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A CONCEPTUAL MODEL OF THE WENDEL-AMEDEE GEOTHERMAL SYSTEM, LASSEN COUNTY, CA

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ABSTRACT

The Wendel-Amedee KGRA is located along the northeastern edge of the Honey Lake Valley in eastern Lassen County, CA. The Valley a complexly faulted graben which lies at the junction of the Modoc Plateau, Sierra Nevada and Basin and Range geologic provences. Interference testing of 3 deep geothermal wells indicates production from a fractured double porosity system. Drilling and testing results, along with earlier geophysical surveys, imagery analysis and isotope geochemistry suggest that the Wendel-Amedee system is part of a large flow system with recharge in the Sierra Nevada to the southwest. Flow is largely confined within fractured basement rock by low permeability volcanic and lacustrine sediments, allowing little communication with shallow groundwater. Waters penetrate to depths of 7000 ft or more beneath the Valley floor and are heated by above average regional heat flow before rising along N-NE trending faults.

INTRODUCTION

Three wells have been completed on the GeoProducts Corp. leasehold near Wendel (Fig. 1). The first two wells were tested individually under artesian flow conditions and the third was pumped as part of an interference test program completed in November of 1986. Earlier work has been discussed in 3 previous GRC proceedings articles and detailed in 3 reports to the U. S. Department of Energy (Juncal et al, 1982, 1984, Benson, 1982, GeoProducts, 1982, 1984, 1987).

GEOLOGIC SETTING

The Wendel-Amedee KGRA is located along the northeastern side of the Honey Lake Valley (fig.2). The Valley lies at the junction of three distinct geologic provinces: the Sierra Nevada, comprised largely of granitic intrusive rocks and bounded by a steep eastern fault escarpment; the Basin and Range, characterized (in this area) by north-northeast trending mountain blocks separated by alluvial valleys; and the Modoc Plateau, consisting of largely Pliocene and younger volcanic rocks with less well-defined structural trends.

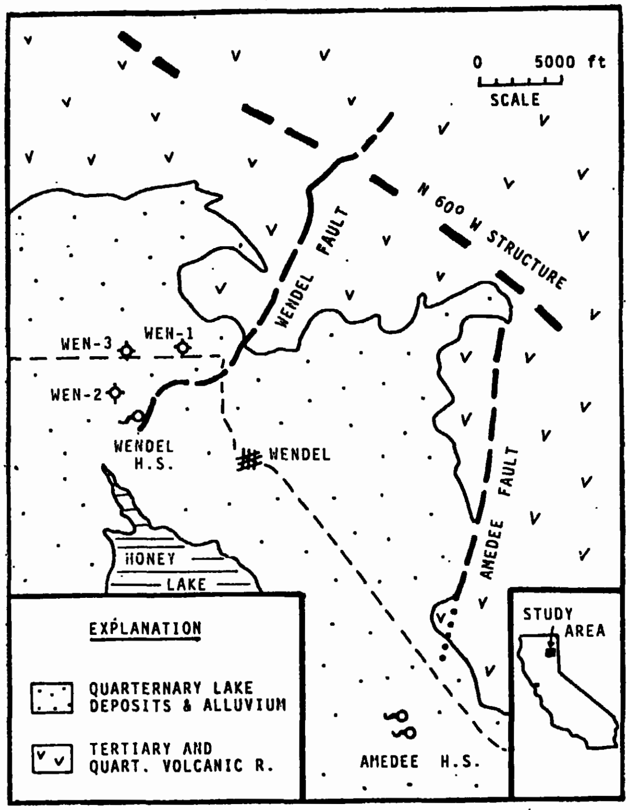

Figure 1. Wendel- Amedee Area.

A forth regional feature could also intersect the Honey Lake Valley and is an important element of the proposed system model. This is the northwest trending Walker Lane fault zone which can be traced continuously from Las Vegas to at least Pyramid Lake and appears to cross the eastern side of Honey Lake possibly continuing as the Antelope Mountain Fault.

