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GEOPHYSICS

Early Investigations

Good data

The earliest geophysical study of Honey Lake valley was a reconnaissance gravity survey carried out by the California Department of Water Resources as part of its groundwater investigations. The gravity survey gives a generalized picture of the subsurface geometry of the valley which was used to locate and estimate displacements on the major faults, as discussed in the section on geologic structure. Details of faulting cannot be delineated at this density of coverage and it is possible that some of the interpreted fault trends in the Wendel Hot Springs area are misleading.

Geophysical studies by Gulf Oil Company included a two-source roving dipole resistivity survey, a seismic ground noise survey, and a very shallow (10 feet) ground temperature survey. These investigations yielded data of uncertain to poor quality which have not been useful in interpreting the geologic structure or the geothermal system. The ground-temperature survey is described elsewhere.

Apparent resistivities within the Honey Lake valley were found to generally decrease away from the mountains, reflecting a probable thickening of clay-rich sediments in that direction. An area of anomalously low resistivities was located near the junction of U. S. highway 395 and the road to Wendel. Resistivity contours as low as 3 ohm-m are shown on the outer edge of the study area, but data points on which the contours were drawn are not shown.

A contoured "microseismic, anomaly map" was provided by Gulf. No explanation accompanies the map, so its relevance to the geothermal system cannot be explored. In reference to this map, Electrodyne (1979) stated that it suggested "a thick overburden of valley-fill deposits in the area," with seismic noise created probably by trains and highway traffic. The results are considered irrelevant to the geothermal system. ?

The Bureau of Reclamation conducted a reconnaissance resistivity survey in the early 1970's consisting of Schlumberger vertical electrical soundings along the northeast margin of the valley and in various other areas of interest. The results were published later along with other geothermal-related studies in a special report (Bureau of Reclamation, 1976a). Several important results of this survey deserve to be noted: (1) the lowest apparent resistivities are associated with the Wendel and Amedee Springs areas; and (2) the lowest apparent resistivity in the entire study (1.7 ohm-m) was found in the Amedee Hot Springs area.

Seismology

A listing has been obtained from the University of Nevada, Reno, of 131 earthquake events within a 30-mile radius of Honey Lake which registered on the northern Nevada seismographic network between 1970 and 1980. Magnitudes ranged from 1.2 to 5.1. Epicenters are plotted in figure 1. Earthquakes for the 10-year period are widespread in the Honey Lake area, and abnormal seismicity was associated with the Fort Sage Mountains at the southeast end of the valley and Antelope Mountain area near Susanville. Both of these areas are cut by major northwest-trending faults, on which much of the activity probably occurred. The Wendel-Amedee area was quiet during this 10-year period.

Investigations Conducted on Behalf of GeoProducts

Electrodyne, Inc. was contracted by GeoProducts to perform exploration geophysical surveys in two phases; (1) a reconnaissance phase, in which gravity, ground magnetic, and scalar and tensor magnetotelluric techniques were employed to identify areas of interest, and (2) refinement phase using DC resistivity soundings and controlled-source time-domain electromagnetic (TDEM) methods for detailed investigations of these areas. The final results of these studies are given in a two-volume report (Electrodyne, 1979).

tad!

Gravity and Magnetic Surveys

The gravity data from the Electrodyne survey are contoured in figure 6 at 1 mgal intervals by GeothermEx, ignoring one measurement on the section line between sections 10 and 20 which appears to be bad. The gravity field decreases from the northeast to the southwest across the study area reflecting both basement relief and the interfingering of low-density valley-fill sediments in the valley center with higher-density lava flows of the volcanic plateau. The overall gradient is relatively steep, averaging about 8 mgal/mile.

The data in the western part of the study area and in the central part of T. 29 N., R. 15 E. show the presence of two distinct steepened (up to 20 mgal/mile) gradients which suggest locations for normal faults. These have been connected in the simplest manner possible in figure 6, but the trends could be misleading due to the lack of control in critical areas. Nevertheless, the presence of multiple faults is indicated. As contoured, the data suggest the fault pattern shown in figure 6.

The gradient just south of Shaffer Mountain could be caused in part by extensions of mapped southeast-trending faults on the southwest side of that mountain, rather than a hypothetical basin-bounding Litchfield fault.

