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Subsurface Stratigraphy, Structure, and Alteration in the Senator Thermal Area, Northern Dixie Valley Geothermal Field, Nevada— Initial Results from Injection Well 38-32, and a New Structural Scenario for the Stillwater Escarpment

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ABSTRACT

Two injection wells (DV 38-32 and DV 27-32) in the Senator thermal area of the northern Dixie Valley geothermal field supply all the injectate reaching the field's northernmost group of production wells. These injectors are also the only wells in the field drilled between the surface trace of the northeast-trending Dixie Valley fault zone, at the base of the Stillwater Range escarpment, and the surface projection of the main geothermal reservoir centered on the fault zone 2-2.5 km to the southeast in Dixie Valley. As such, the Senator injection wells provide new insight into the field's structural geometry, alteration, hydrothermal history, and present-day thermohydrology and injection characteristics.

The shallower (301 m) of the two injection wells, 27-32, penetrated alluvium encapsulating an apparently intact block of Jurassic Boyer Ranch Formation quartzite. The deeper (1168 m) injector encountered the following lithologies, in sequence: alluvium (101-412 m; no samples above the shallower depth); Boyer Ranch quartzite (412-800 m); a mix of the quartzite and Jurassic granodiorite to quartz diorite (granitoid) of the Humboldt igneous complex (800-900 m); essentially all granitoid (900-1055 m); cataclasite (900-1055 m); a massive calcite-fluorite-quartz-adularia vein (1055-1079 m); total lost-circulation (no sample, 1079-1082 m); and Triassic phyllite (1082-1168 m). The cataclasite, mostly derived from a granitoid protolith, contains a downward-increasing component (up to at least 15 vol.%) of brick-red, Tertiary tuffaceous volcanic rock and its comminuted equivalent. The alluvium is intensely silicified below 167 m depth; the quartzite is weakly silicified and sericitized; the granitoid is moderately calcite-chlorite-sericite-albite altered; the cataclasite is intensely calcite-chlorite-sericite-altered and locally silicified; and the phyllite beneath the thick vein underlying the cataclasite is essentially unaltered.

The occurrence in well 38-32 of the red Tertiary volcaniclastic beneath a thick Jurassic rock sequence, given constraints provided by geologic mapping and by rock units penetrated in nearby boreholes, requires a novel structural scenario for Dixie Valley. We suggest that this reverse stratigraphy is most readily (though not uniquely) explained by a large (km-scale) gravity-slide block that collapsed in the past from an oversteepened proto-Stillwater escarpment to glide valleyward over a downdropped fault block with the red volcaniclastic at its top.

The occurrence of 244 m of silicified alluvium in the upper part of well 38-32, and at least 200 m of the same alteration in the alluvium of 27-32, appear to document an earlier and more energetic phase of the Dixie Valley hydrothermal system. Liquid-to-vapor ratios of primary fluid inclusions in quartz in the 38-32 alluvium at about 235 m depth suggest an entrapment temperature in excess of 200°C, and perhaps up to 230°C or even higher. The modern temperature at this depth is slightly higher than 140°C, and that temperature is artificially high because of production-induced fluid drawdown and creation of a vapor cap above this portion of the Dixie Valley (liquid-dominated) geothermal system. Fluid inclusions in the deep vein penetrated by 38-32 also record a cooling trend: Inclusions in early vein calcite were deposited at a minimum temperature of 276°C; those in youngest quartz were precipitated by a boiling hydrothermal fluid at a temperature of about 209°C. For comparison, the modern temperature at the depth of the vein is about 200°C.

Cool groundwater injected into wells 27-32 and 38-32 takes up to 140 days to reach the production wells of section 33. This is ~1.5 to 4.5 times as long as it takes injectate to reach production wells in the central and southern parts of the field from other injection wells a similar distance away. The prolonged return times for the Senator wells imply more tortuous injectate return paths. These convoluted conduits conceptually (1) could direct fluid flow initially away from, rather than toward, the producers; and (2) could involve fluid-diverting blockages along the Dixie Valley fault and allied structures.

