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DOE/ID/12079--127

DE86 002013

CASE STUDY OF THE WENDEL-AMEDEE
EXPLORATION DRILLING PROJECT,
LASSEN COUNTY, CALIFORNIA
USER COUPLED CONFIRMATION DRILLING PROGRAM

Jon Zeisloft, Bruce S. Sibbett and Michael C. Adams

prepared by

Earth Science Laboratory
University of Utah Research Institute

for

U. S. Department of Energy - Idaho Operations Office

September, 1984

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Plate 1 - Log Composite of Well WEN-1.

ABSTRACT

The Wendel-Amedee KGRA is located in Honey Lake basin in Lassen County, California, on the boundary between the Modoc Plateau and the Basin and Range geologic provinces. The regional structural setting of the Modoc Plateau consists of north- to northwest-trending Tertiary to Quaternary normal faulting. Plio-Pleistocene basalt forms the Skedaddle Mountains on the north, and lake deposits of the same age underlie the Honey Lake basin. The Wendel and Amedee Hot Springs occur along the basinward projection of north-northeast trending faults, which do not follow the regional trend, on the north edge of the basin.

The WEN-1 geothermal test well, drilled near Wendel Hot Springs penetrated basalt lava flows to a depth of 2620 ft. From 2620 to 4550 ft basaltic to andesitic ash and minor sandstone beds were penetrated. A conglomerate 500 ft thick overlies granitic to dioritic rocks of probable Cretaceous age which were encountered below 5050 ft. A fault- and fracture-controlled geothermal reservoir occurs in the crystalline rocks.

A variety of geophysical surveys was performed over the project property. Geophysical data helped in establishing the regional structural framework, however none of the geophysical data is sufficiently refined to be considered suitable for the purpose of siting an exploration drill hole.

There are three distinct thermal water sources in the vicinity of the Wendel-Amedee KGRA. Warm sodium bicarbonate waters, with temperatures ranging from 68° to 86°F appear to be conductively heated groundwaters. Medium-temperature sodium sulfate waters from the shallow Prison well were measured at 167°F. The highest temperature water found to date in the Wendel-Amedee KGRA is tapped by WEN-1 at 251°F, sodium sulfate water. The medium-temperature and WEN-1 waters appear to originate in different reservoirs. Waters of Amedee

and Wendel Hot Springs appear to be the result of mixing of these two fluids.

Drilling of reservoir confirmation well WEN-1 took place from Aug. 1 to Sept. 22, 1981. Severe lost circulation was encountered shortly after drilling into the basement crystalline rock, indicating a potential production zone in open fractures from 5190 ft to 5330 ft. Geophysical logs were run in the hole at casing points and at total depth.

Pulse and long-term flow testing subjected the reservoir to a maximum flow of 680 gpm for 75 hours. At that rate, the well exhibited a productivity index of 21.6 gpm/psi; the reservoir transmissivity was 3.5×10^6 md-ft/cp. The maximum bottom-hole temperature recorded during testing was 251°F.

The conceptual model of the geothermal resource at Wendel Hot Springs calls on ground water, originating in the neighboring volcanic highlands, descending through jointed and otherwise permeable rocks into the granitic basement. Once in the basement, the fluid is heated as it continues its descent, and lateral movement as dictated by the hydrologic gradient. It then rises to the discharge point along transmissive faults.

INTRODUCTION

The User Coupled Confirmation Drilling Program (UCCDP) was designed to assist in reservoir confirmation of low- to intermediate-temperature geothermal resources specifically for direct-use applications (Gray et al., 1980).

This program provided for cost sharing of the drilling and testing portions of a geothermal project between the participating entity and the U.S. Department of Energy (DOE). DOE's share of the cost of the project was based on the degree of success of the project. The GeoProducts Corporation project is one of two reservoir confirmation projects under this program.

The project involves land within and in the vicinity of the Wendel-Amedee KGRA, about 20 miles east of Susanville, California, in Lassen County (Fig. 1). GeoProducts owns and leases approximately 16,000 acres in the area with approximately one-half of the leases falling within the Wendel-Amedee KGRA. The property was selected on the basis of highly productive springs issuing boiling water and the presence of faults having the potential for commercial production of even hotter fluids.

GeoProducts' proposal was to generate electricity through an innovative hybrid process by using moderate-temperature geothermal fluids both to dry wood waste from logging operations and to preheat the boiler feedwater and combustion air (GeoProducts Corporation, 1980). When dried, the wood waste would be burned to superheat the feedwater producing steam for electrical generation in a 55 megawatt power plant. GeoProducts was to own and operate the generating plant. Arrangements were made with the California Department of Water Resources (CDWR) to purchase 70 per cent of the electrical output. Local utilities could obtain the option to purchase the remaining 30 per cent. As initially planned the project was to use no auxilliary fossil fuel. If the project were a complete success, approximately 6,400,000 gallons

FIGURE 1 - LOCATION MAP

of fuel oil would be displaced per year. GeoProducts also is exploring several other nonelectric methods of using the geothermal energy including greenhouses, ethanol production, and alfalfa dehydration.

The project is being supported by funding from GeoProducts Corporation, the California Department of Water Resources (CDWR), the U.S. Forest Service and the U.S. Department of Energy (DOE). The CDWR has an interest in the project because of a need for significant amounts of electrical energy to operate the State Water Resources Development System. This system distributes water throughout California from areas of surplus to areas of need by an elaborate system of dams, reservoirs, canals, power plants, and pumping stations. CDWR has placed a high priority on developing energy projects using renewable resources to meet its pumping needs.

Involvement of the U.S. Forest Service in the project is based on:

1. A desire to intensify forest management through the implementation of several biomass removal techniques, especially through the thinning of dense, young timber stands which currently represent a negative economic situation.
2. A desire to minimize expenses. The Pacific Southwest Region currently spends about \$28 million per year treating residue left after timber harvest as a means of reducing fire hazard. If residue can be utilized in an economically viable energy project, some or all of these costs can be avoided.
3. Forest lands have a substantial biomass-energy potential in California and elsewhere. Demonstration of project feasibility can lead to decreased reliance on oil imports and greater energy self-sufficiency.

WENDEL-AMEDEE GEOTHERMAL SYSTEM

GEOLOGY

Regional Setting

The Wendel-Amedee KGRA is located near the junction of three major physiographic provinces: the Basin and Range, the Sierra Nevada and the Modoc Plateau (Fig. 2). To the southwest and south of Honey Lake, Jurassic-Cretaceous quartz monzonite and quartz diorite of the Sierra Nevada province (Benson et al., 1980) form the Diamond Mountains, which are bounded on the north by the northwest trending Honey Lake fault zone (Jennings, 1977). The Late Tertiary to Quaternary basalts and andesites of the block-faulted Modoc Plateau extend to the north and northwest of Honey Lake. The boundary between the Modoc Plateau province and the Basin and Range province to the east is vague. Generally, the Modoc region is dominated by constructional volcanic land forms (MacDonald, 1966), whereas the Basin and Range consists of mountains and alluvium-filled basins.

The regional structural setting at Honey Lake is dominated by Tertiary to Quaternary normal faults which trend northwest in the Sierra Nevada province, northwest to north-northwest in the Modoc Plateau (Jennings, 1977), and north to north-northeast in the Basin and Range, particularly around Pyramid Lake to the east (Stewart and Carlson, 1978). Based on a reconnaissance gravity survey and algal mounds along the Lake Lahontan shore line, the California Department of Water Resources (1963) mapped the west-northwest trending Litchfield fault along the north side of Honey Lake Valley. The Honey Lake fault zone at the foot of the Diamond Mountains (Fig. 2), south of the lake, has been active during Pliocene to Pleistocene and has a cumulative displacement of about 8,000 feet.

SOURCES: JENNINGS, 1977; STEWART AND CARLSON, 1978

EXPLANATION

- Qal - Major areas of alluvium
- Qv - Volcanic rocks
- Tv - Volcanic rocks
- PM - Paleozoic and Mesozoic rocks undifferentiated
- ~ generalized contacts
- representative faults

Modoc Plateau Province

Sierra Nevada Province

Basin and Range Province

SCALE 1:1,000,000
0 10 20 30 Km.
0 10 20 Mi

FIGURE 2

Jurassic-Cretaceous granitic rocks of the Sierra Nevada batholith form the basement complex. The granite is overlain unconformably by Mid- to Late-Tertiary volcanic rocks. The older volcanic rocks are overlain by or interbedded with Pliocene lake deposits which are overlain by Plio-Pleistocene basalts. The major basins like Honey Lake and basins to the east were part of Lake Lahontan, and deposits from this Pleistocene lake cover most of the valley floors. A stratigraphic column for the region is presented by the California Department of Water Resources (1963).

Surface Geology

The Skedaddle Mountains to the north and east, and Shaffer Mountain to the northwest are Plio-Pleistocene basaltic to andesitic volcanos composed of lava flows, cinders and lahars or volcanic breccias (Fig. 3). Low-permeability lahars are a major component of the exposed rocks on Amedee Mountain, but the exposures north of Wendel are mostly lava flows and cinders. Volcanic vents, filled with basaltic plugs form a N60°W trend along the crest of the Amedee and Skedaddle Mountains (Fig. 3) and Shaffer Mountain (NW of mapped area of Fig. 3). A small dike occurs along this trend in Wendel Canyon, and at least two plugs occur on Shaffer Mountain. Dikes between these plugs continue the trend of eruptive centers to the northwest. A small volcanic plug is exposed about one-half mile northeast of WEN-1, in the center of section 13 (Fig 3). The only exposure of silicic volcanic rocks in the immediate area is a rhyolitic flow breccia at the base of Shaffer Mountain, just east of Litchfield. Dacitic to latitic Mid-Tertiary rocks (Tv) are exposed on Bald Mountain.

The Lake Lahontan deposits consist of sand, silt and clay in the valley and beach gravels along the old shorelines. A few of the small, intermittent streams have transported channel gravels a mile or two out onto the fine sediments during low lake periods.

0 5000 Ft.
0 1 2 Km.
Contour Interval: 40 Ft.

Algal mounds at Honey Lake, called tufa by previous investigators, have been cited as evidence of hot springs activity. However, Morrison (1964) showed that Pleistocene lake levels and shore features have been responsible for control of algal mound (tufa) formation. Lake Lahontan algal mound deposits are widespread in the Litchfield to Wendel area and occur throughout the region formerly occupied by Lake Lahontan. Morrison (1964) made an extensive study of the algal mounds in the Carson Desert area at the southern end of Lake Lahontan, and listed occurrences from 3880 to 4355 ft elevation. The most common level of mound development, however, is 4020 to 4190 ft elevation (Morrison, 1964). This correlates with the Honey Lake algal mounds which are most abundant along the 4040 ft contour with nearly all algal mounds occurring above 4020 ft contour (Fig. 3). The algal mounds of this level are of the dendrolite algal structural class and are "formed by algae growing in tufted mats" (Morrison, 1964). Jones (1925) has described similar algal mounds at Pyramid Lake, a few miles east of Honey Lake. Some effort is made here to define clearly the controlling factors in development of the algal mounds to disprove the belief that they are solely a result of geothermal activity (McNitt and Wilde, 1981). Although algal mound development is stimulated by hot springs activity, their distribution is controlled principally by Lake Lahontan levels (Morrison, 1964).

In addition to a favorable lake level, other factors which favor algal mound formation are a stable substratum for attachment, relatively clean but agitated water and favorable water temperature. Attachment sites were rare on the fine sediment valley floor but once an algal head started it provided its own stable base. It should be noted that isolated algal mounds occur where stream channels entered the lake and deposited gravel which provided sites for initial attachment. Water agitation provided oxygen and other nutrients to

the algae. Wave action and currents along rocky headlands, such as near Wendel Hot Springs and Litchfield, therefore favored algal growth. The additional stimulus to algal growth by hot springs is clearly demonstrated at Wendel Hot Springs and associated springs that occur along the projection of the Wendel fault (Fig. 4). Algal mounds up to 5 ft high formed under normal conditions (Morrison, 1964), but in the N 1/2 Sec. 24, T.29N., R.15E. hot spring activity coincident with a favorable rocky headland resulted in algal mounds forming massive structures up to 20 ft high.

Several factors indicate that the algal mounds were not formed by hot springs alone. The geometry of algal mounds varies as a function of water depth. Along the Wendel fault, those portions of the calcareous mounds topographically lower and closest to the present Honey Lake exhibit cores of travertine of hot spring origin surrounded by a massive sheath of algal heads outwardly resembling cauliflower. Robust algal growth in 24-39 ft of water (below 4035 ft elevation) was restricted to hot spring sites along the Wendel fault. Deposits associated with Wendel thermal springs developed on a relatively flat lake bed. By contrast, many non-hot spring related algal deposits occur on rocky headlands projecting into the lake, such as by Litchfield, and throughout the extent of Lake Lahontan on rocky lake bottom irregularities. These types of tufa deposits point out that the presence of tufa mounds alone cannot be taken as evidence of hot spring activity.

