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GEOLOGIC FRAMEWORK OF JURASSIC RESERVOIR ROCKS IN THE DIXIE VALLEY GEOTHERMAL FIELD, NEVADA: IMPLICATIONS FROM HYDROTHERMAL ALTERATION AND STRATIGRAPHY

Susan J. Lutz and Joseph N. Moore
Energy and Geoscience Institute (EGI) at the University of Utah
Salt Lake City, Utah

Dick Benoit
Oxbow Geothermal, Inc.
Reno, Nevada

ABSTRACT

The main reservoir in the Dixie Valley geothermal field of Nevada is hosted in fractured Jurassic rocks within the hanging wall of the Stillwater fault. Within the Jurassic sequence, at least four major stages of alteration related to the fault system can be identified. The paragenetic sequence from oldest to youngest consists of Stage I) biotite-potassium feldspar veins, and epidote-chlorite-calcite veins; Stage 11) sericitization and associated quartz-calcite veins; Stage 111) chalcedonic quartz-dolomite-chlorite/smectite-barite veins; and Stage IV) wairakite-epidote-quartz-calcite veins. Stages I-III predate geothermal activity and are regional in extent, whereas, Stage IV veins are associated with fluids of the modern thermal system.

Jurassic igneous rocks and Miocene basalt in the subsurface are in the same stratigraphic position as in outcrop. This suggests that the Jurassic rocks were already unroofed and near the surface when the Miocene basalt flowed over them. Descent of the present hanging wall started some time after deposition of the basalt flows. The presence of Stage III minerals (chalcedony and dolomite) in both the Jurassic rocks and in the Miocene basalt probably records hydrothermal alteration at shallow depths along the fault. Stage IV alteration (wairakite and epidote) minerals were deposited by fluids of the present geothermal system after these rocks descended to their present depth.

INTRODUCTION

The geometry of the Jurassic reservoir at Dixie Valley is a result of its complex stratigraphy, alteration, and structural history. Drilling records show that once the Jurassic sequence in the hanging wall is penetrated and the Cretaceous granodiorite of the footwall is reached, there is little permeability. The presence and juxtaposition of these brittle Jurassic rocks of the hanging wall against crystalline Cretaceous granodiorite in the footwall appears to be critical to the development of the modern geothermal reservoir.

The Dixie Valley geothermal field produces from two aquifers. The upper subhorizontal aquifer extends southeast from the rangefront fault within Miocene basalts between depths of 7000 to 8000 ft (2300 to 2700 m). The deeper reservoir is in Jurassic rocks at drilled depths of 8100 to 10,000 ft (3330 m). Production data indicate that the Jurassic rocks contain most of the productive fractures in the Dixie Valley field (Waibel, 1987). The highest temperature fluids are located in the northern and central portions of the field. In some wells, individual fluid entry zones may be associated with the locations of Mesozoic faults within the Jurassic section.

The purpose of this paper is to describe the Cenozoic history of the Jurassic rocks in the Stillwater Range and within Dixie Valley based on the stratigraphic relationships and our studies of the alteration mineralogy (Lutz et al., 1996). The objective is to understand how the structural, stratigraphic and alteration characteristics of these Jurassic rocks combined to create the present geothermal reservoir and why surrounding areas are hot but not productive.

STRATIGRAPHIC SETTING

On the eastern side of Dixie Valley, Cambrian to Triassic marine carbonates and siliciclastic rocks crop out in the Clan Alpine Mountains. These Paleozoic rocks are probably present beneath Dixie Valley, but have not been recognized in any of the geothermal wells. The rocks that compose the Stillwater Range just west of the field (Fig. 1) consist of the same sequence of Triassic to Miocene rocks that are present in the drillholes. Isotope and geochemical analyses suggest that the geothermal fluids of the Dixie Valley system have reached thermal and chemical equilibrium with the Triassic calcareous shales and silty carbonates that extend laterally across northern Dixie Valley (Waibel, 1987). Triassic to Jurassic marine siltstones, shales and volcaniclastic rocks are thrust from the west over older rocks along the low-angle Fencemaker thrust fault (Speed, 1976). The Dixie Valley field is positioned near the leading edge of the thrust sheet and the allochthon pinches out at the north end of the geothermal field.