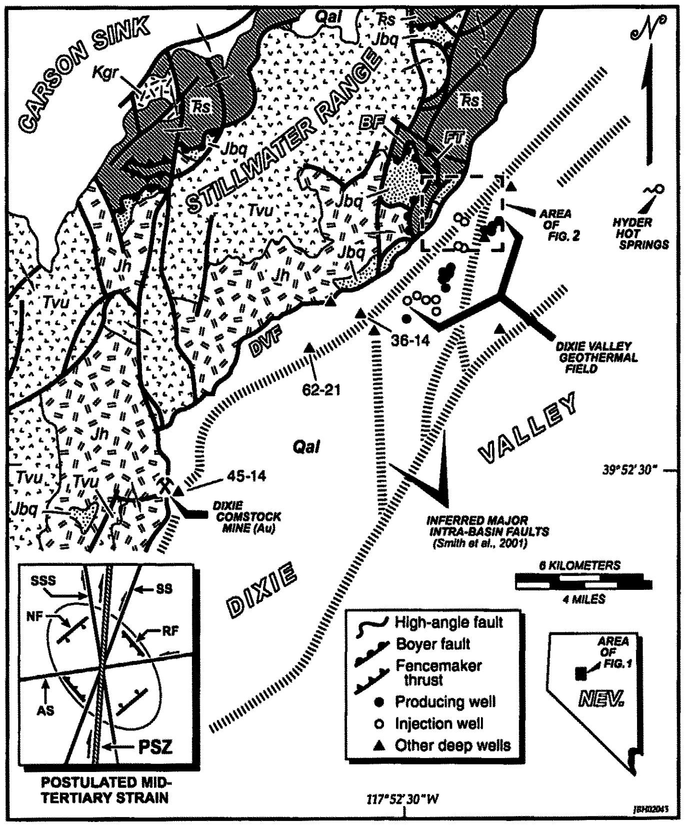

Figure 1. Generalized geologic map of the Stillwater Range, with inferred major intra-basin faults in adjacent Dixie Valley. Geology of the range synthesized and simplified from Willden and Speed (1974), with modifications in the eastern escarpment of the range near the Dixie Valley geothermal field from Plank (1997). Intra-basin faults inferred from integrated geological and geophysical analysis by Smith, *et. al.*, (2001). Inset at lower left is a strain diagram (taken from Christie-Blick and Biddle, 1985) showing fault types and trends that ideally would accompany a right-lateral, principal shear (displacement) zone (*PSZ*) aligned parallel to northerly-trending major fault zones mapped through the Stillwater Range and inferred for Dixie Valley. Rock units abbreviated as follows: *Jh* – Jurassic Humboldt igneous complex; *Jbq* – Jurassic Boyer Ranch Formation (mostly quartzite); *Kgr* – Cretaceous granite; *Qal* – Quaternary alluvium, colluvium, and lacustrine sediments, undivided; *TRs* – Triassic sedimentary and metasedimentary rocks, undivided; *Tvu* – Tertiary volcanic rocks, undivided. Named faults identified as follows: *BF* – Boyer fault; *DVF* – Dixie Valley fault; *FT* – Fencemaker thrust. Additional abbreviations in the inset strain diagram as follows: *AS* – antithetic shear zone; *NF* – normal fault; *SS* – synthetic shear zone; *SSS* – secondary synthetic shear zone; *RF* – reverse fault.

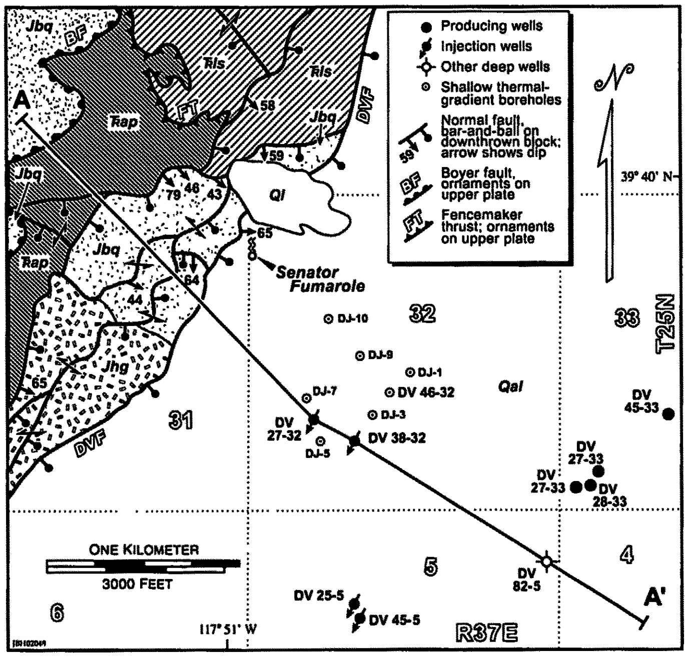

Figure 2. Geologic and borehole map of the Senator thermal area and northern Dixie Valley geothermal field with adjacent Stillwater Range escarpment (please refer to Figure 1 for location). Geologic mapping adapted from Plank (1997). Abbreviations and symbols as follows: *TRls* – carbonaceous limestones of the Triassic Star Peak Group (Silberling and Wallace, 1967); *TRap* –Triassic argillites and phyllites of the "Fumarole Canyon Sequence" (Plank, 1997); *Jbq* – Jurassic quartzite of the Boyer Ranch Formation; *Jhg* – gabbro, diorite, quartz diorite, and granodiorite of the Humboldt igneous complex (Speed, 1976; Dilek and Moores, 1995); *Ql* – Quaternary landslide rubble; *Qal* – Quaternary alluvial, colluvial, and lacustrine deposits, undivided; *BF* – Boyer fault; *DVF* = Dixie Valley fault; *FT* = Fencemaker Thrust.

Introduction

Injection well DV 38-32, completed in 2000 at a depth of 1168 m in the Senator thermal area of the northern Dixie Valley geothermal field (Figures 1 and 2), is one of the field's best performers, accepting injectate at a sustained rate of 127 liters per second at a relatively shallow injection depth (1080 m). Tracer testing has demonstrated that 38-32 communicates effectively with the "section 33" production wells (e.g., 28-33; Figure 2), although the rate of tracer return to the producers is relatively slow for the field (Rose, *et. al.*, 2002). Injection from 38-32 and a nearby, shallower (301 m), companion well, 27-32 (Figure 2), has partially restored production-induced reservoir pressure declines in the section 33 wells; even more auspiciously, the pressure enhancement continues to this day. There is plainly merit in gaining an improved understanding of the permeable subsurface conduit(s) that accept such copious quantities of fluid and are effectively connected with the geothermal reservoir. In this paper, we describe the subsurface geology of the Senator region with emphasis on injection well 38-32, and on those parameters most germane to reservoir permeability, porosity, and fluid flow.

Our study of well 38-32 has also brought to light several intriguing phenomena bearing upon the structural and hydrothermal history of the Dixie Valley field. For one thing, the well intersects Tertiary volcanic rocks beneath several hundred meters of Jurassic quartzite and granitoid, a relationship requiring, for Dixie Valley, a novel structural scenario. For another, 38-32 penetrates 260 m of densely silicified alluvium. The alteration and mineralization in this well and 27-32 apparently record an earlier and more vigorous stage of the Dixie Valley geothermal system. Finally, the principal injection zone in 38-32 is at the base of an apparently 24.4 m-thick, massive hydrothermal calcite-fluorite-quartz-adularia vein that may have developed in the Dixie Valley fault (DVF), believed by many to be the main producing fracture in several of the field's development wells. We will document each of these phenomena, and attempt to explain them in the context of the geothermal resource as well as the broader thermal and mechanical evolution of Dixie Valley and the west-central Basin and Range.

Geologic Setting

Ancient and Modern Fault Patterns

The Dixie Valley geothermal system is located at the western margin of Dixie Valley, a northeasterly-trending, sediment-filled structural trough separated from the Stillwater range, to the northwest (Figure 1), by the DVF, among the most recently active fault zones in this part of the Basin and Range province (Caskey, *et. al.,* 1996). The DVF (or more accurately stated, the DVF *zone*) hosts the 62 MWe geothermal system under production by Caithness Operating Co. At the surface, the DVF shows a zigzag trace dominated by northeasterly-trending segments separated by those oriented essentially north-south (Parry, *et. al.,* 1991; Vikre, 1994). Geologic mapping (e.g., Willden and Speed, 1974; Speed, 1976; Plank, 1997) has shown that this configuration is common throughout the Stillwater Range (Figure 1). The zigzag fault traces define a distinctly rhombic pattern that we address in more detail below.