Morrison (1964) correlated none of the algal tufa deposits (algal mounds) he studied with hot spring activity. Carbonate deposits are not forming at either Wendel or Amedee Hot Springs at the present time. Hot water discharging into a lake will be mixed and cooled, which increases CaCO_3 solubility. Most of the mounds associated with Wendel Hot Springs started from a base above 4020 ft elevation. The mounds at the main Wendel springs (westernmost

springs on Fig. 4) start at about 4010 ft but have growth to 4038 ft. Amedee Hot Springs, at an elevation of 4000 ft, has no significant algal tufa and was in water too deep for algal growth during the favorable lake level. The limited travertine present at Amedee is of subaerial origin. Travertine, with texture and honey-colored banding like cave dripstone, forms a base on which the pale yellowish-brown algal deposits have formed at Wendel Hot Springs. No siliceous sinter is present.

Faults

Faults in the Wendel-Amedee area are poorly exposed and marker units that could demonstrate offset are lacking. All mapped faults on Figure 3 are, therefore, based on geomorphic expression and spring alignments. A topographic expression of the Wendel fault within the mountain areas and the occurrence of springs along the assumed fault trace in the alluvium are fairly convincing evidence for the presence of this fault. Other faults recognized by aerial photo interpretation have trends similar to the north-northeast trending Wendel and Amedee faults.

A second structural trend is suggested by the N60°W alignment of volcanic necks and dikes in the Skedaddle and Shaffer Mountains. This northwest trend is approximately the same as that of the Honey Lake fault and other faults to the south in the Pre-Tertiary rocks. It seems reasonable, therefore, that a N60°W trending fault may be present in the Jurassic-Cretaceous basement rocks and is a zone of weakness along which igneous activity has reached the surface. The fault and cooling joints in dikes and plugs along the fault may provide access for deep circulation and heating of groundwater in the basement rocks.

Although topographic relief along the Amedee fault suggests vertical offset on the order of 1000 ft, no evidence of the fault crossing the saddle in

EXPLANATION

- Qld LAKE DEPOSITS AND ALLUVIUM
- Qlb LAKE LAHONTAN BEACH
- Qt ALGAL TUFA DEPOSITS
- Tia BASALTIC-ANDESITE PLUG
- Tb BASALT LAVA FLOWS
- Tas BASALTIC SCORIACEOUS LAPILLI AND ASH

SYMBOLS

- CONTACT, DASHED WHERE APPROXIMATE OR INFERRED
- FAULT, INFERRED
- PHOTO LINEAR, POSSIBLE FAULT TRACE
- ROADS, LONG DASHES - PAVEMENT
SHORT DASHES - DIRT
- RAILROAD
- GEOTHERMAL WELL
- HOT SPRING, WITHOUT TAIL IS PALEOSPRING
- SECTION CORNER
- STREAM

FIGURE 4 - DETAILED GEOLOGIC MAP OF DEPOSITS IN THE WEN-1 AREA. THE WENDEL FAULT IS THOUGHT TO FOLLOW THE LINE OF SPRINGS AND ALGAL MOUNDS BUT NO ACTUAL FAULT TRACE IS EXPOSED.

the Skedaddle Mountains could be found during field examination. The Amedee Fault appears to die out in Wendel Canyon, but that is where it would intersect a postulated N60°W trending fault.

Subsurface Geology

Subsurface data on stratigraphy and control on structure are available from three drill holes near Amedee Hot Springs and two deep wells near Wendel Hot Springs. These data, along with interpretation and correlation, are presented here.

Gulf 1-ST was drilled about 4000 ft northwest of Amedee Hot Springs (Fig. 3) and bottomed in volcanic rocks at a depth of 5033 ft (McNitt and Wilde, 1980). A lithologic log of Gulf 1-ST is not available, but the well penetrated rocks similar to those in Gulf 2-ST, for which a log is available (Fig. 5). Rocks at the bottom of Gulf 1-ST were dated at 33 m.y. BP (McNitt and Wilde, 1980).

The Amedee No. 1 geothermal well, drilled in the middle of the hot springs, penetrated 770 ft of clay, silt and sand (White, 1967). Below 770 ft, volcanic rock was drilled to the bottom of the hole at 885 ft. Amedee No. 2 was drilled 900 ft south of Amedee No. 1 and penetrated only 250 feet of sediments before entering altered volcanic rocks which continued to the bottom of the hole at 1080 ft (White, 1967). These two wells were apparently drilled on opposite sides of the Amedee fault, and data from them indicate a bedrock displacement of at least 520 ft.

Abbreviated lithologic logs from the two deep wells near Wendel Hot Springs, GeoProducts WEN-1, and Gulf 2-ST, 2 km to the south, are presented in Fig. 5. As evident from these logs, the basalt flows above 3400 ft elevation in WEN-1 terminate between the wells since this interval in Gulf 2-ST is occupied by lake sediments. Lithologic logs of four shallow drill holes along

FIGURE 5 - CORRELATION OF STRAGRAPHC
UNITS BETWEEN WELLS WEN-1 AND 2-ST.
LOG OF 2-ST FROM MCNITT AND WILDE
(1980), WEN-1 LOG BY SIBBETT, THIS REPORT.

with logs of the upper portions of WEN-1 and Gulf 2-ST are presented in Fig. 6. It is clear that correlation of rock units above 3050 ft elevation is not easy in the Wendel Hot Springs area. Major rock units below 2950 ft elevation can be correlated between the two deep wells. The base of a 1800 ft thick accumulation of basalt flows occurs at 1420 ft elevation in WEN-1 and at 1395 ft elevation in Gulf 2-ST, only 25 ft lower. The top of the granitic basement rocks occurs at 1010 ft below sea level in WEN-1 and is 210 ft higher in Gulf 2-ST. A third contact correlated between WEN-1 and Gulf 2-ST is the base of the basaltic rocks at 510 ft below sea level in WEN-1 and 495 ft below sea level in Gulf 2-ST. These old basaltic rocks in WEN-1 between 1420 and -510 ft sea level elevation, were logged as ash and lahars (Fig. 5). The corresponding interval in Gulf 2-ST was logged as sedimentary rocks and basalt flows. The correlations of the granitic rocks below and the basalt flows above suggest that this interval is stratigraphically equivalent in the two wells (Fig. 7).

Overlying the granitic basement rock in the Gulf 2-ST is 300 ft of silicic tuff (?). The corresponding unit in WEN-1 is a 500 ft thick conglomerate (Fig. 5). The conglomerate in WEN-1 consists of clasts of metasiltstone, quartzite and diorite, but no extrusive igneous rocks. The conglomerate, therefore, probably formed during erosional exposure of the Sierra Nevada batholith and predates the Tertiary volcanic rocks.

Based on correlation of the rocks in the two deep holes, several conclusions can be made about faulting in the Wendel Hot Springs area. No large offset has occurred between the well sites during the Tertiary or Quaternary. The top of the basement granitic rocks slopes down to the north, opposite the regional gravity gradient (CDWR, 1963). Offset of the Tertiary rocks by the Wendel fault is minor.

From -1150 to -1290 ft sea level elevation in WEN-1, a faulted and fractured zone of mixed granite and granodiorite was penetrated. Thermal fluid production comes from this zone which contains a quartz vein cutting granodiorite and abundant hematite-stained joint surfaces. Above the fault the basement rocks are granite, and below the fault they are granodiorite with minor granite and quartz dikes.

Slickensides and gouge at depths of 890, 1090 and 4490 ft suggest that three other faults were penetrated in WEN-1. No noticeable fluid production was associated with any of these possible structures and displacement is interpreted to be relatively small based on stratigraphic correlation with the Gulf 2-ST well.

No significant fluid flow was found in WEN-1 from the Tertiary volcanic rocks. High mercury and arsenic concentrations in cuttings of the conglomerate (Plate I) indicate that at least some fluid movement has occurred in these rocks. Pyrite coatings were present on rounded chert clasts in the conglomerate cuttings.

As mentioned above, the fault from which thermal fluids are produced in WEN-1 cuts the granitic basement rocks from 5190 to 5330 ft depth. A spinner log indicates that most of the flow comes from above a granite dike at 5300 ft. The orientation of this fault and possible correlation with the Wendel fault are uncertain. Projection of the eastern trace of the Wendel fault to the fault in WEN-1 at 5330 ft depth indicates a dip of 61° , which is reasonable, although the surface trace suggests a shallower dip to the north (Fig. 4). Structural offset across the Wendel fault cannot be demonstrated based on the stratigraphy in the Gulf 2-ST and WEN-1 wells. Topographic relief along the fault trace in the Skedaddle Mountains suggests 10 to 20 ft of offset, which is possible if a slight structural slope to the south between WEN-1 and

Gulf 2-ST is assumed. This small amount of offset would not likely generate the major structure penetrated in the WEN-1 well. It is possible that the basement fault zone predates the Oligocene (?) volcanic rocks. Slight renewed movement along this pre-Oligocene fault zone may have formed the Wendel fault and provided a channelway for rising thermal fluids. The top of the granitic basement rocks is 210 ft lower in WEN-1 than in Gulf 2-ST. This difference may be due either to faulting prior to the emplacement of the volcanic rocks or erosional relief.

THERMAL GRADIENT DATA

During the spring of 1980, four temperature-gradient holes were drilled by GeoProducts, Inc., north and northwest of Wendel Hot Springs (Fig. 3). The holes were drilled in valley fill sediments and basalt flows (Fig. 6) to depths ranging from 480 to 1325 ft. Temperature logs (Fig. 8) were made on July 1, 1980 by Agnew and Sweet Wireline Service (McNitt and Wilde, 1980). The low gradient in TG-1, 47°C/Km, compared to 84°C/Km in TG-5 and 151°C/Km in Gulf 2-ST, suggest a higher thermal gradient to the southeast near Wendel Hot Springs. Shallow high gradients nearer the hot springs are probably the result of thermal fluids from the Wendel fault flowing into shallow aquifers and, therefore, should not be considered representative of the deep thermal gradient.

Temperature-depth data under static conditions are not available for WEN-1, but if the temperature of about 251°F (121.7°C) (Juncal et al., 1982) in the producing zone at about 5200 ft (1585 m) is used and a mean annual surface temperature of 50°F (10°C) assumed, the indicated gradient is about 70°C/Km. Using the same method for Gulf 2-ST (114°C at 1463 m; McNitt and Wilde, 1980) yields a gradient of about 71°C/Km, and for Gulf 1-ST (110°C at 1524 m) yields

FIGURE 6 - LITHOLOGIC LOGS OF THERMAL GRADIENT HOLES AND THE TOP 1400 FEET OF THE DEEP EXPLORATION HOLES. (FROM MCNITT & WILDE, 1980; EXCEPT WEN-1 LOGGED BY SIBBETT, THIS REPORT.) SEE FIGURE 3 FOR LOCATION OF HOLES.

FIGURE 7 - CROSS SECTION THROUGH TWO DEEP WELLS NEAR WENDEL HOT SPRINGS, AND EXTENDING NORTH INTO THE SKEDADDLE MOUNTAINS.

a gradient of 66°C/Km. The deep hole temperature data, therefore, suggest that the average thermal gradient in the Wendel-Amedee thermal area is about 70°C/km (3.9°F/100 ft) to a depth of about 5000 ft. The regional thermal gradient has been reported as 30°C/km (Kron and Heiken, 1980).

HYDROLOGY

The major tributaries to Honey Lake are the Susan River from the west, Willow Creek from the north and Long Valley Creek from the southeast. Honey Lake Valley is a closed basin, and the lake generally dries up during the summer due to evaporation. Only ephemeral streams drain the Skedaddle and Amedee Mountains near Wendel Hot Springs.

Plio-Pleistocene lava flows and volcano-clastic rocks, which form the Skedaddle Mountains and the highlands to the north, are believed to act as recharge areas for groundwater (CDWR, 1963). Near-surface, cold groundwater from the highlands flows under the northeast margin of Honey Lake Valley through permeable basalt flows and poorly consolidated sand units. Many shallow domestic wells, a few hundred feet deep, produce water from these aquifers, which interfinger with silt and clay beds toward the center of the valley. Flowing wells south of the Amedee Mountains probably produce from aquifers in basalt flows, which are confined by fine lake sediments (CDWR, 1963). Lake Lahontan deposits northwest of Honey Lake and near Herlong, where major streams supplied coarse sediments, contain important sand aquifers for irrigation wells. The Pliocene lake deposits underlying the valley are thought to be of low permeability (CDWR, 1963).

GEOPHYSICAL DATA

Geophysical data pertinent to this project come from several sources. In

the early stages of the project a variety of geophysical surveys was performed by commercial geophysical contractors for GeoProducts (Electrodyne Surveys, 1979). Gulf Oil Company, investigating geothermal potential of the area about 10 years ago, completed electrical resistivity (roving dipole), microseismic and shallow temperature surveys. These data became available to the project via a property lease from Gulf to GeoProducts. In addition to the private surveys, CDWR (1963) had a Bouguer gravity map prepared and a reconnaissance resistivity survey was conducted by the U.S. Bureau of Reclamation (U.S. Bureau of Reclamation, 1976).

Those surveys performed for GeoProducts by, or through, Electrodyne Surveys include reconnaissance surveys of gravity, ground magnetics, scalar AMT-MT and tensor MT. In addition, detailed surveys included dc soundings, single component EM soundings, closely spaced along profiles, and three component EM soundings at specific selected sites.

Interpretations of these data have been presented in a two-volume report (Electrodyne Surveys, 1979). McNitt and Wilde (1980) evaluate and discuss the interpretations for GeoProducts concluding:

"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 sites, 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".