Drilling along the northeast side of the Valley has shown the basin to be filled largely with volcanic flows, mudflows, tuff and volcaniclastic sediment to a depth of approximately 4500 ft. These rocks are probably of Tertiary age, although lavas in the upper 2000 ft may be younger. Although no strongly coherent stratigraphy is traceable between wells, from the standpoint of the geothermal system, this volcanic "unit" can be considered a caprock in that the section is dominated by very low permeability clay-rich lithologies. The volcanic section overlies a sedimentary conglomerate which is also an important element of the system model. This unit is comprised largely of rounded siliceous clasts and although no circulation losses were reported in this section during drilling, very high mercury and arsenic concentrations were found in the cuttings suggesting geothermal water has moved through these rocks.

At approximately 5000 ft, the conglomerate contacts the granitic basement, which includes both true granite(possibly as dikes) and granodiorite, with some quartz veinning. Evidence of fracturing from two of the deep goethermal wells in the area is unequivocal, as indicated by lithologic examination, geophysical logging and and drilling behavior. In the third well similar evidence exists for fracturing/faulting within the conglomerate. In all three wells spinner flowmeter surveys show production from discrete, narrow intervals which can be projected from the Wendel Fault (fig. 1), although teh changing strike of the fault allows for other interpretations (Sibbitt, 1984).

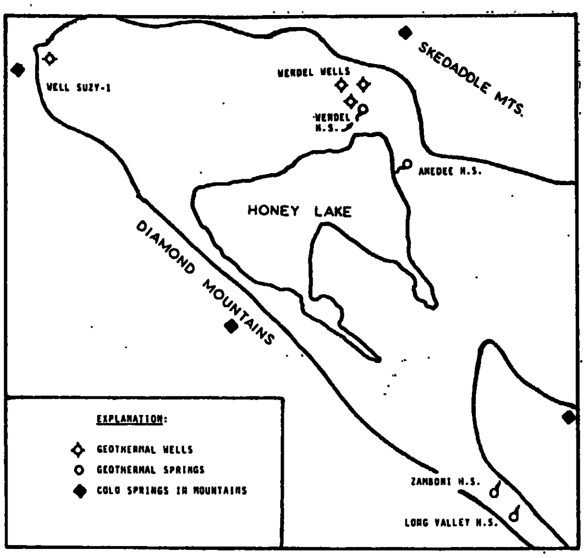

Figure 2. Simplified map of Honey Lake Valley showing approximate locations of major mountain blocks, wells and springs.

The Wendel and Amedee faults may be manifestations of the Basin and Range tectonic style or alternatively, could be second order structures between two strike slip faults related to the Walker Lane zone. If one of these structures cuts across the Valley along the northeastern margin of the Lake (as suggested by imagery analysis), the second could correlate with a N60W trend of volcanic plugs within the Skedaddle Mts. previously mapped by Sibbett (1984, fig. 1). Interestingly, both the Wendel and Amedee faults appear to be terminated by this trend.

INTERFERENCE TESTING

In October of 1986 GeoProducts well WEN-1 was pumped at approximately 1100 gpm while monitoring well WEN-2 with downhole pressure and temperature tools. Both the drawdown and recovery phases of the test are shown on the semi-log plot in figure 3. The drawdown data do not appear to reach a straight line until approximately 3000 minutes, likewise, the recovery data only approach a straight line (poorly defined) late in the recovery period. These plots suggest a conventional radial flow (Theis) model is not appropriate for the Wendel system.

In order to determine a more appropriate model for the test interpretation, the observation well data were plotted on log-log paper. Based on the character of the log-log plots and the results of earlier artesian flow testing (Benson, 1982) a double porosity model was selected for analysis using the type curves of Deruyk et al., (1982).

The conceptual basis of the double porosity model is the assumed existence of two regions of different porosities and permeabilities within the producing formation(s). These two regions may be represented by either: (1) blocks with primary permeability separated by fractures, or (2) interlayered formations with drastically differing permeabilities.