To set the stage for a discussion of fault geometries and origins in the Stillwater Range and adjacent Dixie Valley, we acknowledge the influential paleomagnetic and geologic studies in the region by Hudson and Geissman (1987). These investigators presented compelling evidence from their work (1) that Middle Tertiary deformation here was probably transtensional; (2) that the transtensional stresses were induced by counterclockwise rotation of the west-central Basin and Range (perhaps up to 50°; Hudson and Geissman, 1991); and (3) that these stresses were accommodated largely by right-lateral strike-slip faulting along northwesterly-oriented segments of generally north-south-trending high-angle faults. We agree with these conclusions, but suggest further that the older transtensional fault pattern would have strongly influenced subsequent Basin-Range faulting and fracturing in the region regardless of regional stress reorientations.

Recent geological and geophysical investigations by Smith, *et. al.,* (2001) have shown that the N-S to NE-SW rhombic fault pattern of the Stillwater Range apparently also prevails within and beneath adjacent Dixie Valley (Figure 1). A major north-trending fault inferred by these researchers just southwest of the Dixie Valley geothermal field projects directly to the north into and through the range (Figure 1). This exposed northern projection of the structure hosts one of the largest Pleistocene-Holocene travertine mounds in the region (F. Goff, pers. comm., 2002).

The rhombic fault pattern mapped in the Stillwater Range and inferred for Dixie Valley is geometrically consistent with development in an ideal right-lateral transtensional strike-slip fault regime with the maximum principal horizontal stress (SH_{MAX}) oriented approximately NE-SW (Christie-Blick and Biddle, 1985; Sylvester, 1988). Based on bench experiments and classical geological examples (e.g., along the San Andreas fault zone; Sylvester, 1988), right-lateral transtensional regimes tend to produce distinctive faults with consistent angular relationships as shown in the inset to Figure 1.

We have oriented the theoretical right-lateral principal shear (or displacement) zone (PSZ) for the ideal transtensional regime subparallel to the major north-trending structures mapped through the Stillwater Range and inferred for Dixie Valley (Figure 1). Recalling that Hudson and Geissman (1987) have documented significant right-slip along NW-oriented portions of these structures, we suggest the possibility that such displacement may have affected more or less the entire lengths of the fault zones. The (apparently) missing direct evidence for the broader, additional displacement conceptually could have been obscured or obliterated by later dip-slip movement in the subsequent and still-prevailing extensional tectonic regime.

Provisionally accepting that the north-trending faults are in fact reactivated, right-lateral, transtensional wrench faults, then these master faults ideally should be accompanied systematically by subsidiary structures with the alignment and displacement noted on the Figure 1 inset. We find that the mapped and inferred faults, respectively, of the Range and Valley match this theoretical fracture pattern remarkably well. In particular, mapped, range-bounding normal faults and inferred, intra-basin faults of unknown displacement are commonly northeast trending, closely corresponding to the predicted trend for normal faults in the theoretical transtensional regime. Hickman, *et. al.,* (1997) demonstrate from *in situ* stress and fracture measurements in geothermal wells of the Dixie Valley geothermal field that fractures of this orientation are also the field's major open thermal-fluid conduits.

The right-lateral wrench-fault regime for this region is postulated by Hudson and Geissman (1987) to be Middle Tertiary in age. The corresponding SH_{MAX} for that regime theoretically would exceed the vertical stress and would be oriented roughly NE-SW (e.g., Christie-Blick and Biddle, 1985). Surprisingly, these stress conditions closely approximate those recently measured by Hickman, *et. al.,* (1997) for the basement rocks penetrated deep in wells 66-21 and 45-14, southeast of the currently producing geothermal field (Figure 1). According to these investigators, SH_{MAX} for the wells either matches or slightly exceeds S_V. It seems to us that the latter condition would promote the formation of north-trending strike-slip faults, or the strike-slip reactivation of earlier-formed structures with similar orientations. This observation may be consistent with the conclusions of Bellier and Zoback (1995), who cite geological field data and earthquake focal-mechanism evidence that 1954 displacements along the Dixie Valley and nearby Fairview Peak and Rainbow Mountain faults were principally oblique right-lateral.

Hickman, *et. al.,* (1997) contend that productive fractures in this region are likely to occur only when the configurations and magnitudes of modern principal stresses closely approximate those measured for selected producing wells in the geothermal reservoir, and that these configurations and magnitudes are those matching most closely those expected for the prevailing regional stress field of the west-central Basin and Range (e.g., Zoback and Zoback, 1989). From our preliminary reappraisal of stresses, earthquakes, and fault patterns in the Dixie Valley region, we suspect that this contention may be overly simplistic, and that: (1) many modern fractures and faults are simply reactivated structures formed in older stress regimes; in other words, once broken, and unless completely rehealed, these rocks would tend to fail again and again along those same fractures regardless of subsequent changes in stress orientation; (2) wrench-fault tectonics, with the potential for the creation or augmentation of auxiliary, deeply-penetrating extensional fractures, may have played (and may still play) more of a role in this region than researchers espousing a pure extensional origin for the Dixie Valley field may have envisioned.

