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SITING AND DRILLING RECOMMENDATIONS
FOR A GEOTHERMAL EXPLORATION WELL,
WENDEL-AMEDEE KGRA,
LASSEN COUNTY, CALIFORNIA

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for

✓ GeoProducts Corporation

Oakland, California

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by

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December, 1980

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CONCLUSIONS

1. Honey Lake Valley is a northwest-trending topographic and structural depression filled with up to 5,500 feet of Pliocene to Holocene sedimentary and volcanic deposits. Basement consists of Sierran granitic rocks overlain by a discontinuous veneer of Early to Middle Tertiary volcanic and sedimentary rocks. These rocks crop out on the southwest side of the valley. Upland areas to the northeast are predominantly Plio-Pleistocene andesites and basalts derived from shield volcanoes. The volcanic rocks inter-finger with lacustrine sediments beneath the valley.
2. Shallow ground water flows generally south to southwest through the prospect area within predominantly volcanic aquifers. Many of these aquifers are confined by impermeable sediments, and some are sufficiently pressurized to be capable of artesian flow. Older granitic and volcanic rocks of the basement are essentially impermeable except where they have been tectonically fractured near faults.
3. Well defined normal faults of the Sierra Nevada frontal fault system, with a cumulative displacement of at least 8,000 feet, bound the southwest side of the Honey Lake depression. A similar set of basin-bounding faults has been proposed for the northeast side of the valley, but their continuity, and in some cases their existence, is more difficult to substantiate. Good justification exists for the north-south Amedee fault, which forms a 1,000-foot escarpment on the west side of the Amedee Mountains. The Litchfield and Skedaddle faults, proposed earlier to account for reconnaissance-level geophysical trends, are more speculative.
4. Detailed gravity data acquired by GeoProducts do not validate the Litchfield and Skedaddle faults as major through-going structural features. Some faulting does appear necessary to account for over-steepened gradients in the western part of the study area, but the data are permissive of different fault configurations. Magnitudes of possible fault offsets in the vicinity of Wendel Hot Springs cannot be large. Data from deep wells suggest that most of the gravity gradient between the center and the northeast margin of the valley is caused by interfingering of low-density sediments and high-density volcanic flows.
5. In the vicinity of the GeoProducts leasehold, the Amedee fault is the most conspicuous geologic structure and may provide deep permeability for geothermal fluids. Small-displacement faults may exist near Wendel Hot Springs, based on projections of mapped fault traces, alignments of tufa mounds, and lineations identified on aerial photographs. These probably localize the surface hot springs, but their importance to the deep part of the system (within basement rocks) is

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questionable, based on the apparent lack of major offset on them.

6. Electromagnetic sounding techniques used to investigate the resistivity structure of the valley subsurface are confounded by the lack of adequate interpretation techniques to deal with the very irregular three-dimensional variations in electrical properties. It is clear only that a good conductor lies 1,000 to 3,000 feet deep below more resistive rocks within much of the study area. It is not a homogeneous region, and probably is broken by faults of other discontinuities unresolvable with present interpretation techniques. It is highly doubtful that the conductor can be related solely to geothermal phenomena, though high temperatures locally may contribute to lowered resistivities.
7. Spring waters from Wendel and Amedee Hot Springs are chemically similar and very likely emanate from a single continuous geothermal reservoir. Amedee water is slightly more dilute, possibly due to mixing with cool ground water en route to the surface. Chemical geothermometers predict a reservoir temperature between 250° and 270°F, possibly even as high as 300°F.
8. The geothermal reservoir was penetrated by deep wells near each spring. Honey Lake #1-ST near Amedee Hot Springs was abandoned at 5,033 feet when a temperature survey conducted after only 8 hours of stabilization recorded a maximum temperature of 230°F. There were no indications of permeability in that well. A stabilized gradient was obtained for Honey Lake #2-ST, presently suspended, near Wendel Hot Springs. It showed an isothermal reservoir at 230°F between 3,000 and 4,500 feet, underlain by impermeable basement rocks to total depth of 5,056 feet. Permeability, evidenced by mud losses during drilling, was found at 1,100 feet and at 4,171 feet.
9. The geothermal reservoir occurs within Plio-Pleistocene volcanic rocks which are overlain by a thick blanket of clay-rich lacustrine sediments. Permeability within the reservoir rocks probably is primary, and therefore is stratigraphically rather than structurally controlled. Actual deep circulation and heating, however, probably take place within fault zones at some distance from the site of Honey Lake #2-ST.
10. Temperatures may vary laterally within the reservoir as a function of fluid movements. Scant evidence from deep drilling, supplemented by the results of temperature-gradient drilling by GeoProducts, suggests that the reservoir is hottest in the vicinity of the Amedee fault and cooler near Wendel Hot Springs. It may not be present at all in the western part of the GeoProducts leasehold.
11. The preferred geothermal model developed in this report proposes that deep circulation and heating of geothermal water occurs primarily within fractured basement rocks adjacent to the Amedee fault.

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Ascending thermal water enters subhorizontal volcanic aquifers overlying the basement, flowing south and west to form a geothermal reservoir of great lateral dimension. Wendel and Amedee Hot Springs tap this reservoir at widely separated locations.

12. Faults in the vicinity of Wendel Hot Springs may also supply thermal water to the reservoir, but are considered to be a less likely source than the Amedee fault because the magnitude of faulting is considerably less.
13. On the basis of available data, no calcite or silica scaling or excessive rates of corrosion are anticipated as a result of fluid production from the Wendel Amedee geothermal reservoir. Potentially toxic concentrations of boron and fluorine in the thermal water may make it necessary to re-inject spent fluid into the reservoir.