It is not possible to distinquish between the naturally fractured or multi-layered reservoir model based on flow test data alone (Gringarten, 1982). The geologic and geophysical logs from the three well at Wendel clearly establish a fracture situation; however, there is an element of the multi-layered model also. This latter feature is due to the presence of the 500 ft thick conglomerate formation lying atop the granitic basement in the Wendel area. In both WEN-1 and WEN-3, the production interval is in fractured granite (the conglomerate is cased off), whereas in well WEN-2 the production is from fractures within the the conglomerate. Considering the structural setting of the area (extensive normal faulting) it appears likely that even in the wells producing from fractured granite there is communication getween the granite and the overlying conglomerate.

In the double porosity model the flow during early stages of the test originates from the factures only and the pressure behavior is characterized by the transmissivity and storage coefficient of the fractures. During intermediate stages the blocks with primary porosity (also called the matrix) begin to provide fluid to the fractures until there is pressure equilibrium between the two. During the late stages of the test, both fractures and matrix are produced simultaneously and the pressure behavior reflects a permeability equal to that of the fractures feeding the wellbore and storativity equal to the total of the fractures and the matrix.

The pressure data from WEN-2, taken during the 10 day constant rate test of WEN-1 were plotted vs log t/r and matched to transient interporosity flow type curves using the method of Bourdet and Gringarten (1980). From these type curves values for fracture transmissivity, fracture storage coefficient and matrix storage coefficient were computed, giving 2.47 E+6 md-ft/cp, 6.05 E-5, and 2.01 E-4, respectively. The type curve match also allows determination of the time after which a semi-log (radial flow) approximation is applicable (fig. 3). Using the semi-log staight line method yields a transmissivity of 1.73 E+6 md-ft/cp. These very large permeabilities along with the very rapid response time in the observation well (less than 2 minutes) reflect the fractured nature of the Wendel system.

During the 10 day WEN-1 test, no boundaries were observed. This is consistent with the results of the 1982 test (Benson, 1982) and does not allow for the calculation of reservoir size; however, the radius of drainage was estimated to be 7.95 miles for the 10 day test using the computed T and S values. Although the drainage area and volume of liquid affected by testing is extemely large, there is no assurance that the reservoir temperature is constant. It could be higher or lower in areas beyond the presently developed acreage. It was pointed out by Yeamans (1982) that geothermal flow tests are commonly interpreted to suggest very large volume geothermal reservoirs; yet the reults of step out drilling are often disappointing. For the Wendel- Amedee geothermal system there is some evidence to suggest that the 250°F temperatures may persist over a very large area. A well (Gulf ST-1) 3.5 miles east of Wendel had a bottom hole temperature of at least 250°F at 5000 ft. The Amedee Hot Springs, 5 miles east of Wendel are large volume boiling springs with a geochemical signature almost identical to the Wendel springs and