Lithology

We have focused on the structural setting for the Dixie Valley geothermal field because faults and fractures are undeniably the major controls on thermal fluid flow and storage in this resource. The reservoir rocks are hard, intrinsically impermeable lithologies ranging from Miocene basalt through Jurassic quartzite and gabbro; these units produce commercially only where disrupted by faults and fractures (e.g., Benoit, 1997, 1999). The rocks for the most part are the same ones exposed in the Stillwater Range escarpment to the immediate west, and as mapped in detail by Plank (1997; see also Plank, *et. al.,* 1999); the reader is referred to these sources for more detailed lithologic information. It remains for us in this paper only to mention a key lithology penetrated by injection well 38-32 — a distinctive, brick red volcaniclastic noted previously only at the top of the Tertiary volcanic sequence concealed beneath about 1.5 km of alluvium and lake sediments in the section 33 production wells (Figure 2). We suspect this rock to be either nonwelded ash-flow tuff or a hyperconcentrated-flow- or debris-flow deposit derived from such a tuff. In either case, the volcaniclastic is almost certainly Tertiary in age. Unlike older (Mesozoic) volcanics mapped in the region, it is poorly indurated and contains sparse, uncollapsed pumice and bipyramidal, phenocrystalline quartz.

The Senator Thermal Area

Named for a prominent fumarole in alluvium, the Senator thermal area (Figure 2) has attracted interest during the last five years because of its recent increases in surface thermal activity and outgassing. These processes have severely stressed native shrubs in the aptly-named "dead zone", extending from the surface trace of the DVF in the Senator area to a region of weak fumarolic activity in subsidence-induced fractures in alluvium more than a kilometer to the southeast (Allis et al., 1999). This setting was explored in 1998 by two shallow slim-holes, 46-32 (TD 105 m) and 27-32 (TD 301 m)(Figure 2). Both holes encountered wet steam at temperatures near 150°C (Allis, *et. al.,* 1999).

Well 27-32 penetrates principally alluvium, but the alluvium encapsulates an apparently intact block of Jurassic Boyer Ranch Formation quartzite in the bottom half of the borehole. Both the alluvium and quartzite are silicified (Allis, *et. al.,* 1999), to the point where they superficially resemble one another in cuttings. Testing of 27-32 defined a zone of high permeability within the quartzite block at a depth of 209 m. A long-term tracer test showed that fluids injected into this zone at a sustained rate of 63 liters per second returned to the Section 33 production wells after 140 days (Rose, *et. al.,* 2001).

The deepest well (1168 m) in the Senator area (and the focus of our investigation) is DV 38-32. It is the only deep development well located beyond the main line of production and injection wells (Figure 1) penetrating the DVF at depth. The upper part of 38-32, to a depth of 101 m, was drilled initially in 1999 as a large-diameter well in search of water for injection and pressure augmentation of the geothermal reservoir. The well was unsuccessful in this regard, yielding only minor steam and hot water during air-lift stimulation.

On the basis of the successful injection history of well 27-32, a decision was made in mid-2000 to deepen 38-32 to a depth near 1000 m. The well was deepened (1) to seek fracture permeability associated with suspected intra-basin (or "piedmont") faults; (2) to utilize these permeable faults to expand the injection capacity of the Senator area; and (3) to better understand and define the subsurface geology of the Senator thermal area and "dead zone".

The deepening of well 38-32 was completed in December 2000. A completion diagram and pressure-temperature log for the borehole are shown as Figure 3. Despite locally excellent

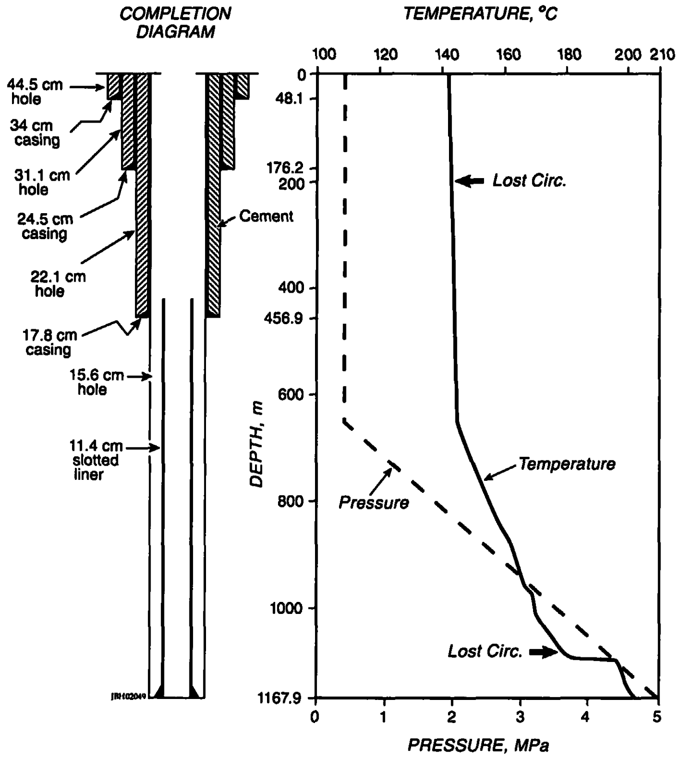

Figure 3. Completion diagram with static shut-in temperature and pressure logs for injection well 38-32. Please refer to Figure 2 for location.

permeability and temperatures reaching 203°C, the well did not sustain flow with air-lift stimulation. Only minor steam was recovered during flow testing. Difficulty in stimulating the well is attributed in part to the small-diameter completion and limited effective well-bore diameter. Currently, 38-32 is utilized for injection of cold augmentation fluid (ground water) as well as cooling-tower overflow. An injection rate of 127 liters per second has been sustained without difficulty for more than two years. A tracer test conducted by Rose, *et. al.*, (2002) demonstrated that the 38-32 injectate takes about 125 days to reach the section 33 production wells. This return time and that from 27-32 (140 days; Rose, *et. al.*, 2001) are significantly slower than the 30-115 day injector-to-producer tracer returns reported for the southwestern part of the geothermal field (Rose, *et. al.*, 2000). We will explore possible explanations for this discrepancy later in the paper.

Lithology and Alteration of Well DV 38-32

Detailed logging and petrographic analysis of cuttings from well 38-32 yielded a number of surprises. The first was that 244 m of rock initially thought to be Jurassic quartzite is actually silicified alluvium. The second was that the quartzite and underlying Jurassic granitoid rest upon cataclasite incorporating conspicuous fragments of a soft, red, Tertiary volcaniclastic. The third surprise, beneath the cataclasite, was a hydrothermal vein of immense apparent thickness (24.4 m); the base of the vein coincides with a total lost-circulation zone that is now the well's principal injection zone.

