A Dual Hypothesis for Thermal-Fluid Advection in the Northern Steamboat Geothermal Field, Nevada—Upflow in Ancient Breccia Pipes; Distributed Outflow in a Low-Angle Extensional Fault Zone

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Keywords

Steamboat Hills, Steamboat geothermal system, Nevada, Basin and Range province, thermal aquifers, low-angle extensional faulting, detachment faulting, "flat faults," listric faulting, fractures, stockworks, breccias, breccia bodies, breccia pipes, hydrothermal alteration, advanced argillic, intermediate argillic, phyllic, propylitic, silicification, veins, euhedral crystals, mineralization, porphyry Cu-Mo, chalcopyrite, molybdenite, magmatic-hydrothermal, thermal-fluid flow, advection, upflow, outflow

ABSTRACT

Results from drilling and geologic logging of six recently completed, shallow- to intermediate-depth wells in the northern Steamboat geothermal field strongly support the premise (Hulen and Johnson, 2004; Johnson and Hulen, 2005) that commercial thermal-fluid entries in this traditionally shallow (<350 m) part of the resource are controlled by an areally extensive, low-angle extensional fault zone. The new geologic data—when integrated with corresponding static temperature/pressure logs and other borehole information—additionally suggest that this gently-inclined, fault-controlled thermal aquifer could be fed from greater depth by an upflow zone exploiting relict permeability in a Cu-Mo-mineralized, magmatic-hydrothermal breccia pipe of probable late Cretaceous age.

Key findings underpinning our new dual hypothesis for thermal-fluid advection at Steamboat can be summarized as follows: (1) As confirmed by each well, the reservoir rock in this part of the field is late Cretaceous Sierran granodiorite; (2) A moderate-temperature (that is, within the 150-180°C range) commercial thermal-fluid entry zone was encountered in all six wells (separated by up to 1.6 km) at ~1200 m elevation and within ~350 m of the modern ground surface. This entry zone (one of lost-circulation when drilled) is typically but not invariably signaled at shallower depths by silicified cataclasite along with euhedral quartz crystals in epithermal veins and breccia cements; (**3**) Above the fluid-entry zone (but not systematically linked to it), the granodiorite in at least three of the wells hosts highly anomalous combined concentrations (0.1-1.4% over 3-m depth intervals) of relatively coarse-crystalline (up to 3 mm) molybdenite and chalcopyrite; (4) The one well drilled through the entry zone and deeper into the granodiorite encountered—as anticipated and below 540 m depth—the sole, spent-fluid injection zone for the entire developed southern sector of the Steamboat field. The injection zone is identified here, for the first time, as a highly porous, chalcopyrite- and molybdenite-bearing granodiorite breccia overprinted by drusy epithermal quartz. The breccia is texturally reminiscent of those found in Mesozoic to early Cenozoic, Cu-Mo-mineralized breccia pipes at numerous locations along the North and South American cordillera. Many of these ancient pipes have surprisingly sizable relict porosities, and if placed conceptually in a modern geothermal system would certainly channel (or store) correspondingly high thermal-fluid volumes: This may be the actual scenario at Steamboat.

The occurrence of Steamboat's shallow productive permeability in a crystalline igneous host rock at essentially the same elevation in six wells up to 1.6 km apart—not to mention repetition of this occurrence in previously-drilled wells—is beyond the realm of coincidence. We contend that this now well-confirmed phenomenon (1) provides nearly unequivocal evidence that the producing horizon here is a major low-angle fault zone; and (2) enhances the odds that similar structures will emerge as important reservoir controls in numerous geothermal systems known and yet to be found throughout the Basin and Range province.

It seems clear that our evolving model of the Steamboat geothermal system must now take into account not only these "flat" thermal aquifers, but also the possibility that deeper thermal fluids here may travel opportunistically in ancient breccia pipes. The (now) more steeply-inclined of these pipes, "beheaded" by permeable low-angle faults, could channel modern hot-water upflow into these structural aquifers for broad distribution throughout the Steamboat resource. As displacements on the low-angle faults are unknown, the locations of the breccia-pipe "heads" are equally conjectural. We

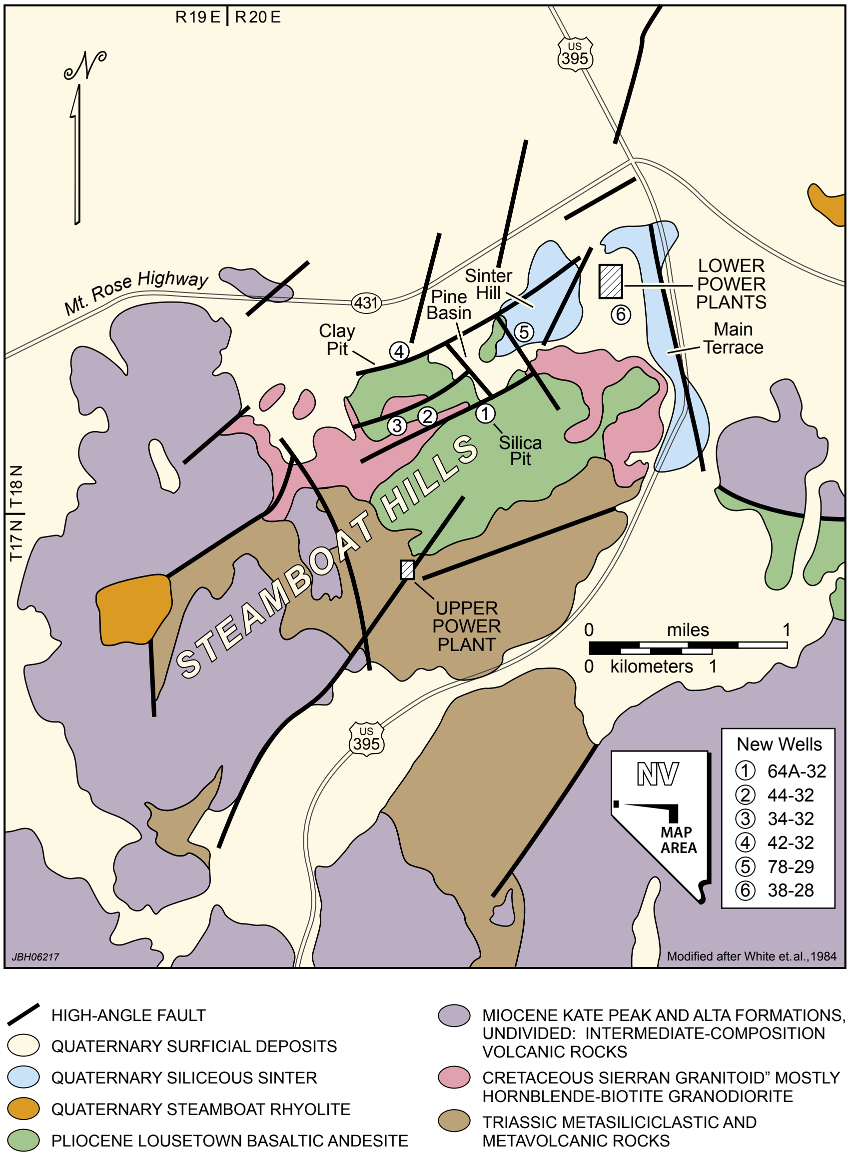

Figure 1. Highly simplified location and geologic map of the Steamboat Hills, showing approximate positions of recently completed geothermal wells and other features discussed in the accompanying text.

speculate that the latter features would have been ideal foci for Steamboat's well known Quaternary phreatic explosions.

