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AN OVERVIEW OF THE GEOLOGY AND SECONDARY MINERALOGY OF THE HIGH TEMPERATURE GEOTHERMAL SYSTEM IN DIXIE VALLEY, NEVADA

A.F. Waibel

Columbia Geoscience
22495 NW Quatama Rd.
Hillsboro, Oregon 97124

ABSTRACT

Lithologic units encountered in the Dixie Valley geothermal field range from Triassic marine sediments to Recent basin-filling sediments. Structural features affecting the location of the geothermal activity include Mesozoic thrusting, late Tertiary normal faulting and Quaternary to Recent normal faulting. The hydrothermal mineral suite is variable, due in part to rock-gas reactions.

INTRODUCTION

The geology of the Dixie Valley Geothermal Field (fig. 1) is quite varied. The stratigraphic sequence, in the order encountered in the majority of the drill holes, includes basin-filling sediments, silicic tuff-rich sediments, Miocene basalt, Miocene sediments, Oligocene silicic volcanics, Jurassic oceanic crust, Jurassic marine sediments, Cretaceous granodiorite and Triassic marine sediments (fig. 2). The most recent published geological mapping for the general area includes Page (1965), Wilden and Speed (1974) and Speed (1976).

The structural history is as complex as the lithology is diverse. Carbonaceous marine sediments of Triassic age are underlying, in thrust-fault contact, Jurassic oceanic crustal rocks. North-striking normal faulting occurred in this area in the Miocene, followed by a superimposed NNE-striking set of normal faults. The Dixie Valley graben and the Stillwater Range are artifacts of the most recent episode of faulting. Highly fractured areas hosting geothermal production appear to be best developed in tensional zones resulting from strike-slip and normal faulting at the intersections of the two generations of normal faults in a manner similar to that described by Aydin and Nur (1982). Recharge for the northern portion of the system is most probably coming from the north.

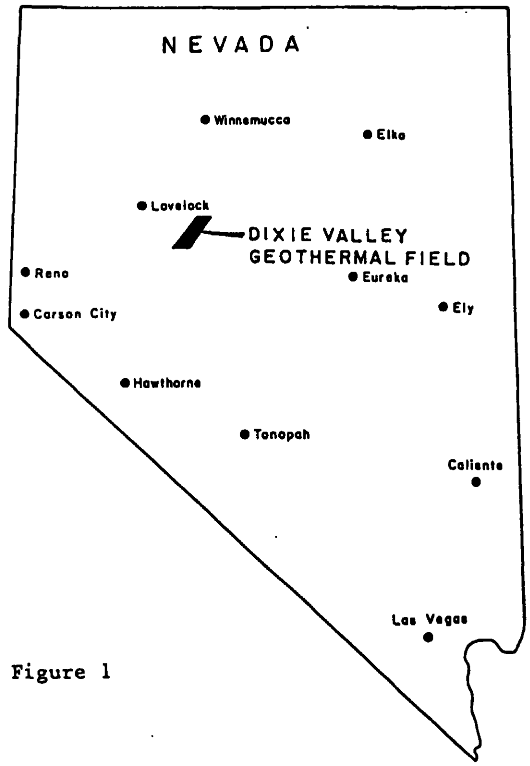

Figure 1

LOCATION OF DIXIE VALLEY GEOTHERMAL FIELD
CHURCHILL COUNTY, NEVADA

LITHOLOGY

Basin Filling Sediments

Horst and graben structure appears to have dominated the Dixie Valley area since the Miocene. The current Dixie Valley basin is asymmetrical with the deepest portions occurring to the west along the Stillwater Range. The basin-filling sediments are observed to be in excess of 7000 feet thick in some of the geothermal wells. Seismic data suggest that toward the center and along the eastern portion of Dixie Valley these sediments are usually no more than 2000 to 3000 feet thick.

