provides an initial description of the retrieved core, and considers implications of preliminary project results for The Geysers' hydrothermal history and for steam production as well as deep core drilling here in the future.

2. GEOLOGIC AND HYDROTHERMAL SETTING

The Geysers steam field exploits the world's largest–known **(657** km[3]; Williamson, **1992)** vapor-dominated geothermal system. The system occurs in a lithologically complex region dominated by subduction–trench–related metagraywackes, metasiltstones, and metashales of the late Mesozoic Franciscan Assemblage (Fig. **1;** McLaughlin, **1978, 1981;** McLaughlin and Ohlin, **1984).** These metaclastic rock types are referred to by Geysers steam–field operators as "graywackes" and "argillites", and these designations will be retained for this paper. The Franciscan rocks, and those of the contemporaneous, compositionally similar, fore–arc–basinal Great Valley Sequence as well as associated ophiolitic masses (Fig. 1), are locally overlain by late Cenozoic volcanic iocks of mainly intermediate to felsic composition. These rocks were extruded from two separate volcanic centers, comprising the Miocene to Pliocene Sonoma Volcanics (Fox et al., **1985)** and the Pliocene to Holocene Clear Lake Volcanics (Hearn et al., **1981)(Fig. 1).** A large **(>100** km[3]), late Cenozoic, felsic pluton — the "felsite" (Schriener and Suemnicht, **1981)** — intruded the Franciscan rocks at depth in The Geysers. The felsite is a composite igneous body ranging in composition from granite to granodiorite and in known age from >1.3 Ma (Dalrymple, **1992)** to **0.57** Ma (Pulka, **1991).** In part apparently cogenetic with the Clear Lake Volcanics (Hulen and Nielson, **1993),** the felsite has produced a thick contact–metamorphic aureole in the enveloping Franciscan rocks. Individual intrusive bodies in the felsite have clearly acted as heat sources for The Geysers hydrothermal system in the past, and may still contribute heat for the modern vapor–dominated geothermal regime.

The Geysers hydrothermal system was initially liquid-dominated, with deeper temperatures at least as high as 400°C (Moore, **1992;** Gunderson and Moore, **1994).** While in this early, hot–water stage, the system modified its host rocks in two significant ways. In what would later become steam–reservoir rock, porosity was created by natural hydraulic fracturing and hydrothermal brecciation, and by dissolution of calcite from Franciscan metamorphic veins (Hulen et al., **1991, 1992;** Gunderson, **1992;** Thompson and Gunderson, **1992;** Hulen and Nielson, **1993).** At the same time, porosity was locally occluded (especially above and around the future steam reservoir) by precipitation of hydrothermal vein minerals (Facca and Tonani, **1967;** White et al., **1971;** Hulen et al., **1991;** Moore, **1992).** These vein minerals, which show a systematic vertical zonation with respect to the felsite, include quartz, K–feldspar, calcite and mixed–layer clays (at higher elevations), illite, chlorite, biotite, epidote, actinolite, clinopyroxene, prehnite, wairakite, datolite, ferroaxinite, and tourmaline (Sternfeld, **1981, 1989;** McLaughlin et al., **1983;** Hulen et al., **1991;** Walters et al., **1992;** Moore, **1992;** Gunderson and Moore, **1994).**