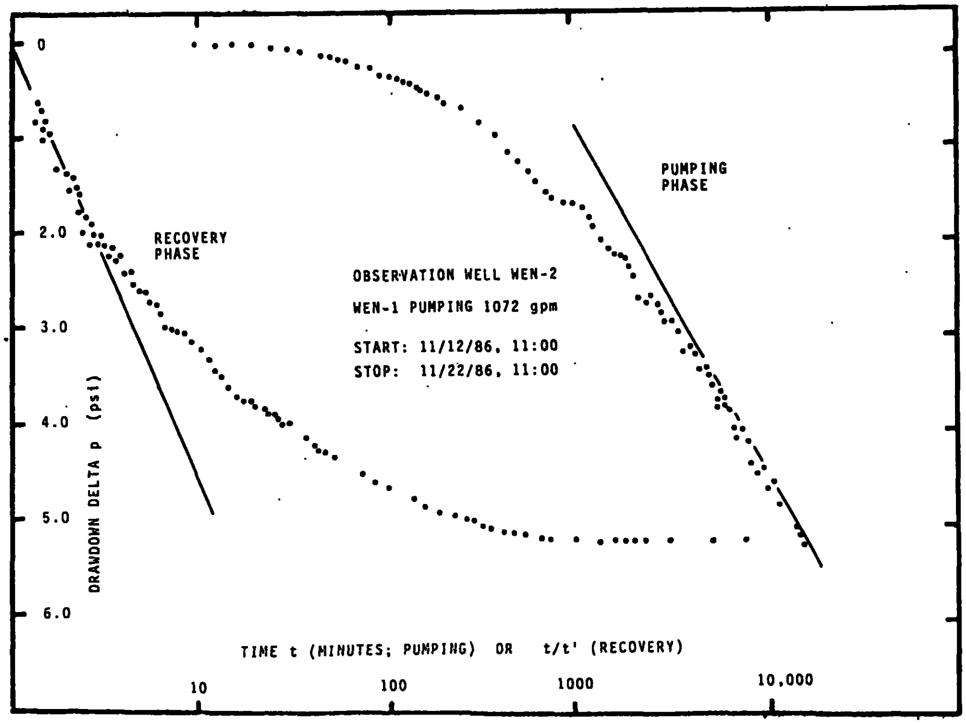

Figure 3. Semi-log plot of downhole pressure versus time for observation well WEN-2 during pumping and recovery of WEN-1.

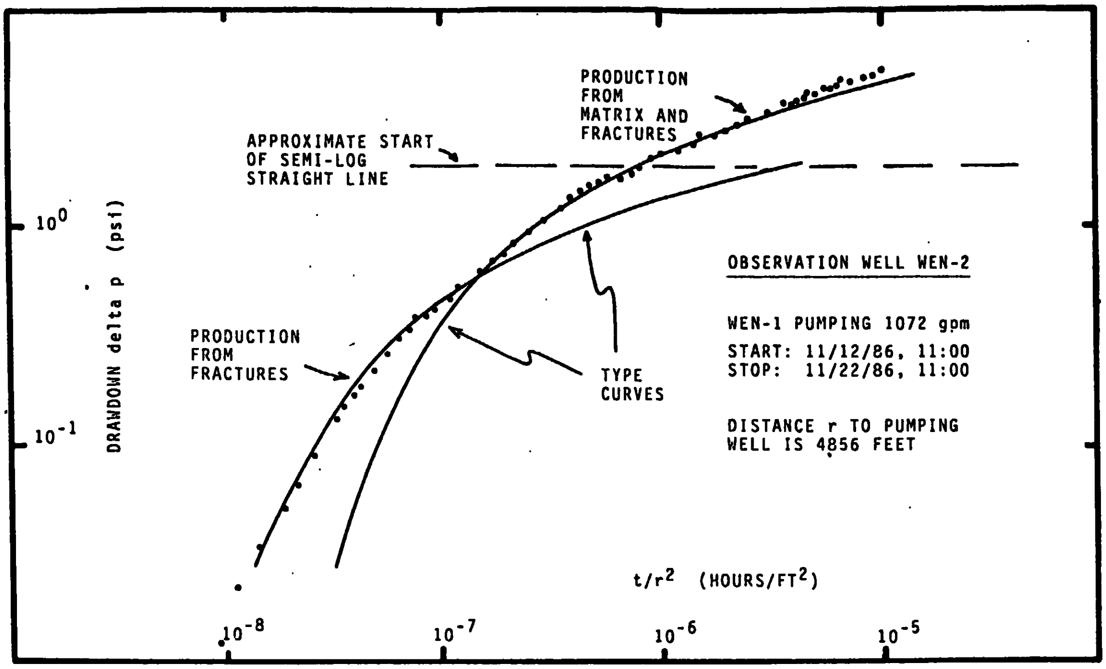

Figure 4. Type curve analysis using the double porosity model with transient interporosity flow.

wells. The Gulf well ST-2 located about 1 mile southeast of Wendel Hot Springs has a temperature of 245°F at 4800 ft which together with the existence of numerous shallow warm wells throughout the area between Wendel and Amedee suggest a hydrologic and thermal continuity. Little is known about the temperature regime at depth to the west however, a well at Litchfield 10 miles to the west which lies along the postulated trend of the Walker Lane zone through the Valley, produces water of similar chemistry at 180°F from a depth of less than 1500 ft.