Introduction

Five production wells (34-32, 38-28, 42-32, 44-32, and 78-29; Figure 1) and a replacement injection well (64A-32; Figure 1) have been completed recently by ORMAT Nevada, Inc., in the Steamboat geothermal field. All six wells are commercial successes. 78-29 now supplies ~170°C reservoir fluid to the new 20MW$_e$, Richard Burdette (Galena I) power plant. 64A-32 has supplanted aging adjacent injector Cox I-1 (not illustrated). The other new production wells will provide thermal fluid to the planned Galena II power plant, and perhaps, along with additional wells yet to be drilled, an envisioned Galena III facility.

From a basic research perspective (not entirely detached from the commercial view), the six study wells have provided valuable new insight into the Steamboat field's hitherto cryptic reservoir controls. We are in the second year of a multidisciplinary research investigation, sponsored jointly by the Department of Energy (DOE; Office of Geothermal Technologies) and ORMAT, aimed at better understanding (1) the nature and significance of low-angle fractures and fracture domains in natural hydrothermal systems of the western United States; and (2) the bearing of such structures on exploration for and development of Enhanced Geothermal Systems (EGS), widely believed to be "the future for power from the Earth" (e.g., Nathwani and Creed, 2002).

Low-angle faults and fractures could be among the more important thermohydrologic elements in western U.S. geothermal systems. The proposed (Hulen et al., 2004; Johnson and Hulen, 2005) premier example of control by these features on thermal-fluid flow is the Steamboat geothermal field (Figure 1), located in the Steamboat Hills, about 20 km south-southeast of Reno, Nevada. The Steamboat system is hosted principally by Mesozoic metamorphic and crystalline igneous rock, yet its productive thermal aquifers are demonstrably subhorizontal (e.g., Mariner and Janik, 1995; DeRocher, 1996). In an earlier report on this phenomenon (Johnson and Hulen, 2005), we (1) extended our investigation of the nature and origin of such "flat-fracture" domains through detailed geologic mapping and field observation in the western Steamboat Hills; and (2) described exposures of actual and likely gravity-slide blocks in the Hills, particularly as these outcrops might relate to the configuration of major thermal-fluid channels at depth.

The five new production wells studied in detail for this phase of our investigation penetrated fracture systems typical of the northern, traditionally shallower, portion of the Steamboat resource beneath (1) the "Clay Pit" (Figure 1); (2) the basaltic andesite-covered gentle northeastern slopes of the Steamboat Hills; (3) the western portion of Pine Basin; (4) Sinter Hill, a largely chalcedonic sinter mound; and (5) the area between Sinter Hill and the "Main (sinter) Terrace". The deeper injection well, near the "Silica Pit" (Figure 1), encountered not only the shallow thermal aquifer, but also a deeper high-permeability zone utilized for years in now-abandoned Cox I-1 to inject the bulk of the southern Steamboat field's spent production fluids. New geologic data and insight from the six new wells has led to significant revision of our conceptual model of the geologic framework and tectonic-magmatic-hydrothermal history of the Steamboat geothermal system; and of the subsurface permeability architecture controlling the system's consistently productive, moderate- to high-temperature thermal-fluid flow.

Regional Geologic Setting

The Steamboat Hills (Figure 1) comprise an east-northeast-oriented group of low-relief, rounded, and conspicuously hummocky hills just east of and slightly separated from the steep eastern range front of the Sierra Nevada (here called the Carson Range). The Hills are part of the Carson Segment of the Walker Lane (Stewart, 1988), at this latitude a structurally intricate, ~100 km-wide belt separating the Sierra Nevada microplate from the "typical" Basin and Range to the east (e.g., Parsons, 1995). The Carson Segment is characterized by northeast-trending, high-angle, left-lateral, strike-slip to oblique-slip faults. These structures are believed to facilitate displacement transfer between the northerly-trending, oblique-slip faults at the Sierra Nevada range front and the northwest-trending strike-slip faults that are the signature features of the Walker Lane as a whole.

The oldest rocks exposed within the Carson Segment are Late Triassic to Jurassic metasiliciclastic and metavolcanic rocks (Stewart, 1999), intruded extensively by Jurassic to Cretaceous stocks, plugs, and dikes ranging in composition from diorite to granite, and emplaced as satellitic plutons flanking the giant composite Sierra Nevada batholith. These older rocks are overlain unconformably by the medial to distal portions of regionally extensive, Oligocene to early Miocene, felsic ignimbrite sheets erupted from caldera sources farther inland to the east and southeast. Overlying the erosionally dissected ash-flow tuffs are andesitic to dacitic flows and flow breccias and minor lacustrine sedimentary rocks of the Miocene (18-15 Ma) Alta Formation (Castor et al., 2002). Alta-volcanic intrusive equivalents—plutons including the Davidson diorite in the nearby Comstock mining district—are locally exposed throughout the region. The Alta Formation is overlain by a second, similar, major intermediate-composition volcanic sequence, the Miocene (15-12 Ma) Kate Peak Formation (Vikre et al., 1988; Castor et al., 2002). Younger volcanic units throughout the Carson Segment are much more local in distribution, and range in composition from basalt to rhyolite. Representatives of this younger volcanic group found in the Steamboat Hills are discussed later in this report.

Geology and Thermohydrology of the Steamboat Hills and Vicinity

Note*—This section differs little from its counterpart in Johnson and Hulen (2005). It is updated from the earlier manuscript, but is included here mainly for clarity and context, and so that the present paper can serve as a "stand-alone" document for ensuing investigation of the Steamboat geothermal system.*

The geology of the Steamboat Hills (Figure 1) has been described in detail by White et al. (1964) and White (1968), classic papers that provide the basis for the following synopsis and discussion.