Those geophysical studies done for Gulf Oil Company were also reviewed by McNitt and Wilde (1980) who felt those "investigations yielded data of uncertain to poor quality which have not been useful in interpreting the geologic

structure or the geothermal system."

In summary it can be said, that although numerous and varied geophysical surveys were conducted over the project area, only generalized interpretations resulted. No specific interpretation contributed to the selection of the site for the drilling of WEN-1.

HYDROGEOCHEMISTRY

Introduction

Several hot spring vents are active within Honey Lake basin. These vents exist as two closely clustered groups and have been designated as Wendel and Amedee Hot Springs (Fig. 3). In addition to these natural sources of thermal water, three deep wells also tap thermal aquifers. These are GeoProducts WEN-1, the Susanville Prison well and Gulf 2-ST with maximum temperatures of 251°, 167°, and 95°F, respectively. The locations of these wells are shown in Fig. 9. Production depths for WEN-1 and Gulf 2-ST are 5280 ft and 1089 ft, respectively. No information on the depth of the Susanville Prison well was available at the time of this report.

Amedee and Wendel Hot Springs discharge boiling fluids of 205°F from Lake Lahontan sediments. The total flow from all Amedee Hot Springs vents has been estimated as 1057 gpm (White, 1981). Russell (1885) estimated the flow from Wendel Hot Springs to be 750 gpm. In 1909 by contrast, Waring (1915) measured the discharge at 175 gpm. The dramatic reduction in values was attributed both to an actual decline of the spring productivity and to partial blocking of the vent with thrown stones. During the siting and drilling of WEN-1, all geologists involved estimated the aggregate flow from the various vents of Wendel Hot Springs to be closer to Russell's estimate. No measurements of the flow are known from recent years.

FIGURE 9 - HYDROGEOCHEMICAL SAMPLE LOCATION MAP

Although both hot spring groups are associated with travertine deposited during Lake Lahontan time, neither appear to be presently depositing calcite. Amedee Hot Springs, however, is actively depositing mercury sulfides on Lake Lahontan sediments (White, 1981). A geothermal test well drilled at Amedee Hot Springs in the early 1960's (White, 1967, p. 598) showed that the hot spring waters are composed of 225°F fluid which has mixed with cooler fluid at 403 ft resulting in a 219°F fluid. No previously published subsurface data for Wendel Hot Springs exist.

Methods of Investigation

Water samples, collected during the winter of 1982, were taken from the hot springs, cold springs, irrigation and domestic wells, and geothermal wells shown in Fig. 9. The samples were filtered through a .45 μ membrane filter with a peristaltic pump and stored in polyethylene bottles. The containers were precleaned with 20% nitric acid and deionized water and rinsed with filtered sample water. An untreated sample and two acidified splits (one with 1% HCL and one with 20% HNO₃) were collected at each sample site.

The pH and bicarbonate concentration were determined at the time of collection on pressure-filtered samples using a selective ion meter with a Ag/AgCl combination pH electrode and by sulfuric acid titration (Presser and Barnes, 1974), respectively. Potassium, fluoride, chloride, sulfate and total dissolved solids were determined on filtered samples by atomic absorption spectrophotometry, specific ion electrode, silver nitrate titration and gravimetry, respectively. The remaining major and minor elements listed in Table 1 were determined by inductively coupled plasma spectrometry using methods described by Christensen et al. (1980). All samples were analyzed within one month of collection.

Discussion

Characterization of water types

Chemical compositions and calculated geothermometer temperatures of the samples collected are listed in Table 1. Five of the samples were taken from hot springs, two from cold springs, two from irrigation wells, two from deep (> 300 m; 990 ft) thermal wells, and twelve from cold and warm domestic wells. A water sample of the geothermal production well, WEN-1, was collected by GeoProducts, Inc., during the spring of 1982 and analyzed by ESL.

A trilinear plot (Fig. 10) of major ion ratios was used to characterize the water samples by the method of Piper as discussed in Hem (1970). In addition, Cl/B ratios have been plotted against Na/SO₄ (Fig. 11) and Na/Cl (Fig. 12).

All collected waters with measured temperatures above 86°F (30°C) group closely on the trilinear plot and are sodium sulfate in character, while those below 86°F are scattered and are sodium bicarbonate in character (Fig. 10). Waters collected from a spring and a well north of Honey Lake basin are respectively calcium and calcium-magnesium in character, suggesting that the sediments in Honey Lake basin give the cold waters their sodium bicarbonate character. The total dissolved solids contents (TDS) (Table 1) of the waters with measured temperatures between 68°F and 86°F (20°-30°C) are almost uniform (206-258 ppm). The TDS values for waters with measured temperatures below 68°F (20°C) range from 180 to 1940 ppm TDS, indicating heterogeneous source rocks for the cold groundwaters.

Relationships between the Cl, SO₄, Na, and B concentrations in the waters sampled are shown in Figs. 11 and 12. Inspection of these figures shows that these waters do not display trends found in most geothermal systems. Ratios of SO₄/Cl in geothermal fluids generally decrease as temperature increases

TABLE 1. CHEMICAL ANALYSES AND GEOTHERMOMETER TEMPERATURES

	THERMAL WATERS (>30°C)					WARM WATERS (>20°C; <30°C)			
Sample	Amedee HS	Wendel HS ¹	Prison Well	Gulf 2-ST	WEN-1 ²	WA-9	WA-12	WA-16	WA-21
Well Depth (m) or Spring(s)	S	S	~600	1532	1758	30	91	S	shallow
Measured Temp. (°C)	96	96	75	35	96	22	27	27	22
pH	8.8	8.3	8.7	8.7	8.3	7.8	7.3	7.9	7.3
TDS ³	838	1021	660	1010	1320	206	216	204	258
Na ³	224	280	159	271	349	48	44	37	58
K	6	8	3	5	20	10	9	6	3
Ca	20	20	16	16	38	6	8	14	3
Mg	0.02	<.1	0.11	0.13	<.5	2	3	5	1
SiO ₂	108	125	83	93	130	43	44	33	49
Li	0.09	0.11	0.05	<.05	0.26	<0.05	<0.05	<0.05	<0.05
B	4.5	5.6	3.5	6.6	7.7	0.3	0.3	0.2	.2
SO ₄	282	340	247	346	410	26	28	20	19
Cl	153	185	96	205	284	20	19	14	16
F	4.7	4.2	3.9	3.8	6.5	0.2	0.2	0.2	0.3
Alkalinity (HCO ₃)	54	53	66	78	73	122	120	120	150
Na-K-Ca (Mg) ⁴	123	128	69	112	158	83	63	63	69
Chalcedony ⁵	115	125	99	106	127	64	66	52	71
Quartz ⁵	136	143	124	129	152	95	96	83	101

¹Analysis U-2, taken from Mariner et al. (1976).

²Sample taken after water flashed at atmospheric pressure.

³ TDS and element concentrations are in ppm.

⁴ Method of Fournier and Truesdell (1973) and Fournier and Potter (1979); Temperatures are in °C.

⁵ Method of Fournier (1973); Temperatures are in °C.

TABLE 1 (Cont.)

Cold Waters (<20°C)

Sample	WA-5	WA-7	WA-8	WA-10	WA-11	WA-13	WA-18	WA-19	WA-20
Well Depth or Spring(s)	25	155	155	30	91	30	shallow	shallow	shallow
Measured Temp(°C)	17	14	13	14	15	14	14	14	14
pH	7.9	8.8	8.8	7.6	7.6	7.3	7.3	7.4	7.9
TDS ³	180	818	636	492	400	264	378	378	1940
Na ³	39	288	241	101	98	55	68	80	588
K	8	4	2.3	13	5	7	8	10	18
Ca	8	2	6	28	14	5	28	10	39
Mg	5	2	2	14	7	3	10	4	22
SiO ₂	36	45	36	58	66	59	55	48	55
Li	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
B	0.1	1.2	0.7	0.5	0.7	<.125	0.1	0.3	2.1
SO ₄	23	58	2	121	29	41	13	20	260
Cl	15	49	13	23	15	8	15	11	367
F	0.2	1.0	1.0	0.3	0.3	0.2	0.4	0.3	0.8
Alkalinity (HCO ₃)	122	668	701	266	302	149	297	197	1015
Na-K-Ca (-Mg) ⁴	32	30	62	32	45	39	60	54	29
Chalcedony ⁵	56	67	56	79	86	80	77	70	77
Quartz ⁵	87	97	87	109	115	110	106	100	106

FIGURE 10 - PIPER PLOT OF THERMAL AND NON-THERMAL WATERS SAMPLED IN THIS STUDY.

FIGURE 11 - Na_2SO_4 VS. Cl/B MOLAR RATIOS

FIGURE 12 - Na/Cl VS Cl/B MOLAR RATIOS

because of the retrograde solubility of calcium sulfate minerals and the increased scavaging of Cl at elevated temperatures. Steam-heated hot or warm waters also display an inverse relationship as a result of increasing SO_4 from H_2S oxidation (Mahon et al., 1980). The normal relationship of decreasing Cl/B atomic ratio with increasing temperature is also not true for a majority of the water samples taken in Honey Lake basin. Thus the groundwaters in Honey Lake basin do not appear to be a fluid source for the geothermal system.

The silica and cation geothermometers were calculated for the waters sampled and are listed in Table 1. According to Fournier (1973) the quartz geothermometer works best for well waters where subsurface temperatures are above about 302°F and the wallrock has an excess of normative quartz. Fournier further states that in some aquifers below 212°F, and perhaps up to 302°F, chalcedony rather than quartz apparently controls the dissolved silica content. Subsurface temperatures higher than 251°F (Juncal et al., 1982) have not been recorded in the vicinity of Wendel and Amedee Hot Springs. Furthermore, mafic volcanics are predominant in this area down to about 4500 ft. This would suggest that chalcedony is the silica geothermometer polymorph most applicable to thermal waters flowing through mafic rocks in the Wendel-Amedee area. The thermal water from WEN-1, however, flows from silicic intrusive rock at a depth of about 5300 ft and may be in equilibrium with quartz.

The chalcedony and quartz geothermometer temperatures for the thermal waters are plotted vs. B in Fig. 13. The general trend of increasing temperature from the Susanville Prison well to Amedee Hot Springs, Wendel Hot Springs and WEN-1 is similar to the trend shown on the Cl vs. B plot for these thermal waters (Fig. 14). The best fit for the regression line shown in Fig. 13 was obtained using chalcedony geothermometer temperatures for the Prison well and the hot springs, and the quartz geothermometer temperature for WEN-1. Gulf 2-

FIGURE 13 - GEOTHERMOMETER TEMPERATURES VS BORON CONCENTRATIONS FOR THERMAL WATERS. REGRESSION LINE BASED ON CHALCEDONY GEOTHERMOMETER TEMPERATURES FOR AMEDEE H.S., WENDEL H.S., AND SUSANVILLE PRISON WELL FLUID AND ON QUARTZ GEOTHERMOMETER TEMPERATURE FOR WEN-1 FLUID. (r = correlation coefficient)

FIGURE 14 - Cl/B RELATIONSHIPS OF WATERS SAMPLED IN EASTERN HONEY LAKE BASIN.

ST falls off the trend, and its predicted temperatures are substantially higher than the measured temperature of 95°F. These disparities may be due to reequilibration of fluid in a low-permeability formation.

Cation geothermometer temperatures show a greater scatter (Fig. 13) than silica for the thermal waters. Both the quartz and cation geothermometers indicate an original temperature of 302°F to 320°F (150°C to 160°C) for WEN-1 fluid.

Geothermometer indicated temperatures for cold and warm water from Honey Lake basin should be viewed with caution. Fournier (1979) states that cation geothermometer results are dubious when applied to magnesium-rich waters. In addition the magnesium correction factor (Fournier and Potter, 1979) is not calibrated for waters with an RMg (magnesium to total major cation ratio) over 35. The RMg values for the warm and cold waters in Honey Lake basin range from 23 to 45.

Cl/B as an Exploration Tool

The atomic ratio of Cl/B has been used in several areas to characterize geothermal aquifers. Stefansson and Arnorsson (1975) utilized the Cl/B atomic ratio to define the areal extent of geothermal systems in the Southern Lowlands of Iceland. In New Zealand, Mahon (1970) combined Cl/B atomic ratios in reservoir rocks with Cl/B data from experiments on rock/water interactions to predict vertical and areal changes in the geothermal composition of the reservoir rocks. These predictions were subsequently verified by drilling. Upwelling geothermal fluid at Roosevelt KGRA was mapped by Ross et al. (1982) by plotting and contouring boron and chloride contents of groundwaters.

All of these studies have assumed negligible contributions of boron from the cold groundwaters which mix with the thermal fluids. For most areas this is a valid assumption. For example, median boron concentrations for streams

in the U.S.S.R (Turekian, 1969) and the U.S.A. (Livingstone, 1963) have been estimated as 0.01 and 0.0116 ppm, respectively. This is much less than the range found in hydrothermal waters (Gmelin, 1954), 0.5 to 1000 ppm. However, saline lakes also range from 0.5 to 1000 ppm in boron concentration (Gmelin, 1954). Where geothermal vents are located near volcanic vents in an arid closed basin, as at Honey Lake, there is a strong likelihood that the sediments will contain highly soluble borate minerals. Borax deposits are found exclusively within these environments (Kistler and Smith, 1975). Thus, a low concentration of B in the cold groundwaters in Honey Lake basin cannot be assumed. Therefore, an effective exploration tool in environments where a very low concentration of B cannot be assumed is to plot the B and Cl concentrations from thermal and non-thermal fluids. Fluids related by mixing will plot as a straight line.