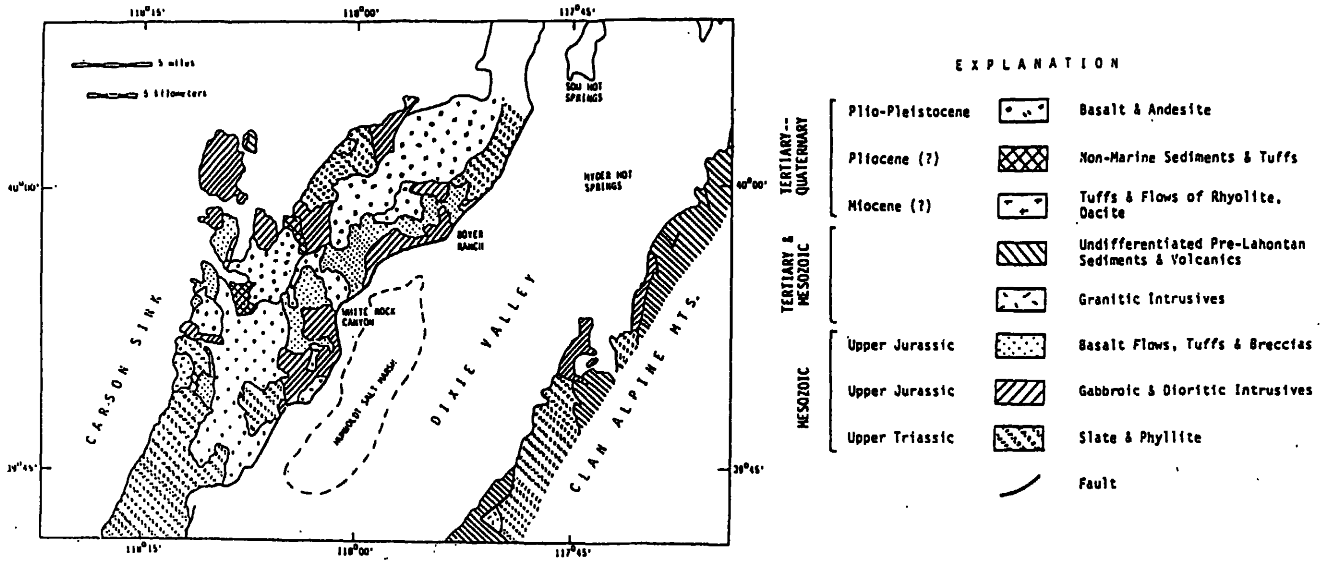

Figure 2 Generalized geology of the Dixie Valley, Nevada, area (from Denton, et al, 1980).

The composition of the fill which makes up the basin sediments is somewhat variable. Toward the center and along the eastern portions of the valley the section is predominantly reworked silicic tuffs, eroded from the Clan Alpine Range. Along the Stillwater Range the contributing rock types are more varied. Reworked silicic tuffs tend to be predominant among the deepest (earliest) sediments in the geothermal production area. With decreasing depth the sediments are usually variations of a pebble conglomerate with a clay matrix. Near the discharge of major Stillwater Range drainages (i.e. Cottonwood Canyon) conglomerates are most common and horizons of clay and silt are minor. Areas away from major drainages have basin-filling sediment sections dominated by clay, silt, and sand-size particles while conglomerate horizons are less common.

Cobble and sand-rich horizons within the basin-filling sediments are able to support pore space permeability and fluid movement. Fracture permeability occurs but is not common in this section. The abundance of clay, and the moderate to poor lithification in these sediments, are not conducive to the propogation of fault related fracturing. The total lithostatic pressure is low enough, however, to permit permeability of limited duration to occur along normal faults. The permeable zones hosting geothermal fluids are, in most cases, readily identifiable by the shift in stable mineral phases resulting from geothermal fluids with low oxygen activity interacting with oxidized basin-filling sediments.

Miocene Basalt

The Miocene basalts overly Miocene lacustrine sediments, and are overlain by as much as 6000 to 7000 feet of basin-filling sediments in the area of the geothermal field. These same basalts crop out as high as 8000 feet in elevation in the Stillwater Range. Page (1965) estimates the age of these basalts to be Pliocene or younger. A K-Ar date of a sample from the Stillwater Range, analyzed for Sunedco in 1981, shows an age of 8.5 $\pm$ .4 million years. Outcrops in the Stillwater Range show the basaltic volcanic sequence to be quite varied in form, ranging from flat-lying lava flows to agglutinates, scoria and palagonite tuffs characteristic of evolved maar complexes. In the area of Kitten Springs Pass, about five miles northwest of the Dixie Valley geothermal field, the palagonite tuff sequence is approximately 800 feet thick. The basalt section as observed in geothermal drill holes is often abbreviated due to normal faulting. Observed thicknesses in the drill holes range from less than 300 ft. to greater than 1900 ft.