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RECOMMENDATIONS

1. Three drillsites are recommended, based on the geothermal model developed in this report: (a) Site AM in the center of the SE $\frac{1}{4}$ of Section 23, T. 29 N., R. 16 E.; (b) Site WEN-W near the center of Section 24, T. 29 N., R. 15 E.; and (c) Site WEN-E in the southwest corner of Section 13, T. 29 N., R. 15 E. These sites were selected to test the portion of the geothermal reservoir underlying the GeoProducts leasehold as close as possible to suspected deep-circulation conduits within the Amedee fault and the Wendel Hot Springs fracture system.
2. For re-injection of waste fluids, use of the Honey Lake #2-ST should be used, if possible. An alternate injection site for a well at site AM is suggested in Section 31, T. 29 N., R. 16 E.
3. The anticipated production interval is between 3,500 and 5,000 feet. Permit depths and contracted rig capacity should be at least 6,000 feet to accommodate uncertainties in the geologic section and in the subsurface temperature distribution.
4. A comprehensive temperature-logging program should include (a) monitoring flowing mud temperatures, (b) bottom-hole readings with a maximum-reading thermometer, (c) pausing occasionally to measure temperature build-up on bottom, and (d) continuous logging from the surface to total depth after termination of drilling and after at least 1 month of stabilization.
5. Equipment should be on hand to record accurately and continuously mud temperature, mud volume, and penetration rate. The recommended sampling interval for cuttings is 10 feet.
6. The geophysical log suite should include Compensated Formation Density-Compensated Neutron (with gamma-ray and caliper) logs and Dual Induction Laterolog (with spontaneous potential), or equivalent, to be run at total depth and, if possible, before setting 9-5/8 inch production casing.
7. On-site supervisory personnel should consist of a drilling engineer and a geologist, who will work together, in consultation with GeoProducts and its partners, to insure that drilling practices are both technically and operationally sound.
8. A water supply of 1,000 bbl per day should be secured prior to spudding the well so that drilling will not be held up if it becomes necessary to drill with no returns in lost-circulation zones.

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9. The drilling sump should be large (capacity 700,000 gallons or more) to accomodate fluid produced during long-term well tests.
10. Complete specifications are given for drilling, casing, and completing the proposed GeoProducts geothermal well.

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INTRODUCTION

The purpose of this report is to review and interpret all available exploration data relevant to the GeoProducts Leasehold in the Wendel-Amedee KGRA and, on the basis of this interpretation, to recommend locations and procedures for drilling geothermal production wells capable of supplying fluid at a temperature of 250°F or greater. GeoProducts has supplied published and proprietary data listed in appendix A. Additional published sources of information are included in the reference list at the end of the report. Unpublished earthquake data obtained from the Seismographic Station, University of Nevada, Reno, and Well logs for a deep oil test drilled on The Island were also used in writing the report. Useful information about Gulf's Honey Lake #1-ST geothermal test were supplied by Glen Campbell of Gulf Minerals. George Zebal also answered questions about the local geology.

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STRATIGRAPHY AND GEOLOGICAL HISTORY

The geology of the Honey Lake area was investigated and mapped by the California Department of Water Resources (1963). Later work by George Zebal (1975) for GeoProducts and incidental field observations by Electrodynne (1977?, 1978, 1979) have added some modifications to the original mapping and interpretations of the C.D.W.R. Detailed descriptions and summaries of local geology are given by the C.D.W.R. and Zebal, and by Koenig (1975, 1976). A summary of those aspects which are pertinent to the geothermal system is provided here. A simplified geologic map of the Honey Lake area is shown in figure 1.

Honey Lake Valley is a west-northwest trending topographic depression bounded by a high-angle Sierra front fault on its southwest side and by a Pliocene volcanic plateau on its northeast side. The basin, which began forming in Pliocene time, is filled to a depth of 2,000 to 5,000 feet with sediments and volcanic rocks. Underlying these is a basement complex consisting of Mesozoic granitic rocks of the Sierra Nevada Batholith and overlying Early to Middle Tertiary volcanic rocks. These rocks crop out in the mountains on the southwest side of the valley. To the northeast the basement is mostly buried beneath Pliocene and younger volcanic rocks.

Throughout most of the Early Tertiary Period the site of present-day Honey Lake Valley was characterized by terrain of low to moderate relief. The geomorphic regime was basically erosional, and only scattered small basins collected sediments. Andesitic and rhyolitic volcanic rocks which may have blanketed the area at one or more times between the Eocene and Miocene Epochs were deeply dissected by the time a broad basin began to subside on the east side of the Sierra Nevada in the Pliocene. As in much of the Basin-and-Range province, basin subsidence was accompanied by the extrusion of large volumes of andesite and basalt magma. Damming of westward-flowing streams by lava flows and/or continued faulting, created a large lake within the depression. The Pliocene lake was larger than the present Honey Lake Valley. In the Antelope Mountains there are remnants of lake deposits perched hundreds of feet above the valley floor. Extensive lake deposits probably of the same age underlie Secret Valley, 10 miles to the north and about 400 feet higher in elevation.

The timing of Late Tertiary events leading to the present geologic and topographic configuration of the Honey Lake Area is somewhat uncertain, partly because inferred age relationships have not been substantiated by radiometric age dates of the various volcanic rocks. Evidently subsidence along faults, extrusion of lava, and sedimentation within the Late Tertiary basin progressed simultaneously, each affecting and being affected by the others. The locus of all three activities may have shifted continuously

FIGURE 1. Simplified geologic map of the Honey Lake area showing epicenters of earthquakes that have occurred since 1970. Geology adapted from Geologic Map of California, Westwood Sheet, 1969, C.D.M.G. and Geologic Map of Nevada, 1978, U.S.G.S. (Skedaddle and Litchfield faults from Northeastern Counties Ground Water Investigation, 1962, C.D.W.R.)

EXPLANATION

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during the evolution of the present basin. In the subsurface of Honey Lake Valley clay-rich sediments interfinger in a complex way with basaltic and andesitic volcanic rocks which emerged from vents on the northeast side of the valley. The presence or absence of lake beds interbedded with or underlying the volcanic pile at Shaffer and Amedee Mountains is a matter of conjecture.

It is clear, however, that by early Pleistocene time the Pliocene lake bed dried up, and the broad subsiding Pliocene basin had been fragmented into a number of closed sub-basins, among them the present Honey Lake Valley. Volcanic activity in the early Pleistocene produced fluid basaltic lava which flooded many of the lowland areas. Major flows descended from the west into the western extremity of Honey Lake Valley near Susanville. Others approached the valley from the north, filling valleys between older Pliocene volcanoes.