Delineated faults associated with The Geysers field include northwest–trending, high–angle, dextral strike–slip faults related to the
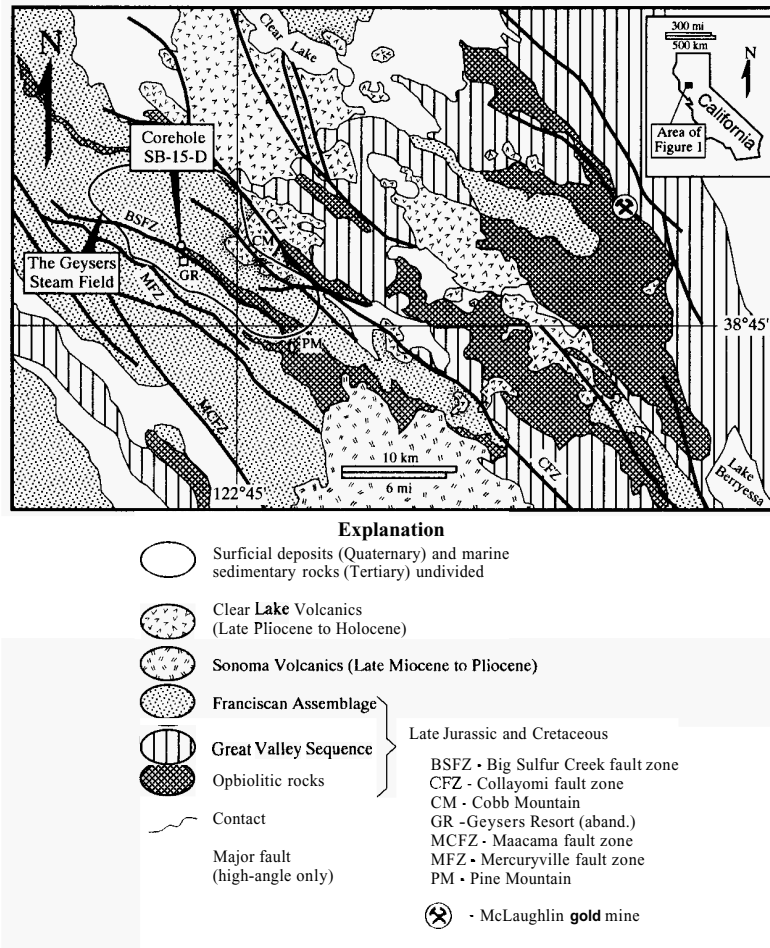
Figure 1. Location and generalized geologic map. Geology modified from McLaughlin (1978) and Donnelly-Nolan et al. (1993).

San Andreas system (McLaughlin, 1981; Oppenheimer, 1986), and low– to high–angle thrust faults of probable Franciscan age (McLaughlin, 1981; Thompson, 1992). Thompson (1992) has presented evidence that the surface expressions of most of these faults bear little relation to the major steam–bearing conduits intersected at depth. It should be noted, however, that the major Collayomi and Mercuryville fault zones (Fig. 1) apparently bound the steam field, respectively, to the northeast and southwest.

3. DRILLING — PLANS vs REALITY

Drilling plans for the GCP were governed by the need to ensure safety and work within budgetary constraints and mechanical limitations of the designated coring rig while meeting three principal project objectives: (1) maximize core recovery; (2) retrieve selected cores to the surface under pressure; and (3) convert SB–15 to an injection well at the close of coring operations. The initial design (Fig. **2A)** called for installation of new 21.9 cm casing within the original 27.3 cm production casing to a depth of about 140.2 m, followed by cleanout of the original open hole to total depth of 1260.3 m using a 19.7 cm rock bit. Two 17.8 cm casing segments, each about 609.6 m in length, would then be installed as a guide for the 12.7 cm CHD–134 coring rods, and coring would proceed until the project's allocated funds were exhausted.

Adverse initial drilling conditions forced a major modification of the original drilling plan. The first major problem: a downhole packer, required for cementing the 21.9 cm casing in place, slipped down the hole and required multiple fishing operations. The packer was successfully retrieved, but argillite–rich zones centered at 197.5 m and 348.4 m later caused severe sloughing problems, repeatedly bridging the hole and preventing the cleanout necessary to begin coring operations. Two cement plugs were set between 152.4 m and 235.3 m to cure the upper and most troublesome sloughing zone (Fig. 2B). ***An*** attempt to drill through the two plugs and reenter the original hole

failed, and at about 228.6 m a new hole sidetracked into 100% graywacke. It was decided at this point to abandon the original deep–coring plan and to use the sidetrack to core ahead in the shallow steam reservoir originally exploited by SB–15; this well had intersected productive steam entries as shallow as 330.7 m (Unocal drilling records). Rotary drilling of the sidetrack was extended to 250.8 m to ensure a separate course from the original well. 17.8 cm casing then was installed to a depth of 248.7 m as a guide for the CHD–134 coring rods, and rotary drilling was extended an additional 0.6 m with a 15.2 cm rock bit to confirm borehole integrity. Actual coring commenced at a depth of 251.5 m, and 236.8 m of continuous CHD–134 core *(8.5* cm dia.) was obtained to the final depth of 488.3 m. Core recovery was 100%. 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 point, a total loss of circulation occurred, and the hole was drilled to total depth without drilling–fluid returns.