Lithology

Mesozoic (probably Triassic) siliciclastic to calcareous metasedimentary rocks and minor intermediate-composition metavolcanic rocks exposed widely in the southeastern half of the Steamboat Hills (Figure 1) are intruded by a composite stock consisting of at least three phases of hornblende- and/or biotite-bearing Sierran granitoid of probable late Cretaceous age (Flynn et al., 1993). These rocks are overlain locally in the study area by andesitic flows, flow breccias, and lahars assigned both to the Alta and Kate Peak Formations (Figure 1). The 2.2-2.5 Ma Lousetown Basaltic Andesite unconformably overlies both formations, and includes olivine basalt flows as well as pyroxene andesite. Lousetown cinder cones mark vent locations at the crest of the Hills. The Steamboat Hills are co-axial with a chain of 1.12-1.52 Ma rhyolitic volcanic centers (Silberman et al., 1979) extending from near the western edge of the knolls (Figure 1) to a point about 15 kilometers to the east-northeast. The 1.12-1.15 Ma rhyolite dome in the western Steamboat Hills is too old to be the intrusive equivalent of a felsic magma chamber still providing heat for the active geothermal system. However, this chamber could readily have heated a prior manifestation of the system in the not-too-distant past.

All of the above units are blanketed locally by Pleistocene to Holocene surficial deposits, including fan and stream gravels, glacial outwash, and lacustrine sediments. Gravels near the sinter deposits are opal-cemented. Phreatic-explosion lithic tuffs are found within and adjacent to the northern Steamboat Hills, and are likely present above the granitic basement in several of the geothermal wells studied for this phase of our investigation.

Late Pliocene to Holocene Hot-Spring and Phreatic-Eruption Deposits

The Steamboat geothermal field is famous for its siliceous sinter mounds and notable for its phreatic-eruption deposits (e.g., White et al., 1964). The sinters, about a square kilometer in aggregate areal extent, range from wholly chalcedonic varieties likely pre-dating the Lousetown Basaltic Andesite, to entirely opaline types considered to be mid-Pleistocene to Holocene in age. Radiocarbon dating of pollen and plant fragments in opaline sinter penetrated by a northern Steamboat corehole yielded ages ranging from 6.3 ka to 11.5 ka (Lynne et al., 2003). The thickest Steamboat sinter accumulations clearly mark major long-lived hydrothermal discharge zones.

Quaternary phreatic-eruption craters and associated lithic-pyroclastic debris have been documented unambiguously at the northern edge of the Steamboat Hills (White et al., 1964), and have long been suspected by ORMAT geoscientists to occur locally and more cryptically elsewhere in the field. Later in this report, we will discuss "sandstones," in some of the new production and injection wells, that are much more likely to be texturally equivalent phreatic-explosion tuffs and corresponding, subterranean microbreccias.

Structure

High-angle faults mapped or inferred from photolinears in the mostly "float" (colluvium; talus; skree)-covered Steamboat Hills are of three principal orientations—northeast, northwest, and northerly (White et al., 1964). The northwest- and northeast-trending faults mirror, respectively: (1) the right-lateral, strike-slip, principal displacement zones of the Carson Segment of the Walker Lane Belt; and (2) the left-lateral, strike-slip to oblique-slip faults that are kinematically linked to the former structures (see above and Stewart, 1988). Northerly-trending high-angle normal faults—so-called "Basin-and-Range" structures—are associated with the prominent and similarly-oriented opaline sinter deposit of the "Main Terrace," along and flanking U.S. Highway 395 at the eastern edge of the Hills (Figure 1). However, the youngest hot-spring vents in the Main Terrace clearly formed in northwest-trending, high-angle tension gashes.

The Steamboat Gravity Slides

In-progress geologic mapping by the authors and Gregory D. Nash (EGI) has revealed that much of the Miocene Kate Peak Formation volcanic cover (at least 8 km^2) in the western half of the Steamboat Hills (Figure 1) is actually chaotic breccia in a previously much more extensive gravity-slide complex derived from the Sierran highlands to the west. Clasts in the gravity-slide breccia range from centimeter- to 20-m-size, and include not only Kate Peak andesites and lahars but also small amounts of Sierran granitoid and Triassic metamorphic rock. A basal part of the slide breccia, consisting of intensely fractured and locally rubblized metasiliciclastic rock a little west of the central crest of the Hills (Figure 1), until recently was commercially mined—without the need for explosives (Peter van de Kamp, 1995, personal communication)—for road ballast and other aggregate applications. A main goal of our investigation is ascertaining the relationship (if any) between these large-scale gravity slides and shallow, subhorizontal, thermal-fluid aquifers in the northern Steamboat Hills.

Hydrothermal Alteration and Mineralization

The rocks of the Steamboat Hills have been affected extensively not only by the modern geothermal system, but by a succession of older systems active at unknown intervals since probably the late Cretaceous. The gaudy, exposed, advanced argillic (or "acid-sulfate") alteration spatially associated with late Quaternary siliceous sinter is broadly contemporaneous with these hot-spring deposits, but is still an active process (White, 1968): Steaming ground and fumaroles genetically affiliated with the advanced argillic alteration are prominent features of the modern geothermal field.

The advanced argillic alteration affects Cretaceous granitoid, the Lousetown Basaltic Andesite, the Alta and Kate Peak Formations, and surficial deposits including phreatic lithic tuff. This type of alteration, in the extreme case, is notable for complete destruction or transformation of all major rock-forming phases except quartz, resulting in a soft, porous, commonly whitish and powdery aggregate dominated by the quartz with kaolinite and alunite (Schoen and White, 1967; Schoen et al., 1974), and locally accompanied by native sulfur and cinnabar.

In northern Steamboat geothermal wells, advanced argillic alteration gives way progressively downward into: (1) a less acid-stable, smectite-rich argillic assemblage; (2) an underlying mixed-layer illite-smectite (I/S) assemblage; then (3) propylitically altered and locally sericitized (I/S and illite), silicified, and (rarely) adularized host rock (White et al., 1964; Schoen and White, 1974). Geologic mapping, well-logging, and mineralogic analysis completed by the authors since these pioneering studies has shown that all of these geologically recent alteration assemblages overprint more coarsely-crystalline clay-sericite (quartz-I/S), phyllic (quartz-illite or -muscovite), and propylitic alteration that must have developed in the older hydrothermal systems.

The Geothermal System

Although high-angle faults prevail at the surface of the Steamboat Hills (Figure 1), the principal producing thermal-fluid aquifers (155-235°C) at depth are clearly subhorizontal features (van de Kamp and Goranson, 1990; Sorey and Colvard, 1992; Mariner and Janik, 1995; De Rocher, 1996; Johnson and Hulen, 2005). These gently-dipping and likely fault-controlled aquifers form two tiers—a deeper, higher-temperature (200-235°C) zone at an average depth of about 900 m in the vicinity of the "upper power plant" (Figure 1); and a shallower, moderate-temperature (155-180°C) tier that now variously supports or will support the "lower power plants" at the northeastern edge of the Steamboat Hills. Van de Kamp and Goranson (1990) and DeRocher (1996) suggested that these thermal aquifers are the productive portions of two separate geothermal systems. Sorey and Colvard (1992) and Mariner and Janik (1995), on the other hand, provided compelling geochemical evidence that the two "tiers" are actually interconnected portions of the same system.