In the Wendel Springs area little support is found for the placement of the Litchfield fault favored by Zebal based on tufa alignments. These must have been controlled by minor ruptures at the basin margin. A northwest-trending fault appears to contribute to the steepened gravity gradients in Section 9, possibly extending to Section 22, as shown in figure 6. The odd contour configuration in Section 7 may be caused by a small fault or may be an artifact caused by a bad measurement. Little justification is found for major offset on the Skedaddle fault or for its southwest extension through Wendel Hot Springs. A north-south-trending gravity gradient at the eastern end of the study area is no doubt caused by the nearby Amedee fault.

There is no convincing evidence for local densification of valley-fill sediments by precipitation of intergranular $CaCO_3$ from thermal groundwater, as suggested by Electrodyne (1979) to account for variations in electrical resistivity in Sections 9 and 15. The postulation of excess mass in this area was made on the basis of residual and second-derivative gravity maps. As generation of these maps requires additional approximations and interpretations over and above those involved in the original contouring, they are reliable only for enhancing suspected features in areas where control is good. They should not be used to generate new interpretations.

Bravo!

A ground magnetic survey using the same stations as the gravity survey yielded a very "noisy" magnetic map which, even when numerically smoothed, is difficult to interpret. Total magnetic relief is small, only about 1,500 gammas. This is surprising, in view of the prevalence of mafic volcanic rocks in the area. However, Electrodyne's (1979) suggestion of widespread geothermal-related alteration in the subsurface is not considered realistic. On the whole, magnetic variations do not correlate well with surface features or gravity trends.

Evaluation of Electromagnetic Soundings

With regard to the EM data, it is our opinion that too much interpretation has been made of data that inherently contradicts the assumptions used in the interpretation. Specifically, it is clear that there are major electrical inhomogeneities in the area but it is very doubtful that the techniques used could resolve the vertical faults hypothesized in this interpretation. This is because the interpretation is based on one dimensional models, whereas the data clearly show that the actual configuration is not one dimensional. To reconcile two different vertical sections that are a few kilometers apart one must, with this approach, insert a fault. There is a fault between almost every receiver station on the N-S profile of soundings from source 5 (Figure 14, Electrodyne Surveys, 1979, Vol. I) and large numbers of faults are located on the basis of the ESP soundings on the EW profile lines (e.g., Figure 46, Electrodyne Surveys, 1979, Vol. I).

These data could only be interpreted in such a manner if a two or three dimensional model was used to fit the data.

The contradictions evident within the data sets are even more serious:

The intermediate resistive layer seems to be of very great importance in this study, but its existence is doubtful. The modified Schlumberger soundings show a sequence of layers of increasing conductivity to depths of 3,000 feet, but no resistor was encountered or even sensed in these soundings. Sounding 4.3, Figure 10 of Electrodyne Surveys, 1979, Vol. I actually resolved the top of a conductor at 3,200 feet. The ESP soundings generally parallel the resistivity interpretation, that is, resistive near surface becoming conductive at one to two thousand feet. There is no suggestion of the resistive intermediate layer in these data. Consider, for example, the final interpretation of ESP profile line 6, east end (Figure 46, Electrodyne Surveys, 1979, Vol. I). The resistivities (all in the 4-8 ohm meter range) are confidently interpreted to 4,000 feet. The ESL soundings from source 5 along a N-S profile crossing profile line 6 (5.05, 5.06, and 5.07 in particular) show, on the other hand, a highly resistive zone ranging in depth from 2,000 to 3,000 feet.

It is important to note that the ESL soundings from source 5 are orthogonal to the ESP soundings from source 2 that were used for the east end of profile line 6. In the region in question, around ESL soundings 5.06 (Figure 5, Electrodyne Surveys, 1979, Vol. I), the currents from each source would be orthogonal. It is likely that the different interpreted sections are caused by some two to three dimensional regional feature which interacts differently with these two primary current directions.

Error bars are not included on the apparent-resistivity estimates. The data accuracy would have to be very good to allow a section as detailed as that of sounding 5.09 (pages 391-392, Electrodyne Surveys, 1979, Vol. II) to be interpreted from the data shown. Similarly the resolution of zones only 2 ohm meters different in resistivity in the ESP profiles would be very difficult without very high instrument accuracy.