The presence of Jurassic igneous rocks is restricted to a fault-bounded NW-SE trending belt west of the Dixie Valley field, in the West Humboldt and Stillwater Ranges, and east of the field in the Clan Alpine Mountains. These rocks were described and mapped by Speed (1976) as the "Humboldt Lopolith". The "lopolith" has been interpreted in a variety of ways by different geologic workers. In general, it is complex of igneous rocks consisting of basalts, diorites, and gabbros that overlies marine sandstones, siltstones, and shales. The Humboldt complex is more than 4000 ft (1200 m) thick in the northeastern Stillwater Range, where it commonly occurs in fault contact against quartz arenite of the lower Jurassic Boyer Ranch Formation (Dilek and Moores, 1995). Waibel (1987) describes the Jurassic section as an allochthonous fragment of oceanic crust that has been thrust over Triassic marine shelf sediments to form an ophiolite sequence. Dilek and Moores (1995) describe the Humboldt igneous complex as consisting of a comagmatic suite of intrusive and extrusive rocks that became tectonically intercalated with older shallow marine sediments in a continental margin arc setting.

The thicknesses of the Jurassic and Triassic sections in the drillholes are highly variable, and the rocks id

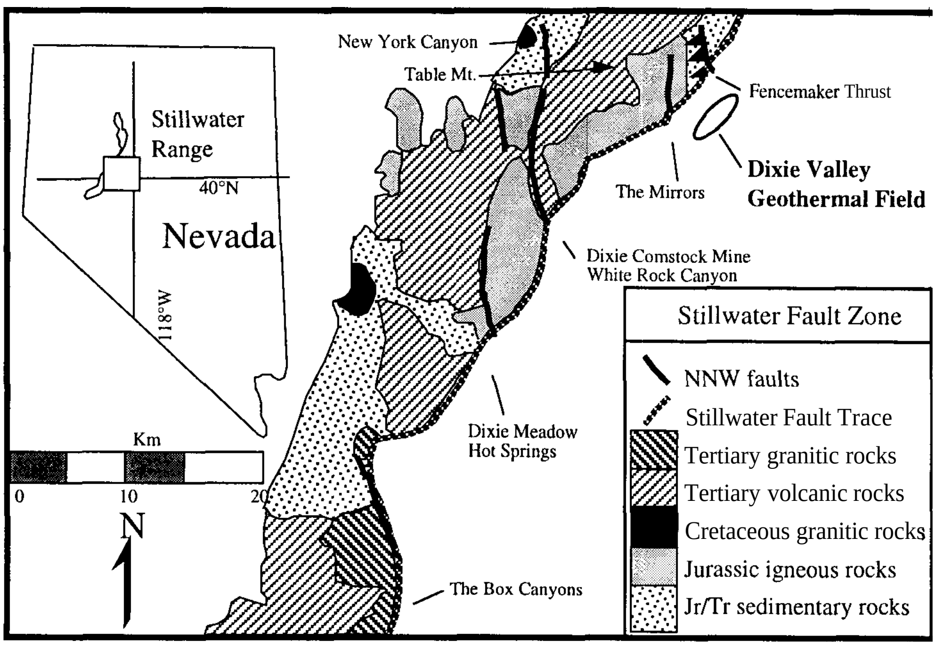


Fig. 1. Generalized geologic map of the northern Stillwater Range (modified from Willden and Speed, 1974; Speed, 1976; and Parry et al., 1991). Jurassic reservoir rocks at the Dixie Valley geothermal field are located along a NE segment of the Stillwater fault, north of NNW-trending structures at White Rock Canyon and Mirrors, and southwest of the NE edge of the Fencemaker allochthon.