B and Cl have been plotted for the Honey Lake basin fluids (Fig. 14). Regression lines based on B and Cl concentrations were calculated for cold ($< 68^{\circ}\text{F}$), warm ($68-86^{\circ}\text{F}$) and thermal ($> 86^{\circ}\text{F}$) waters. Inspection of this plot shows a distinct linear trend among the thermal waters, indicating that the thermal fluids are related by mixing and/or boiling. The regression line calculated for the cold groundwaters ($< 68^{\circ}\text{F}$) does not pass near any thermal water points, suggesting that no simple mixing between these cold waters and the thermal waters has occurred, i.e. the cold water must have chemically evolved prior to mixing.

The regression line based on the warm waters does not intersect any thermal water points, although the warm and thermal regression lines are almost parallel. The near parallelism of the two trends suggests that 1) no simple mixing relationship exists between the thermal and warm waters, and 2) similar processes control the Cl/B ratios in warm and thermal waters.

The Cl/B ratios can be used to calculate the proportions of the various end-member fluids which may have combined to produce the thermal springs and wells. Mixing proportions were calculated for three cases (Table 2). Case 1 involves mixing the WEN-1 production fluid at its measured temperature and a hypothetical 57°F groundwater. The Cl and B concentrations for the hypothetical groundwater were determined by the intersection of the thermal water regression line and the average groundwater chloride concentration (Fig. 14). Case 2 involves mixing WEN-1 production water with the Susanville Prison well water at their measured temperatures. Case 3 uses WEN-1 fluid at its average chemical geothermometer temperature and Susanville Prison well fluid at its measured temperature as end-members. These three hypotheses can be further treated by calculating the temperatures of the fluids that would be produced by mixing the various end-members. Results of these calculations as well as measured temperatures are listed in Table 2.

It can be seen from the calculations that Case 1 mixing proportions do not give a good fit for predicted vs. measured temperatures. For Case 2 the predicted temperatures are more reasonable but still below measured temperatures in some areas. Case 3 provides the closest fit. However, the 225°F (107°C) measured subsurface temperature of the fluid which discharge from Amedee Hot Springs can be matched by raising the temperature of the Susanville water in Case 3a by 18°F (Case 3b). Case 3 predicts that fluids which discharge from Wendel Hot Springs have a higher subsurface temperature than those discharging from Amedee Hot Springs. This relationship is consistent with the temperatures predicted by chemical geothermometers for the hot spring fluids (Fig. 14).

The largest discrepancy between measured and predicted temperatures is for the Gulf 2-ST well. The permeability in this well has been shown to be

TABLE 2. FLUID MIXING CASES

	CASE 1			CASE 2		CASE 3		
	Measured Temperature(°C)	% Dilute Component	Predicted Mixing Temp(°C)	% Dilute Component	Predicted Mixing Temp(°C)	% Dilute Component	Predicted Mixing Temp(°C)	
WEN-1	124	0	124	0	124	0	3a 155	3b 155
GULF 2-ST	35	24	98	30	109	30	131	134
Wendel H.S.	96+	35	86	50	100	50	115	120
Amedee H.S.	96+	49	70	70	90	70	99	107
Prison	75	68	49	100	75	100	75	85
Groundwater	-	100	14.					

Case 1 - Diluting WEN-1 fluids with 14°C groundwater.

Case 2 - Diluting WEN-1 fluids with Prison well water at measured T°.

Case 3 - Diluting WEN-1 fluids at geothermometer T° with Prison well water at measured T°.

very low (McNitt and Wilde, 1980). Thus, conductive cooling would be a reasonable interpretation for this water.

Conclusions

Interpretation of a hydrogeochemical survey of the northeast portion of Honey Lake basin indicates a mixing relationship between fluids from thermal wells and hot springs. Mixing proportions were estimated from boron and chloride, conservative elements which display an excellent linear trend among the thermal waters sampled. The high-temperature end member appears to be similar to the fluid from GeoProducts production well WEN-1. Silica and cation geothermometers indicate a temperature to 302°F to 320°F for this fluid, although the present subsurface temperature for this well is 251°F (Juncal et al., 1982). The low-temperature end member has a temperature close to 185°F and is similar in temperature and fluid chemistry to the Susanville Prison well. This may indicate the presence in eastern Honey Lake basin of a low-salinity, medium-temperature fluid source distinct from the reservoir being tapped by WEN-1. Shallow, medium-temperature stratabound aquifers are known to exist (Benson et al., 1980) below Susanville on the western edge of Honey Lake basin.

Mixing relationships indicate that fluid produced from the Gulf 2-ST well has cooled from approximately 266°F to its measured temperature of 95°F by conductive cooling in a low permeability formation.

Warm (68° to 86°F) waters in eastern Honey Lake basin appear to be conductively heated groundwaters. Quantification of cold and thermal water mixing in Honey Lake basin based on boron and chloride is complicated by the probable presence of boron minerals in Lake Lahontan sediments.

MERCURY SOIL SURVEY

Introduction

A mercury-in-soil survey was conducted in the project area by the authors. Soil mercury geochemistry has been used for several years to define anomalies associated with geothermal systems (Matlick and Buseck, 1976; Phelps and Buseck, 1978) and faults within a high-temperature geothermal system (Klusman and Landress, 1978; Capuano and Bamford, 1978). Although the Wendel-Amedee system does not appear to be a high-temperature system and thus has a lower vapor pressure, mercury sulfides are known to precipitate from Amedee Hot Springs water (White, 1967). This mineralization suggests that significant concentrations of mercury are present in the vapor phase of the geothermal system, and that mercury concentrations in soil could be used to locate vapor-permeable faults in or near the geothermal system. Location of such faults could be useful in the siting of future geothermal wells in Honey Lake basin.

In order to test the utility of soil mercury surveys at the Wendel-Amedee KGRA, two traverses were run near Wendel Hot Springs, one across the projection of the Wendel fault, northeast of the springs (A-A' on Fig. 15), and one northwest of the springs (B-B on Fig. 15). In addition, several samples were taken from three sites and one traverse near Amedee Hot Springs to determine whether the mercury mineralization at the hot springs is reflected in the soil geochemistry (C-C' on Fig. 15).

Samples of soil were collected at 200 ft intervals along traverses crossing suspected faults and surficial geothermal deposits. The samples were collected in plastic bags from 6 in below the ground surface. At the laboratory, the samples were dried, sieved to -80 mesh, and analyzed on a Jerome Model 301 Gold Film Mercury Detector.

FIGURE 15 -LOCATIONS OF Hg SOIL TRAVERSES. GEOLOGIC STRUCTURES TAKEN FROM SIBBETT, THIS REPORT. FOR EXPLANATION OF ANOMALOUS AND THRESHOLD Hg VALUES SEE TEXT.

FIGURE 15 (continued)

Results and Discussion

The statistical methods used to calculate the local background and threshold values for the mercury (Hg) concentrations in the study are those discussed in Levinson (1974) and Sinclair (1974). A background population of 0 to 45 ppb Hg was determined based on the change in slope of a cumulative frequency diagram of a log Hg concentration plot using all of the data from the three traverses. Three sample suites near active vents were not used in the statistics due to excessively high mercury values from suspected mercury mineralization.

A threshold value of 18 ppb Hg was chosen as base of the upper two percentile for the background population, which corresponds to the base of the upper 92 percentile for the anomalous population. Mercury concentration profiles along traverses A-A', B-B' and C-C' are shown in Fig. 16 and listed in Table 3. The values above threshold values are marked on Fig. 15.

It can be seen on Fig. 15 that although there is no exact correlation of mapped faults and anomalous mercury-in-soil levels along traverses A-A' and B-B', most of the highest mercury values occur near the mapped faults. The highest value of Hg found along these traverses was taken in alluvium.

Anomalous values of mercury occur along traverse C-C' at the surface trace of the Amedee Fault in bedrock and also west and downdip of the surface trace in alluvium. This suggests that mercury can be used to detect vapor-permeable faults in the Wendel-Amedee geothermal system.

Samples taken at Amedee Hot Springs and warm springs along the Wendel Fault display levels of mercury in excess of 50 ppb (WP2, AM6, AM24-26). The broad range of values obtained in replicate analyses of these samples suggest the presence of discrete mercury minerals in these samples. Mercury mineralization in Honey Lake basin has previously been sampled for only in vents at

FIGURE 16 - Hg CONCENTRATION (ppb) IN SOIL SAMPLES FROM TRAVERSES A-A', B-B', AND C-C': SAMPLE INTERVAL OF TRAVERSES IS 60.6 m (200ft.). LOCATION OF TRAVERSES SHOWN IN FIGURES 16a AND 16b.

TABLE 3. MERCURY SOIL SURVEY ANALYSES

<u>Sample No.</u>	<u>ppb Hg</u>	<u>Sample No.</u>	<u>ppb Hg</u>	<u>Sample No.</u>	<u>ppb Hg</u>
00W	5	1800E	10	AM-20	5
200W	5	2000E	5	AM-21	5
400W	5	2200E	10	AM-22	20
600W	5	2400E	10	AM-23	5
800W	15, 15 (R)	2600E	10	AM-24	70, 60 (R)
1000W	5	2800E	5	AM-25	995, 290 (R)
1200W	5	3000E	15	AM-26	75
1400W	5	3200E	< 5	AM-27	5
1600W	15, 10 (R)	3400E	< 5	AM-28	< 5
1800W	5	3600E	< 5	AM-29	< 5
2000W	5	3800E	< 5	AM-30	< 5
2200W	10	4000E	< 5	AM-31	< 5
2200WS	5	4200E	< 5	AM-32	30
2400W	< 5	4400E	< 5	AM-33	< 5
2600W	< 5	4600E	< 5	AM-34	< 5
2800W	5	4000W	< 5	AM-35	< 5
3000W	5	4200W	5	AM-36	< 5
3200W	10	4400W	5	AM-37	< 5
3400W	5	4600W	5	AM-38	< 5
3600W	< 5	4800W	5	AM-39	< 5
5 cm		5000W	10	AM-40	< 5
3800W	< 5	AM-1	10	AM-41	< 5
10 cm		AM-2	10	AM-42	< 5
3800W	< 5	AM-3	15	AM-43	< 5
15 cm		AM-4	15	AM-44	< 5
3800W	< 5	AM-5	10	AM-45	< 5
20 cm		AM-6	155, 5 (R)	AM-46	< 5
3800W	< 5	AM-7	10	AM-47	< 5
25 cm		AM-8	10	AM-48	< 5
3800W	< 5	AM-9	10	AM-49	< 5
30 cm		AM-10	10	AM-50	< 5
3800W	< 5	AM-11	< 5	AM-51	< 5
200E	10, 15 (R)	AM-12	5	WP-2	90, 85 (R)
400E	5	AM-13	5		
600E	5	AM-14	< 5		
800E	10	AM-15	10		
1000E	5	AM-16	10		
1200E	5	AM-17	10		
1400E	10	AM-18	15		
1600E	25	AM-19	10		

(R) = Replicate analyses

the Amedee Hot Springs.

Conclusions

At the Wendel-Amedee geothermal prospect anomalous mercury-in-soil concentrations occur near mapped faults and the basinward extensions of these faults. Discrete mercury mineralization occurs in soil at Amedee Hot Springs and near warm springs along the Wendel Fault. Detection of vapor-permeable faults in a fracture-controlled geothermal system such as Wendel-Amedee may be useful for siting production wells.

RESERVOIR CONFIRMATION, WEN-1

INTRODUCTION

As part of their obligations under the terms of the cooperative agreement, GeoProducts contracted to GeothermEx, Inc. for a thorough evaluation of existing geologic data (McNitt and Wilde, 1980). That study recommended well locations AM, WEN-W, and WEN-E as shown on Fig. 17. The reader is referred to the GeothermEx report for a detailed treatment leading to the three choices. The AM site was the first choice of GeothermEx, and was the recommended drill site. It was chosen with the objective of producing fluid from the reservoir close to where it enters the volcanic aquifers from fractures in the crystalline basement (the Amedee fault) and where reservoir temperatures were thought to be higher than those encountered by Gulf 1-ST. Site WEN-E, located on the east side of the fracture system in the northern part of Section 24, T29W., R15E., would have taken advantage of the higher gradients found on that side of the fracture, whereas site WEN-W, located on the west side of the fracture in the northwest corner of Section 13, was chosen so that the hole would approach, or intersect, the fault zone near the planned depth of 3500 ft (Fig. 17).

Field work in the area by the authors resulted in identification of substantially greater permeability in the bedrock near Wendel than in the Amedee Mountains. The decision was made jointly by GeoProducts and DOE to locate the hole at WEN-W, which is the location where drill hole WEN-1 was drilled. Subsequent fault analysis based on aerial photograph interpretations and observations along the Wendel Fault led to a recommended drill site in the NW 1/4, SW 1/4, Sec. 13, T29N, R15E. Final adjustment of the site due to archaeological and access considerations placed the project drill hole in SW

FIGURE 17 - DIAGRAMMATIC NW-SE CROSS SECTION THROUGH THE WENDEL - AMEDEE GEOTHERMAL AREA, SHOWING PROPOSED WELL LOCATIONS.