This was the last major development in the evolution of the valley. Later changes in physiography are limited to small-scale faulting, stream erosion, and deposition of alluvial and lacustrine sediments. During the Pleistocene ice ages Honey Lake Valley became the westernmost basin occupied by Lake Lahontan, a mammoth body of water which covered much of northwestern Nevada. Fine-grained Lahontan sediments (silt and clay) blanketed the valley floor to depths of several hundred feet. At higher elevations coarser near-shore deposits are preserved. Since then the Pleistocene Lake Lahontan has gradually dried up, leaving only a few scattered remnants such as Honey Lake and Pyramid Lake. Under present arid conditions deposition of sediments occurs primarily on alluvial fans adjacent to steep escarpments. Some fine-grained material is carried into the basin by streams and by wind currents and deposited as a thin mantle overlying the Lahontan lake beds.

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GEOLOGIC STRUCTURE

The dominant structural feature in Honey Lake area (figure 1) is the northwest-trending zone of en echelon normal faults forming the southwest side of the valley which juxtaposes Sierra basement rocks of the Diamond Mountains against Cenozoic sedimentary rocks.

Cumulative displacement on these faults is at least 8,000 feet, based on topographic relief of 2,500 feet at the escarpment and the estimated 5,500-foot depth to basement at the deepest part of the Valley (C.D.W.R., 1963). The Honey Lake fault zone may have been active as early as the Late Mesozoic (GeoProducts, 1976), but reactivation in the Late Cenozoic no doubt contributed significantly to the development of the Pliocene sedimentary basin.

The Fort Sage Mountains at the southeast end of the valley and Bald Mountain at the northwest end are underlain by fault-bounded "outliers" of basement rocks located valleyward from the Honey Lake fault zone. The northwest-trending fault escarpment on the northeast side of the Fort Sage block is parallel to the Honey Lake fault system and is believed to have become active at about the same time. The Fort Sage Mountains are separated from the Diamond Mountains by the narrow Long Valley graben. Faulting on the sides of Bald Mountain is less easily related to the Honey Lake fault system, but there has been speculation about a subsurface fault connection between the two uplifted blocks. This does not appear to be borne out by sparse gravity data for Honey Lake Valley (Bureau of Reclamation, 1976a). Nevertheless the two fault blocks may have similar origins related to splintering of the Honey Lake fault zone.

Other faults are believed to bound Honey Lake Valley on its northeast side. These faults have much smaller (but still essentially unknown) offsets, and have a variety of orientations. The Antelope Mountain Fault northeast of Susanville is parallel to the Honey Lake fault zone and likewise is responsible for bringing basement rocks to surface exposure. It may be part of the same fault system.

The Litchfield fault was mapped by the C.D.W.R. (1963) on the north side of the valley primarily to account for a nearly east-west-trending steep gravity gradient located by a reconnaissance gravity survey. Its surface expression is questionable over most of its course; it has been mapped as concealed by Quaternary sediments. Tufa mounds near Wendel Hot Springs and east of Litchfield have been used to infer its location.

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In the GeoProducts lease area much speculation was accorded its location by Electrodyne (1977?, 1978, 1979), based on various lines of geophysical evidence, most of them equivocal. Again, the steep gravity gradient paralleling the northeast side of the valley was the most compelling evidence for significant offset on the Litchfield fault. Deep drilling data from the Wendel and Amedee Springs areas show, however, that the granitic basement is at least 5,000 feet deep northeast of the steep gradient, and therefore, the gradient is more likely due to the contrast in density between the thick basalt section found in the wells and the lake sediments to the south with which the basalts interfinger.

Faulting may account for some of the very steep local gravity gradients delineated by the detailed gravity survey conducted for GeoProducts, but the data do not mandate an interpretation of a single continuous basin-bounding fault. Composite displacement on oblique-trending faults, such as those which have been mapped on the south side of Shaffer Mountain, could permissively account for some of the observed gravity trends.

The north-south-trending Amedee fault is the most readily defined fault in the prospect area and is responsible for the steep western escarpment of the Amedee Mountains. This fault was justifiably extrapolated southward through Amedee Hot Springs by the C.D.W.R., but extensions farther south are more conjectural, probably based on the apparent truncation of the Fort Sage Hills horst block.

The so-called Skedaddle fault (Zebal, 1975) crosses the Amedee fault at the head of Wendel Canyon and follows the base of the Skedaddle Mountains west-southwest toward Wendel Hot Springs. A line of tufa deposits extending through the springs justifies the valleyward extrapolation of this fault through the hot springs. Gravity data, though sparse in this area, suggest that vertical offset on the Skedaddle fault is not large. Topographic expression also is more subdued compared to that of the Amedee fault.

The validity of the Skedaddle fault as a major structural feature is therefore called into question. Minor structural disruption in the vicinity may localize Wendel Hot Springs, as suggested by aligned tufa mounds which trend generally (but not uniformly) to the northeast. A subparallel fault mapped by the California Division of Mines and Geology in volcanic rocks northeast of Wendel Hot Springs may also play a role in this. The fault has an estimated vertical offset of 100 to 200 feet, based on topography, and probably dips toward the northwest. In addition, a southwest-trending lineation has been identified on aerial photographs which projects directly into the hot-springs area. The lineation appears

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to be a geologically recent fault rupture of the land surface. Its relation to topography suggests a northwestward fault dip, but the sense of displacement is unknown.

The magnitude of vertical offset on individual basin-bounding faults of Honey Lake Valley is not known with certainty. As mentioned, cumulative vertical displacement on faults on the southwest side of Honey Lake is at least 8,000 feet. GeoProducts (1976) has estimated offsets of 2,000 to 5,000 feet for the Litchfield, Amedee, Fort Sage, and Antelope Mountain faults, and over 1,000 feet for the Skedaddle fault. The values for the Litchfield and Skedaddle faults, if they exist, seem a little too large, judging from their lack of clear surface expression.

Numerous faults have been mapped in the hills surrounding Honey Lake Valley. Two trends predominate: northwest-southeast, parallel to the Honey Lake fault zone, and northeast-southwest. Displacements on these faults are unknown, but topographic expressions are weak, which suggests that offsets are generally small. Faults of both sets cut the youngest (Quaternary) volcanic formations. None are shown in the immediate vicinity of the GeoProducts lease area, but southeast trending faults on the flank of Shaffer Mountain project toward the southwest corner of the area.