Coring in SB–15–D was accomplished with a Universal 5000 coring rig, utilizing a triple–tube wireline coring and core–retrieval system (Hulen et al., 1994). The key element of this system is a thin–walled, longitudinally split (stainless steel) or seamless (aluminum) inner liner in a wireline–retrievable inner tube. The core is guided into this liner as drilling proceeds. When the liner is full, **or** when downhole conditions prevent further advance of the hole, the inner tube is drawn to the surface using the wireline. The liner is then gently pumped from the inner tube. This technique is superior to conventional wireline coring in two important ways. First, there is no need to hammer on the retrieved inner tube to dislodge jammed core, a practice which can destroy a rock's original texture. Thus, delicate features like fault gouges can be readily recovered and examined in a condition approximating *in situ.* Secondly, cores retrieved in seamless aluminum liners can be sealed immediately at the surface to minimize the escape of contained fluids. A number of these capped cores are being utilized by the GCP's collaborating investigators for short–range remote–sensing experiments (for example, X–ray CT
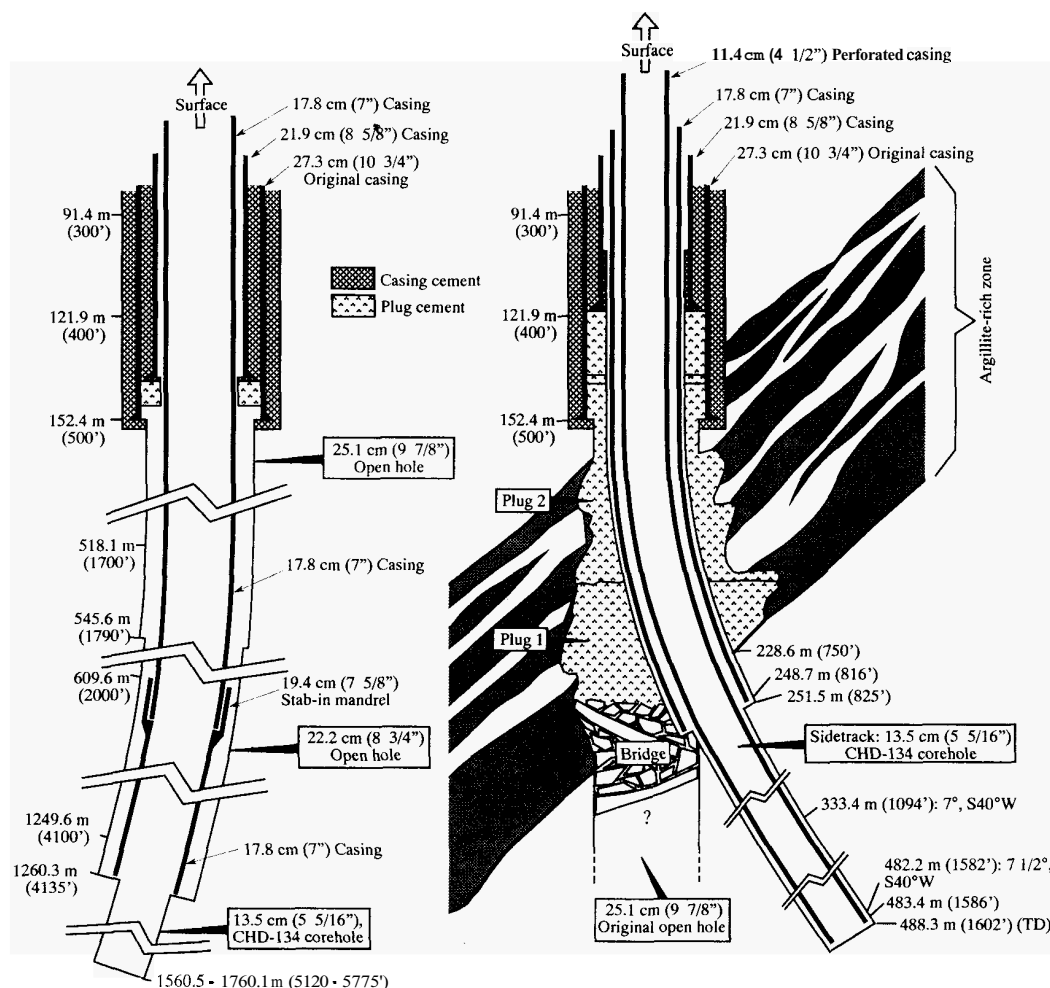
Surface