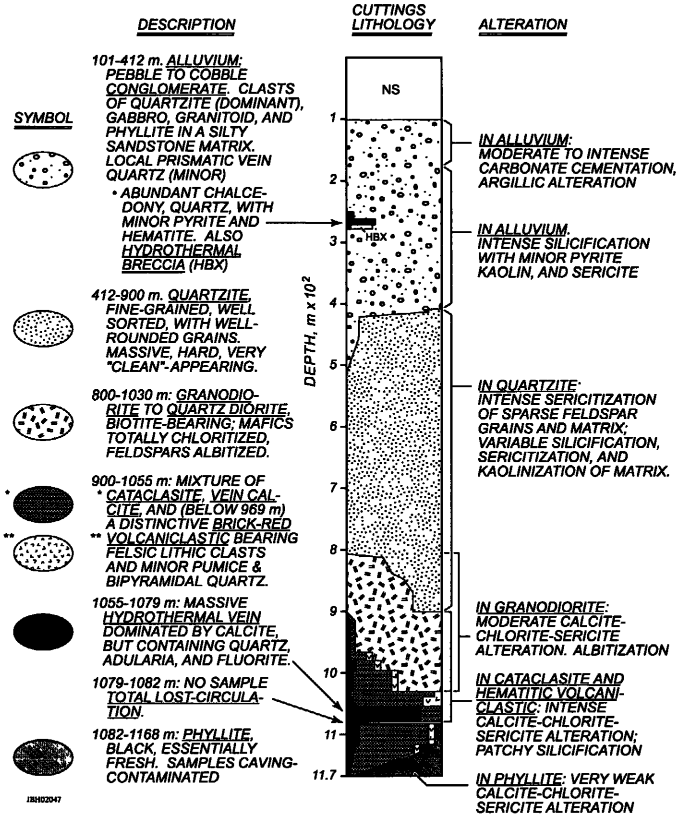

Figure 4. Generalized lithologic and alteration log for injection well DV 38-32.

38-32 penetrated six main lithologic units (Figure 4): (1) alluvium; (2) quartzite; (3) granodiorite or quartz diorite, collectively termed "granitoid"; (4) cataclasite and ultracataclasite; (5) a massive hydrothermal vein between 1049 m and 1079 m; and (6) phyllite between 1082 m and total depth at 1168 m. The interval 1049-1052 m was a total lost-circulation zone during drilling, and is now the principal injection conduit. The cataclasite unit beneath the granodiorite contains significant amounts of Tertiary tuffaceous volcaniclastic rock and its comminuted equivalent.

No samples were available from the surface to a depth of 101 m. Between that depth and 168 m, however, the well encountered semi-consolidated, clay-altered and carbonate-cemented, silty to sandy pebble conglomerate, with largely broken pebbles of quartzite, gabbro, diorite, and phyllite in a clay-rich, silty to sandy matrix. Between 168 m and 412 m, this conglomerate is highly silicified, superficially resembling the underlying quartzite. However, pebbles of the actual, "clean" quartzite are clearly distinguishable in the more lithologically variable and "dirtier" matrix of the alluvium. At about 260 m, the alluvial cuttings also contain minor hydrothermal breccia and vein (?) chalcedony. Silicification of the alluvial sequence is accompanied by pyrite, kaolin, and mixed-layer illite/smectite. The altered alluvium contains higher-than-background concentrations of gold, silver, and the so-called "pathfinder" elements like antimony and arsenic.

Underlying the alluvium, to a depth of 762 m, is Boyer Ranch quartzite, also prominent in the Stillwater escarpment to the west (Figure 2). The quartzite consists of >95% fine-sand-size, rounded quartz grains embedded in a matrix with various proportions of sericite, quartz, and minor kaolin. The rock is distinguished from alluvium by the former's brilliant pale yellowish- to salmon-white coloration and absence of darker-colored grains of phyllite, gabbro, and other lithologies.

The quartzite passes gradually downward into a medium-grained, biotite-bearing granodiorite or quartz diorite (granitoid; 762-969 m) that is moderately calcite-chlorite-sericite-albite altered. Original mafics in the granitoid are wholly chloritized, and original feldspars are altered to albite and sericite. The rock is tentatively identified as an intrusive phase of the allochthonous Jurassic Humboldt igneous complex (e.g., Dilek and Moores, 1995). Throughout its extent, the granitoid is accompanied by minor amounts of self-derived, commonly slickensided cataclasite.

This fault rock and even finer-grained ultracataclasite dominate the cuttings between 969 m and 1055 m. Surviving coarser chips in the comminuted debris are principally incipiently crushed granitoid, but include up to 15% hematitic, tuffaceous volcaniclastic rock. The volcaniclastic contains felsic to mafic lithic fragments, pumice, and scattered, bipyramidal quartz phenocrysts liberated from the matrix to survive as isolated grains. Chips of the granodiorite and the volcaniclastic in the cataclasite are commonly lensoidal in appearance and entirely bound by slickensided surfaces; they appear to be "augen" developed around more resistant portions of the protolith during crushing and granulation.

Beneath the cataclasite, and spanning the interval 1055-1079 m, is an unusually thick, massive, fine- to coarse-crystalline hydrothermal vein (Figure 4). The vein is dominated by calcite, but also contains fluorite, quartz (massive and prismatic), and adularia. The paragenesis is complex, but cross-cutting and infilling relationships indicate that the last phases precipitated were quartz, adularia, and bladed calcite.

Fluid inclusions in blocky (not bladed) calcite and quartz from the massive vein described above were analyzed by J.N. Moore (EGI, Univ. of Utah) in cuttings from the depth interval 1058-1061 m. Only secondary, two-phase, liquid-rich inclusions were found in the calcite. Homogenization temperatures for this carbonate ranged from 268°C to 283°C (average 276°C); salinities from 0.3-0.7 wt.% NaCl equivalent (average 0.6 wt.%, or 6000 ppm). Both primary and secondary inclusions were found in quartz encapsulating adularia; no differences in either homogenization temperature or salinity were found between the two inclusion types. Homogenization temperatures ranged from 208°C to 214°C (average 209°C); salinities from 0 to 0.5 wt.% NaCl equivalent (average 0.2 wt.% or 2000 ppm). The assemblage quartz + adularia (+ bladed calcite in this case) suggests deposition from a boiling fluid. Therefore, homogenization temperatures for the quartz-hosted inclusions represent the true temperatures of fluid entrapment.