Pliocene sediments exposed on the tip of the Island have been deformed into a faulted anticlinal structure. It is debatable whether this structure is caused by lateral compressive deformation (GeoProducts, 1976) or to vertical displacements on underlying bedrock faults. However, the northwest-southeast orientation of faults and the alignment with the uplifted Fort Sage and Bald Mountain fault blocks suggest that the surface folds and faults formed by soft-sediment draping over buried fault blocks.

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HYDROLOGY

Honey Lake Valley is an enclosed hydrologic basin fed by major streams entering it from large drainage areas to the northwest (Susan River), the north (Willow Creek), and the southeast (Long Valley Creek). Small intermittent streams drain mountain slopes on the northeast and southwest sides of the basin. Water-table measurements in the valley (C.D.W.R., 1963) indicate that Susan River and several small creeks are effluent streams, i.e., fed in part by ground water over part of its course, while Long Valley Creek is influent, i.e., contributing to the ground water reservoir. Water movement both at the surface and below it is toward Honey Lake. In normal years the influx of water to the basin approximately balances that discharged by evaporation.

Figure 2 summarizes the hydrologic characteristics of rocks in Honey Lake Valley. Greatest permeability is associated with (1) medium- to coarse-grained sediments in alluvial fans, near-shore lake deposits, and certain sandy beds of the Lahontan Lake sediments, and (2) Pleistocene basalt flows and scoria beds. Because of restricted occurrence and/or primary location in high areas, not all of these deposits are important to the ground-water regime of Honey Lake Valley. None are believed to play a significant role in the circulation of geothermal fluids, since they are all relatively young and occur near the land surface.

Of the deeper Cenozoic units shown in figure 2, only the Plio-Pleistocene basalts and andesites offer the prospect of significant reservoir capacity for ground water. Permeability within these rocks is both primary (intergranular and vesicular) and secondary (due to joints and fractures). Beneath the GeoProducts lease blocks flows, tuffs, breccias, and agglomerate interfinger with lake sediments of the Plio-Pleistocene sedimentary basin. Some of these have good water-bearing potentials as well. Excellent permeability, sufficient to cause numerous severe drilling problems, was encountered by the Neaves Petroleum Honey Lake Island No. 1 well in Section 11, T. 27 N., R. 15 E. (figure 2). The lithologic log for that well is incomplete because of frequent losses of circulation, but permeability appears to be associated with medium- to coarse-grained quartzose sands, possibly marginal basin deposits. Beneath the GeoProducts leases, however, the Plio-Pleistocene sediments are mostly clay rich and impermeable and are unlikely to yield large quantities of water. They serve rather as aquacludes separating and confining volcanic aquifers, some of which are sufficiently pressurized by elevated recharge channels in the nearby mountains to generate artesian flow.

Older Cenozoic volcanic rocks (C.D.W.R.'s "Sierran volcanics") have low to moderate primary or secondary permeability locally. Their

GEOLOGIC FORMATIONS IN HONEY LAKE VALLEY (from C.D.W.R., 1963)

GEOLOGIC AGE		GEOLOGIC FORMATION	STRATIGRAPHY	APPROXIMATE THICKNESS IN FEET	PHYSICAL CHARACTERISTICS	WATER-BEARING CHARACTERISTICS						
CENOZOIC	QUATERNARY	RECENT	SAND DEPOSITS	Qs	0-25	Qsd: Loose, wind-blown sand.	Highly permeable but located above water table, hence contains little water.					
			LAKE DEPOSITS	Ql	0-25							
			BASIN DEPOSITS	Qb	0-50	Ql: Unconsolidated silt and clay, contains alkali.	Very low permeability and of little importance to ground water.					
			INTERMEDIATE ALLUVIUM	Qol	0-100							
			LANDSLIDES	Qls	0-50	Qb: Unconsolidated sand, silt, and clay. Often contains alkali.	Low permeability. May yield small amounts of water to domestic wells.					
			ALLUVIAL FANS	Qlf	0-300							
		PLEISTOCENE	NEAR-SHORE DEPOSITS	Qps	0-400	Qal: Unconsolidated sand, silt, and gravel with lenses of clay.	Moderate permeability. Yields small to moderate quantities of water to wells.					
			LAHONTAN LAKE DEPOSITS	Qpl	0-700	Qls: Unconsolidated mixtures of rock, sand, and clay.	Moderate permeability. May yield moderate quantities of water to wells in Hidden Valley.					
						Qf: Unconsolidated gravel, sand, and silt, with some clay lenses.	Moderate to high permeability. Yields large quantities of water to wells. May contain confined water.					
			PLEISTOCENE VOLCANIC ROCKS	BASALT	Qpvb	50-500	Qps: Unconsolidated, poorly cemented, bedded gravel, sand, and silt.	Highly permeable. Frequently occurs above water table. Where saturated yields large quantities of water to wells and sumps.				
							Qpl: Poorly consolidated, bedded sand, silt, and clay.	Permeability ranges from low to high. Contains important aquifers in Honey Lake Valley. Often yields large quantities of water to wells.				
	PLIO-PLEISTOCENE		VOLCANIC ROCKS	BASALT	TQvb	4000	Qpvb: Jointed basalt flows containing zones of scoria.	Moderate to high permeability. May yield large quantities of water to wells. Acts as forebay for ground water recharge.				
							Qvpv: Bedded mudflows and tuffs.	Low permeability, unimportant to ground water.				
							TQvb: Jointed, fractured flows of vesicular basalt with some pyroclastic rocks.	Moderate permeability, may yield moderate amounts of water to wells. May contain confined water. Important as forebay for ground water recharge.				
		TQvp: Pale-colored bedded tuff.					Unimportant to ground water.					
	TERTIARY	PLIOCENE	PLIOCENE LAKE DEPOSITS	Tpi	0-5000	Tpi: Bedded, consolidated sandstone, tuffaceous siltstone and diatomite.	Generally of low permeability. Locally may yield moderate quantities of water to wells. Contains confined water.					
						Tpvp: Massive, cemented tuff and mudflows.	Essentially impermeable.					
			PLIOCENE PYROCLASTIC ROCKS	Tpvp	1000	Tsvb, Tsva, Tsvp, Tsv: Flows of fractured basalt, andesite, and minor amounts of other types of lava. Massive mudflows and tuffs.	Permeability ranges from poor to moderate. Basalt is generally above zone of saturation, is underlain by impermeable rock, and is unimportant to ground water. A few areas may contain perched ground water. Andesite and pyroclastic rocks are essentially impermeable.					
		PRE-PLIOCENE	SIERRAN VOLCANIC ROCKS	BASALT	Tsvb	2000	Tsvb, Tsva, Tsvp, Tsv: Flows of fractured basalt, andesite, and minor amounts of other types of lava. Massive mudflows and tuffs.	Permeability ranges from poor to moderate. Basalt is generally above zone of saturation, is underlain by impermeable rock, and is unimportant to ground water. A few areas may contain perched ground water. Andesite and pyroclastic rocks are essentially impermeable.				
									ANDESITE	Tsvo	Tsg: Semi-consolidated gravel, sand, and clay.	Low to moderate permeability. Yields water to many springs. Not important to ground water in Honey Lake Valley.
									PYROCLASTIC ROCKS	Tsvp		
			AURIFEROUS GRAVELS	Tsg	?	Tfs: Consolidated, cemented sandstone.	Essentially impermeable.					
			GOLD RUN SANDSTONE	Tgs	?	JKgr: Massive, poorly jointed diorite. Locally weathered and decomposed.	Impermeable where fresh. Decomposed rock may yield small quantities of water to wells and sumps.					
		FORT SAGE SANDSTONE	Tfs	?								
MESOZOIC		JURASSIC TO CRETACEOUS	BASEMENT COMPLEX	GRANITIC ROCKS	JKgr	?						