11.4 cm (4 1/2") Perforated casing

17.8 cm (7") Casing
21.9 cm (8 5/8") Casing
27.3 cm (10 3/4") Original casing

Surface

17.8 cm (7") Casing
21.9 cm (8 5/8") Casing
27.3 cm (10 3/4") Original casing

91.4 m (300')

Casing cement
Plug cement

121.9 m (400')

152.4 m (500')

25.1 cm (9 7/8") Open hole

518.1 m (1700')

17.8 cm (7") Casing

545.6 m (1790')

609.6 m (2000')

19.4 cm (7 5/8") Stab-in mandrel

22.2 cm (8 3/4") Open hole

1249.6 m (4100')

17.8 cm (7") Casing

1260.3 m (4135')

13.5 cm (5 5/16"), CHD-134 corehole

1560.5 - 1760.1 m (5120 - 5775')

Figure **2A.** SB-15-D: Original design

91.4 m (300')

121.9 m (400')

152.4 m (500')

Plug 2

Argillite-rich zone

Plug 1

228.6 m (750')
248.7 m (816')
251.5 m (825')

Bridge

Sidetrack: 13.5 cm (5 5/16") CHD-134 corehole

?

333.4 m (1094'): 7°, S40°W

482.2 m (1582'): 7 1/2°, S40°W
483.4 m (1586')
488.3 m (1602') (TD)

25.1 cm (9 7/8") Original open hole

Figure **2B.** SB-15-D: Modified configuration and completion

scanning; Bonner et al., 1994), in order to establish the configurations and amounts of entrapped fluids as well as the nature of the pore networks hosting them.

The GCP was essentially trouble−free once coring was underway. Not only was complete core recovery attained, but two 3−m−long cores, centered at approximately 434.3 m and 486.7 m, were brought to the surface under pressurized (0.90 Mpa) conditions, in an experiment devised by Unocal's Eric Withjack (Hulen and Nielson, 1994). Tritiated water was added to the drilling system during coring of the upper sample to enable later determination of the extent of drilling−fluid invasion into the core. Both cores were immediately frozen in dry ice (solid CO_2) at the surface while under pressure to inhibit fluid escape, specially packaged in dry ice, and shipped to a laboratory for analysis of total liquid saturation. This experiment represents the first attempt to recover and quantitatively measure *in situ* fluid saturation in the reservoir rocks of a vapor−dominated geothermal system.

4. GEOLOGY AND INFERRED STEAM−RESERVOIR CONDITIONS

Sidetrack SB−15−D penetrated a rock sequence dominated by fractured, veined, weakly metamorphosed Franciscan graywacke with minor argillite (Fig. 3). This sequence is apparently disrupted in the corehole by two major, throughgoing fluid conduits. The upper conduit corresponds to the total lost−circulation (TLC) zone encountered during drilling at 417.3 m. A second conduit, in the interval 472.4−488.3 m (exact depth indeterminate), was inferred from a Sandia National Laboratories temperature survey. The survey was conducted immediately following cold water injection into the partially thermally reequilibrated corehole three weeks after drilling. Both the TLC zone and the inferred deeper fluid channel corresponded to abrupt downhole temperature decreases, presumably caused by greater invasion of the cold injectate into the formation at these locations. We believe it highly likely that had SB-15−D been drilled with

air rather than water−based "mud", both of these fluid−loss zones would have been steam entries.