In hand specimen the basalt flows range from aphanitic hypocrystalline to porphyritic. Thin-section specimens show the crystal compositions most commonly to include plagioclase (An_{50} or greater), clinopyroxene, olivine, and opaque iron-titanium oxide. Millimeter-size phenocrysts of olivine are present in many, though not all, of the specimens. The rock texture ranges from pilotaxitic to ophitic.

In outcrops the basalt alteration is characterized by oxidation of femic minerals, zeolite and calcite alteration of plagioclase, and devitrification of glassy matrix. This is a typical surface alteration suite resulting from downward percolation of oxygenated meteoric water. Two distinct alteration mineral suites are observed in the Miocene basalt section in drill holes. The effects of weathering are plainly visible in portions of the basalt chips recovered during drilling. Other portions of the basalt show a later overprinting of alteration resulting from interaction with geothermal fluid of low oxygen activity.

Miocene Sediments

The Miocene lacustrine sedimentary section is conformably overlain by Miocene basalt, and is conformably underlain by silicic volcanic tuffs of late Oligocene age. The sediments are composed of intercalated volcaniclastics, carbonaceous siltstone, and silicic volcaniclastic tuff. The section is observed in a truncated form in many of the drill holes in Dixie Valley due to normal faulting.

The upper portion of the section consists of intercalated volcaniclastic sediments and carbonaceous siltstone. The volcaniclastic sediments appear to be derived predominantly from silicic volcanics and tuffs. Authigenic chlorite and illite alteration predominate in the groundmass and detrital subhedral to euhedral quartz is usually present in minor amounts. The dark brown to black carbonaceous siltstone horizons are fissil and often pyritic. Attempts to separate and identify microfossils from the siltstone have been made to more precisely bracket the age of sedimentation. To date these attempts have been unsuccessful due to the poorly preserved state of the fossils.

The lower portion of the sedimentary section is composed of silicic tuffaceous sediments with only minor carbonaceous siltstone horizons. Authigenic illite and chlorite dominate the mineralogy of these reworked devitrified silicic volcanics. Detrital subhedral to euhedral quartz, originally a primary component of the silicic tuffs, is present in minor amounts. The basal boundary of this sedimentary unit is not distinct. A progression is observed from reworked silicic tuffs, to primary devitrified silicic tuff, to primary welded silicic tuff. The latter is part of the Oligocene silicic volcanics.

Clays represent the dominant mineralogy in this sedimentary section. As a result, tectonic strain tends to cause plastic deformation rather than brittle failure and rock breakage. It is unusual, therefore, to find significant fracture related permeability within this sedimentary section. Fault related permeability would likely be limited and transitory.

Rock-water-gas interaction between the sediments and the geothermal system is limited due to the low potential for porosity and permeability. The thermal effects of the geothermal system, however, can be observed. The formation clays are predominantly illite, non-expanding Fe-bearing clays, and fine crystalline authigenic chlorite. The present phyllosilicate suite is the result of very low-grade metamorphism of smectite clays. Organic matter in the carbonaceous siltstone is near thermal maturity. Gas chromatograph monitoring during drilling indicates that methane is the only hydrocarbon currently being generated from these sediments.

Oligocene Silicic Volcanics

Oligocene silicic volcanics dominate the Clan Alpine Range to the east of the Dixie Valley geothermal field, and are present in the Stillwater Range to the south and west of the geothermal field. These volcanics are only rarely encountered in the geothermal drill holes, however. In the Clan Alpine Range intercalated beds of cemented and welded tuffs are in excess of 4000 feet thick. Oligocene tuff cropping out in the Stillwater Range seldom exceeds a few hundred feet thick. These volcanics have only rarely been encountered in the geothermal drill holes, where the section appears to often be faulted out by basin-bounding normal faults. A single good, though incomplete, section of these silicic tuffs is observed in one well, where a 180 foot section of predominantly welded biotite-quartz-sanidine tuff is overlain by Miocene sediments. A normal fault contact truncates this section with the foot wall consisting of Jurassic oceanic igneous rock.