thin-section appear deformed, brecciated and metamorphosed. The Humboldt complex contains a sericitized and veined hornblende diorite or anorthosite unit that is present in most of the drillholes. In some drillholes, andesitic to basaltic extrusive rocks overlie plutonic rocks in the igneous complex. Underlying lower Jurassic-Triassic marine rocks of the Boyer Ranch Formation occur in a characteristic stratigraphic package consisting of an upper quartz arenite unit, a shaly siltstone to sandstone, and a basal carbonate unit. The Boyer Ranch Formation rests on deformed turbiditic limestones and pelitic rocks of the Star Peak Group (Dilek and Moores, 1995). Petrographically, the Triassic rocks can be described as carbonaceous and deformed metasediments, consisting of marble, calcareous schist and phyllite. The presence of these Triassic rocks within the Jurassic marine package and repeated sequences of the Jurassic quartz arenite-carbonate package possibly identify the locations of Mesozoic faults in the drillholes (Lutz et al., 1996).

In the Stillwater Range, three imbricate lithologic packages of Triassic and Jurassic strata are separated by the Fencemaker and Boyer faults (Plank, 1996). These thrust sheets were intruded by Cretaceous intermediate to silicic magmas similar to those of the Sierra Nevada batholith. In the geothermal field, Cretaceous granodiorite is found below a depth of 6000 ft (2000 m), where it defines the footwall of the Stillwater fault. Lost circulation zones are associated with the faulted contact between the granodiorite and overlying Jurassic rocks in the hanging wall. To the west of the field, a similar Cretaceous intrusive body is exposed in New York Canyon (Fig. 1), where it occurs in fault contact with Triassic sedimentary rock along the western edge of the Stillwater Range.

The Table Mountain basalt (Fig. 1) caps the Stillwater Range at an elevation of about 7200 ft (2400 m) and also produces seismic reflections in Dixie Valley at an elevation of 3840 ft (1280 m) below sea level (Okaya and Thompson, 1985). This relatively flat-lying Miocene basalt is present in the Dixie Valley drillholes (Benoit, 1992; Waibel, 1987) where it unconformably overlies either Miocene lacustrine deposits, Oligocene tuff, or Jurassic igneous rocks. In the Box Canyons area (Fig. 1), Parry et al. (1991) noted that a 3.5 km thick package of Oligocene tuffs and rhyolites was eroded from the underlying Jurassic through Oligocene rocks before deposition of the Miocene basalt flows. In the central and southern portions of the Stillwater Range, Oligocene to lower Miocene rocks related to the Stillwater caldera complex are moderately to steeply tilted and cut by NNW striking faults (John, 1995). **As** in the northern part of the range, these older faults and tilted fault blocks are overlapped by flat-lying Miocene basalt flows (Hudson and Geissman, 1987).

In the northern Stillwater Range, the complex outcrop pattern of rotated, faulted, and intruded Triassic and Jurassic rocks is similar to the stratigraphic relationships observed in the rocks in the subsurface. Other than younger fracturing and the 3 to 4 km of offset along the Stillwater fault, we can envision this same complexity in the Mesozoic rocks in the geothermal reservoir, located less than 5 kms away from the exposed east face of the Stillwater Range.

STRUCTURAL SETTING

Fluid flow in the Dixie Valley reservoir is generally believed to be controlled by the still-active Stillwater fault. However, the fault zone architecture and permeability structure along the fault has changed through time and along the fault plane so that portions of the fault became permeable while other parts became sealed. Caine et al. (1996) classify the Stillwater fault system at the Mirrors locality (Fig. 1) as a combined conduit-barrier where the core of the fault zone has acted as a short-lived, syndeformational fluid flow conduit that then rapidly sealed to form a barrier to fluid flow.

Paleomagnetic data and geologic mapping at White Rock Canyon (Fig. 1) in areas south of the geothermal field indicate that Tertiary rocks and underlying Jurassic gabbro were rotated 25° counterclockwise during deposition of Oligocene ash-flow tuffs (Hudson and Geissman, 1987, 1991). Hudson and Geissman determined that the rotation was accomplished by right-lateral strike-slip movement on northwest-trending faults. This rotation did not affect the Miocene basalts in the Stillwater Range that date at **13** to 17 Ma (Nosker, 1981), so the high-angle normal faulting that controls the present physiography is post-middle Miocene (Hudson and Geissman, 1991).