The massive hydrothermal vein hosting the above-described fluid inclusions records a complex hydrothermal history that remains to be fully elucidated. At this stage of our investigation, however, we feel confident in stating that the older blocky calcite and fluorite record deposition from a non-boiling fluid that was: (1) slightly more saline than the modern geothermal reservoir (0.6 wt.% vs. ~0.2 wt.%); (2) much higher in temperature than the current value at this depth; and (3) heating rather than cooling prior to mineral precipitation (calcite and fluorite have retrograde solubilities). It also seems certain that the younger quartz, adularia, and bladed calcite were deposited from boiling water of essentially the same salinity as the modern geothermal reservoir, and at a temperature just slightly higher than presently prevailing at the depth of the vein (209°C vs about 200°C).

Immediately beneath the thick vein described above is a total lost-circulation zone (1079-1082 m; now the main injection conduit), then, to total depth (1168 m), black phyllite heavily contaminated with cuttings caved principally from the vein and overlying cataclasite. The phyllite is essentially unaltered, and differs little in appearance from argillites and phyllites of the Triassic "Fumarole Canyon Sequence" mapped by Plank (1997) in the upper plate of the Fencemaker Thrust in the Stillwater escarpment to the west.

Discussion and Conclusions

There are several intriguing questions raised by the rock sequence and hydrothermal alteration/mineralization encountered in well 38-32, and by the injection characteristics of this well and nearby 27-32: (1) Why is a comminuted Tertiary volcanic rock positioned here beneath a 557-m Jurassic rock package?; (2) Are the massive hydrothermal vein and accompanying total lost-circulation deep in 38-32 developed in the main DVF?; (3) If so, why is the fault so permeable here, yet so tight at greater depth in nearby well DV 82-5 (Figure 2; Hickman, *et. al.*, 2000)?; (4) How does the thick zone of silicified alluvium above the Jurassic sequence in 38-32 relate to the currently active hydrothermal system?; (5) Why does water injected into 27-32 and 38-32 take so long to reach the nearby section 33 production wells? We address each of these questions below.

(1) The Jurassic-Over-Tertiary Question

The first thing that comes to mind when unusual cuttings like those from 38-32 are encountered from a rotary drill hole is contamination. For example, the cuttings could be caved from higher in the borehole. There are two reasons why this could not be the case for the deep, red Tertiary volcanics in the 38-32 cataclasite. First, no such volcanics were encountered at shallower depth. Secondly, even if such rocks had been penetrated, they would have been isolated behind casing at the time the cataclasite was drilled (Figure 3). Moreover, the nearest such Tertiary volcanic units exposed are kilometers distant along the edge of and within the Stillwater Range. Accordingly, we accept the older-over-younger arrangement in 38-32 as real, and have attempted to explain its origin.

The Role of the Boyer Fault: Is the Boyer fault (Figure 2) directly responsible for the Jurassic-over-Tertiary relationship documented for 38-32? We think not. This commonly gently-dipping structure, spanning parts of the Stillwater Range and two adjacent ranges to the west and east, is characterized by Jurassic over contemporaneous or Triassic lithologies (Speed, 1976; Dilek and Moores, 1995; Plank, 1997; Johnson and Barton, 2000). To our knowledge, there are no documented occurrences where the Boyer fault either overlies extrusive Tertiary volcanic rocks or incorporates such rocks in cataclasite. Most investigators believe the Boyer fault to be Jurassic in age. Plank (1997), however, on the basis of mid-Miocene dikes disrupted by the feature, suggests that the Boyer fault could be a Cenozoic structure, a product of Basin-Range extension. As the aforementioned dike disruption is an isolated occurrence, we propose alternatively that it could reflect local and limited Cenozoic reactivation of a Jurassic-age Boyer fault. In any case, there are no Tertiary volcanics, much less the conspicuous red ones found at depth in 38-32, caught up in the Boyer fault zone in the Stillwater escarpment immediately to the west (Plank, June 2002, pers. comm.). For these reasons, we favor an alternative hypothesis to explain 38-32's curious reverse stratigraphy.

The Gravity-Slide-Block Scenario: Based on the available evidence, we suggest that injection well 38-32 could penetrate a relatively intact gravity-slide block that pushed into an ancestral Dixie Valley over downdropped Tertiary volcanics following footwall failure of a proto-DVF. The conceptual structural history for the slide portrayed by Figures 5A to 5E non-uniquely satisfies the constraints provided by logging of wells 38-32, 27-32, and 82-5, and by geologic mapping in the nearby Stillwater escarpment (Plank, 1997)