Welded portions of the Oligocene silicic tuffs are brittle and generally fracture when subjected to strain. Poorly welded and cemented aspects of the tuff sequence are generally soft and undergo plastic deformation rather than structural failure when subjected to strain. The potential for fracture permeability is good in the highly welded portions of the tuff and low in the poorly welded and cemented portions of the tuff.

Cretaceous Granodiorite

A silicic plutonic rock is observed in a number of the drill holes. The mineralogy of the rock is distinctly different from the igneous rocks of the Jurassic oceanic crust. Where least altered this rock consists of quartz, plagioclase, biotite, muscovite, hornblende, and minor K-feldspar, sphene, rutile, and Fe oxide. The mafic minerals usually are slightly chloritized. In a few areas where the rock has been strongly altered the mafic minerals have been almost completely replaced by chlorite, the plagioclase has been albitized, secondary K-feldspar has formed at the expense of muscovite, and secondary epidote and calcite are present in minor amounts. The less altered portions of this rock can best be described as quartz monzonite to granodiorite.

The genetic and structural relationship of this silicic intrusive to other igneous rocks in the area is not clear. It is typically observed as a foot wall in fault contact with Jurassic rock. The mineralogy and texture resemble intrusives cropping out along the west side of the Stillwater Range in the New York Canyon area that have been dated as late Cretaceous. This would place the intrusive event after the allochthonous thrust faulting and would explain thin fingers or layers of granodiorite observed within thrust fault zones as intrusive sills.

No commercial geothermal production has been developed from the granodiorite in the Dixie Valley geothermal field. The rock is mechanically competent and should fracture when under stress. Fracture permeability would tend to slowly be sealed in the unaltered granodiorite as calcic plagioclase is altered to albite, calcite and epidote.

Jurassic Spilite

The Jurassic section in the Stillwater Range is complex and diverse, and the term "spilite" is used in possibly a misleading way. The predominantly igneous suite ranges from spilitic basalts, keratophyres, and trondhjemites to albitites, plagiogranites, and gabbro. The minerals commonly present include plagioclase (generally An 5-15), hornblende, calcite, augite, biotite, Fe-Ti oxides, and minor epidote, pyrite, sphene, apatite, and rutile. Chlorite is observed as a very common alteration product of hornblende, augite, and biotite. Locally lenses of sedimentary rock, most commonly siltstone, are observed within the igneous series.

Published work on the area (Willden and Speed, 1974; Speed, 1976) describe the Jurassic igneous rock as a locally intruding lopolith. Autochthonous thrusting has been associated with the intrusion of the lopolith. Field and laboratory evidence suggests an alternative interpretation; that the entire Jurassic igneous section is an allochthonous fragment of oceanic crust, thrust over Triassic marine shelf and slope sediments. The most obvious points leading to this re-interpretation include extensive sodium metasomatization, pervasive secondary calcite, and abundant lamellar plates, lenses and nappes, markedly disrupting specific lithologic and stratigraphic continuity. The "lopolith" is remarkably similar to igneous portions of ophiolites observed in many places throughout the world.

The large blocks of spilite, keratophyre, and trondhjemite rock tend to be very brittle and are capable of maintaining good fracture permeability. The albitite and plagiogranite are somewhat less prone to host good fracture permeability. The prevailing mineral assemblage (albite, calcite, chloritized hornblende, chloritized biotite, and chloritized augite) tend to be stable in the chemical and thermal environment of the currently active geothermal system.

The mineral suite is not mechanically stable in the cataclastic environment of thrust faulting, shear planes, and nappes. The mafic minerals are usually altered to serpentine and chlorite; the albite tends to be broken up into small angular fragments; and the calcite tends to recrystallize as a matrix mineral. The result is lenses of mechanically unstable rock within the more competent formation. While these lenses have the potential of hosting permeability, the permeability does not always have good communication with major geothermal production, and the formation tends to slough during well flowing.

Jurassic Marine Sediments

Jurassic shallow marine sediments are observed in the Stillwater Range to the west of the Geothermal field. Compositionally these sediments consist of carbonate, quartzite, and minor conglomerate. Willden and Speed (1974) refer to these sediments as the Boyer Ranch Formation, and describe the carbonate and conglomerate as basal and the quartzite or quartz arenite as the upper unit. The continuity of this section is not obvious in the Stillwater Range. Thrusting of the Jurassic oceanic crust clearly involved the Boyer Ranch Formation. Portions of the sediments can be observed overlying, overridden by, and mechanically incorporated into, the allochthonous oceanic crust. The Boyer Ranch Formation may represent shallow marine sedimentation in a closing basin, bounded in part by the encroaching oceanic crustal block.