FIGURE 2. Hydrologic characteristics of rocks in the Honey Lake Valley.

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distribution in the subsurface is unknown. Some of the age-equivalent sedimentary formations may be moderately permeable also, but are unimportant overall because of their scarcity. Mesozoic basement rocks have no primary permeability whatsoever and are only sparsely jointed where they are not broken by faults. In most cases they will yield no water.

All of the units mentioned may be permeable, however, where they are cut by recently active faults. Brittle rocks, such as the Mesozoic granodiorites or the more competent Cenozoic volcanic rocks, may sustain fracturing in the general vicinity of faults. In softer sedimentary rocks secondary permeability is more likely to be confined to the actual zone of rupture. Tectonic fracturing is naturally intensified in zones with multiple or intersecting faults. Such zones provide the necessary permeability for the deep circulation of geothermal fluids within otherwise impermeable basement rocks. They are prime targets for deep drilling when near-surface reservoirs are of inadequate temperature.

Most of the ground-water recharge enters permeable volcanic rocks in upland areas, principally to the west where rainfall and permeability (within Pleistocene volcanic rocks) are greatest. The water moves within both confined and unconfined aquifers toward Honey Lake. Most of the ground water originates as precipitation within the surface drainage basin. However, no known groundwater barrier separates the more elevated Secret Valley to the north, hence some water may enter the Honey Lake basin via volcanic aquifers beneath Shaffer Mountain and the Skedaddle Mountains.

The hydrologic interaction between cool ground water recharging the shallow ground-water reservoir and thermal ground water circulating in fractures deep within basement rocks is as problematical as it is important to understand. In volcanic terranes the ground-water flow, because of the stratigraphic and structural complexity and the extreme variability in hydrologic properties of the rocks, may follow tortuous routes between points of origin and destinations. This flow may involve haphazard vertical movements as well as horizontal movements, due to the presence of both overpressured and underpressured aquifers and the existence of vertical passageways (faults and joints) connecting them at various places.

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GEOCHEMISTRY

Geochemical data available for this review of the Wendel-Amedee Hot Springs area are from reports by White and others (1963), White (1967), Hardt and others (1975), Reed (1975), the Bureau of Reclamation (1976a, 1976b), Mariner and others (1976), and a small amount of proprietary information, including correspondence and chemical analyses, provided by GeoProducts. An Environmental Assessment by the Bureau of Land Management (1978) reproduces data from the reports by White and others (1963) and the Bureau of Reclamation. An additional report on the southeastern part of Honey Lake Valley (Hilton, 1963) has been reviewed only briefly as it mostly treats an area outside the one of interest here and, within the area of interest, it duplicates the work by Mariner and others (1976). A small amount of chemical data generated by the U. S. Geological Survey in the early 1900's is not referenced separately here, as it is reproduced by Hardt and others (1975).

The early reports by White and others (1963) and White (1967) include tabulations of several chemical analyses but contain little interpretive discussion which is pertinent to the prediction of temperatures at depth. One analysis tabulated by White (1967) is of water from an 885-foot deep flowing well drilled at Amedee Hot Springs in 1962. This water has a composition equivalent to that of the surface springs.

Hardt and others (1975) tabulated only five complete chemical analyses of groundwaters, which appear also in Reed (1975) and the Bureau of Reclamation (1976a). In addition, to make predictions of temperatures at depth they applied a silica mixing model to Wendel and Amedee Hot Springs, warm waters in Susanville, and several cool groundwaters. Suggested temperatures at depth ranged from 112°C to as high as 255°C.* The authors noted uncertainties about the significance of the suggested temperatures, but failed to consider two of the important assumptions which underlie the application of silica mixing models, as emphasized by Fournier and others (1974) and Fournier and Truesdell

*The data table in which these temperatures are listed is reproduced also in the reports by the Bureau of Reclamation (1976a), and Bureau of Land Management (1978). For the present report the mixing model was re-calculated using Hardt and others data to check for errors, with the discovery that the 255°C temperature is incorrect, and should be 106°C. The correct range of temperatures in the Hardt and others (1975) table is 112°C to 208°C.

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(1974) of the U. S. Geological Survey who developed the technique: First, the technique was developed for application to spring waters which issue at high flow rates at temperatures below boiling. Wendel and Amedee Hot Springs, however, are both boiling and so the silica mixing techniques described by Fournier and Truesdell may not apply to them. Second, the rest of the samples considered by Hardt and others (1975) were well waters, not springs, and therefore, they also are not covered by the model's basic assumptions.