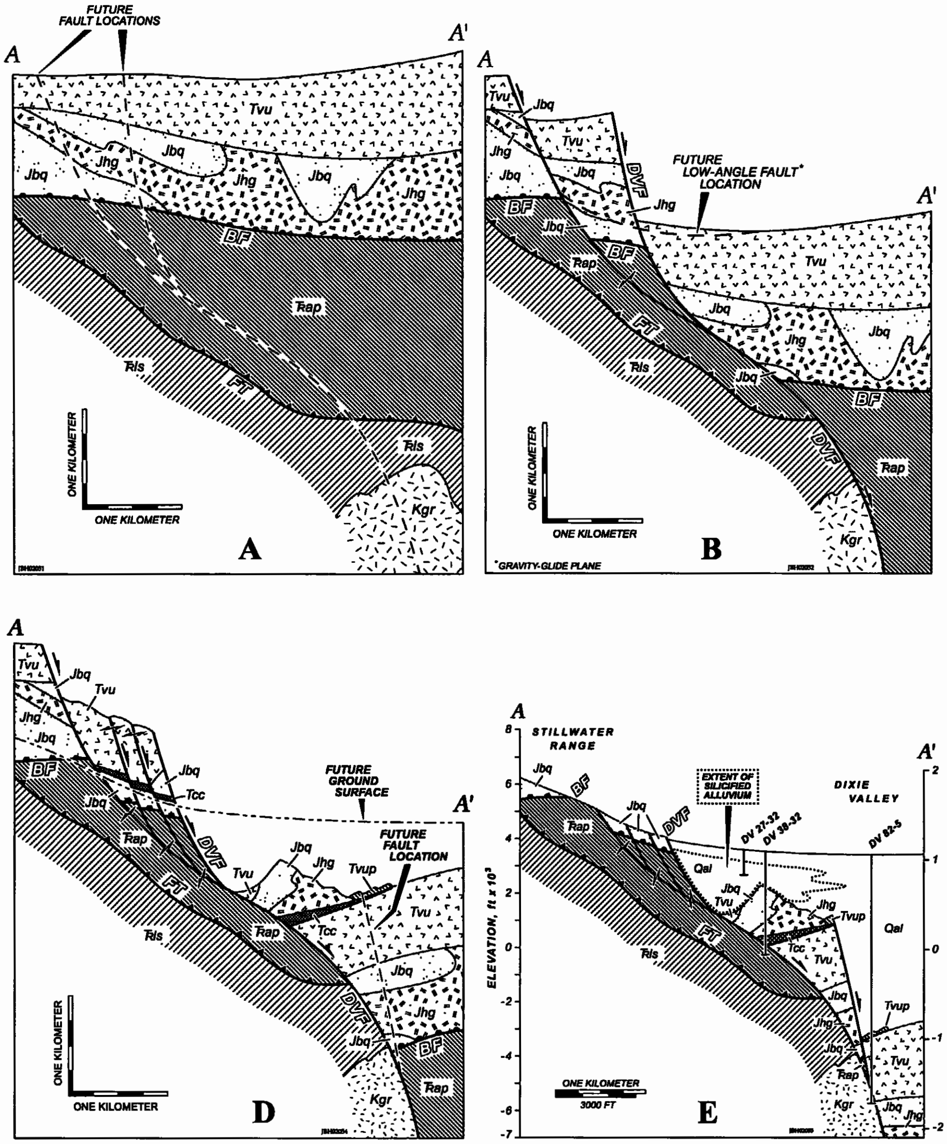

Figure 5. Sequential conceptual model for structural evolution of the northern Dixie Valley geothermal field, leading to emplacement of Jurassic quartzite and granitoid above Tertiary volcaniclastic rock, as encountered in well DV 38-32.

- 5A – Configuration of major lithologic and structural units prior to onset of major Basin-Range normal faulting. Abbreviations same as in Figure 2, except *Tvu* = Tertiary volcanic rocks, undivided, and *Kgr* = Cretaceous granite.
- 5B – After early major normal displacement along the range-front fault zone encompassing the proto-Dixie Valley fault.
- 5C – After valleyward movement of a large gravity-slide block over Tertiary volcanic rocks. A zone of slickensided cataclasite (*Tcc*) has developed at the base of the slide, and a small welt of deformed Tvu (*Tvup*) has accumulated at the toe of the feature.
- 5D – After segmentation and downdropping of the slide block along the Dixie Valley fault.
- 5E – Inferred present-day configuration, after further major faulting has placed the Tertiary volcanic sequence in contact with underlying Cretaceous granite.

Figure 5A shows the envisioned (and highly simplified) configuration of major geologic units prior to the onset of Basin and Range normal faulting. An undivided mafic to felsic Tertiary volcanic sequence overlies Jurassic Boyer Ranch Formation quartzite intruded by near-contemporaneous granitoid and gabbro of the Humboldt igneous complex (e.g., Dilek and Moores, 1995). These rocks, in the upper plate of the Boyer Fault (BF), overlie Triassic phyllites and argillites of Plank's (1997) Fumarole Canyon Sequence, in turn separated from underlying Triassic limestones of the Star Peak Group (Silberling and Wallace, 1967) by the regional Fencemaker Thrust (FT). The limestones are shown on the figures as intruded at depth by a stock of Cretaceous granite, encountered in the immediate vicinity (e.g., deep in well 82-5; Figures 2 and 5A-5E) only in the footwall of the presumed DVF (Plank, 1997). Shown on Figure 5A are the future locations of the DVF and an envisioned minor splay from that structure. Following Plank, *et. al.,* (1999), a "ramp-and-flat" geometry is adopted for the future DVF. We favor this configuration for the structure because it seems highly likely to us that the dip of a major normal fault would vary thusly with the competence of the formations disrupted. However, we concede that Blackwell, *et. al.'s,* (1999) "high-angle-fault-and-splay" model for the DVF could be used to construct an equally plausible structural history leading to the sequence of rock units observed in DV 38-32.

In Figure 5B, the proto-DVF and its splay have undergone major normal displacement, so that the undivided Tertiary volcanic sequence (at the top of which lies the distinctive red volcaniclastic) is positioned valleyward and beneath a gravitationally unstable fault slice. An incipient failure surface is shown for a conceptual gravity slide that would likely develop under these circumstances. The failure surface is envisioned as developing along a fortuitous discontinuity provided by the contact between Jurassic granitoid and quartzite.

In Figure 5C, the fault slice has collapsed, and the resulting gravity slide has pushed downward and outward over the downdropped Tertiary volcanic sequence. The hard quartzite and granodiorite in the slide block have remained relatively intact. The slide, about 1.5 km in length and more than 0.5 km thick, has developed a cataclasite layer at its base. Where the slide has overridden the volcanic sequence, the cataclasite has incorporated a significant amount of the brick-red volcaniclastic. The volcaniclastic is additionally imagined to have been pushed and crumpled outward as the slide advanced into the valley. Three future fault locations are noted on the figure. One will be the DVF itself; two others will be relatively minor splays of this structure.

Those three faults have developed as portrayed on Figure 5D. Major normal motion along the DVF has placed the now-bisected gravity-slide block in the position it will be when drilled by DV 38-32. On Figure 5E, a final major normal fault displacement has downdropped the Tertiary volcanic sequence into structural juxtaposition with Cretaceous granite, as intersected by borehole DV 82-5.