The graywacke−argillite sequence hosting these fluid conduits is clearly of turbiditic origin, an interpretation made for similar rocks in the northwest Geysers by Sternfeld (1989). The graywackes are fine to medium (and rarely coarse) grained, and commonly show graded bedding and load structures. The interstratified argillites — metashales and metasiltstones — are dark gray to black, organic−rich rocks with flame structures locally present at contacts with overlying graywackes. The argillites in the lower portion of the hole appear more competent than those at higher elevations, commonly breaking across rather than along bedding planes or micaceous microshears. The apparently greater competence of the deeper argillites could be due to metamorphic recrystallization, hydrothermal alteration, or a combination of both processes. This textural discrepancy may help explain the difference between Geysers steam−reservoir rock and overlying caprock, when both occur in the same lithologies. Less competent caprock argillites (metashales) would absorb applied stresses by slippage along bedding planes and microshears, thereby remaining relatively impermeable. More competent reservoir argillites would respond to the same stresses by brittly fracturing, with resultant increase in porosity and permeability.

The entire length of the SB−15−D core is weakly to intensely fractured (Fig. 3), but much of the fracturing appears to be drilling−related. Many fractures are hackly and subperpendicular to the core axis, and probably represent a type of core "disking", a phenomenon caused by drilling−induced relief of overburden pressure. Numerous other fractures occur along generally high−angle veinlets, but even these may be largely artificial. Several such veinlet−controlled fractures were observed to form or to widen spontaneously as the core cooled to ambient temperature following retrieval. Other high−angle fractures cutting the core are decorated by dip−slip, oblique−slip, and strike−slip slickensides. Although some geoscientists have asserted
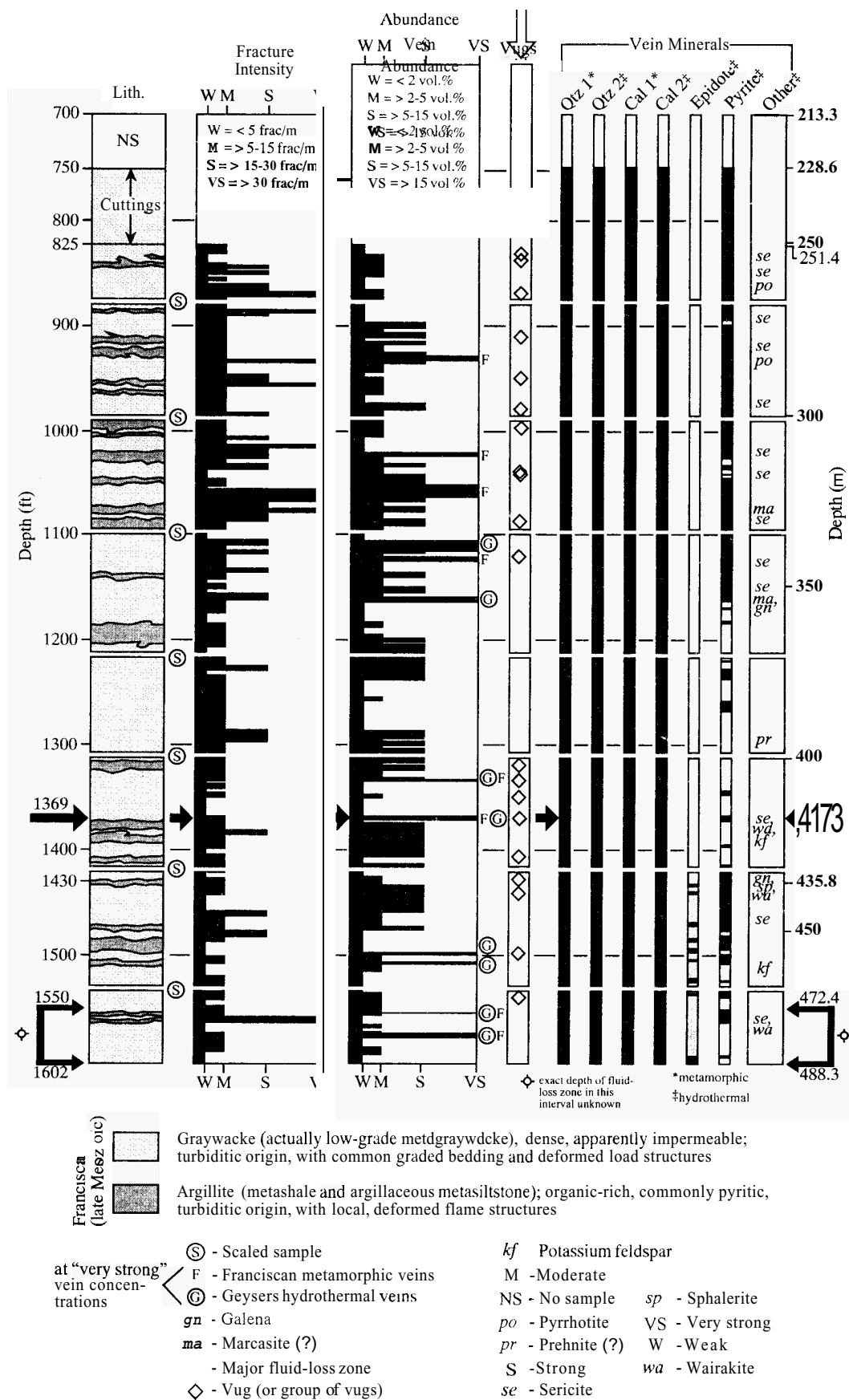
Figure 3. Summary field geologic log for corehole SB-15-D. Geology by Jeff Hulen, Dennis Nielson, Dave Serr, Richard Dickerson, Gene Suemnicht, Pat Dobson, and Tom Powell.