Parry et al. (1991) recognized a change in extension direction along the Dixie Valley-Stillwater fault system from predominately NE to SE at about 10-13 Ma. This age corresponds to K-Ar dates of 11 to 15 Ma obtained from sericite along the NNW-trending White Rock Canyon (Vikre, 1994). In general, segments of the Stillwater fault which are oriented to the NNW exhibit strong sericitization related to the early extension and may be sealed in the present stress regime. Segments of the fault which are oriented to the NE are characterized by younger carbonate alteration and are normal to the present-day extension direction.

The NE segment of the Stillwater fault that controls the Dixie Valley geothermal system is north of White Rock Canyon and the 1954 earthquake rupture that terminates near Dixie Meadow hot springs (Fig. 1). The NNW fault along White Rock Canyon is a major structural feature that separates a southern block of Jurassic gabbroic rocks from a northern block that crops out adjacent to the geothermal field. The Cretaceous granodiorite on the west side of the Stillwater Range has also been affected by this fault, where it occurs on the upthrown (western) side. The occurrence of a similar granodiorite at depth in the geothermal field implies significant throw on NNW-trending structures prior to the development of the modern Stillwater fault. Within the geothermal field, the granodiorite is present at depths to 10,000 ft (3330 m).

The intersections of the NNW faults with the NE segment of the Stillwater fault are sites of active and fossil hot spring activity along the range front. The intersection of White Rock Canyon with the Stillwater fault is associated with hot spring sinter at the Dixie Comstock Mine (Vikre, 1994), and quartz breccias at the Mirrors locality (see below) may represent stockwork mineralization associated with now eroded hot spring deposits near the intersection of another NW fault with the Stillwater fault (geologic map of Speed, 1976). The age of contemporaneous (?) sinter located about 3 km southwest of the Section 18 wells is estimated to be about 9000 years (Waibel, 1987). Waibel collected a similar sample from the Senator Fumeroles in which the possible age range was 150,000 to 300,000 years. At the Dixie Comstock Mine, the quartz breccia and associated gold mineralization is estimated to be mid-Pleistocene (Vikre, 1994). At the sinter localities, uplift since the hot-spring deposits formed is estimated to be 200 to 330 ft (67 to 100 m). Bell and Katzer (1990) suggest that most of the displacement along the eastern Stillwater Range has taken place during the last few million years.

Productive zones in some Dixie Valley wells occur in a fracture network near the bottom of the hanging wall rather than at the Jurassic igneous-Cretaceous granodiorite contact (Benoit, 1992). In well 73B-7, the productive zone may be located up to 1000 ft (330 m) above the rangefront fault and possibly, along a reactivated Mesozoic thrust fault that places the Jurassic igneous complex against Triassic metasediments (Lutz et al., 1996). Barton et al. (1996) have identified large-aperture hydraulically conductive fractures in the bottom of well 73B-7 that strike northeast and dip about 60° to the southeast. Borehole measurements of stress orientation and magnitudes in well 73B-7 by Hickman and Zoback (1993) indicate that these fractures are critically stressed, potentially active shear planes in the ESE extensional stress regime at Dixie Valley.

ALTERATION MINERALOGY

Multiple thermal, structural, and metasomatic events have affected the rocks within Dixie Valley and the Stillwater Range. Our studies have concentrated on the post-Oligocene alteration associated with the fault system, and in particular, the alteration produced during the later episode of extension and development of the geothermal reservoir. The superposition of alteration assemblages is used to assess thermal and chemical changes that have occurred as movement along the Stillwater fault progressed and as the Dixie Valley geothermal system evolved.

Within the Jurassic sequence, four major stages of alteration related to the fault system can be recognized (Fig. 2). The paragenetic sequence from oldest to youngest consists of Stage I) biotite-potassium feldspar veins, and later epidote-chlorite-calcite veins; Stage 11) widespread sericitization and associated quartz-calcite veins; Stage III) chalcedonic quartz-dolomite-chlorite/smectite-barite veins; and Stage IV) wairakite-epidote-quartz-calcite veins.