1/4, SW 1/4, Sec. 13, T29N,R15E, where it was subsequently drilled.

An environmental analysis was completed prior to drilling, and was approved by DOE. Drilling permits were issued by the California Division of Oil and Gas on June 18, 1981 and the water disposal plan was approved by the Lahontan Regional Water Quality Control Board on June 17. The Lassen County land use permit was obtained on July 13 and site preparation activities commenced July 15.

DRILLING OF WEN-1

The drilling activities began with site preparation. The drilling site, measuring approximately 300 ft x 270 ft, was located immediately north of County Highway 320 about 1-1/2 mi northwest of Wendel. The pad was constructed of an initial 12 to 14 in base of road-bed grade aggregate with a 5 in cap of fine aggregate.

A reserve pit measuring approximately 100 ft x 100 ft x 10 ft was constructed on the north side of the drilling pad to contain ~ 800,000 gal of mud. This pit proved adequate for all drilling operations until the well was airlifted on September 16, 1981. The flow from the well then required the construction of a channel and auxiliary pit of dimensions similar to the first pit. The water was pumped to a disposal point 1/2 mile north of the well.

Water for drilling fluid make-up was provided by a 225 ft water well drilled on the northwest corner of the pad about 150 ft west of WEN-1. This well, which was completed with 8-in plastic slotted liner and was gravel packed from bottom to the ground surface, produced water at 250 gpm. The water well was not operational until August 15th, so during the first two weeks of drilling, water was hauled from an irrigation well about 3 miles away.

The drilling history of the WEN-1 well has been adequately reported by

GeoProducts Corporation (1982). Pertinent parts of that history are given in Appendix B. A plot of drilling time vs. depth is given as Figure 18. All depth measurements, unless otherwise noted, are from the Kelly Bushing (K.B.) which was 14 ft above ground level. Throughout the drilling operations, deviations and temperature surveys were taken nominally every 150 ft. Hole deviation was kept within 1°30' to 2°30' through much of the hole except for three short intervals where it reached 2°45'; this was substantially below the allowable limits detailed in the drilling bid specifications.

Bottom-hole temperature results are discussed below. The drill hole and casing profile is shown by Fig. 19. Appendix C summarizes the drill bits used and their productivity. It was the original intent to include here a cost-per-foot analysis of the bits in the differing lithologies, to aid in reducing bit cost in subsequent drill holes. Since the cost of individual bits was not available to the writers and since some of the bits were DOE surplus, such an analysis would not be valid. Overall bit cost was \$18,793.31 or \$3.23/ft, which is not highly meaningful due to the reduced cost of some otherwise expensive bits. A table detailing rig-time distribution during the drilling of WEN-1 is given as Appendix D.

WELL TESTING

Thermal Data

Temperatures were monitored throughout the drilling and recorded at each logging run. To aid in decisions of drilling procedure, drilling fluid composition, casing cement composition and safety, and temperature of the returning drilling fluid were recorded continuously at the flow line (Fig. 20). This information was also useful in estimating the thermal gradient in the drill hole and allowed projections of temperature to be expected at the target

FIGURE 18 - DRILLING TIME/DEPTH (MODIFIED FROM GEOPRODUCTS CORPORATION, 1982)

FIGURE 19 - DIAGRAMMATIC DRILL HOLE AND CASING PROFILE OF GEOPRODUCTS, WEN-1

FIGURE 20-MUD RETURN TEMPERATURES (MODIFIED AFTER GEOPRODUCTS, 1982)

depth. In addition to these surface readings, the temperature was measured with two maximum reading thermometers (Fig. 21) each time a deviation survey was run (approximately every 100-200 ft). During the drilling process at times of non-circulation, temperature build-up readings were taken to give an approximate idea of the hole's rebound from the relatively cooler drilling fluid. A comparison reveals a close parallel between return drilling-fluid temperatures and bottom-hole temperatures. Drilling with cold surface water below 5300 ft was necessitated by severe lost circulation, and rendered temperature data invalid below that point.

A two-day temperature build-up was allowed at 5287 ft in order to project an equilibrium bottom hole temperature, by the method of Roux et al. (1980), before committing to the cost of the intermediate casing. Results of this projection are shown on Figure 22 and indicate a maximum expected temperature of 248°F-261°F). GeoProducts (1982) points out that "this method of equilibrium-temperature estimation is not entirely reliable and typically underestimates true equilibrium temperature." Subsequent testing proved the temperature projection to be valid, however.

The temperature of the hole was logged by Gearhart on Sept. 19, 1981, upon reaching TD (Fig. 23), and gave a maximum reading of 248°F. Later logging by EG&G, Idaho showed a slight warming of the well (Fig. 23). There was no significant difference between EG&G's logs of Nov. 11 and Nov. 19, 1981.

Flow Data

EG&G, Idaho was responsible for the flow test and engineering considerations on this project. Although EG&G has not published their results, this brief summary is included here to provide some discussion of the flow data.

Shortly after the production logging was completed, and the rig was released, the testing period began. Much of the following discussion is modi-

FIGURE 21 - BOTTOM HOLE TEMPERATURES (TAKEN WITH MAXIMUM READING THERMOMETER DURING DEVIATION SURVEYS). MODIFIED FROM GEOPRODUCTS CORPORATION, 1982.

FIGURE 22 - TEMPERATURE BUILD-UP AT 5287 FT. USING MAXIMUM READING THERMOMETERS, squares represent pressure jacketed thermometer, circles represent thermometer open to bottom-hole pressures. The highest temperature registered the same on both thermometers. ABSCISSA IS LOG SCALING OF DIMENSIONLESS HORNER TIME MAXIMUM PROJECTED TEMPERATURE 120-127°C (248-260°F) (FROM GEOPRODUCTS, 1982)

FIGURE 23-TEMPERATURE LOG DATA OF WEN-1

fied from GeoProducts (1982). The wellhead assembly used for the short-term flow test (Fig. 24) consisted of a 12-in, 3000 API production "T" with a 6-in ANSI outlet directly above the hydril. Wellhead pressures were measured using a Bourden tube gauge. Flowline temperatures were recorded with bimetal and mercury-in-glass thermometers. The artesian flow rate was controlled by a gate valve on the blooey line and measured by using a 3-in orifice plate with a differential pressure gauge. Flowline temperature and pressure were monitored during flow at four discrete discharge rates.

An initial flow rate of approximately 535 gpm was sustained for 35 minutes. This was followed by a flow rate of approximately 600 gpm for 30 minutes, then a rate of approximately 635 gpm for 160 minutes. The flow line temperature rose from an initial 125°F to 229°F within 30 minutes, and to 232°F for the duration of the test (110 minutes). The wellhead pressure recovered to 43 psig within 20 seconds. A preliminary specific capacity of approximately 20 to 26 gpm/psi was calculated from the data. The capacity calculation together with the recovery data suggested a highly productive well.

Although the flowline temperature of 232°F was relatively low, maximum bottom hole temperatures of 247.7°F and 248.3°F were obtained using a Gearhart temperature tool and an Amerada temperature bomb, respectively, immediately following the flow test. These data, together with other evidence of downhole disequilibrium suggested that considerably higher temperatures would be obtained at the wellhead during long-term production, and provided input to a long-term testing plan.

A two-part test format consisting of three short-term pulse/recovery tests followed by a longer-term, constant-flow test was submitted to DOE on October 12, 1981. Testing was conducted by GeoProducts' technical staff with

FIGURE 24 - FLOW TESTING WELL HEAD ASSEMBLY (MODIFIED FROM GEOPRODUCTS CORPORATION, 1982)

assistance from scientists and technical personnel from EG&G, Idaho, who supplied much of the wellhead and down-hole instrumentation. The wellhead assembly for the test consisted of a 12-in, 3000 API production "T" with a 6-in 300 ANSI flowline connected to the master valve through a 12-in adaptor flange. The master valve was a 400 ANSI WKM power seal gate valve. The flowline was fitted with a 3-in orifice plate and continuous-recording digital differential pressure meter for measuring the discharge rate. Pressures were monitored by mechanical gauges and a continuous recording digital quartz meter on the flowline and by a wireline pressure meter downhole. Temperatures were monitored by a mercury thermometer and digital quartz thermocouple on the flowline and a digital thermocouple downhole.

Testing began on November 11, 1981 with initial temperature logging of the hole. The temperature profile is shown in Fig. 23 and indicates a very sharp change in gradient around 200 ft (depths are approximate only) and a slight gradient reversal around 5286 ft. The sharp reduction of the gradient uphole was the first suggestion of a break in the well casing. This break (discussed below) was also indicated by some minor "sticking" around 200 ft while bringing the temperature tool out of the hole.

On November 12 to 14, three pulse tests were performed at gradually increasing discharge rates. Unfortunately, the downhole pressure and temperature tools malfunctioned, so no subsurface data were obtained for any of the tests. Throughout the pulse tests, water was carrying significant sediment, which was thought to indicate that the well was still developing. More likely, however, this sediment was coming in through a split in the casing between 200 and 250 ft.

The likelihood of a casing break became more apparent during the constant flow test conducted with the throttle valve full open from November 15 through

the 21st. Wellhead pressure began decreasing somewhat and surging was noted in the discharge steam on November 19th, at which time temperature, caliper and spinner logs were run. The temperature logs shown on Fig. 23 reveal a strong similarity between the logs of Nov. 11 and Nov. 19. The sharp gradient change in the upper portion of the hole logged Nov. 11th was not present on Nov. 19th due to the flowing of the well.

The caliper tool malfunctioned and the data obtained were useless although some "disturbance" was indicated at approximately 230 ft. This "disturbance" was confirmed as a casing break by the spinner survey of November 19, (Fig. 25) as well as by a later survey on November 22nd (Fig. 26). The spinner survey of November 19 shows a considerable increase in fluid velocity near 230 ft which should not exist within intact casing. The spinner survey of November 22nd also showed this phenomenon. The abrupt velocity increase noted below 776 ft is due to a reduction in casing inside diameter from 12.6 to 8.9 in.

Due to this strong evidence of a parting in the surface casing, the long term flow test was terminated on November 22nd. A plug was set in the 9-5/8 in casing at about 850 ft to prevent further flow in the top part of the well and to facilitate repair operations. As a final confirmation step before casing repair operations were undertaken, a televiewer survey was run downhole to assess the nature of the well damage.

The borehole television inspection of the casing was performed by Northwest Underground Surveys of Boise, Idaho from the wellhead to 774 ft depth at the top of the 9-5/8 in liner hanger. The survey revealed one defective joint of casing from approximately 210 to 250 ft. The coupling joints of the casing both showed distortion. In addition, several distinct cracks could be traced vertically for several feet. Although clear elsewhere, the water in the well

FIGURE 25-SPINNER SURVEY, NOV. 19, 1981 (Well flowing about 335gpm during test) Log by EG+G, Idaho, modified from GeoProducts, 1982.

FIGURE 26 - SPINNER SURVEY, NOV. 22, 1981 (Well shut in)
Log by EG+G, Idaho modified from GeoProducts 1982.

was clouded between 209 and 259 ft with suspended particulate material. In this same interval the pipe wall was coated with a probable flocculent which may have obscured other cracks. It was concluded that a continuous casing break existed the full length of the joint of casing from 210 to 250 ft. That problem had to be corrected before the long-term well test could proceed.

Remedial Casing Operations

The cracked casing was repaired in the period February 4-18, 1982. The 2-stage plan consisted of sealing the split casing itself with cement, then cementing a 10-3/4 in liner in place to cover completely the defective zone. It was decided to place the liner top at 185 ft depth, rather than tying it back to the surface to provide the option to install a larger-diameter pump if the well characteristics so dictated.

The double-staged squeeze cement job appeared to seal the cracked area. On drilling out, the bottom of the cement (and hence the bottom of the crack) had set at 236 ft. A Midway liner hanger tieback receptacle provided the connector of the remedial casing to the existing liner hanger. From a J-slot liner hanger at 186 ft, 18 joints of 10-3/4 in casing were placed to connect with the tieback receptacle and provide an adequate overlap of the cracked interval. After two unsuccessful attempts, the casing was properly cemented on the third attempt. Class H cement 275 ft³ was used with 3% CaCl₂ and Halliburton Thixset components A and B. Pressure testing 6 and 9 hours later indicated the cementing of the 10-3/4 in casing was a success.

The excess cement was drilled out as was a bridge plug which had been set at 850 ft depth, and the debris pushed to the bottom of the well. For the following four days, the water level in the well continued to rise as the upper part of the well heated up. Recovery of the well was assisted with a small pump lift for about fifteen minutes, after which time the well flowed on

its own. Preparations were made to resume flow testing, allowing several days for the well to flow and clean the well bore.

Following the casing repair, a revised testing plan was submitted to DOE-ID, it was approved as submitted. The plan originally called for three short-term pulse tests, followed by a longer constant-flow/recovery test and finally by a long-term open flow test. This format was modified in the field to the following: an eight hour 230 gpm flow, stepped to 465 gpm for eight hours followed by an eight hour recovery period, an eight hour 670 gpm constant flow test with an eight hour recovery, a three day 620 gpm constant flow test followed by a sixteen-hour recovery and a fifteen-day 620 gpm constant flow test with a twenty-four hour recovery period.