Typical production from the "shallow-tier" thermal aquifer is about 8000 liters per minute of dilute (~3000 ppm total dissolved solids), sodium-chloride water at a temperature of about 165°C from a major fracture zone in granodiorite at an elevation of ~1200 m (data from ORMAT field-development records). In this typical well, temperatures below the producing fracture zone show a slight progressive reversal down to the borehole's total depth. In cores from the "slim holes" drilled in this part of the field, the structures controlling major thermal-fluid entries are seen to comprise fractures with individual apertures up to several centimeters in width.

Major upflow zones feeding the lower and upper tiers of the Steamboat geothermal system have been hypothesized (e.g., Mariner and Janik, 1995), but not actually encountered. It has long been assumed that the "parent" upflow for the system is beneath the higher-temperature (~900 m) lower-tier thermal aquifer in the vicinity of the upper power plant (Figure 1). However, none of this area's numerous deep wells (up to ~1.6 km) have encountered evidence for such a feeder.

Based on spatial relationships among hydrothermal alteration, siliceous sinter, and radiometrically-dated volcanic rocks, Silberman et al. (1979) estimated that the geologically recent Steamboat geothermal system began to form at ~3 Ma. These authors conceded that if this age is realistic, the system almost certainly has been intermittently rather than continuously active for such a long span of time. In other words, the system has been repeatedly rejuvenated, either by influx of new magma batches, or through re-faulting and re-fracturing during periods of particularly intense seismicity, enabling "deep-circulation" heating. Multiple episodes of hydrothermal activity are recorded in the Steamboat Hills by: (1) Extinct hot-spring vents in portions of the field distant from recent hot springs; (2) hydrothermal alteration clearly pre-dating the Lousetown Basaltic Andesite in some portions of the field, but just as clearly post-dating the formation in other sectors; (3) intense alteration at most thermal-fluid entries, but minimal alteration at some. The evidence for long-term but intermittent hydrothermal activity at Steamboat permits the possibility that structural controls for this activity have also varied with time. It is within this context that we examine the potential roles of low-angle extensional faults, gravity slides, and ancient breccia bodies in the Steamboat field's intricate hydrothermal evolution.

Geology of the New Wells

Methods and Procedures; General Observations and Comments

The new wells at Steamboat were drilled in the northeastern part of the field, where thermal-fluid production has traditionally been from shallow elevations on the order of 1200 m (ORMAT field-development records). Three of the wells (34-32, 42-32, and 44-32; Figure 1) were completed in a previously undrilled region west of the historic Silica Pit; and two production wells (38-28 and 78-29) were drilled in the already partially developed Sinter Hill-Main Terrace area (Figure 1). A replacement-injection well (64A-32; Figure 1) relevant to this study had been drilled in 2004 in close proximity to deteriorating injector Cox I-1 (not illustrated), which for years had been accepting, without apparent limit and at a rate of several hundred thousand kg/hr, all the spent production fluid from the deeper and hotter lower-tier thermal aquifer in the southern part of the field. All six of the new wells were commercial successes.

Detailed geologic descriptions and logs for two of the new wells (34-32 and 64A-32; Figures 2 and 3) and summary descriptions of two others (42-32 and 44-32; Figure 1) from among the drilled six are the basis for further discussion. For each of these wells, lithology and hydrothermal alteration/mineralization, along with evidence for structural or hydrothermal disruption (gouge, crush microbreccia, veinlets, and variously-textured breccias), were used in combination to help constrain active and extinct fluid channels. Modern commercial thermal-fluid entries were identified using a variety of parameters including: those noted above; information from drilling (e.g., lost-circulation zones); and static temperature/pressure profiles.

Lithology

The six subject wells penetrated mostly hornblende-biotite granodiorite (Figures 2 and 3), which in the northern Steamboat field is the host rock for the shallow-tier thermal aquifer. The granodiorite is medium-crystalline, and consists primarily of quartz, K-feldspar, plagioclase, and biotite, with accessory hornblende and magnetite and trace to minor amounts of titanite (sphene). In wells from which shallower cuttings were collected, the granodiorite is overlain by Lousetown Basaltic Andesite flow rocks, breccias, and affiliated scoria; and by arkosic sandstone or what could be, just as readily, compositionally equivalent, phreatic lithic tuff (Figures 2 and 3). If the latter characterization is correct, the tuff was probably erupted from vents such as the well-known one at the northern edge of the Steamboat Hills.