X-ray diffraction analyses of the Stage II sericite in the geothermal reservoir indicate the presence of

OUTCROPS (S TO N) BOX CANYONS Parry et al., 1991	DIXIE COMSTOCK MINE Vikre, 1994	MIRRORS Lutz et al., 1996	GEOTHERMAL RESERVOIR WELL 45-33 RD-2 Lutz et al., 1996	ALTERATION STAGE	STRATIGRAPHIC HISTORY	STRUCTURAL HISTORY
line gr. quartz + kaolin quartz+calcite	Stage 3 calcite Stage 2 quartz Stage 1 quartz	calcite quartz + kaolin	wairakite+calcite+quartz quartz+chlorite	STAGE IV	Present-day ?,000 to 350,000 years fossil hot spring terrace	Pleistocene-Holocene normal faults 3.5 km of displacement NW-SE extension
calcite+hematite clay+zeolite	calcite+barite	chalcedony+barite dolomite+goethite	chalcedony+dolomite +calcite+barite chlorite-smectite+ hematite+pyrite	STAGE III	Veins in Miocene basalt (<13 Ma)	10-13 Ma
	sericite K-Al 11-15 Ma	quartz+calcite(?) sericite (illite)	quartz+calcite+sphene sericite (illite-smectite)	STAGE II	13 Ma Miocene Basalt 17 Ma	Middle Miocene normal faults 2.0-2.5 km of displacement NE-SW extension
sericite K-Ar 21-25 Ma					22 Ma Oligocene rhyolite ash-flow granitic rocks (K-Ar of biotite at 28 Ma)	Late Oligocene-Early Miocene rotational, NW-striking right-lateral faulting
epidote +chlorite		epidote + chlorite	epidote + chlorite + + calcite	STAGE I		
biotite + potassium feldspar		biotite + potassium feldspar	biotite + potassium feldspar		32 Ma	

Fig. 2. Summary chart of alteration studies along the Stillwater fault and Dixie Valley geothermal system. Heavy lines block assemblages that may be related to the same mineralogic, stratigraphic and structural events. Stages I-III represent older, fault-related hydrothermal assemblages. Stage IV is related to the present geothermal system.

mixed-layer illite-smectite with about 20 to 40% smectite interlayers. These interlayered clays generally form at temperatures between 180" and 200°C.

Stage III mineralization postdates Stage II sericitization of the rocks and predates formation of the Stage IV wairakite veins of the modern geothermal system. The presence of chalcedonic quartz, dolomite, and barite in the Stage III assemblage records formation temperatures of below 180°C (Fournier, 1985; Browne, 1993). The Stage III assemblages suggest the presence of cool basinal fluids in the fault zone before the high-temperature geothermal system developed in the Jurassic rocks.

Fluid inclusions analyses of vein quartz associated with Stage IV wairakite yielded homogenization temperatures of about 240°C. The presence of wairakite-quartz veins in the upflow zone is consistent with the measured 248°C temperature of the production fluids (e.g., Henley and Ellis, 1983).

At the Mirrors outcrop, located about 5 km west of the geothermal field (Fig. 1), portions of the fault zone are characterized by extensive silicification, kaolinization and hydrothermal brecciation (Lutz et al, 1996). The Mirrors breccias consist of highly-altered rock and vein fragments in a matrix of fine-grained quartz and kaolin (Forster et al., in press). Many of the clasts in the silicified breccia are carbonate vein fragments, containing ferroan dolomite, chalcedonic quartz, goethite and traces of barite. Because this Stage III assemblage is also present in sericitized rocks below 8000 ft (2670 m) in well 52-18, the mineralogy of the fault zone can be linked from the surface to the subsurface.

DISCUSSION

The Stage I through III assemblages appear to be regional in extent and occur both in the present footwall and in the present hanging wall of the Stillwater fault. There are some differences between the alteration assemblages described from the Box Canyons

40-50 km to the southwest (Parry et al., 1991), from the Dixie Comstock mine 15 km to the southwest (Vikre, 1994), and from our studies at the Mirrors outcrop 5 km west of the field, and within the Dixie Valley geothermal reservoir (Lutz et al., 1996). But, in general, all three studies identify sericite assemblages that are related to older episodes of faulting, and younger clay-carbonate alteration (Fig. 2).