The wellhead instrumentation and assembly for these tests were the same as those used during the testing in November (Fig. 24). Lawrence Berkeley Laboratory (LBL) assisted with the short-term testing by collecting downhole temperature and pressure data (Benson, 1982). For the fifteen-day test, no downhole instrumentation was set until the last day of the testing period when an Amerada pressure bomb was set at 5200 ft to monitor the recovery period. Prior to testing, temperature and spinner surveys were conducted which indicated that measured bottom-hole temperature was 248°F and that ~ 80% of the flow came from one fault zone.

To draw from Benson's (1982) discussion:

"The well was flowed artesian at four rates. Rates of 220 gpm, 440 gpm, and 680 gpm were held at nearly constant values for a duration of approximately twelve hours each. The fourth flow rate, 620 gpm, was held nearly constant for a period of seventy-five hours. At each flow rate the downhole pressure quickly stabilized and showed little or no change for the duration of the flow period. Both wellhead and downhole temperature rose steadily

throughout the test. The wellhead temperature rose from 240°F to 242.2°F reflecting heating of the wellbore. The bottomhole temperatures increased from 246.7°F to 250.1°F over the test period." The test results are shown in Fig. 27.

Benson (1982) provides an in-depth mathematical evaluation of the productivity, pressure transient data, skin value (indicative of wellbore damage) and other aspects of the testing. The interested reader is referred to that reference.

The Productivity Index of data from WEN-1 showed a notable decline from 48.9 gpm/psi at 220 gpm to 21.6 gpm/psi at 680 gpm. Such losses are usually attributed to the pressure drop through the production liner and flow up the well bore. Since bottom-hole pressures were used in this analysis, it is concluded by Benson (1982) that this declining proportionality to flow is the result of flow characteristics in the reservoir, namely to turbulent flow in the near-wellbore reservoir.

The complex hydrologic conditions in WEN-1 are indicated in various ways. Earlier geophysical logs (sonic, caliper) showed the open interval of the well to be fractured and washed out. These effects were indicated on the spinner log by considerable fluid velocity fluctuation, which correlated with hole size variations through the production zone. No fluid production occurs below approximately 5330 ft; however, the thickness of the actual producing zone is not presently known due to the large hole diameter variations. The lower boundary of the producing zone roughly correlated with the slight gradient reversal observed on the temperature logs.

After addressing problems of skin value, near-wellbore velocities in fractures of differing number, size and density, Benson (1982) concludes that the reservoir transmissivity is 3.5×10^6 md-ft/cp. She further stated that

FIGURE 27 - TEST DATA FROM WEN-1 WELL TEST. (AFTER BENSON, 1982).

these pressure data do not appear to be influenced by any reservoir boundaries (but qualifies that by stating that "the relatively small drawdown and difficulty in analyzing the drawdown data may obscure boundary effects."). One shallow hot well and the spring level at Wendel Hot Springs were periodically monitored and no differences of flow or fluid level were observed.

In summary, flow testing revealed that the highly transmissive production zone of WEN-1 occurs in a narrow interval of fractured granitic rock probably related to a fault zone. A capacity of 21 gpm/psi was obtained at the maximum flow rate of approximately 680 gpm.

WELL LOGGING

Geophysical logs provide the best means to evaluate the physical properties of subsurface lithologic units as demonstrated by their extensive use in the petroleum, minerals and geothermal industries. Logging of the WEN-1 well took place in three runs, prior to setting surface and intermediate casing strings and upon reaching total depth (T.D.). Gearhart Industries, Inc. performed the logging, which was of generally good quality (exceptions only occurred at places where the drill hole was severely washed out). The repeatability, depth agreement and internal calibration of the logging tools were all satisfactory.

The objectives of the logging program were to 1) evaluate the lithologies encountered in the drill hole, 2) evaluate the properties of the targeted reservoir and its contained fluid, and 3) provide correlation with other wells in the area.

The first logging run was conducted on August 8, 1981, with correlation as the primary objective. Dual induction-laterolog (DIL) and temperature (TEMP) logs were run from the base of the conductor pipe, 96 ft to 1012 ft, in

an open hole filled with fresh water mud.

On September 1, 1981, the second logging run was conducted after experiencing total loss of circulation at 5304 ft. The interval logged was from bottom of surface casing, 1007 ft to 5280 ft, in open hole filled with fresh water mud. Hole caving prevented the logging tools from reaching the drilled T.D.; the missed interval was logged during run three. Run two included DIL, compensated density log (CDL), compensated neutron log (CNL) with gamma ray (GR) and caliper (CAL), borehole compensated sonic log (BHC) with seismic spectrum (SS), gamma ray, caliper and integrated travel time (ITT); also temperature logs were run before and after the main suite. Two maximum reading thermometers, one jacketed and one open to borehole pressures were run with each tool.

The final suite of logs was run upon reaching total depth at 5837 ft. The logs were run in an open hole filled with formation water, with the well flowing from a two inch bleeder line. The same suite of logs that was run over the second interval plus a dipmeter log was scheduled for the final interval. However, several modifications to this schedule were made after the temperature tool caught on a bridge at 5337 ft during the first trip into the hole. Additionally, rough spots were encountered at several other depths, and for this reason the nuclear-source-bearing CNL-CDL tool, which requires forceful contact with the borehole wall, was not run. For the same reason, and also due to the massive nature of the granodiorite reservoir rock, the dip meter was also eliminated. Other tools were run as in the intermediate logging, including two passes with the temperature tool.

Although certain equipment and operational difficulties, including a malfunctioning temperature probe, were encountered during logging, these problems are not reflected in the final set of logs with one exception; this was the

oversight in jacketing the maximum reading thermometer (MRT) which was run with each tool. Because Gearhart personnel did not place the O ring in the jacket, both MRTs run during the final log were open to borehole pressure. Although some disagreement exists over the reliability of the MRT, it is generally thought to be more accurate when pressure jacketed.

Plate 1 is a compilation of all of the geophysical logs run in WEN-1, along with a lithologic log of the drill-hole cuttings for comparison. This presentation is computer-generated from digital data recorded on magnetic tapes during the logging. Since such data were not available for the first logging run, the compilation begins at the base of the surface casing at 1016 ft depth. The log responses agree well with the lithologies through the entire drill hole. The geophysical logs together with the WEN-1 lithologic log allow interpretations, with reasonable confidence, of the strata drilled. A detailed discussion of the statistical relationships between rock type and the geophysical log responses for the rock units above the production zone is given in GeoProducts (1982).

The portion of WEN-1 above 5068 ft depth either exhibited no significant porosity/ permeability or was at subproduction temperature. That section of the hole is now cased and will not be discussed here in detail. It is interesting to note, however, that like the production zone, at each place where the geophysical logs indicated fault intercepts, namely 870 to 900 ft, 1090 ft and 4490 ft, slickensides and gouge were evident in the drill cuttings.

Overall, the gamma-ray log responses best reflect the different lithologies drilled. An example of this occurs at 2610 ft depth, where there is a contact between basalt flows above and lahars below. This contact is characterized by relatively low radiation in the basalt, with 2-3 times that amount of radiation in the partially to strongly altered lahars. The DIL log

also indicates this contact by high resistivity in the basalt and much lower resistivity in the lahars. A similarly sharp contact is seen at 4550 ft depth, where lahar material is above a conglomerate of quartz, metasiltite and diorite clasts. Correlations between the rock units found in WEN-1 and those of previously drilled holes are discussed in detail in the geologic section above.

The fractured reservoir, from which WEN-1 produces, is prominently revealed between 5190 ft and 5320 ft depth on most of the logs (Plate 1). The caliper log reveals severe drill hole washout from 5138 to 5314 ft. Some intervals are as much as eleven inches greater in diameter than the drill bit (Fig. 28), probably representing the maximum the caliper arms could open in the fractured hole enlargements. An unresolved question in the interval of the hole below the intermediate casing is the general hole enlargement of 2-4 in above bit size in a granite-granodiorite section. Normally, a drill hole in such rock would be very close to the size of the drill bit.

The sonic information between 5195 and 5328 ft depth (Plate 1 and Fig. 28) supports the fractured scenario represented by the caliper log. The travel time of the sonic energy is dramatically longer in the fluid-filled, enlarged hole than it is in zones of relatively solid rock. Additionally, substantial interference is shown by the seismic spectrum log in that interval, indicating a fractured zone.

The gamma-ray log in the same interval is quite ambiguous, as might be expected in a sporadically oversized, water-filled hole. Thus, the gamma-ray log does not contribute to reservoir evaluation.

Porosity logs normally provide a reasonably accurate evaluation of reservoir properties in stratigraphic situations encountered in petroleum exploration. Porosity tools indirectly measure the percentage of small, fluid-filled

FIGURE 28 - GAMMARAY - CALIPER - SONIC LOG THROUGH PRODUCING INTERVAL OF WEN-T

pores in a given volume of rock around the sonde. With a neutron porosity tool, the apparent porosity in a crystalline rock will be erroneously high due to the presence of hydrous minerals (Nelson and Glenn, 1975). In the case of WEN-1, although no accurate porosity percentage is possible, the water-filled fractures are clearly defined (Plate 1) by high-porosity spikes in a zone of very low porosity.

For reasons stated above, the bulk density log was not run through the entire production interval. The bulk density tool did, however, encounter the top of the fracture zone at the bottom of the second logging run. At that time, two low-density, spike anomalies were recorded, representing a response averaging the density of liquid-filled fractures within a rock mass.

The sonic-derived porosity values are erratic since some readings are in all rock and adjacent readings are entirely in fluid-filled fractures; some readings are in a combination of the two. The sonic log shows, without doubt, the presence of the major fractures (Plate 1).

The neutron tool, responding to the presence of water in rock pores, will also give erratic results for the same reasons as will the sonic tool. In this case, the only practical way to evaluate the reservoir is by flow testing.

Of the electric logs, the SP values are ambiguous and do not strongly reflect the fractures indicated on the other logs. The induction log, on the other hand, reflects the fracture zone as an interval of lower resistivity.

PROJECT SUMMARY

Drill hole WEN-1 was a technical success; a geothermal reservoir was confirmed. The project met the objectives of the User Coupled Confirmation Drilling Program and provided much new geologic data as well. Although there are many unresolved questions concerning the Wendel hot spring system (and the presumably similar Amedee Hot Springs), some definite advances have been made.

Geologic mapping and related work have led to a better understanding of the Wendel fault. The Wendel fault projects from exposures in the foothills of the Skedaddle Mountains through the aligned algal mounds and hot springs to the south. Using surface (and aerial photograph) measurements of the fault dip, calculations were made to locate a site where WEN-1 would intersect the fault at approximately 5000 ft depth.

In the course of the field work, a previously unrecognized, northwest-trending row of basic volcanic centers was documented. From Hot Spring Peak in the Amedee Mountains, through the intervening Skedaddle Mountains and ending at Shaffer Mountain to the northwest of the mapped area are a series of at least 4 basic volcanic centers. Each of these includes a central neck with flows and ejecta beds dipping away from the neck. These volcanic deposits closely parallel the topographic boundary of the northern Honey Lake basin and probably owe their existence to a zone of crustal weakness through which the magma reached the surface. The significance of this northwesterly structural zone is that it likely contributes to the deep circulation of ground water which subsequently issues as the Wendel and Amedee Hot Springs.

Geochemical contributions from this project included explaining the differences between thermal waters and cold groundwaters in the Wendel-Amedee KGRA and vicinity. The degree of mixing of thermal and cold water in the produced fluid from WEN-1 is reflected in the chemical geothermometers of that

fluid. The geothermometers indicate a temperature of 302°-320°F whereas the temperature of the produced water is 251°F, suggesting mixing of the thermal fluid with cold waters. Mixing was also an important factor in the formation of the fluid that was produced from the Gulf 2-ST well. There are still a large number of unknowns to be answered before the hydrogeochemistry of the Wendel-Amedee KGRA is well understood.

The authors' conceptual model of the geothermal resource is a relatively simple one. Groundwater originating in the volcanic highlands to the north and east is believed to descend through permeable volcanic rocks (via joints and primary porosity such as basal flow breccias), and flow into the granitic basement along fractures and faults. The fluid continues its descent, plus lateral movement dictated by the hydrologic gradient, then rises toward the local discharge sites along transmissive faults, having exceptional vertical permeability. The areal position of the hot spring vents is dictated by fault geometry and, to an extent, the boundary between permeable volcanic rocks and the relatively impermeable lacustrine sediments of the Lake Lahontan valley-fill.

The thermal fluid becomes partially mixed with medium-temperature water en route to the hot spring vents. Above the basement, no significant permeable strata were penetrated in WEN-1 at a depth where fluids of economic temperatures could be produced. It therefore appears that the geothermal resource at Wendel (and presumably at Amedee) will most likely be produced from faults cutting the crystalline basement. However, the conglomerate overlying the crystalline basement may serve as a reservoir where matrix materials are permeable.

ACKNOWLEDGEMENTS

This work was supported by funding from the Division of Geothermal and Hydropower Technology, Department of Energy under contract DE-AC07-80ID12079. We would like to thank C. E. Mackelprang for his contributions to the geophysical section. P. M. Wright, D. Foley, J. N. Moore, and D. L. Nielson of ESL/UURI and Mr. Kevin Johnson of GeoProducts critically reviewed the manuscript. We thank GeoProducts Corporation for their cooperation throughout the project in providing data, air photos, etc.; their interim report to DOE contributed greatly to portions of this report. Gulf Oil Company has kindly released various geophysical data to us, for use in the project. The authors greatly appreciate the support of Joan Pingree who typed the manuscript and of Connie Pixton and Patrick Daubner who drafted the illustrations.