Such inconsistencies in the basic model render all higher order interpretations rather suspect. The methods used for this survey (ESP and ESL soundings) seem quite appropriate but the data quality may not be up to the detail derived from it. In general, the electric source EM soundings are properly understood. They are indeed sensitive to resistive layers in the section whilst MT and magnetic source techniques are not. On the other hand they are also sensitive to relatively near surface conductivity inhomogeneities which may mask deeper effects even at lower frequencies. A combination of DC resistivity and inductive EM is the ideal combination.

dipole-dipole

The authors have done a good job with the interpretation techniques available, but the overall interpretation has been carried too far. It is unfortunate that this survey illustrates one of the major problems in current electrical and EM practice: it is possible to get good data with modern instrumentation but the interpretation techniques using any but simple geologic models are far behind. We would certainly not recommend any additional field studies.

Some additional numerical treatment of existing data might be useful, but this probably would not be cost effective, due to the very high cost of even two dimensional models for electric dipole sources ($5,000 in computer cost alone).

It is clear, in summary, that a good conductor lies beneath relatively resistive surface rocks. The depth to this conductor, which seems to be present beneath all the area encompassed by the receiver site, varies from 1,000 feet to 3,000 feet. It is not a homogeneous region and probably is broken up by faults or other regional discontinuities. The precise location of major faults, fracture zones, or other specific features is not possible with the interpretations used in this survey.

SUMMARY AND DISCUSSION

The existence of a potent magmatic heat source in the Honey Lake region is unlikely. Although many volcanic rocks in the area are geologically very young, they are of a type (basalt) which rarely crystallizes in large subsurface magma chambers. Nevertheless, heat imparted to the crust during passage to the surface and by the cooling of numerous small dikes may have significantly warmed the crust locally. It is the warm crust of the Modoc Plateau on the north side of the Honey Lake basin that is considered to be the heat source for the geothermal fluid of the Wendel-Amedee system, rather than the Sierra Nevada granitic rocks to the southwest, which have long been recognized to be abnormally cool. Heating takes place by circulation deep within the crust. Water present in the volcanic aquifers beneath the GeoProducts leasehold almost certainly has circulated to significantly greater depths elsewhere in the system.

The highest subsurface temperature measured to date in the Wendel-Amedee geothermal system is 240°F, which is the bottom-hole temperature of the Gulf exploration well Honey Lake 2-ST drilled one mile southeast of Wendel Hot Springs. This temperature was measured in the conductive part of the temperature profile, which extends from 4,600 feet to TD at 5,056 feet. It is doubtful, therefore, that sufficient permeability exists in this interval to support significant production. In contrast, large losses of circulation occurred in a zone extending from 4,271 to 4,340 feet, where the stablized temperature is 232°F. Temperature profiles taken before and after a limited flow period, however, indicate that the only interval produced was at 600 feet (just below the casing set at 550 feet) and the temperature of the produced fluid was only 115°F. The zone from 4,271-4,340 feet may not have been brought into production because of damage done to the zone during drilling and completion rather than because of an inherently low permeability.

Although reliable production information is lacking, it appears that the Gulf well has identified a 230°- 235°F reservoir extending from 3,000 to 4,500 feet in depth. The reservoir rock is composed of basalt flows interbedded with lake sediments and is capped with impermeable lake sediments which result in a confining pressure sufficient to produce artesian conditions. The Amedee Fault provides a permeable passage through the cap rock and overlying sediments which allows the confined reservoir fluid to reach the surface at Amedee Hot Spring. A similar, but less obvious fault probably provides access to the surface at Wendel Hot Springs.

The large size and relatively uniform temperature of the reservoir are indicated by similar chemical compositions and similar geochemically inferred reservoir temperatures at Wendel and Amedee springs, which are located five miles apart. Temperatures within the

Wendel-Amedee system may range between 250°F and 270°F and locally be as high as 300°F. The U. S. Geological Survey has estimated from geochemical data that the mean reservoir temperature is 259° ± 13°F (Muffler, 1979). Silica-mixing results previously published suggest reservoir temperatures much higher than this (up to 491°F), but these are discounted because of the insufficiency of evidence concerning the degree of mixing that has occurred. The highest temperatures will be found where the thermal fluid enters this apparently large reservoir, perhaps near a fault which provides fracture permeability for deep circulation and warming of the thermal water. The exploration data has been reviewed with the specific objective of selecting drilling locations close to probable areas of fluid entry into the reservoir.