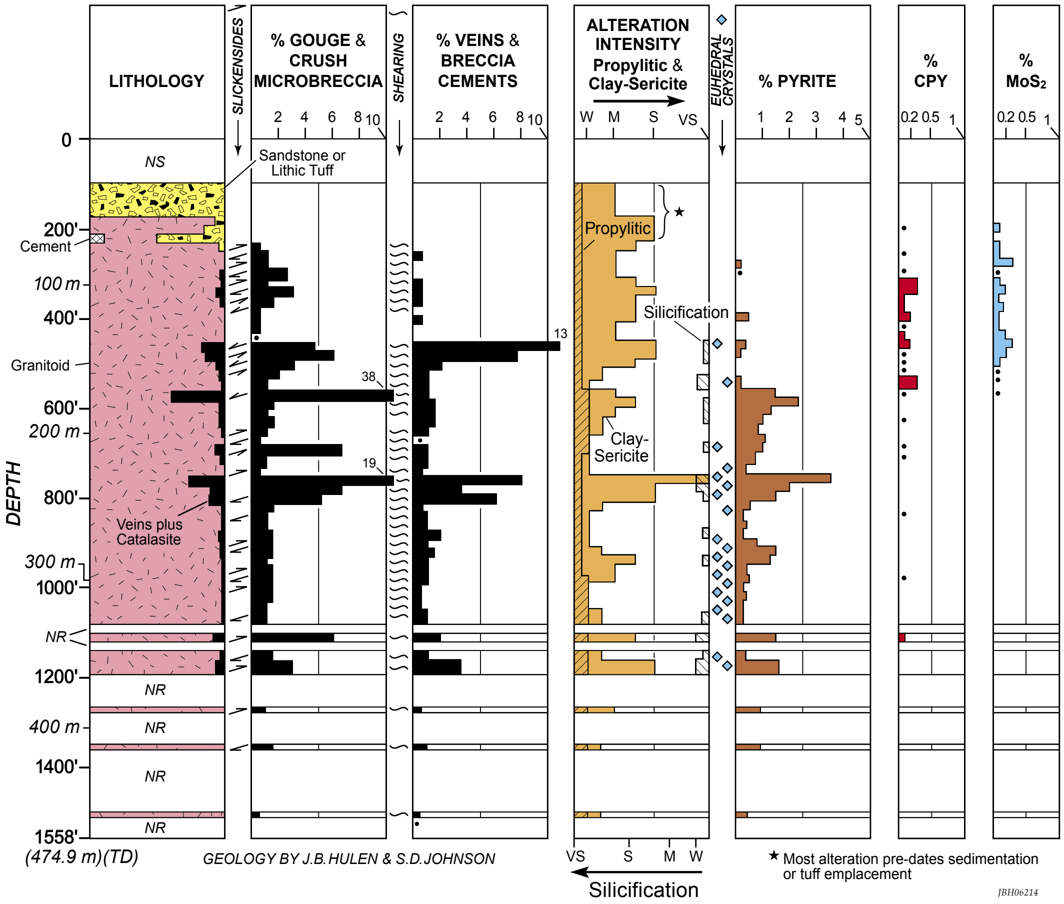

Figure 2. Summary geologic log for production well 34-32, in the north-central Steamboat geothermal field (Figure 1). Please also see the accompanying Explanation. As targeted, the well encountered a "flat-fault"-controlled, moderate-temperature thermal aquifer at about 340 m depth. In this well and the others shown on Figure 1, the geologic parameters signaling the deeper presence of the thermal aquifer are silicified cataclasite and euhedral quartz crystals in epithermal veins. Molybdenite and chalcopyrite in the granitoid host rock of 34-32 are distinctly *anti*-correlated with the fluid-entry zone, and are believed to record a magmatic-hydrothermal system of likely late Cretaceous age.

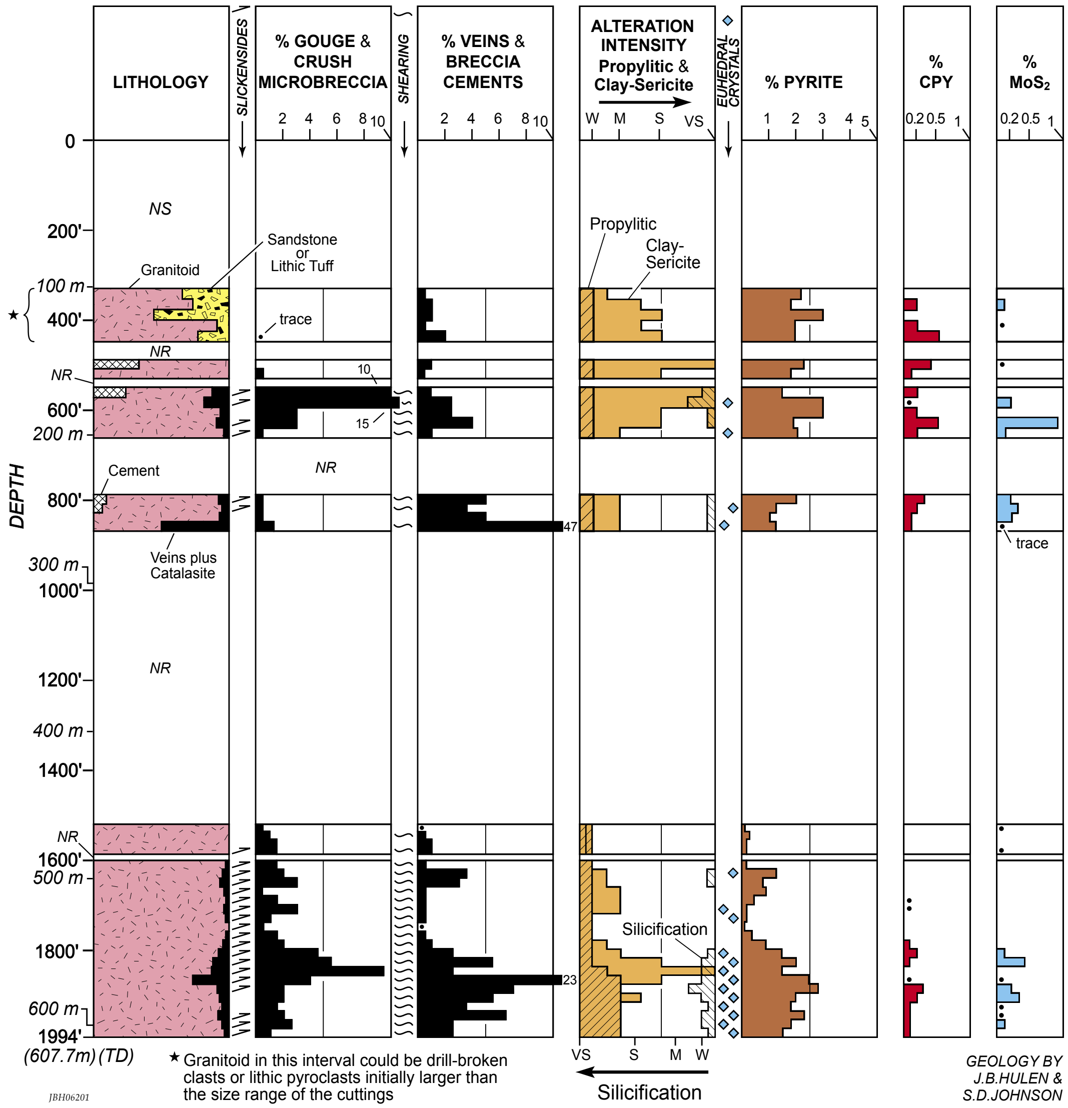

Figure 3. Summary geologic log for Steamboat injection well 64A-32 (Figure 1). Please also see the accompanying Explanation. The "upper-tier" structural aquifer penetrated in well 34-32 (Figure 2) was also encountered in 64A-32, but at about 270 m depth. The deepest portion of the well, in the depth range 540 m to >608 m, coincides with a highly porous and permeable, Cu-Mo-mineralized breccia, clasts of which are coated with drusy epithermal quartz. This zone accepts—apparently without limit—all of the spent production fluid from the deeper and hotter southern part of the Steamboat field (in the vicinity of the "upper power plant"; Figure 1). We hypothesize that the injection-zone breccia is part of a late Cretaceous, magmatic-hydrothermal breccia pipe with considerable relict porosity.

Evidence for Rock Rupture

Granodiorite in the study wells is extensively disrupted by gouge and crush microbreccia (as distinct from drilling-produced "bit gouge"; Hulen and Sibbett, 1982), features that appear in nearly every 3-m sample examined (Figures 2 and 3). This pervasive cataclasite distribution recalls that observed in large-scale gravity slides (French, 1993) and in detachment-fault upper plates (e.g., Hulen et al., 2005, 2005b) that have moved significant distances but have remained relatively intact while escaping wholesale rubblization.