REFERENCES

- Benson, S., Goranson, C., Noble, J., Schroeder, R., Carrigan, D., and Wollenberg, H., 1980, Evaluation of the Susanville, California, geothermal resource: LBL-11187-UC-66a., DOE contract W-7405-ENG-48, 100 p.
- Benson, S. M., 1982, Well test data analysis from a naturally fractured, liquid-dominated hydrothermal system: Geoth. Res. Council, Transactions, v. 6, p. 237-240.
- California Dept. of Water Resources, 1963, Northeastern counties ground water investigation: Dept. of Water Res., Bull. 98, 224 p.
- Capuano, R. M., and Bamford, R. W., 1978, Initial investigation of soil mercury geochemistry as an aid to drill site selection in geothermal systems: Univ. Utah Research Inst., Earth Science Laboratory Report No. 13, 32 p.
- Christensen, O. D., Kroneman, R. L., and Capuano, R. M., 1980, Multielement analysis of geologic materials by Inductively Coupled Plasma-Atomic Emission Spectroscopy: Univ. Utah Res. Inst., Earth Science Lab. Rept. 32, 32 p.
- Electrodyne Surveys, 1979, Geophysical survey evaluation, Honey Lake prospect, Wendel-Amedee, CA, KGRA, vols. I & II: report prepared for GeoProducts Corporation, Oakland, CA.
- Fournier, R. O., 1973, Silica in thermal waters: laboratory and field investigations: in J. W. Clark, ed., Proc. Inst. Symp. Hydrogeochem. Biogeochem., Japan, p. 122-139.
- Fournier, R. O., 1979, A revised equation for the Na/K geothermometer: Geotherm. Res. Council, Trans., v. 3, p. 221-224.
- Fournier, R. O., and Potter, R. W. II, 1979, Magnesium correction to the Na-K-Ca chemical geothermometer: Geochem. Cosmochim. Acta, v. 43, p. 1543-1550.
- Fournier, R. O., and Truesdell, A. H., 1973, An empirical Na-K-Ca geothermometer for natural waters: Geochim. Cosmochim. Acta, v. 37, p. 1255-1275.
- GeoProducts Corporation, 1980, Wood fuel heat enhancement using geothermal energy, 2 vols., Technical Proposal submitted to U.S. Department of Energy in response to solicitation DE-SC07-80ID12139.
- GeoProducts Corporation, 1982, Interim Technical Progress Report submitted to U.S. Department of Energy, Idaho Operations Office.
- Gmelin, 1954, Handbuch der anorganischen chemie: Bd. 13. Bor. Weinheim, Verlag Chemie.

- Gray R. A., Prestwich, S. M., Wright, P. M., and Dolenc, M. R., 1980, User Coupled Confirmation Drilling Program: Geothermal Resources Council Transactions, vol. 4, p. 783-785.
- Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Surv. Water-Supply Paper 1473, 363 p.
- Jennings, C. W., 1977, Geologic map of California: Calif. Div. Mines Geol., Map 2.
- Jones, J. C., 1925, The geologic history of Lake Lahontan: in Quaternary climates: Carnegie Inst., Washington Pub. 352, p. 1-150.
- Juncal, R. W., Gertsch, W. D., and Johnson, K. R., 1982, WEN-1: First successful well in the Wendel-Amedee KGRA: Geoth. Res. Council, Transactions, v. 6, p. 281-284.
- Kistler, R. B., and Smith, W. C., 1975, Boron and Borates: in S. J. Lefond, ed., Industrial Rocks and Minerals, AIME, New York, N.Y., p. 473-477.
- Klusman, R. W., and Landress, R. A., 1978, Secondary controls on mercury in soils of geothermal areas: Jour. Geochemical Exploration, v. 9, no. 1, p. 75-91.
- Kron, A., and Heiken, G., 1980, Geothermal gradient map of the conterminous United States: Los Alamos Scientific Lab., Map LA-8476.
- Levinson, A. A., 1974, Introduction to Exploration Geochemistry: Applied Publishing Ltd., Calgary, Canada, 612 p.
- Livingstone, D., 1963, Chemical composition of rivers and lakes: U.S. Geol. Survey, Prof. Paper 440-G, p. G1-G64.
- MacDonald, G. A., 1966, Geology of the Cascade Range and Modoc Plateau, in Bailey, E. H., ed., Geology of Northern California: Calif. Div. Mines & Geol., Bull. 190, p. 65-96.
- Mahon, W. A. J., 1970, Chemistry in the exploration and exploitation of hydrothermal systems: Proceedings of the United Nations Symposium on the Development and Utilization of Geothermal Resources, Pisa 1970, V. 2, p. 1310-1322.
- Mahon, W. A. J., Klyen, L. E., and Rhode, M., 1980, Neutral sodium-sulfate-bicarbonate waters: J. Japan Geoth. Energy Assoc., v. 17, no. 1.
- Mariner, R. H., Presser, T. S., and Evans, W. C., 1976, Chemical composition data and calculated aquifer temperature for selected wells and springs of Honey Lake Valley, California: U.S. Geol. Survey, Open-File Rept. 76-783.
- Matlick, J. S. III, and Buseck, P. R., 1976, Exploration for geothermal areas using mercury: a new geochemical technique, in Pezzotti, C., ed., Proc. 2nd U.N. Symposium on Development and Use of Geothermal Resources: U.S. Govt. Printing Office, v. 1, p. 785-792.

- McNitt, J. R., and Wilde, W. R., 1980, Siting and drilling recommendations for a geothermal exploration well, Wendel-Amedee KGRA, Lassen County, California: GeothermEx, Inc., Berkeley, Calif., for GeoProducts Corp., Oakland, Calif., 51 p.
- Morrison, R. B., 1964, Lake Lahontan: Geology of Southern Carson Desert, Nev.: USGS Prof. Paper 401, 156 p.
- Nelson, P. H., and Glenn, W. E., 1975, Influence of bound water on the neutron log in mineralized igneous rocks: SPWLA Sixteenth Annual Logging Symposium, New Orleans, Louisiana, June, paper M.
- Phelps, D. W., and Buseck, P. R., 1978, Natural concentrations of Hg in the Yellowstone and Coso geothermal fields: Geothermal Resources Council, Transactions, v. 2, p. 521-522.
- Presser, T. S., and Barnes, I., 1974, Special techniques for determining chemical properties of geothermal water, U.S. Geol. Survey, Water-Resour. Inv. 22-74, 11 p.
- Ross, H. P., Nielson, D. L., and Moore, J. N., 1982, Roosevelt Hot Springs geothermal system, Utah-case study: Am. Assoc. Pet. Geol. Bull., v. 66, no. 7, p. 879-902.
- Roux, B., Sanyal, S., and Brown, S. L., 1980, An improved approach to estimating true reservoir temperature from transient temperature data: Paper presented at the 1980 California regional meeting of the SPE of the AIME, Los Angeles, Apr. 9-11.
- Russell, J. C., 1885, Geological history of Lake Lahontan--A Quaternary lake of northwestern Nevada: U.S. Geol. Survey, Monograph 11, 288 p.
- Sinclair, A. J., 1974, Selection of threshold values in geochemical data using probability graphs: Jour. Geochemical Exploration, v. 3, p. 129-149.
- Stefansson, V., and Arnorsson, S., 1975, A comparative study of hot-water chemistry and bedrock resistivity in the southern lowlands of Iceland: Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, 20-29, May, 1975, 2, p. 1207-1216.
- Stewart, J. H., and Carlson, J. E., 1978, Geologic map of Nevada: U.S. Geol. Surv. Map MF-930, 1:500,000.
- Stewart, J. H., and Carlson, J. E., 1977, Million-scale geologic map of Nevada: Nev. Bur. Mines Geol., Map 57.
- Turekian, K. K., 1969, The oceans, streams and atmospheres: in Wedepohl, K. H., ed., Handbook of Geochemistry, v. 1, Berlin-Heidelberg-New York: Springer, p. 297.
- U.S. Bureau of Reclamation, 1976, Susanville Geothermal Investigations, California: special report.

Waring, G. A., 1915, Springs of California: U.S. Geol. Survey, Water-Supply Paper 338, 410 p.

White, D. E., 1967, Mercury and base-metal deposits with associated thermal and mineral waters: in Barnes, H. L., ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rhinehart and Winston, Inc., p. 575-631.

White, D. E., 1981, Active geothermal systems and hydrothermal ore deposits: Econ. Geol. 75th Anniversary Volume, 1981, p. 392-423.

APPENDIX A
LITHOLOGIC LOG OF GEOPRODUCTS WEN-1 WELL

DRILL HOLE WEN-1, GeoProducts Corp.
LOCATION SW 1/4 Sec. 13, T29N, R15W, Lassen Co. Calif.

LOGGED BY Sibbett
Jan, 1982

GRAPHIC LOGS										2		
DEPTH feet	ALTERATION						Slicken sides	fault breccia gouge	GRAPHIC GEOLOGY	unit intervals	DESCRIPTIONS	
	Calc.	Chlor.	2nd clay	hem	Pyrite	Op.						
											30' sample interval	
										1090-1370	Andesite, dk gy, uniform. GR log. few < 1mm pheno. plag., alt. Softness of chips suggest minor alt.	
1200											1/3 chips of alt tuff as above	
20										1200-1250	but GR log suggest uniform andesite continues	
40												
60												
80											Clay-sericite alt. of some andesite chips increases, minor tra calc.	
1300											1300-1370	prob. flow base, more fract. & flow brec., poss. minor tuffac. sed., lignite LCM
20												
80												
1400										1370-2620	Basalt, dk gy to olive gy., ~30% pheno 2mm plag. xls, olivine. Dk grn. alt. clay, bowlingite or chlor + clay mix, few small vesicles	
20												
1500											Clay alt. is prob. deuteritic	
1600											1580-1620	diff. lava flow, fresher, poss. basaltic-andesite comp.
											1620-1650	mix bas & tuff flow base & interbedded tuffac. sed.
1700											1650-	flow top, vesicular, few amygdulites, dk. grn., few red chips, grn clay 40% 1mm plag laths, olivine alt. to bowlingite, clear zeolites Zeol. amygdulites-prob. analcime
												Dk. grn-alt. material prob. a mix of mont. & bowlingite clays plus poss. chlor. & caladonite, prob. deuteritic alt.
1800												Zeol. amygdulites with grn. coating
1900												part. alt. pyroxene xls are hem. stain olive alt. to iddingsite
2000												stilbite-sheaflike xls euh. analcime crystals abundant zeolite amygdulites
2100												

DRILL HOLE WEN-1, GEOPRODUCTS
LOCATION

LOGGED BY Sibbett

DRILL HOLE WEN-1
LOCATION

LOGGED BY Sibbett

GRAPHIC LOGS											unit intervals	DESCRIPTIONS 10' sample intervals
DEPTH feet	ALTERATION						Slicken sides	fault breccia gouge	GRAPHIC GEOLOGY			
	calc.	chlor	2nd clay	hem	pyrite	ep.						
											2620-4550	Basaltic ash or lahars (cont.) Mixed basalt-andesite litho in clasts Tr. caladon, chips w/ few olive-brn chips of mudst. w/ coarse sand grains of lithic crystal sand more abundant in some zones chalcedony amygdule
3200												
20												
40												
60												
80												
3300												
3400												
3500												Note: Appears to be all volcanoclastic or ash-lahar type deposit but isolated lava flows may be present & overlooked depending on sample mixing & caving
3600												
3700												3700-3710 possible basalt lava flow
3800												
3900												

DRILL HOLE WEN-1
LOCATION _____

LOGGED BY Sibbett

GRAPHIC LOGS											5
DEPTH feet	ALTERATION						Slicken sides	fault breccia gouge	GRAPHIC GEOLOGY	unit intervals	DESCRIPTIONS 10' sample interval
	calc.	chlor	2nd clay	hem	pyrite	ep.					
4200										4550	mix basaltic-andesite lithologies, fresh & clay-chlor? alt., abundant coarse sand lithic & xl. grains few mudst. chips, poss. clay matrix lost by drilling & washing few zeo amygdules, poss. lahars, ash cone deposit
4300											chalcedony chip.-amyg? fresh pyroxene xls
4400											change to coarser chips at 4360, < sand euh. qtz xl., few gry chalcedony or qtzt Increased chert or metasiltst. dk gy
4500										Fault	Clear qtz chips or grains? Few qtzt chips G.R. & caliper log indicate fault at 4470 few mudst. & lithic Ss chips
4600										4550-5050	Conglomerate, clasts of metasiltst. qtzt, plutonic rock of diorite to mon? poss. few vol. clasts but may be caving. pyrite is within clasts
4700											few rounded chert clasts-blk. Mix litho. of chert, qtzt & plutonic few rounded clasts-chert, lithic Ss chips
4800											Rounded & polished chert clasts few carbonate chips py coating on rounded chert pebble calc intergranule in qtzt clasts
4900											matrix material not seen in cuttings poss. lost during drilling & washing
5000										5050-5100	bio. granite? medium grain, bio fresh abundant qtz
5100											Litho change in samples at 5070 by logs

DRILL HOLE WEN-1
LOCATION _____

LOGGED BY Sibbett _____

GRAPHIC LOGS											6	DESCRIPTIONS																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									
DEPTH feet	ALTERATION						Slicken sides	Fault breccia gouge	GRAPHIC GEOLOGY	Unit intervals																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																											
	Calc.	Chlor	2nd clay	Hem	Pyrite	Ep.																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															

DRILL HOLE WEN-1
LOCATION _____

LOGGED BY Sibbett

APPENDIX B

WEN-1 DRILLING HISTORY

(This appendix is edited from the GeoProducts text only to the extent of providing consistency of figures, appendices, etc.). The deep drilling started at 10:50 pm on August 1, 1977 and proceeded for the next 51 days, to September 22. The drilling time profile is shown in Figure 18 of this report. The bit record is shown in Appendix C. Presented here is a general overview of the drilling period. The dates and depths shown on Figure 18 correspond to data on the daily morning reports. Minor discrepancies between the time profile and the time sequence of events discussed below are due to shift differences in data collection and recording times.