The quartz arenite portion of the Boyer Ranch Formation is lithified and tends to host open permeability along fault planes. Outcrop evidence suggests, however, that it is not prone to extensive fracture propogation. The rock is composed largely of lithified quartz grains and should be chemically and mineralogically stable in the geothermal system.

The basal carbonate and conglomerate portion of the Boyer Ranch would likely fracture under stress, though the fractures would tend to reseal with recrystallization. Dolomitic portions of the carbonate show the development of serpentine along fault and shear planes. Both fracture permeability and mechanical stability would likely be quite variable in the basal carbonate portion of the Boyer Ranch Formation.

Triassic Marine Sediments

Calcareous carbonaceous shale, siltstone, and silty carbonates crop out in the Stillwater Range underlying the allochthonous Jurassic oceanic crustal rock. Fragments and lenses also occur incorporated into the lamellar shear zones within and near the base of the Jurassic oceanic block. These carbonaceous marine sediments are correlative to the Favret Formation, a lower member of the Star Peak Group.

In fresh hand-specimen the marine sediments are commonly black to gray, variably carbonaceous, variably pyritic siltstone to dark gray carbonaceous limestone. A few of the outcrop exposures show siltstone which has been oxidized to light gray, light green-gray, and purple. Within the drill holes of the geothermal field the Triassic sediments are observed as cataclastized lensed in lamellar shear zones within the Jurassic rocks.

Mechanically the Triassic sediments will deform rather than fracture and fail when subjected to strain. Dolomite-bearing horizons form secondary serpentine during deformation. These characteristics make this formation a poor host for geothermal production.

The presence of these sediments at depth, below the thrust fault, plays an important role in the character of the geothermal system. The Favret formation is rich in hydrocarbons and is sub-mature in exposures to the northeast of Dixie Valley. The maturation level is much higher in the hottest portion of the geothermal system. Much of the gas associated with the geothermal fluid likely originates in the metamorphosing Triassic sediments in the deep portions of the geothermal system. CH_4, H_2S, N_2, NH_3 and CO_2 are likely derived from late stage thermal degradation of organic matter and sulfur compounds in the carbonaceous sediments.

STRUCTURAL HISTORY

Geothermal production in Dixie Valley is related to an extended, complex network of fault and fracture permeability. The combined tectonic history is, therefore, an important component in interpreting the production potential of any given location within the geothermal field. Three major faulting patterns are recognized in the vicinity of the Dixie Valley Geothermal Field. The first of these is thrust faulting; the second and third are both normal faulting.

Thrust faulting of Jurassic oceanic crustal rocks over Triassic shelf-related marine sediments is observed in the Stillwater Range. This thrust faulting event is part of the last in a series of crustal shortening events that involved allochthonous thrusting of deep marine strata over older rocks (Antler Orogeny, Devonian-Mississippian; Sonoma Orogeny, Triassic; and Nevadan Orogeny, Jurassic-Cretaceous).

The Jurassic oceanic rock has undergone differential movement along horizonal planes within the overthrusting block resulting in horizonal cataclastic zones. Inclusions of marine sediments, including argillite, sandstone, and locally, limestone, into the thrusting Jurassic plate, are observed in outcrops along the Stillwater Range. Turbulence in zones along the leading edge of the thrust block, and locally within the block, has resulted in the development of small scale melange-like features. These features usually include cataclastized fragments from both the underlying Triassic strata and the overlying Jurassic strata. Serpentinization of portions of the Jurassic mafic igneous rocks and of Triassic dolomitic sediments is common within these melange-like features.

The Stillwater Range-Dixie Valley area of Nevada appears to have been structurally quiet from the Cretaceous through the Oligocene. Subsequent to the eruption of silicic volcanism in the late Oligocene a series of north-striking normal faults developed. The best surface expressions of these faults can be observed along the western edge of the Clan Alpine Range and in the White Rock Canyon area in the Stillwater Range. Seismic data show similar north-striking patterns to continue into Dixie Valley, now buried by basin filling sediments (fig. 3). The surface expressions of this episode of normal faulting show evidence of rotation, suggesting that these were listric faults. The relationship between the timing of the late Miocene basalt eruptions and the north-striking normal faulting is unclear. Field evidence shows quite clearly that both Jurassic and Oligocene rocks were affected by this fault movement. No outcrops show a similar rotational relationship involving the Miocene basalt.