Evidence for profound dilational faulting in the study wells was the total loss of drilling fluid that took place in all six boreholes (Figures 2 and 3) at ~350 m depth. Occurring in the same narrow elevation range (1150-1250 m) in wells spaced up to 1.6 km apart, these lost-circulation zones coincide with the shallow-tier thermal aquifer penetrated throughout the northern Steamboat geothermal field.

Hydrothermal Alteration

The study-well granodiorite is pervasively hydrothermally altered to a greater or lesser extent (Figures 2 and 3). Propylitic and clay-sericite alteration affect the intrusive in almost every sample. "Clay-sericite" alteration for this paper is a provisional classification based strictly on examination of the cuttings with a conventional binocular microscope. From this perspective, clay-sericite encompasses argillic (smectite), intermediate argillic (mixed-layer I/S), and phyllic (quartz-illite or quartz-muscovite) alteration, as well as superimposed, still-active, advanced argillic (kaolinite ± alunite) alteration in the upper reaches of the boreholes. Planned petrographic and X-ray diffraction studies of the altered rocks will enable more refined characterization of the constituent alteration types and their textural and paragenetic relationships.

The clay-sericite and propylitic alteration assemblages encountered in the study wells are clearly the combined products of the active and extinct hydrothermal systems. Based on empirical mineral/temperature relationships (Browne, 1996), various secondary-mineral geothermometers for the wells indicate hydrothermal paleotemperatures of at least 300°C in altered rocks where modern temperatures nonetheless are as low as 40°C.

Dilational Breccias and Microbreccias

The granodiorite penetrated in the study wells has locally undergone intense dilational brecciation, recognizable by a distinctive "jigsaw-puzzle" texture (e.g., Sillitoe, 1985) even at the scale of the drill chips. This texture is especially common in the 60-m-thick breccia zone at the bottom of well 64A-32 (Figure 3). Evidence for voluminous open space in this breccia

EXPLANATION FOR SUMMARY GEOLOGIC LOGS OF STEAMBOAT GEOTHERMAL WELLS 34-32 AND 64A-32

Lithology

●	ARKOSIC SANDSTONE OR PHREATIC LITHIC TUFF, POORLY-SORTED, VERY FINE- TO COARSE-GRAINED; OVERALL LIGHT GRAY-BUFF; WEAKLY CONSOLIDATED; QUARTZ AND FELDSPAR GRAINS ANGULAR TO SUBANGULAR; BIOTITE GRAINS “SHREDDY,” INITIALLY SHINY BLACK BUT NOW LIGHT TO MEDIUM BRONZY-BROWN; CLASTS ARE WEAKLY CEMENTED IN PART WITH WHITISH CLAY ± MICROCRYSTALLINE GRAYISH PYRITE; ASSOCIATED, >1.5 MM GRANITOID CHIPS ARE PROBABLY DRILLING-DISAGGREGATED PEBBLES, COBBLES, OR LITHIC PYROCLASTS.
●	HORNBLENDE-BIOTITE GRANITOID, PROBABLY GRANODIORITE; FINE- TO MEDIUM-CRYSTALLINE; SUBHEDRAL-GRANULAR TEXTURE; 7-10% BIOTITE,1-2% HORNBLENDE, 15-20% QUARTZ, 1% MAGNETITE, TRACE TITANITE (SPHENE); REMAINDER PLAGIOCLASE>POTASSIUM FELDSPAR.
◐	VEINS, VEINLETS, BRECCIA CEMENTS, GOUGE, AND CRUSH MICROBRECCIA, UNDIVIDED.

Alteration

▨	PROPYLITIC: MAFIC MINERALS PARTIALLY TO COMPLETELY ALTERED TO CHLORITE ± MINOR CALCITE AND RARELY EPIDOTE; FELDSPARS (ESPECIALLY PLAGIOCLASE) WEAKLY ALTERED TO CHLORITE ± TRACE TO MINOR CALCITE AND EPIDOTE; TITANITE (SPHENE) GENERALLY ALTERED TO LEUCOXENE ± CALCITE; SECONDARY ALBITE LIKELY, BUT CONFIRMATION WILL REQUIRE PETROGRAPHY.
■	CLAY-SERICITE: FELDSPARS (ESPECIALLY PLAGIOCLASE) ALTERED TO MIXED-LAYER ILLITE/SMECITE ± MICROCRYSTALLINE MUSCOVITE (ACCOMPANYING MOLYBDENITE AND CHALCOPYRITE); OVERPRINTED BY ARGILLIC AND ADVANCED ARGILLIC ALTERATION ABOVE ABOUT 200 m DEPTH.
☐	SILICIFICATION: GOUGE, CRUSH MICROBRECCIA AND (LESS COMMONLY) FELDSPARS AND MAFIC MINERALS ALTERED TO MASSIVE MICROCRYSTALLINE QUARTZ (MOSTLY <50 µm GRAINS)

Abbreviations

BTE	BIOTITE
BXCF	BRECCIA-CEMENT FRAGMENTS
CAL	CALCITE
CHL	CHLORITE
CMT	CEMENT
CPY	CHALCOPYRITE
DIA	DIAMETER
FSP	FELDSPAR
GEN	GENERALLY
GG	GOUGE
HM	HEMATITE
HEM	HEMATITE
m	METERS
M	MODERATE
MED	MEDIUM
MFC	MAFIC
mm	MILLIMETERS
µBX	MICROBRECCIA
µXLN	MICRO-CRYSTALLINE
MoS_2	MOLYBDENITE
NR	NO (DRILLING) RETURNS
NS	NO SAMPLE
PY	PYRITE
S	STRONG
SER	SERICITE
SMPL	SAMPLE
TD	TOTAL DEPTH
VS	VERY STRONG
VVF	VEINS AND VEIN FRAGMENTS
XLN	CRYSTALLINE
XL(S)	CRYSTAL(S)
XRD	X-RAY DIFFRACTION

Symbols

%	PER CENT
⫽	SLICKENSIDES
•	TRACE
'	FEET
&	AND
◇	EUHEDRAL HYDROTHERMAL CRYSTALS
∽	SHEARING AND GRANULATION
µ	MICRO(N)
±	WITH OR WITHOUT
<	LESS THAN
≤	LESS THAN OR EQUAL TO
>	GREATER THAN

Alteration-Intensity Index

Apparent intensity	% of rock altered to secondary phases
VS	>50
S	20–50
M	5–20
W	1–5
VW	0.1–1
•	<0.1

JBH06216

is provided by clasts (up to 10 mm in diameter) almost entirely coated with epithermal drusy quartz. In some of the larger chips, the actual interclast pores are partially preserved in the drill-broken remains of quartz-cemented clast aggregates.