that slickensided fractures in core are almost always drilling−induced (e.g. Blackbourn, 1990), we believe that those in the SB−15−D core are natural features. The stresses applied to the rock by the triple−tube coring system are considered insufficient for the production of slickensides.

Two types and relative ages of veinlets are common in the SB−15−D core. Older veinlets, with a wide variety of forms, are randomly−oriented and up to several cm in width. They appear megascopically to consist entirely of massive, milky−appearing white quartz and calcite, and have been interpreted as Franciscan regional−metamorphic features (Lambert, 1976; Sternfeld, 1981, 1989; Hulen et al., 1992). Younger veinlets, by contrast with their older counterparts, are readily detached from their walls and are commonly refractured. They are generally high−angle (relative to a plane normal to the core axis), with straight margins and commonly uniform widths (average 0.5−1.5 mm). These veinlets consist dominantly of colorless and clear to semi−transparent white euhedral quartz and calcite (commonly the bladed or "fishscale" variety) and pyrite. This assemblage is locally accompanied by potassium feldspar, white to light gray−green micaceous−appearing clay (iillite and mixed−layer illite/smectite and chlorite/smectite), wairakite, prehnite (?), and (below 435.8 m) epidote, with trace to minor amounts of pyrrhotite, chalcopyrite, galena, sphalerite, and possibly marcasite (arsenopyrite?). Most or all of these minerals were deposited by the high−temperature hot−water system which preceded the current vapor−dominated regime (Sternfeld, 1981, 1989; McLaughlin et al., 1983; Moore, 1992).

Certain minerals and textures observed in the younger SB−15−D veinlets are indicative of physical/chemical conditions during mineralization. The epidote found below 435.8 m implies depositional temperatures of at least 220−240°C (Browne, 1984). The bladed calcite occurring throughout the core indicates that the mineralizing fluids were at least intermittently boiling (Tulloch, 1982). Individual calcite blades are commonly corroded (R. Fournier, pers. comm., 1994), and some are coated with sericite (illite or mixed−layer illite/smectite). We interpret the calcite etching and sericite as evidence that the veins were invaded by late−stage, mildly acidic steam condensate.

The veinlets in the SB−15−D core locally contain prominent vugs up to several cm (average <1 cm) in diameter. The vugs are of two types and origins. Irregular to lobate vugs in the older (Franciscan) veinlets appear to have formed by hydrothermal dissolution of metamorphic calcite. These cavities are typically lined with the same secondary phases (for example, bladed calcite) which form the younger Geysers hydrothermal veinlets. The late−stage veinlets also contain angular, irregular vugs resulting from incomplete fracture filling. The TLC zone at 417.3 m coincides with a composite Franciscan metamorphic and Geysers hydrothermal vein cluster containing large numbers of both types of vugs.