Another respect in which the Hardt and others (1975) report is deficient is that cation temperatures are discounted as inapplicable to the waters of the Honey Lake-Susanville area. These are temperatures of water-rock interaction at depth calculated from the contents of dissolved calcium, potassium and sodium, with occasional application of a correction for dissolved magnesium. It is correct that this geothermometer may not be applicable to cool or slightly warm groundwaters in the basin sediments of Honey Lake Valley, but we strongly disagree with discounting cation temperatures of the thermal waters of the area. The only justification supplied by Hardt and others (1975) for discounting the cation temperatures of the hot waters in the area was "widespread occurrence in this area of basalt," the mineral composition of which was said to not favor application of the cation geothermometer. Other rock types are abundant in the volcanic section, however, and the comment concerning applicability is not correct. Successful use of the cation geothermometer in volcanic areas has been quite well documented, particularly since the mid-1970's.

Reed (1975) concluded that Wendel and Amedee Hot Springs are probably fed by the same source at depth, at a minimum reservoir temperature of at least 140°C (284°F), indicated by quartz solubility. The cation temperatures are slightly lower (see below) and it was reasonable of Reed to favor the higher quartz temperature as indicating the minimum temperature of the reservoir. Since the time of Reed's report, however, extensive experience in applying the silica geothermometer was shown that at temperatures below about 150°C the quartz geothermometer can be less reliable than the chalcedony geothermometer for estimation of temperatures. A correction for high pH water, such as Wendel and Amedee springs, is also available now.

The Bureau of Reclamation (1976a) tabulates only the five analyses of groundwaters, which appear also in Reed (1975) and Hardt and others (1975), but reports consideration of over 232 additional groundwater analyses from throughout Honey Lake basin, mostly obtained from the California Department of Water Resources. Water temperature, conductivity, and silica (quartz) temperature were plotted on maps, with correlations seen between these parameters and major fault systems and geophysical

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resistivity anomalies. The anomalies occur along the north side of Honey Lake valley, and include an area of low resistivity and slightly warm groundwaters up to several miles wide and over ten miles long beneath the Wendel-Amedee area. The silica data are said to suggest that a major part of the Honey Lake-Susanville region is underlain by a low-temperature geothermal reservoir, with rough geographic zonations of inferred temperatures from about 80°C to 120°C, based upon the solubility of quartz. It should be noted, however, that it is risky to draw quantitative conclusions concerning conditions at depth from silica concentrations in cool groundwaters.

The Bureau of Reclamation (1976b) reported nineteen new well and spring water analyses in the western part of Honey Lake Valley sampled specifically for geothermal investigations. Wendel and Amedee Hot Springs were not included, as the report emphasizes the Susanville area. Chemical geothermometers were tabulated and quartz solubility temperatures indicated as preferred. The Bureau of Reclamation report also lists temperatures predicted at depth in the Susanville area based upon silica mixing calculations. The approach used in suggesting the mixing model temperatures is essentially equivalent to that used by Hardt and others (1975). We believe that the results are probably misleading, but have not studied the Susanville data sufficiently to conclude whether mixing there is indicated by other chemical parameters.

Mariner and others (1976) reported chemical analyses of 15 groundwaters from the northeast and east parts of Honey Lake Valley, including the hot springs. Chemical geothermometers were tabulated, and the authors noted the good agreement between the chalcedony and cations geothermometers.

Chemical data from the reports above are reproduced herein as table 1, parts A through E, and a set of proprietary analyses provided by GeoProducts appears as part F. Locations of all the samples are shown on figure 3. In order to reinterpret the data all analyses were initially processed to convert concentrations in milligrams/liter to milliequivalents/liter, which enables a check on ionic balance. Data were found to be of good quality, with differences between total anions and total cations of generally less than about 4%. However, the GeoProducts analyses all showed differences of at least 10%. Two of these are of waters also represented in the other tabulations, and comparisons suggest that sulfate as reported in the GeoProducts data is systematically too high. At least one of these analyses is by Morse Laboratories in Sacramento. Information concerning the origin of the other analyses is not available.

Table 1 - Part A

QUALITY OF WATER FROM WELLS IN SPRINGS IN
HONEY LAKE AREAAnalysis of Waters from Amedee Spring

Species	Concentration in ppm
SiO ₂	96.0
Al ₂ ⁺	0.23
Fe ₃ ⁺	
Fe	0.01
Mn	0.00
Ti	0.16
As	0.02
Ca	16.0
Mg	0.0
Sr	0.0
Ba	0.05
Na	227.0
K	6.8
Li	0.0
NH ₄	0.5
HCO ₃	27.0
CO ₃	10.0
SO ₄	288.0
Cl	160.0
F	4.5
Br	0.2
I	0.1
NO ₂	0.00
NO ₃	0.0
PO ₄	0.40
B	4.1
H ₂ S	0.2
Sb	n.d.
Hg	n.d.

Source: White and others (1963), data also
appear in Bureau of Land Management
(1978).

Table 1 - Part B

QUALITY OF WATER FROM WELLS IN SPRINGS IN
HONEY LAKE AREA

Analysis of Waters from Amedee No. 1
Geothermal Well (885 feet, drilled 1962)*

Species	Concentration in ppm
Ca	16
Mg	0.1
Na	22.8
K	5.1
Li	0.3
HCO ₃	12
CO ₃	18
SO ₄	274
H ₂ S	0.5
Cl	160
B	3.7
TDS (evap. at 180°C)	830
pH	8.9

(Analyst, Robert Schoen, U. S. Geol. Survey)
Source: White, 1967

*This well is at Amedee Hot Springs. Its casing was pulled after drilling, and it now discharges as a vigorously flowing spring. Temperature was 98°C in October 1964.