The jigsaw-puzzle textures of the deep 64A-32 breccias could indicate formation by (1) implosion in a dilational fault zone; (2) hydrothermal explosion; (3) rock collapse into an underground cavity; or (4) a combination of all these processes. Textures indicating granulation, shearing, and slickensiding in rock chips from this breccia zone would seem to support the fault-zone origin. However, these features clearly post-date the brecciation, and (as in the upper plate of the low-angle fault-controlled aquifer) could record pervasive (as opposed to fault-focused) post-breccia cataclasis.

The presence of significant amounts of molybdenite, chalcopyrite, and secondary muscovite in the deep 64A-32 breccia favors rock rupture by magmatic-hydrothermal mechanisms (modes 2 and 3 above). Many such breccias throughout the world are richly mineralized and cemented with a wide variety of hydrothermal phases (features recording high paleo-permeability). Those breccias are also commonly affiliated, genetically and spatially, with relatively coarse-grained phyllic alteration, as in 64A-32. The breccia bodies that still retain considerable relict porosity probably formed not by hydrothermal explosion, but by rock collapse into large (tens to hundreds of meters across) magmatic-vapor bubbles (Norton and Cathles, 1973). We will pursue this possibility for Steamboat in the “Discussion and Conclusions” section of the present report.

Hydrothermal Veins and Breccia Cements; Mineralization

Most cuttings samples from the study wells contain at least minor amounts of hydrothermal open-space-filling material, including hydrothermal veinlets and breccia cements along with whole drill chips of compositionally equivalent material (Figures 2 and 3). The latter are likely derived from veins and interclast cements that exceed the size of the cuttings (typically 0.5-5 mm). The open-space-filling minerals, accounting for up to 50% of 20-m-composite samples in the two exemplary wells, consist principally of quartz ± calcite and probably adularia in various proportions with lesser pyrite and marcasite (and probably other metallic phases). Calcite-rich veins appear “clean” and white, and typically contain only traces of of pyrite and marcasite. Quartz-rich veins are commonly “polluted” with rock debris, and have much higher sulfide concentrations (up to 10%), locally including conspicuous molybdenite and chalcopyrite.

In whole cuttings samples, combined amounts of molybdenite and chalcopyrite range from a trace to 1.4% over 6-m drilling intervals, and up to 2.5 % over 3-m intervals. These ore sulfides occur (1) as fine- to relatively coarse-crystalline (up to 3 mm), granodiorite-hosted disseminations without *apparent* fracture control; and (2) as similarly-textured crystals and crystalline aggregates with or without pyrite in massive translucent white quartz. Concentrations of the ore sulfides over intervals of tens of meters approach currently commercial grades in some porphyry Mo-Cu orebodies (say, 0.15% MoS_2 and 0.1% Cu).

Discussion and Conclusions

The occurrence of the shallow-tier thermal aquifer at essentially the same elevation throughout the northern Steamboat field—and in wells up to 1.6 km apart—exceeds the constraints of coincidence. We contend that this relationship provides nearly unequivocal evidence for shallow thermal-fluid distribution in a subhorizontal normal fault zone. Furthermore, there is no reason to believe that this is a rare phenomenon in western U.S. geothermal systems. It is highly likely that such gently-dipping fault-controlled thermal aquifers are integral elements of numerous moderate- to high-temperature geothermal systems identified and certainly yet to be found throughout the Basin and Range province.

Observations and measurements from our ongoing investigation of the Steamboat geothermal field to date have led us to the following conclusions, speculations, and revised conceptual geologic model (see also Figure 4) for the northern part of the field:

- The field's upper-tier thermal-fluid aquifer is a low-angle extensional fault zone spanning at least 3 km^2 and essentially confined throughout this area to the narrow elevation interval 1150-1250 m. Field mapping has revealed extensive low-angle faulting and gravity sliding throughout the Steamboat Hills (this paper and Johnson and Hulen, 2005), but at seemingly too high an elevation range for obvious connection to the upper-tier aquifer. Johnson and Hulen (2005) also noted widespread listric faulting at multiple scales throughout the Steamboat Hills. The larger of these listric faults conceptually could sole into the upper-tier fault zone; the smaller could bound rotated hanging-wall blocks. Additional detailed mapping should thoroughly test these possibilities.
- In drill cuttings and cores, the upper-tier aquifer is commonly but not invariably signaled at shallower elevations by anomalous concentrations of silicified cataclasite along with euhedral quartz crystals in epithermal veinlets and breccia cements (Figures 2, 3, and 4). The granodiorite hosting these features is altered to propylitic and clay-sericite assemblages not particularly well correlated with the aquifer.
- Porphyry-type Cu-Mo mineralization is found locally above the upper-tier aquifer. In this structural position, the mineralization shows no systematic relationship to the aquifer.
- On the other hand, similar Cu-Mo mineralization in injection well 64A-32 coincides directly with a 540 m to >608 m-deep, highly porous and permeable breccia (Figures 3 and 4) that is also the zone accepting the entire spent-fluid yield from the southern part of the Steamboat resource. This breccia "sponge" is likely of ancient magmatic-hydrothermal origin, but it has undergone subsequent cataclasis. Conceptually, this cataclasis could have taken place in the upper plate of a still-deeper sub-horizontal extensional fault zone. We suggest that this deeper "flat fault" could be the one controlling the Steamboat field's higher-temperature "lower-tier" thermal aquifer.