The development of the current high-angle NNE-striking normal faulting that defines the Stillwater Range and Dixie Valley physiographic features is relatively young, and is superimposed over the earlier two tectonic features. The uplift of the Stillwater Range occurred after the late Miocene basalt eruptions, as is evidenced by the flat-lying basalt flows and palagonite tuffs which occupy some of the highest elevations within the range. The onset of this last episode of faulting, therefore, could be no older than late Miocene to early Pliocene. Historic earthquakes along the basin-range boundaries attest to the continuing activity.

The NNE pattern of extensional faulting, superimposed on earlier N-striking normal faulting, has resulted in differential movement of the blocks which make up the Stillwater Range. The older N-striking faults exhibit subsequent strike-slip movement, a reaction to current WNW extension. The combination of dip-slip movement on the NNE-striking faults and strike-slip movement on the N-striking faults has resulted in localized zones of tension and compression along the western portion of Dixie Valley similar to the basin structures described by Aydin and Nur (1982). The tensional features form asymetrical rhombograben-

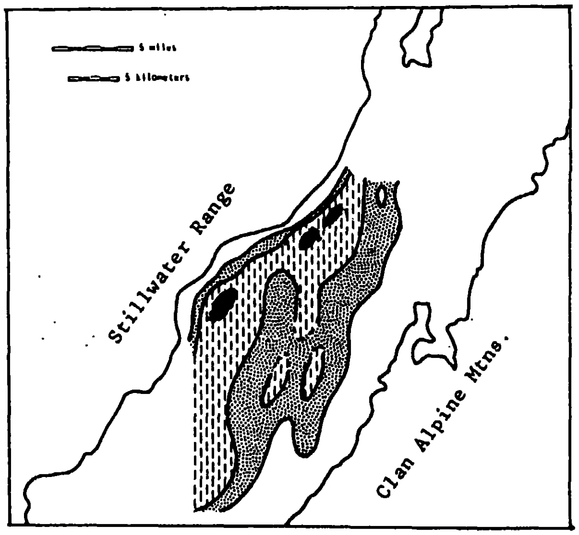

Figure 3 Estimated thickness of the Tertiary to Recent section in Dixie Valley, Nevada, based on seismic data from Sunedco, Southland Royalty and Amoco.

3000 to 6000 feet thick

6000 to 7500 feet thick

greater than 7500 feet thick

like structures bound by steeply dipping normal faulting toward the Stillwater Range and by shallow dipping normal faulting toward the vally. These features are identifiable on many of the seismic lines which cover much of the northern portion of Dixie Valley (Waibel, 1985). Figure 3 shows localized deep basins associated with the north-trending normal faulting in the central to eastern portion of the valley and with the more recent combined normal and strike-slip faulting along the western edge of the valley. Increased fault and fracture permeability associated with the localized rhombograbens plays a major role in hosting geothermal fluid. The degree to which pereability develops in these structures is modified, however, by the physical characteristics of the rock involved at any givel location.

The occurrance of faults or fractures within a brittle rock in itself does not guarentee production. Fault planes are not always "planer". Normal faults associated with extentional tectonics in Dixie Valley tend to undulate somewhat. This unevenness results in portions of fault planes being under high compression and impermeable, regardless of the rock type involved. Conversely other portions will be under tension and support open spaces possibly tens of centimeters wide.

HYDROTHERMAL MINERALOGY

Multiple thermal and metasomatic events have affected the rock that now makes up the areas of Dixie Valley and the Stillwater Range. Each of these events have left a mineralogical signature in the host rock. The temperatures of most of these metasomatic events appears to have ranged from 50 to 250°C, similar to the range of temperatures in currently active Dixie Valley geothermal systems. As a result, many of the secondary minerals are stable in, and characteristic of, more than one thermal event. The mineralogical effects of fossil thermal events must be distinguished from those of the currently active system before any interpretations pertaining to this current system can be made. Detailed mineral associations and morphologies are employed to assist in separating the effects of individual thermal events. It is possible in many cases, through careful observation, to identify which mineral occurrances are associated with the current geothermal activity.