Although the general quality of the exploration data is excellent, the scale on which it has been obtained, the distribution of data points, and the degree of interpretation are uneven.

For example, although there is good regional geologic mapping coverage, a detailed geologic map of the prospect area (say at 1:24,000) showing structural details in exposed volcanic rocks and the distribution of individual tufa mounds in the Wendel area does not appear to have been made. With regard to the uneven distribution of data, almost all the resistivity and temperature-gradient data have been taken in the area to the west of the Skedaddle Fault, but little information has been obtained in the vicinity of the Amedee Fault.

In spite of these shortcomings, it is still possible to make a reasonable interpretation of the data because (1) both geophysical and geochemical interpretations are constrained by data obtained from deep exploration drilling; and (2) conceptually, the geology of the area appears to be relatively straightforward and uncomplicated. Our interpretation of subsurface geologic and temperature data is summarized in the cross-section of figure 11. The location of this section, and the locations of our recommended drilling sites are shown on plate 1 (in pocket).

Fluid entry to the reservoir from the Litchfield Fault is not considered likely, because evidence for the existence of this fault in the vicinity of the geothermal reservoir is highly questionable, as noted earlier. Evidence from the deep Gulf wells at Wendel and Amedee has shown that steep gravity gradients on the northeast side of the valley are caused mainly by the density contrast between sediments in the center of the basin and interfingering with basalt flows to the northeast, rather than by up-faulted granitic basement.

In the absence of a substantiated basin-bounding fault, conceivably, thermal fluid could be entering the reservoir horizontally from the north along permeable lava beds or from below the reservoir along steeply-dipping faults. good

It is doubtful that the fluids originate within Honey Lake basin because:

1. Near-surface thermal activity is concentrated on the northern edge of the basin. Steep faults at the western and southeastern basin margins and within the basin do not carry thermal fluids to the surface.

2. The potential volcanic heat sources of the Modoc plateau are located entirely to the north and northeast of the basin.

3. The regional pattern of groundwater movement is from the volcanic uplands toward lower elevations in the Honey Lake basin.

If permeable lava flows provide the only ingress to the reservoir, then any drilling location along the northeast boundary of the leasehold between Wendel and Amedee Hot Springs might be suitable. However, we believe it prudent in recommending drilling sites to consider the possibility that thermal fluid is entering the reservoir from fault zones. As the Amedee Fault has sufficient fracture permeability to provide a flow at Amedee springs of 700 gpm, it may also have sufficient permeability at depth to provide significant flow into the reservoir at temperatures that may be higher than 232°F. The direction of flow may be either directly up the fault, in which case fluid would be coming from faulted granitic basement beneath the reservoir, or laterally along the fault from the north. Most probably the flow has both an upward and southward component.

Faults which appear to localize Wendel Hot Springs also could provide deep fracture permeability in basement rocks. Although their displacements are smaller, fracturing could be enhanced by branching or intersecting fault configurations. Subsurface projections of the fracture system cannot be made with certainty. A mapped fault northeast of the springs is down to the northwest. Based on the reasonable assumption that tensional faulting is involved, it is concluded that the fracture probably dips toward the west. The southwest-trending photo lineation which projects into the hot springs also has an apparent northwest dip.

Unfortunately, little geophysical or temperature-gradient data exist which would be useful in choosing between a site near the Amedee Fault or near Wendel Springs. On the basis of presently available information, a location near the Amedee Fault is favored because:

1. The greater displacement on the Amedee Fault outweighs the possibly greater complexity of the Wendel Hot Springs fracture system as a determinant of fracture permeability. The Amedee Fault may itself have buried or unmapped branches which offset

the latter difference.

2. Probable equilibrium temperatures in Honey Lake #1-ST near Amedee Hot Springs (estimated to be at least 275°F at the bottom of the hole) are higher than those in Honey Lake #2-ST near Wendell Hot Springs.

The lack of positive indications of permeability during drilling of Honey Lake #1-ST should not be too discouraging. Permeability in most volcanic rocks is a haphazard phenomenon which must be treated statistically. The high temperature in that well assures that reasonable permeability exists in the area.

We believe, therefore, that a drill site located near the west (downthrown) side of the Amedee Fault, and as far north as the lease boundary will allow, is the best location for obtaining high-temperature fluid within the leasehold. A location near Wendel Hot Springs is regarded as a reasonable second choice for deep drilling.