Parry et al. (1991) describe early biotite+K-feldspar and chlorite+epidote assemblages that are related to deep (6 km) hydrothermal alteration and burial along the fault system. We recognize these assemblages as Stage I alteration in both surface and subsurface samples near the geothermal field. Parry et al. (1991) describe sericite and older epidote-biotite assemblages as filling the NNW-trending veins, and younger carbonates and zeolites that fill NE-trending veins. Their K-Ar dates of the early sericite range from 21 to 25 Ma.

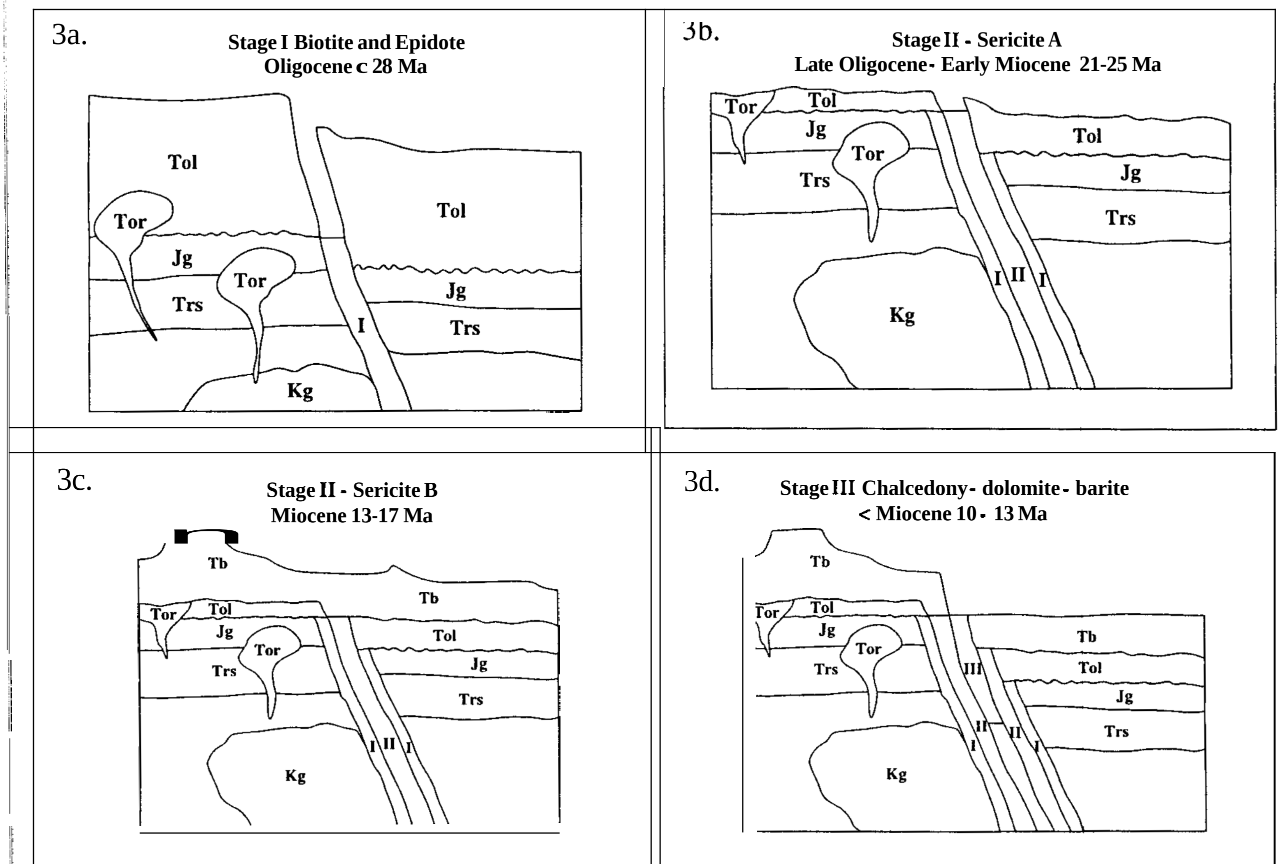
Closer to the geothermal field, Vikre (1994) describes three stages of hydrothermal mineralization in quartz breccia from the Dixie Comstock mine, two early quartz assemblages and a late Stage *3* calcite assemblage. His Stage I and 2 quartz assemblages probably correlate to our Stage IV alteration. Vikre also describes older sericite and calcite+barite assemblages that may correspond to our Stage II and III assemblages, respectively. K-Ar dates of the sericite yielded ages of 11 to 15 Ma. U-Th dates of his Stage *3* calcite yielded an age of >.35 Ma.