The earliest thermal and metasomatic event recognized in the rocks of the Stillwater Range involves the Jurassic oceanic crustal rocks which Speed (1976) refers to as the Humboldt Lopolith. The pre-alteration rocks of this group were predominantly basalt, diabase, gabbro, and locally more leucocratic fractionations of this suite. The major primary mafic minerals are clinopyroxene and hornblende with local occurrences of biotite. Extensive sodium metasomatization is manifested in very extensive albitization and local scapolitization of plagioclase. Secondary calcite occurs both disseminated within the rock and in veins. Chloritization of mafic minerals is ubiquitous, and varies in degree from minor to near complete replacement of the mafics. Additional secondary minerals, including epidote, pyrite and chrysotile, are irregularly distributed throughout portions of the Jurassic igneous suite. The postalteration rock suite includes spilite, keratophyre, trondhjemite, albitite, and plagiogranite.

The spilitic rock suite of the Jurassic section in the Stillwater Range is typical of the igneous rock suites observed in many ophiolite complexes. The sodium metasomatization may likely have occurred while this section was still in a marine environment. A reasonable sodium reservoir to support this type of extensive alteration would be sea water.

A second metasomatic event, confined to the Jurassic oceanic rocks, involves silica and iron oxides. Along the eastern edge of the Stillwater Range this event is represented by quartz filled veins in association with specular hematite replacement of Jurassic spilitic rock. Fragments up to 15 cm across within the fault zone are observed to be completely replaced by hematite. Thin-sections of rock samples from the host rock in the vicinity of these quartz-filled faults show specular hematite replacement of the rock outward from the veins. Along the western margin of the Stillwater Range, in the Buena Vista Hills, specular hematite and magnetite replacement of Jurassic spilitic rock has been locally intense enough to allow for commercial mining of iron ore.

Neither the sodium metasomatization nor the quartz-hematite mineralization has been fully investigated. The timing and possible relationship between the two events has not been determined. Convection of water in the Jurassic rock was clearly involved in thermal energy and chemical changes associated with both the sodium metasomatization and the hematite-quartz mineralization. It is possible that both of these secondary features developed at or near the same time, while these rocks were still part of an ocean environment.

Additional thermal and metasomatic events in the Dixie Valley-Stillwater Range area include contact metamorphism associated with Cretaceous plutonic intrusives as well as Oligocene silicic volcanism. Evidence of the former is observed in the Stillwater Range to the south of the current geothermal activity. The older secondary mineral suites are characterized by skarns and quartz-calcite veins. These alteration zones are observed to contain predominantly sub-economic sphalerite, chalcopyrite and galena in a gangue of epidote, garnet, pyrite, quartz, calcite and magnetite. The Chalk Mountain, La Plata and I.X.L. Mining Districts are in these contact metamorphic areas.

Toward the southern end of Dixie Valley, contact metamorphism and hydrothermal activity are associated with Oligocene and early Miocene silicic volcanism. Hydrothermal activity resulted in precious metals, quartz, adularia, and local minor fluorite being deposited in breccia, fault, and contact shear zones. The Wonder and Fairview Mining Districts are examples of this activity.

The most recent volcanism in the Dixie Valley area is the late Miocene eruption of basalt. Subvolcanic dikes are observed in the Stillwater Range to the west of the geothermal field. Contact metamorphic effects are usually limited to a few tens of centimeters away from the edge of the intrusives and consist mainly of chloritization. No hydrothermal activity has been observed to be associated with this event.

Hydrothermal mineralization associated with the currently active geothermal system varies with temperature and type of host rock. The fluid has low oxygen activity, low total dissolved solids, limited sulfur activity (Benoit, 1987), and is likely saturated in methane. The character of the fluid appears to be influenced by low-grade metamorphism of carbonaceous marine sediments. Precipitation mineralization in the deeper production from Jurassic igneous rock is usually limited to quartz. Host rock alteration by the hot fluid is limited to pyrite, forming at the expense of Fe-Ti oxide. The host rock is already at a chlorite-albite grade of greenschist metamorphism and is chemically stable in the presence of the hot fluid. Calcite veining, as observed in cuttings from production zones within the Jurassic section does not appear to be co-genetic with the druse quartz which is currently forming. Both the calcite veining observed in the well cuttings and the abundant calcite veining observed in the Jurassic section in the Stillwater Range are probably artifacts of much earlier sodium metasomatization.