Table 1 - Part C

QUALITY OF WATER FROM WELLS AND SPRINGS IN HONEY LAKE AREA

Sample Number	Location	Name	Date Sampled	Producing depth (m)	Altitude (m)	Water Temp. (°C)	pH	Conductivity (micromhos/cm)	Discharge (1 min.)
BR-1	NE/NE Sec. 6, T. 29 N., R. 12 E., M.D.	Roosevelt Swimming Pool	7/18/73	90(?)	1,295	35.8	8.01	254	Pumped
BR-2	SE/NE Sec. 6, T. 29 N., R. 12 E., M.D.	Latter Day Saints Church	7/18/73	169-181	1,268	48.8	7.87	1,070	800 Pumped
BR-3	SW/SE Sec. 23, T. 29 N., R. 15 E., M.D.	Wendel Hot Springs	7/17/73	spring	1,231	95.6	8.38	3,340	1,200
BR-4	NE/SW Sec. 30, T. 29 N., R. 16 E., M.D.	Southern Pacific Railroad	7/17/73	93	1,223	28.2	8.33	332	300 Pumped
BR-5	NW/NE Sec. 8, T. 28 N., R. 16 E., M.D.	Amedee Hot Springs	7/17/73	spring	1,219	95.1	8.43	2,860	500

Chemical Constituents (in mg/l)

Sample Number	Cations									Anions			Others		Calculated dissolved solids
	Li	Na	K	Rb	Mg	Ca	Zn	F	Cl	HCO ₃	CO ₃	SO ₄	SiO ₂	B	
BR-1	<0.01	20	3.8	<0.01	3.4	19	0.043	<0.1	2.0	120	1	11	53	<0.02	233
BR-2	0.05	140	4.6	0.02	1.6	24	0.009	1.2	64	68	1	190	62	1.4	558
BR-3	0.12	280	7.5	0.04	<0.1	18	0.015	4.1	190	50	1	360	120	5.5	1,040
BR-4	0.01	58	8.0	0.01	2.2	6.0	<0.005	0.2	17	112	1	32	42	0.22	279
BR-5	0.08	250	5.5	0.02	<0.1	14	<0.005	4.4	160	44	2	300	95	4.0	879

Trace constituents below detection:

Cs <0.1, Mn <0.01, Fe <0.06, Cd <0.01, Co <0.04, Cu <0.02, Ni <0.04, Pb <0.1

Source: Bureau of Reclamation (1976a), data also appear in Reed (1975).

Table 1 - Part D

QUALITY OF WATER FROM WELLS AND SPRINGS IN HONEY LAKE AREA

Sample Number	Water Temperature (°C)	Field Electrical Conductivity $\mu\text{mho/cm}$	pH	Total Dissolved Solids (TDS)	Calcium (Ca)	Potassium (K)	Magnesium (Mg)	Sodium (Na)	Chlorides (Cl)	Sulfate (SO ₄)	Bicarbonate (HCO ₃)	Silica (SiO ₂)	Boron (B)
GTS-1	15.8	285	7.2	230	19	6	8	29	4	18	146	66	0.14
GTS-2	15.8	248	7.6	199	14	7	4	28	4	12	129	58	0.12
GTS-3	61.0	955	7.6	690	32	8	1	177	98	260	36	66	1.88
GTS-4	26.6	600	8.1	446	11	3	2	136	52	148	95	38	1.32
GTS-5	16.8	564	7.7	388	29	5	12	71	41	108	117	52	0.66
GTS-6	22.2	527	7.3	364	21	4	7	81	38	84	132	44	0.78
GTS-7	16.0	205	7.8	138	20	2	9	9	1	8	135	34	0.06
GTS-8	14.5	607	7.8	424	21	6	12	98	19	100	220	52	0.34
GTS-9	15.7	422	7.5	315	22	7	10	51	16	60	150	60	0.14
GTS-10	22.4	890	7.6	634	36	12	23	121	50	240	162	64	1.52
GTS-11	16.7	722	7.9	471	15	5	9	138	57	60	277	60	0.58
GTS-12	17.3	724	8.1	472	16	5	10	137	55	68	276	58	0.58
GTS-13 ¹	14.3	644	7.9	419	21	4	10	118	16	40	350	50	0.24
GTS-14 ²	16.2	1,800	7.5	1,040	63	13	34	233	424	8	354	54	0.22
GTS-15 ³	13.4	765	8.0	508	19	5	9	148	58	64	326	48	0.34
GTS-16 ⁴	18.6	1,550	7.8	950	19	14	15	318	168	8	732	62	0.58
GTS-17 ³	18.2	855	7.9	541	23	8	11	155	82	36	356	60	0.58
GTS-18	14.8	475	8.0	343	10	4	5	100	11	18	297	50	0.40
GTS-19	13.9	712	8.0	488	8	7	4	150	17	24	354	62	0.68

Note: All samples analyzed had Zinc content less than 0.05 mg/l.

¹H₂S odor; ²H₂S odor, milky dissolved gas; ³slight H₂S odor; ⁴strong H₂S odor, greenish color.

Source: Bureau of Reclamation (1976b).

Table 1 - Part E

QUALITY OF WATER FROM WELLS IN SPRINGS IN HONEY LAKE AREA

Sample Number	Springs and wells	Temperature (°C)	pH	concentrations in mg/l											Dissolved Constituents ²
				SiO ₂	Ca	Mg	Na	K	Li	Alka- linity as HCO ₃ ¹	SO ₄	Cl	F	B	
U-1	Shallow well (4 km NW of Wendel Hot Spring)	22.5	9.0	49	2.7	0.2	60	1.9	0.01	130	20	8	0.22	<1.0	272
U-2	Wendel Hot Spring	95.5	8.26	125	20	<.1	280	8.0	.11	53	340	185	4.2	5.6	1,021
U-3	Shallow well at Wendel Hot Spring	94.5	8.78 ³	86	12	<.1	190	5.5	.06	83	220	120	2.9	3.5	723
U-4	Warm spring (2 km NE of Wendel Hot Spring)	27	8.20	34	10	4.3	43	5.5	<.01	118	21	12	.15	<1.0	248
U-5	Observation well (1 km SE of Wendel)	28	8.22	43	6.2	2.2	56	8.5	.01	115	28	18	.15	<1.0	277
U-6	Amedee Hot Springs #1 (north vent)	76	8.49	100	16	<.1	235	5.5	.08	49	280	160	4.6	3.7	853
U-7	Amedee Hot Springs #2 (middle vent)	92	8.41	100	16	<.1	235	6.0	.08	48	290	160	4.6	3.8	863
U-8	Amedee Hot Springs #3 (south vent)	96	8.36	98	15	<.1	235	5.7	.08	57	280	155	4.6	3.8	854
U-9	Artesian well #1	15	9.00	29	4.2	.9	57	2.6	.01	118	22	12	.15	<1.0	246
U-10	Artesian well #2	23	8.44	32	5.3	1.0	47	1.8	<.01	99	20	11	.17	<1.0	217
U-11	Artesian well #3	26.5	8.23	38	5.4	2.0	39	4.6	<.01	97	16	9	.13	<1.0	211
U-12	Irrigation well (CV Ranch)	26	8.12	34	3.3	1.6	43	3.3	<.01	97	17	10	.12	<1.0	209
U-13	Windmill east of Duck Lake	14	8.18	63	27	13	120	9.7	.04	369	28	43	1.5	<1.0	674
U-14	Irrigation well at Duck Lake	18	7.73	54	44	13	25	8.5	.03	267	8	3	.54	<1.0	423
U-15	Hot well at Roosevelt Plunge	33	8.07	57	20	3.1	18	4.2	<.01	122	5	2	<.1	<1.0	231