The first lost circulation zone was encountered at 88 m (290 ft), 9 hours after the cement plug in the conductor pipe was tagged. The fluid loss was total (~ 475 bbls) and occurred in the same coarse alluvial strata in which the fresh water well was completed. Six lost circulation material (LCM) pills were pumped in (168 sacks of cedar fiber, cottonseed hulls and pellets, nut seal, and Kwik-Seal), followed later by 2 chemical plugs (sodium silicate/calcium chloride mix) when returns could not be obtained in the intervals between the LCM pills. When very poor returns were obtained after the second chemical plug was set, drilling continued ahead without returns to 76 m (249 ft) at which time the LC zone was finally sealed with a cement plug. Sixty hours were devoted to curing this LC problem before drilling resumed.

Throughout the drilling operations, deviations and temperature surveys were taken nominally every 46 m (150 ft). Bottom hole temperature results are discussed in the main body of the report under Well Testing. At depth 310 m (1016 ft), the 13 3/8-in surface casing was set. Dual induction and temperature logs were first run and the hole further conditioned for running

the casing. When cementing of the casing was attempted, no cement returns were observed at the surface. Three water displacements were made at 10-15 minute intervals, still without cement returns to the surface. A top outside cement job was then undertaken with 64 m (210 ft) of 1-in. pipe run down the annulus of the 20-in casing and 114 sacks of cement (with 1:1 Perlite) were pumped in. Additional cement (104 sacks) was pumped in at 58 m (190 ft), and finally the cement pressure system was hooked to the 20-in. casing head, and the annulus filled until returns were noted at the surface. The BOP stack was changed in preparation for drilling the 12 1/4-in hole below the surface casing. Total time spent at depth 310 m (1016 ft) was 96 hours of which 11 percent was due to logging, 46 percent to casing and cementing time, and the remainder to stack and drilling assembly changes. (See Appendix C for a complete time breakdown of the drilling operation.)

Good progress was made from the time drilling resumed August 11, until a depth of 1617 m (5304 ft) was reached on August 30. Only routine surveys, bit changes, hole conditioning periods, rig servicing, and some problems with the rig wireline temporarily interrupted drilling operations. Geologic formations encountered during the period consisted primarily of clay, lake bed sediments, coarse conglomerate and basalt rock. Granite cuttings were observed for the first time on August 27 between 1524 and 1555 m (5000 and 5100 ft), disposing of the supposition that a geothermal resource might be found near the 1524 m (5000 ft) target depth in a relatively continuous but faulted volcanic formation.

The strategy adopted for this phase of the drilling operation was to avoid the permanent commitment of 914-1219 m (3000-4000 ft) of 9 5/8-in casing until positive indications existed that the chances were good of having a commercial well. Such indications would include a dramatic increase in bottom

hole or flowline temperature, coupled hopefully with a rather continuous interval of broken volcanic rock somewhere between 1067 and 1524 m (3500 and 5000 ft). Neither of these circumstances occurred.

Some circulation losses were first noted at depth 1596 m (5236 ft), about 61 m (200 ft) into the granite about 4 pm on August 29. The loss was about 30 bbl/hr and remained roughly at that level while drilling was in progress for the next several hours. At 3 am the following morning total loss of circulation occurred at depth 1617 m (5304 ft).

This lost circulation occurrence, correlated with the existence of microfractures having been observed in the granite cuttings, gave rise to optimism that the drilling had encountered the fault at very near the 1524 m (5000 ft) level which had been the nominal target of the drilling effort. As the drilling schedule profile indicates, however, the following several days were as fraught with problems as the preceding 2 1/2 weeks had been free of them.

A wireline service was obtained to provide temperature information during a 12 hour buildup. After some difficulty with the instruments, a 226° temperature was recorded at depth 1615 m (5299 ft). The decision was made to run and tack the 9 5/8-in casing at that point after a complete suite of geophysical logs was run and the LCZ protected by a 46 m (150 ft) sand plug. Three sand plugs were set, each time with significant settling, until the top reached 1567 m (5140 ft). A cement plug was then set on the sand with the top at 1561 m (5120 ft). Seven hours later, on running back in the hole, a bridge was encountered at depth 1187 m (3894 ft) which consumed another day's time in reaming and cleaning. When the hole was sufficiently cleaned and conditioned, the 9 5/8-in casing was set with the bottom at depth 1545 m (5068 ft) and a liner hanger inside the 13 5/8-in casing at depth 233 m (764 ft), thus

providing a 74.4 m (244 ft) overlap.

In circulating prior to cementing the casing, the returns were lost to the formation. A chemical plug of sodium silicate and calcium chloride was pumped in and displaced without success. Another chemical plug was pumped in, this time ahead of casing cement, and again a pressure test would not hold and no returns were obtained from subsequent circulation. A cement bond log was run to determine to what extent the cement was being placed behind the casing; the results of the logging run, however, were ambiguous but suggested that some cement had probably been placed. A second cementing job was undertaken. Pressure back on the cement system reached 3000 psi, suggesting that a good cement job had been obtained in the bottom part of the hole and preparations were made to resume drilling.

Below depth 1617 m (5304 ft) water was used as the drilling fluid, and occasional light gel sweeps were employed to clean the hole. To depth 1768 m (5800 ft), continuous fluid losses were noted, eventually reaching over 300 bbl per hour suggesting that the drilling was deepening the possible production zone first encountered at depth 1617 m (5304 ft). At 1768 m (5800 ft), the decision was made to run a production logging suite. On running the sonic log, however, the tool would not descend below 1622 m (5323 ft) so the logging crew was released. Two Dresser-Atlas air compressors, each rated at 1500 cfm and 1000 psi (sea level) were brought to the site to airlift the hole and possibly help deepen it by air drilling. The hole was making 1200-1800 gpm and considerable time was spent over the next two days pumping the sump down and constructing an auxiliary sump. Continued drilling with the aereated system was much slower than had been expected, averaging only about 1.5-2 m/hr (5-6 ft/hr). At depth 1779 m (5837 ft), the production interval logs were run consisting of temperature, dual induction/SP, and BC Sonic/caliper. An

initial 6 hour flow test was also conducted. A three inch orifice plate and differential pressure gauge was installed in the flow line and the flow rate controlled by a butterfly valve. The initial wellhead pressure was 40 psig and flow temperature was 106°C (222°F). The final well head parameters during this 6-hr. flow test were 111°C (232°F) and 103 Kpa (15 psig) with the flow estimated at 41 l/s (650 gpm). When shut in the wellhead pressure recovered to 296 Kpa (43 psig) in 20 seconds. A final temperature log was run indicating 119.8°C (247.7°F) at TD which was confirmed by an Amerada Bomb recording 120.2°C (248.3°F).

Given the unexpectedly slow rate of drilling with the air system, the safety problems to the crew created by the large amount of hot water developed, a decreasing temperature gradient and the fact that the rig had developed a slight tilt toward the sump as a result of soil washout and settling, the decision was made to cease drilling operations. The rig was released at 8 pm on September 22.

APPENDIX C
DRILLING BIT RECORD

Bit No.	Mfgr/Type	Size	Footage			Hours	Condition****
			In	Out	Drilled		
UB #1	HTC/21J	17 1/2"	40	208	168	13	45 I
RB #2	HTC/J33	17 1/2"	208	463	255	28	45 1/16
RB #3	SM/2JS	17 1/2"	463	1016	553	45	34 1/16
RB #4	SM/3JS	12 1/4"	1016	1220	204	28	22 I
NB #5	HTC/J33	12 1/4"	1220	3251	2031	118	46 1/16
NB #6	HTC/J44	12 1/4"	3251	4620	1369	115	43 1/32
RB #7	SM/3JS	12 1/4"	4620	5110	490	39	No Cond.
NB #8	HTC/J44	12 1/4"	5110	5275	165	19	45 I
NB #9	SEC/S88	12 1/4"	5275	5307	32	3	12 I
NB #10	SM/F4	8 3/4"	*	*	*	11	53 3/8
RB #11	SM/F3	8 3/4"	5009	5410**	401***	42	53 1/8
NB #12	SEC/M84F	8 3/4"	**5442	5707	265	26	22 I
RB #13	SM/4G4	8 3/4"	5707	5837	130	6.5	No Cond.

Bit Designations:

UB - Used Bit
RB - Rebuilt Bit
NB - New Bit

Manufacturer:

HTC - Hughes Tool Co.
SM - Smith Tool
SEC - Security

* DB #10 made no new hole; was used for reaming and drilling-out cement and cementing tools.

** Depth error discovered between bits #11 and #12 by strapping the drill string.

*** DB#11 drilled cement and 103' of new hole.

**** Standard oil field bit wear grading system, where by tooth, bearing and gauge wear are evaluated. Tooth and bearing degradation are indicated by the first and second digits, respectively. These two parameters are rated from 1 to 8 with 8 being totally worn-out. The last notation indicates the degree by which the bit is out of gauge, given in inches (i.e. 1/16) or, I if still in-gauge. (Example: 54 1/4 indicates the teeth are 5/8 worn-out, the bearings are 4/8 worn-out and the bit diameter is 1/4 inch smaller than when new).

APPENDIX D
WEN-1 RIG TIME DISTRIBUTION

Date	Drilling	Circulate Cond. Mud; Survey	Rig Repair; Service	Trips	Casing	Logging	Cure LC	Change BH & Wellhead Assembly	Other*
Aug 1	1.5								
2	8.5		.5	1			14		
3	4	3.5	.5	9.5			7.5		
4	11	.5	3.5	1.5			7.5		
5	22	1.5		.5					
6	19	.5		4.5					
7	21.25	1.5	1.25						
8	5.5	3.5	.5	5.5	3	3		3	
9			.5	1	22.5				
10			.5		13				
11			3.5					10.5	
12	18.75	2.5	.25	1.5				20.5	
13	14	.75	1.5	7.75				1	
14	18.75	3.5	.75	1					
15	22	2							2.25
16	20.25	1	.5						
17	21.25	2.25	.5						
18	22.25	1	.75						
19	14.25	2.5	.75	5.5					1
20	18.25	4.75	1						
21	17.25	1	.25	4.25				.5	.75
22	22.5	1	.5						
23	14.75	3	.25	6					
24	22.75	.5	.75						
25	16.25	2	.75	2					
26	17.25	2		3					3
27	23	1							1.75
28	4.5	5	4	8				2.5	
29	16	1.5	.25	4				.5	
30	3	.5		3	17.5				1.75
31					24				

APPENDIX D
[continued]

Date	Drilling	Circulate Cond. Mud; Survey	Rig Repair; Service	Trips	Casing	Logging	Cure LC	Change BH & Wellhead Assembly	Other*
Sept 1						19.5	4.5		
2				6			18		7
3		13		4					
4		7		4	3			10	
5				1	9		14		13.5
6		5	1	4.5					
7		.5	.5	3.5		16	2.5	1	
8		1		10	12				1
9	18.75	3.25			2				
10	12	4		5.25					2.75
11	23	1							
12	16.25	1.25		4.75					1.75
13	23			1					
14				2		8		4	10
15		1		2				14	7
16		4		12					8
17		5	9						10
18	7	5		5					7
19				3		16		5	
20						10		7	7
21				2		18		4	
22						8		4	6
TOTALS	519.75	99.75	25	147.5	64.5	140	68	87.5	91.5

*Includes wiping hole, reaming, magnaflux collars, procuring compressors for air drilling, pumping sump, digging new sump, flow test, etc.

APPENDIX E - DRILLING FLUID
(from GeoProducts Corporation, 1982)

A Gel-Benex fluid system was used through the first 91 m (300 ft) of the hole while drilling through the alluvial materials. The weight was maintained at 8.6-8.8 (lb/gal) and the viscosity at 40-45 (sec/qt). Bicarbonate and soda ash were also used as required for cement contamination.

The system was changed when sticky clay was encountered below 91 m (300 ft) by adding lignite as a dispersant. This Gel-Lignite system was used to 1617 m (5304 ft) with caustic and bicarbonate added as required. Mud weight was maintained at 65-68 lb/cubic ft and viscosity at 38-45.

Below what was thought to be the fault and possible production zone at 1617 m (5304 ft), a water-polymer system was used. Drispac (CMC) and later Cypan were added to the water to clean the hole and control fluid losses.

A mud engineer was provided by the service company (Professional Drilling Fluids) and was on-site throughout the drilling operation. Total expenditure for mud, related materials, and services was \$54,364.