Hydrothermal mineral reactions within the Miocene basalt are substantially different from the reactions observed in formations underlying the basalt. Major chemical reactions between the basalt and the geothermal system involve oxidation of hydrogen sulfide and methane, reduction of the iron in hematite and albitization of relict plagioclase. The resulting alteration minerals include chlorite, pyrite, albite, calcite and localized epidote. Precipitation minerals include quartz, chlorite, and epidote or Ca-zeolites. The occurrences of epidote and laumontite tend not to overlap except in those areas where a retrograde shift in mineral stability from epidote to laumontite has occurred. No mineral-chemical evidence for mixing of geothermal and non-geothermal water in the basalt has been identified.

The marked difference between the hydrothermal mineral assembleges in the two mafic igneous units is the combined result of the presence of different secondary mineral phases prior to the introduction of the geothermal fluids and the composition of the geothermal fluid. Buried Miocene basalt remains oxidized where unaffected by geothermal fluids, with reddish hematite as a major Fe mineral. The Jurassic spilitic series has been albitized and partially chloritized prior to the current geothermal activity. The significant change within the geothermal fluid as it passes through the Jurassic section is a limited conductive heat loss. This results in slight but steady silica oversaturation, manifested by the precipitation of druse quartz along fracture surfaces. The reduced geothermal fluid, and associated H_2S and CH_4 gases, react with the weathered Miocene basalt. The major reactions involve oxidation of gases by hematite and sodium replacement of calcium in plagioclase. From these chemical reactions iron, sulfur, carbonate and calcium are available to form the hydrothermal minerals observed in the cuttings.

Geothermal fluids discharging into the basin filling sediments react with the rock in a manner similar to the fluids in the Miocene basalt. In the sediments, however, the temperature of the fluids has decreased to below the epidote and wairakite stability range for a near-neutral pH. Lower temperature mineral reactions in the sediments involve smectite altering to illite, hematite altering to chlorite, and precipitation of quartz, chlorite, and laumontite or heulandite.

Age estimates have been made on two hydrothermal silica specimens from the geothermal system using the ionium/thorium method (Struchio, personal communication). The facilities at the Argonne National Laboratories in Argonne, Illinois were used. The first sample is of dense clear cryptocrystalline silica from a silicious sinter hot spring deposit in section 15, T24N, R36E. The hot spring is no longer active, and the area has been uplifted by ongoing normal faulting along the Stillwater Range front. Total uplift since the hot springs deposits formed may be as much as 200 feet. The estimated age of this deposit is determined to be 9,000 $\pm$ 2,000 years.

A second sample was collected for dating from hydrothermally precipitated cryptocrystalline silica near the Senator Fumaroles in section 32, T25N, R37E. This sample formed near the boiling plane below the topographic surface. Subsequent uplift by normal faulting along the Stillwater Range front now positions this rock 250 feet above the Dixie Valley floor. The age of this sample is much less difinitive, with a maximum possible age of 300,000 years and a minimum possible age of 150,000 years.

CONCLUSIONS

Geothermal production in the Dixie Valley field is defined by fault and fracture permeability. Rather than being strata bound, permeability is defined by, and varies with, the physical characteristics of each rock type. The production potential of a rock is best defined by its mechanical and mineral-chemical stability. The existence of open fractures is dependent on the presence brittle rock; rock that will fail rather than deform under tectonic strain. In the Dixie Valley, field producing fractures are, therefore, most likely to occur in brittle igneous rock, and least likely to occur in soft clay-rich sedimentary rock with secondary hydrous Mg minerals. Subsequent to fracturing, the longevity of permeability is dependent upon the mineral and chemical stability of the rock in the presence of geothermal fluid and gas.

The secondary hydrothermal minerals associated with the high temperature geothermal system in Dixie Valley do not lend themselves to the rote or blind "mineral=temperature" interpretation presented for many other geothermal fields. The Dixie Valley field is likely not unique in this feature, as secondary minerals are an artifact of multiple populations of chemical components reacting with each other in variably changing conditions. Secondary minerals can be used as useful tools in reducing exploration and production drilling costs only after site-specific constraints on rock-water-gas reactions are developed.

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