CONCEPTUAL GEOTHERMAL SYSTEM MODEL

The geothermal system at Wendel can be demonstrated to be a dynamic flow system rather than a bounded reservoir. As such, it is comprised of the basic elements of any hydrologic flow system: a recharge source, a path of flow or circulation, and a discharge zone.

At Wendel, as in most geothermal systems the discharge zone has been the focus of investigation. Thermal waters discharge to the surface along N-NE trending faults at both Amedee and Wendel. The chemical similarity between the deep well water and the high volume Hot Springs indicates a rapid rise of fluids from depth with little conductive heat loss or mixing with shallow groundwater. In addition to the Spring discharge, the abundance of warm groundwater and shallow hot wells in the area suggests significant subsurface discharge of system fluid, although some of this is probably due to conductive heating. The evidence of a large natural discharge is consistent with the results of pumping tests which showed small pressure drawdowns in observation wells and the lack of system boundaries within at least 8 miles.

While the discharge zone(s) of the system is readily identifiable, the recharge area and the circulation path between the two are considerably less obvious. For the Wendel-Amedee system, as for the Honey Lake basin as a whole, recharge would be expected from the area of most precipitation/snowpack, which is the Sierra Nevada (Diamond Mts.) to the west. The relatively high elevation of the range is also important to provide the hydraulic head necessary for penetration to depths of high temperature.

Analysis of the stable isotope data shown on figure 5 also supports the Sierran recharge hypothesis. The deuterium levels in the geothermal waters differ significantly from those in the cold wells and springs. Generally depleted (more negative) values of deuterium correlate with a higher elevation of precipitation (lower temperature of condensation) for a given area, although considerable variation can occur in the eastern Sierra depending on air flow patterns (Friedman and Smith, 1970). Friedman and Smith (1972 also not-

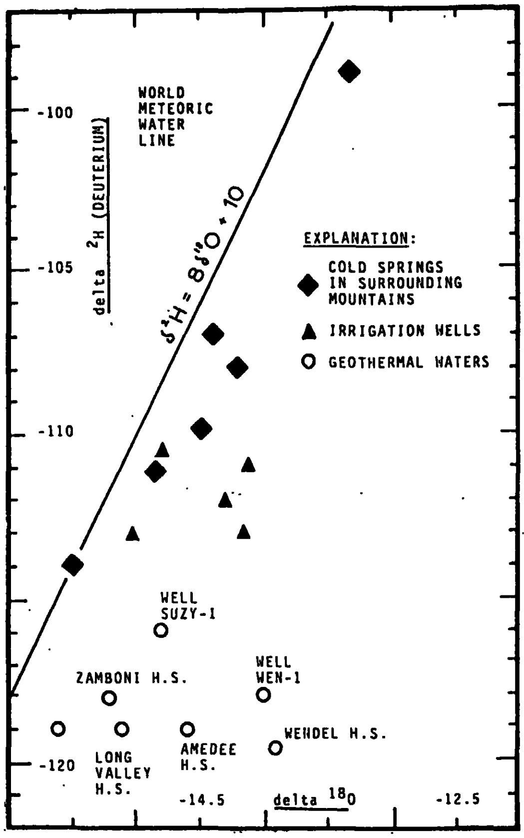

Figure 5. Plot of stable isotope data from Honey Lake Valley region.

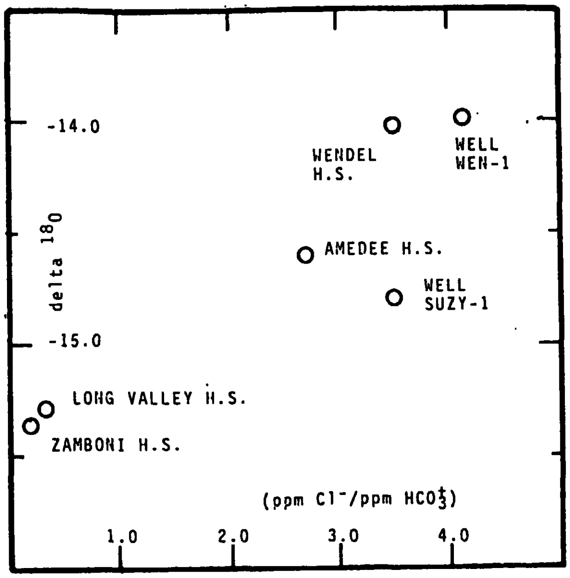

Figure 6. Plot of chloride/bicarbonate ratio versus oxygen 18 content for geothermal waters in the Honey Lake region.