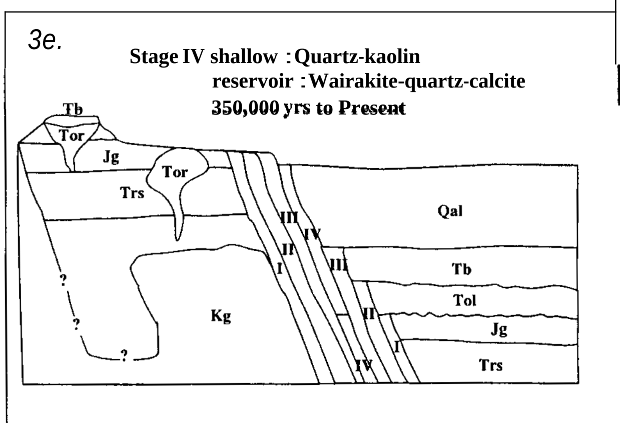
Vikre (1994) suggests three major epochs of faulting along the Stillwater Range; during the Oligocene-Miocene, middle Miocene, and Quaternary. Sericite samples at the **Box** Canyons, dated at 21-25 Ma by Parry et al., may have formed along Oligocene-Miocene rotational faults. The sericite at the Dixie Comstock mine, dated at 11 to 15 Ma by Vikre, may represent alteration along mid-Miocene normal faults. We don't know the age of the sericite in our Stage II alteration in the geothermal reservoir, but it is likely to be closer to the age of sericite along White Rock Canyon than to the sericite of the Box Canyons.

The young Pleistocene-Holocene normal faults at the Dixie Comstock mine are associated with ore-forming quartz breccias. At the Mirrors outcrop, intensely silicified rocks within the fault zone may represent the basal portions of quartz stockwork associated with an overlying thermal spring, similar to the quartz-rich fault breccias described by Vikre (1994). These quartz breccias may be the near-surface equivalents to Stage IV alteration in the geothermal reservoir. At the Dixie Comstock mine, isotope data show that the quartz breccia was deposited by water that resembles modern deep geothermal fluid in Dixie Valley (Vikre, 1994). In addition, fluid-inclusion microthermometry and stable isotope analyses of quartz show that the ore-forming fluid at the mine was a 180°C, near-boiling meteoric water (Vikre, 1994).

In the Dixie Valley geothermal reservoir, the superposition of Stage IV minerals (wairakite, epidote) upon Stage III minerals (chalcedony, dolomite, barite) can be interpreted in two ways. One interpretation is that the chalcedony-bearing veins in the hanging wall simply represent cool hydrothermal alteration along the fault before the high-temperature geothermal system developed. Alternatively, the low-temperature minerals may represent alteration from earlier times, when displacement along the fault was less, and the hanging wall was located at shallower depths. **As** displacement increased through time, the hanging wall was displaced to its present depth, and hot fluids of the modern geothermal system circulated in the fractured Jurassic rock to deposit the high-temperature minerals.