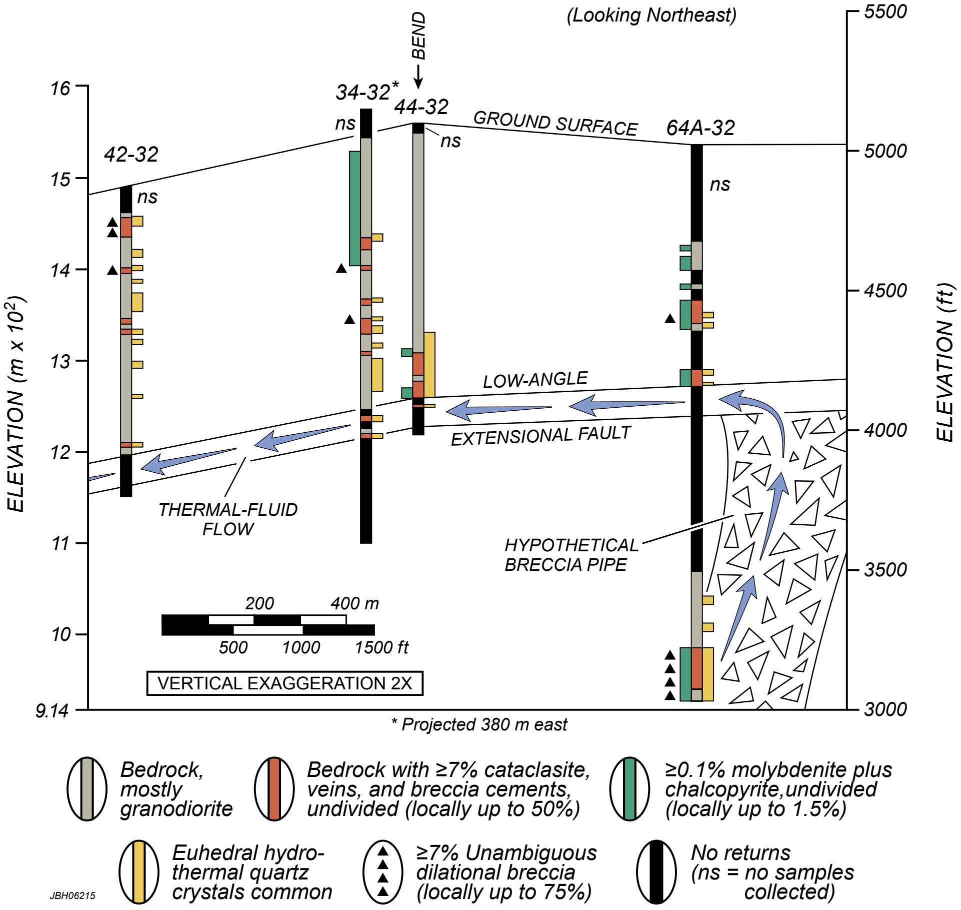

Figure 4. Revised conceptual model for thermal-fluid upflow and outflow in the northern part of the Steamboat geothermal field. Key elements of the model, based on recent drilling results, are (1) an upflow zone controlled by relict porosity and permeability in a fossil magmatic-hydrothermal breccia pipe channeling hot fluid into (2) an areally extensive low-angle extensional fault that truncates the top of the pipe. The "flat-fault" thermal aquifer, perhaps additionally fed from below by other such ancient breccia bodies, distributes hot fluid throughout the northern Steamboat geothermal field.

Based on these findings, we have modified our initial low-angle fault model for the Steamboat geothermal field to propose the following dual hypothesis: The upper-tier thermal aquifer is fed from below by one or more upflow zones opportunistically exploiting, as we surmise in well 64A-32 (Figure 4), breccia bodies ("pipes" for simplicity of reference) inherited from a long-extinct, Cu-Mo-bearing magmatic-hydrothermal system probably affiliated genetically with the late Cretaceous Steamboat granodiorite.

At the scale of the cuttings ($\leq$10 mm-diameter chips), the Cu-Mo-bearing breccia is texturally reminiscent of Mesozoic to early Cenozoic, porphyry-style breccia pipes such as those at Hanover-Fiero (southwestern New Mexico); Patagonia (south-central Arizona); and elsewhere along the North and South American cordillera (Norton and Cathles, 1973; Saegert et al., 1974; Norton, 1982; Sillitoe, 1995; and D.L. Norton, pers. comm., 2006). Textural relationships among breccia fragments and their drusy-quartz coatings in the deep breccias of well 64A-32 permissively point to much larger clasts (and correspondingly larger interclast pores) that were fragmented during the drilling process, and perhaps earlier during post-breccia cataclasis.

Despite their age, many of the ancient breccia pipes retain considerable interclast porosity. For example, La Caridad pipe (Sonora, Mexico), has abundant angular cavities ranging from 2 to 10 cm in diameter (Saegert et al., 1974). The Whim Hill and Lee Hill pipes in southwestern New Mexico's Santa Rita district have interconnected openings ranging "from pinhole- through football- to human-sized" (D.L. Norton, pers. comm., 2006), and the Four Metals pipe in southern Arizona's Patagonia district has been likened to "a rubble pile…[with] enormous open spaces" (Norton, 1982). If these older pipes were placed conceptually into a modern geothermal system, there is no doubt that they would readily store and transmit large volumes of thermal fluid. We contend that this could be precisely the case in the Steamboat geothermal field.

Figure 4 graphically portrays our revised northern Steamboat conceptual model. According to the model, gradually cooling, higher-temperature thermal fluids—initially heated by "deep circulation"—ascend in an upflow zone controlled by a fossil, Cu-Mo-bearing, probable late Cretaceous breccia pipe that has retained much of its initial porosity and permeability. The breccia pipe has been "beheaded" by the areally extensive low-angle fault zone that is also the Steamboat field's upper-tier thermal aquifer. Hot fluids in the truncated upflow zone are diverted into this gently-dipping structure beneath a fractured and brecciated but overall hydrothermally sealed caprock. With few exceptions, Cu-Mo mineralization above the low-angle fault zone is not obviously breccia-controlled. However, this upper-plate mineralization could readily be part of the larger magmatic-paleohydrothermal system within which the breccia pipe formed.

The location of the displaced upper part of the conceptually beheaded breccia pipe is still a matter for conjecture, as the direction and magnitude of displacement on the truncating low-angle fault zone remain to be determined. In the realm of pure speculation, such pipe tops, if they closely approached or even breached the recent ground surface, would have been ideal foci for Steamboat's well-known and locally large-volume late Cenozoic phreatic eruptions.

The roles that the newly-recognized, older mineralized breccias at Steamboat play in the field's deeper permeability architecture are also conjectural subjects at this stage of the investigation. Certainly, the hotter, "lower-tier" thermal aquifer, like its shallower counterpart to the north, could be fed from even deeper levels in a pipe-controlled upflow zone. There is also the intriguing possibility that the postulated but enigmatic connection between the upper- and lower-tier aquifers (see Mariner and Janik, 1995) is a breccia-pipe segment truncated at its top *and* base by low-angle extensional faults.

Final Note: Drilling Success and Technology Transfer

Results of this DOE-ORMAT-supported investigation have demonstrated beyond doubt the practical value of government-industry collaborative geothermal research. While clearly (as DOE-specified) relevant to the entire geothermal industry, our low-angle-fault research also has been instrumental in ORMAT's recent Steamboat drilling success. Drilling plans for the three new "step-out" wells west of the Silica Pit (Figure 1) took into account proximity to previously mapped high-angle faults, but the actual drilling target was the shallow, "flat-fault" thermal aquifer hypothesized in our 2004 grant proposal (Hulen and Johnson, 2004), and essentially confirmed shortly thereafter. All three wells penetrated the productive, gently-dipping structure in the predicted narrow depth range, and all three wells are set to supply copious volumes of thermal fluid for the Galena II electric-power plant.

While no longer considered part of DOE's EGS program in the strictest sense, this research project and its findings thus far are clearly germane to the conceptual creation of Enhanced Geothermal Systems. The locations, configurations, and controlling local stress regimes of known or potential "Steamboat-type" low-angle fracture zones in extensional tectonic regimes can be discounted only at risk in the design and implementation of EGS fracture-stimulation procedures.

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