5. DISCUSSION AND CONCLUSIONS

Despite adversity, the drilling phase of the GCP successfully achieved its three prime objectives. Over 200 m of continuous core were obtained, at least a large portion of which was retrieved from within the vapor-dominated geothermal reservoir. Two cores were brought to the surface and frozen under pressure to preserve the rocks' indigenous fluids. Finally, 11.4 cm perforated casing was installed to a depth of 483.4 m, to prepare the hole for use as a water injector. Several suites of samples were specially sealed on site for collaborating investigators' complementary permeability, porosity, fluid saturation and composition, thermal, and hydrothermal−history investigations (Hulen and Nielson, 1994). These studies, anticipated to span 1−3 years, should furnish a wealth of new reservoir data useful to steam−field operators for improving forecasts of steam supply and character for the field's remaining duration.

The full extent to which SB−15−D penetrates The Geysers reservoir remains to be established, but several lines of evidence suggest that much of the corehole is in steam−reservoir rock. The two fluid−loss zones at 417.3 m and in the interval 472.4−488.3 m almost certainly would have been steam entries if air had been the drilling fluid, so the rock between 417.3 m and total depth (488.3 m) is by definition within the reservoir. The initial steam entry in SB−15, the original production well, occurred even higher, at 330.7 m. We do not know the orientation of the controlling conduit for this and several slightly

deeper entries in SB−15, but since the sidetrack must be very close to the original well at this depth, we believe it likely that the reservoir extends upward to at least this level in both holes.

The new Geysers corehole certainly samples only the uppermost portion of the graywacke−hosted steam reservoir, most of which, field−wide, is devoid of calcite (Walters et al., 1992; Hulen et al., 1992; Moore, 1992). Franciscan calcite in most of the reservoir has been replaced by epidote and other calc−silicates or has been hydrothermally leached. Younger hydrothermal calcite is found only in the reservoir's upper reaches. Both metamorphic and hydrothermal calcite are common throughout the SB−15−D core (Fig. 3), with the former variety only locally leached to form vugs. Epidote occurring with calcite in the lower portion of the corehole signals approach to deeper and more typical, calcite−free steam−reservoir rock.

At this stage of our investigation, we cannot assess the degree to which fractures in the SB−15−D core contributed to reservoir porosity and permeability. Despite use of the triple−tube coring system and careful handling of the retrieved core, it is clear that a large number of these fractures were created or enhanced by drilling−induced or drilling−released thermal or mechanical stresses. The common hackly disk−like fractures described above are certainly artifacts. Many fractures along preexisting, high−angle hydrothermal veins, if not newly−formed, were enlarged during drilling and subsequent cooling of the core (some of these fractures opened with an audible "snap" as they were being examined). The sealed cores now being scanned through their encasements (for example, Bonner et al., 1994) will certainly provide additional data for characterizing the **SB−15−D** fracture network. However, for future Geysers (and similar) coring projects, we suggest that borehole imaging logs would also be valuable for measurement of fracture orientations and apertures *in situ*

The triple−tube coring system utilized for the GCP did permit recovery of delicate features like clay−rich fault gouges and spongy−textured carbonate−dissolution networks which would otherwise have been destroyed. Moreover, many of the 3 m cores retrieved intact by this method hosted hundreds of fractures, and would have been rubble had conventional wireline coring been employed. *Also*, in this high−temperature environment, triple−tube coring was the only practical way to collect sealed samples such as those being utilized for fluid−saturation and related experiments by the GCP's collaborating investigators. We strongly endorse the use of this coring method for similar drilling projects in the future.

The GCP core is archived at the Earth Sciences and Resources Institute Geothermal Sample Library. One longitudinal half−split of the core is available for judicious sampling in support of legitimate research; interested investigators are encouraged to contact Jeff Hulen or Dennis Nielson.

This project has proven the utility of continuous wireline coring as a tool for exploration in The Geysers and similar vapor-dominated geothermal regimes. It is highly probable that deep (>1500 m) wireline coring into the heart of The Geysers steam reservoir could be smoothly and successfully accomplished.

6. ACKNOWLEDGEMENTS

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core photography. Pat Dobson and Tom Powell of Unocal and independent geologist Gene Suemnicht provided valuable core–logging assistance. An anonymous reviewer contributed numerous helpful suggestions for improving the manuscript's content and clarity. Illustrations by Bob Turner.

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