The early stages I-III of alteration in the geothermal reservoir are similar to those described from outcrops along the Stillwater fault. This suggests that rocks in both the present footwall and the present hanging wall underwent the same alteration history during the time when these alteration minerals were deposited. However, there are slight differences in the footwall and hanging wall assemblages. In the footwall, the sericitic alteration consists of illite. The presence of illite without smectite interlayers suggests that it formed at temperatures above 220°C. In the hanging wall, our X-ray diffraction work indicates the presence of mixed-layer illite-smectite with variable amounts of interlayered smectite. Some of the mixed-layer clay contains up to 40% intarlayered smectite which corresponds to a formation temperature of about 180" to 200°C. Hence, the differences in the sericitic clays between the footwall and the hanging wall suggest that when the sericite (illite and illite-smectite) formed, the hanging wall rocks were shallower than they are today. Although these rocks experienced the same alteration event, subsequent move-





Qal Quaternary alluvium
Tb Miocene basalt
Tol Oligocene latite tuff
Tor Oligocene rhyolite
Kg Cretaceous granodiorite
Jg Jurassic gabbro
Trs Triassic metasediments

Figure 3. Schematic representations of alteration events in Jurassic rocks as the fault system evolved (the orientations of Mesozoic thrusts and Cenozoic faults are not illustrated).

3a. Deep burial along ancestral faults produced Stage I assemblages in Oligocene rocks.

3b. After uplift and erosion of up to 3.5 km of Oligocene rocks, Stage II sericite formed along NW faults.

3c. Flat-lying Miocene basalt unconformably overlies unroofed Tertiary and Mesozoic rocks. Stage II sericite at White Rock Canyon is the same age as these basalts.

3d. Change in fault orientation to NE and deposition of Stage III by cool, basinal fluids along shallow portions of the fault.

3e. Emplacement of the high-temperature geothermal system along the fault to produce the Stage IV assemblages. Three kms of offset since the mid-Miocene has produced overlapping of the Stages I - IV assemblages in the Jurassic rocks.

ment along the normal fault has juxtaposed these two slightly different sericitic clays.

In the footwall, Stage III alteration only exists as vein fragments within the silicified fault zone rocks. The Stage III veins became fragments of fault zone material that were incorporated into the later Stage IV quartz breccias. Displacement along the normal fault caused between two and three kms of offset between the chalcedonic quartz in vein fragments at the surface in the footwall and the chalcedonic quartz veins between 6000 ft and 10,000 ft (2000 m to 3300 m) in the hanging wall.

In the geothermal reservoir, productive zones in the Jurassic rocks vary in mineralogy and proximity to the fault depending on position within the geothermal field. In well 45-33, Stage IV wairakite occurs in the hottest portion of the field presumably within a narrow zone of upwelling. To the south, the geothermal field is wider and a secondary graben can be defined. Southern well 52-18 originally produced 230°C fluid, but because of relatively low permeability, it has been placed into service as an injection well (Benoit, 1992). The Jurassic rocks in well 52-18 are strongly carbonate and sericite altered and appear to have remained partially sealed since being altered during Stage I1 and III events.

SUMMARY

Major structural-stratigraphic boundaries of the Dixie Valley geothermal reservoir include: to the north, the leading edge of the Fencemaker allochthon which carries the Jurassic igneous complex, and to the south, White Rock Canyon which separates unproductive NNW-oriented fault segments from productive NE-oriented fault segments. The eastern and western limits of the geothermal system are restricted to the narrow band of fracturing associated with the Stillwater fault. The upper and lower limits of the reservoir are, respectively, the lithologic contact between Jurassic igneous rocks and younger sedimentary rocks, and the Mesozoic (Boyer and/or Fencemaker) faults at the base of the Jurassic section.

In the northern portion of the Dixie Valley geothermal field, chalcedonic quartz and mixed-layer illite-smectite with about 50% smectite interlayers are present in rocks that currently produce fluids with temperatures up to 248°C. These assemblages formed when the hanging wall was at shallow depths. Progressive downdropping of the hanging wall along the Stillwater fault resulted in the superposition of higher temperature alteration minerals (wairakite) on the relict lower temperature phases (chalcedony and illite-smectite).

The geothermal reservoir at Dixie Valley is maintained in an open network of fractures developed where crystalline portions of the Jurassic igneous complex in the hanging wall are juxtaposed against Cretaceous granodiorite in the footwall. Figure **3** schematically depicts the kinematic and alteration history of the Jurassic rocks along the Stillwater fault and the evolution of the system through time. The final figure (3e) illustrates the alteration banding, and structural and stratigraphic relationships of the modern Dixie Valley geothermal system.

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