ed that above normal snow pack correlates with colder storms in general. The combination of these two effects is that the best recharge years are characterized by precipitation which is more depleted in deuterium. These studies, along with recent work by Ingraham and Taylor (1986) which shows a correlation between deuterium depletion and distance from the coast along the prevailing storm paths, indicate recharge from the higher elevations in the northern Sierra Nevada, east of the crest, should average -115 to -120 per mil. Shallow groundwaters in the Valley, on the other hand, may recieve a significant amount of recharge from infiltration of stream or lake water which has been effected by evaporation and is therefore enriched (less negative) in deuterium.

An alternative explanation for the low deuterium levels in the geothemal water is that it is greater than 10,000 years old and was recharged during a period of colder worldwide climate. While not unreasonable, the similarity in deuterium content between the Wendel-Amedee area and the two hot springs in Long Valley which emerge along the Sierran frontal fault suggest a common source and yet the Long Valley waters are far less evolved geochemically. This is less consistent with very old waters than it is with a north to northeastern migration of recharge across the region. Figure 6 shows a plot of the oxygen isotope data versus chloride-bicarbonate ratio for the Honey Lake geothermal waters. Because increasing Cl/HCO_3 and increasing ^{18}O content both correlate with increased residence time, flow from southwest to northeast is suggested by the plot.

If the Diamond Mountains are the source of the geothermal system recharge, the Honey Lake fault which bounds the southwestern side of the Valley is a logical conduit for downward flow. This fault and other structures further east in the mountain block can be reasonably expected to extend to depths of 10,000 ft or more and would have fracture permeability maintained by recent and ongoing siesmicity in the region (Vetter and others, 1982). Much of the seismic activity in the area is recorded along the Walker Lane and near the Antelope Mtn. fault zones suggesting the potential importance of structures along the eastern side of Honey Lake Valley.

Recharge from the eastern flank of the Diamond Range would move downward beneath the Valley, gradually heating by conduction from the rock along the flowpath. The most reasonable source of heat is the above average regional flow (Blackwell, 1982), which accumulates in the chrystalline basement rock due to the insulating effects of the thick, clay-rich, low thermal conductivity valley fill material.

For the Wendel waters a minimum depth of circulation of approximately 7000 ft beneath the Valley floor is required to heat a 45°F recharge water to system maximum temperature (based on geothermometry) of 268°F using gradients measured in 4 TG holes drilled in the area.

Water circulating to these depths would flow in response to both a potential difference and a density difference. For the Wendel-Amedee system, flow within the fractured granitic basement may also be controlled by the deep seated, probably near vertical Walker Lane fault zone. The Wendel and Amedee hot springs may be localized in part by the intersection of the NW trending Walker Lane structure with the normal-NE striking Wendel and Amedee faults near the eastern margin of Honey Lake. Or as previously mentioned the Wendel and Amedee faults may be second order features related to strike slip movement on Walker Lane trends.

SUMMARY

The Wendel-Amedee KGRA appears to be part of a large flow system, with recharge provided from meteoric sources in the Diamond Mts. The geothermal fluids flow under structural control beneath the Honey Lake Valley. Due to the low permeability of the valley fill the flow is largely confined to fractures within the basement rock. Heat has accumulated in these rocks due to a higher than average regional heat flow and the insulating effects of the overlying clay-rich material. The fluid circulates to a depth of 7000 ft or more and is heated conductively before rising along N-NE trending faults, possibly near the intersection of these faults with a major regional structure which cuts the Valley longitudinally along its east side. The clay-rich material overlying the granite basement acts as a cap, effectively preventing communication with the shallow groundwater system in the valley fill. The rapid rise from the basement fractures to the surface is accomplished without significant near surface mixing.

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