Gabriel Plank (pers. comm. with Hulen, June 2002) has noted that if the Boyer fault were dipping toward the valley along an unstable, proto-Stillwater escarpment, this structure itself, with an already-developed basal cataclasite zone, might readily be reactivated to form a gravity slide. This scenario has the virtue of greater simplicity that that depicted for Figure 5, but we have not evaluated it with a similar time-series of balanced cross sections consistent with surface and subsurface geologic constraints. Richard Smith (Idaho National Engineering and Environmental Laboratory, pers. comm. with Hulen, June 2002) has suggested alternatively that the red-volcaniclastic-bearing cataclasite zone penetrated by 38-32 conceivably could involve a stranded, high-angle fault slice of the DVF. We believe this explanation to be somewhat less likely, based on the absence of the red volcaniclastic either in the DVF or associated high-angle faults where exposed at the edge of the range to the west.

Assuming our gravity-slide block scenario to be valid, such features are of course not unknown in extensional tectonic regimes; one was even inferred earlier by Plank (1997) for the southern part of Dixie Valley geothermal field. The basis for Plank's (1997) inference was the occurrence of Tertiary rhyolite tuff at the top of the sub-alluvial basement in one well, and the absence of the tuff in this position in all other nearby wells. We add here that this tuff occurrence could also be explained as a buried erosional remnant.

Paleozoic carbonate gravity-slide blocks up to 2 km long and 100 m thick, entirely encapsulated in Pliocene valley fill, have been encountered deep in Railroad Valley in eastern Nevada, where these features host some of the valley's oil reservoirs (Bortz and Murray, 1979; French, 1991, 1993; Herring, 1994). Even though the slide block penetrated by 38-32 is now essentially impermeable, there is potential for such blocks to constitute viable geothermal reservoir rocks in this field or elsewhere in Dixie Valley.

(2, 3) The Massive 38-32 Hydrothermal Vein and the DVF

Although we believe it likely that the deep calcite-fluorite-quartz-adularia vein penetrated by 38-32 does in fact occupy the DVF, we cannot conclusively prove that this is the case. At 24.4 m apparent width, the vein is likely to be at least several meters in true width even if it is quite steeply dipping. Such a thickness argues in favor of the vein having been deposited in a large, frequently sealed and re-opened fracture zone. The DVF, reactivated in southern and central Dixie Valley as late as 1954 (Caskey, *et. al.,* 1996) is the most logical, but not the only, candidate for such a structure. The lack of permeability in 82-5 remains unexplained; however, selective reactivation of only portions of the DVF is likely due to compartmentalization along the fault. The 82-5 zone appears to remain largely sealed despite being located within the influence of the DVF.

(4) Silicified Alluvium and the Modern Hydrothermal System

Massive silicification in alluvium encountered in wells 27-32, 38-32, and 46-32 is spatially accompanied by low pressure steam that is also present in less pervasively altered (silicified) alluvium in the DJ-series thermal-gradient holes (Figure 2). The static fluid level measured in 38-32 is near a depth of 645 m (Figure 3), implying that nearly all of the silicified alluvium (see Figure 5E) is likely to be vapor dominated. Field evidence supports this concept, since neither modern hot springs nor hot-spring deposits of any age are found in the Senator area. Reservoir leakages consist of fumarole activity associated with the DVF surface trace, as well as minor steam leakages up to perhaps 100 m higher in elevation (usually near contacts beween Triassic argillite/phyllite and Jurassic quartzite). The latter leakage zones indicate that permeability pathways other than the primary DVF are present along the range front. Minor fumarolic activity is also associated with subsidence fractures in alluvium just east of boreholes DJ-3 and 46-32 (Figure 2).

Allis, *et. al.,* (1999) showed a conceptual geologic and thermal-fluid-flow section, nearby and subparallel to our section A-A' (their Figure 5), on which silicified alluvium and shallow landslide debris flanking the Stillwater Range interfinger with the impermeable playa sediments encountered in the section 33 production wells. The cross section of Allis, *et. al.,* (1999) was prepared before 38-32 was deepened below 101 m, but the section remains conceptually sound. Other than the likelihood of a large buried slide block here, the only major change to the section required by drilling results from 38-32 is that coarser, initially more permeable, but now silicified alluvium is much thicker and extends farther out into the valley than first imagined.

Primary fluid inclusions in hematite-stained quartz at about 235 m depth in 38-32 still await microthermometric analysis. However, based on their estimated liquid to vapor ratios (about 2/1) we believe it all but certain that these inclusions will yield homogenization temperatures in excess of 230°C. This value is about 90°C higher than the modern measured temperature at this depth, and even this temperature (about 140°C) is artificially high because it reflects production induced or enhanced vapor-dominated conditions. The point to make here is that the silicified and quartz-adularia-veined alluvium penetrated by wells 38-32 and 27-32 in the Senator thermal area likely records an earlier, more expansive, higher-temperature phase of the liquid-dominated Dixie Valley geothermal system.

(5) Prolonged Injectate Return From the Senator Wells

Waters injected into wells 27-32 and 38-32 take 125-140 days to reach the section 33 production wells (Rose, *et. al.*, 2001, 2002). These return times are considerably longer than those recorded for fluids traveling similar distances in other fault-controlled injection pathways in the field. For example, returns from section 5 southward to section 7 require less than 115 days. Injection from section 18 requires as little as 30 days to return northward to section 7. The injectate pathways from the Senator injection wells to the section 33 wells must be more tortuous than the injector-to-producer channels followed in the southern part of the field.

The principal injection zone in well 27-32 is in fractured quartzite encapsulated by silicified alluvium. Injectate flow from this well initially could be away from the production wells and toward the range front and/or could involve partial filling of fractures and relict primary pores in silicified alluvium prior to reaching more direct percolation pathways provided by the DVF. Delayed injectate from 38-32 is more difficult to explain. However, the fact that the (apparent) DVF is impermeable at depth in well 82-5 (Figure 2) means that this fault is at least locally sealed in the northern part of the geothermal field. The extent of the sealing is unknown, but it seems likely that such blockages could impede and divert injectate in such a way that it would take longer to reach the target production wells than if a direct and throughgoing fracture conduit were available.

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