¹Total alkalinity as bicarbonate.²Dissolved constituents are a total of the major element concentrations in milligrams per liter.³pH measured at 32°C.

Source: Mariner and others (1976).

Table 1 - Part F

QUALITY OF WATER FROM WELLS IN SPRINGS IN HONEY LAKE AREA

	Water Sources on Site						
	GP-1	GP-2	GP-3	GP-4	GP-5	GP-6	GP-7
	Irrigation Well	Old Magma Test Well	Domestic Well	Wendel Hot Springs	So. Pacific Well ¹	Howard Well ²	Ferguson Well ³
Estimated Flow Rate (gpm)	100	700	50	350	95	65	800
Turbidity (NTU)	4.7	NT	NT	NT	NT	NT	NT
pH	7.4	8.0	7.6	7.8	8.0	8.1	8.1
Temperature (°F)	68	210	160	206	65	65	57
<u>Chemical Analysis (ppm)</u>							
Total Dissolved Solids	203.0	887.0	655.0	690.0	223.0	513.0	302.0
Calcium	9.8	15.2	9.4	9.5	5.2	NT	NT
Magnesium	4.25	<1.0	1.4	1.3	2.0	NT	NT
Sodium	40.5	245.0	194.0	199.0	52.0	NT	NT
Potassium	7.6	7.6	5.1	5.2	8.7	NT	NT
Sulphates	50.0	410.0	400.00	350.00	42.0	149.0	120.0
Chloride	20.0	164.0	128.0	127.0	23.2	35.3	25.7
Fluoride	0.4	3.6	3.7	3.8	0.3	NT	NT
Iron	0.08	<0.04	0.08	<0.04	<0.04	NT	NT
Manganese	<0.01	<0.01	0.03	0.02	<0.01	NT	NT
Copper	<0.05	NT	NT	NT	NT	NT	NT
Boron	<0.1	0.4	3.4	3.6	0.3	<0.1	<0.1
Phosphorous	<0.05	NT	NT	NT	NT	NT	NT
Carbonates as CaCO ₃	Nil	Nil	Nil	Nil	Nil	NT	NT
Bicarbonates as CaCO ₃	94.0	53.0	55.0	56.0	96.0	NT	NT
Nitrate-Nitrogen (NO ₃ -N)	NT	1.5	0.4	0.1	0.9	NT	NT

NT = Not Tested

¹So. Pacific R. R. Well is 0.8 miles SE of site.²Howard Well is 0.8 miles east of site.³Ferguson Well is 2 miles east of site.

Source: Provided by GeoProducts, Analysis GP-1 by Morse Laboratories, Sacramento, CA; origin of other analyses not available.

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Figure 4 is a trilinear composition diagram showing 27 analyses of waters from a region within a 4 to 12 mile radius of Wendel and Amedee Hot Springs shown within the outlined area on figure 3. Each sample point is labeled with the number corresponding to its location in figure 3. All of the analyses of table 1 from within this area are included, except for the data from part D, which for the reasons given above, are considered to be unreliable, and the analyses of Amedee Hot Springs in parts A and B, which are essentially identical to analyses of Amedee in other parts of table 1, and which have been left out of figure 4 for the sake of simplicity. Table 2 describes the physical characteristics of the sample points represented on figure 4.

Figure 5 displays the same diagrams as figure 4, but the data points are labeled with the salinities of the samples, rather than the sample number. Figure 5 shows that the groundwaters fall into three groups based upon composition and salinity. One group comprises Na-Ca-Mg-HCO₃ waters with salinities of 4.4 to 6.2 meq/l. These are all cool waters from wells and one spring described as warm but only at 27°C (U-4) located along the northern fringe of the valley. Several of the wells are artesian, and others are distinguished by being located north of the eastern end of the Antelope Mountain Fault. This group of waters represents shallow meteoric recharge into the basin sediments of Honey Lake Valley, and probably also into the deep geothermal system(s) of the valley, through the volcanic rocks to the north and through coarse-grained sediments along the valley border. The waters cluster along a tight linear trend in composition which suggests the mixing of end-members. However, there is no trend in salinities and the variations may instead represent a pattern of volcanic rock composition, plus the effect of cation exchange as waters from the uplands encounter clays in basin sediments.

In contrast to the dilute recharge waters, samples from wells in the interior of Honey Lake Valley scatter over a wide range of composition and have salinities of about 11 to 34 meq/l. The cation compositions of these waters are essentially coincident with the trend of recharge waters, but the anions are much more varied, probably due to dissolution of small, local evaporite deposits enriched variably in Cl, SO₄ and HCO₃ within Pleistocene lake sediments.

The third group of waters is represented by Wendel and Amedee Hot Springs, plus a shallow hot well at Wendel (U-3) which apparently taps a mixture of the spring water and cool recharge. Plots of B, Li and SiO₂ versus Cl indicate that the cool-water fraction in the U-3 well sample may be as high as about 30%, mixed with 70% Wendel Hot Springs water.

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Table 2

Descriptions of groundwater sample locations
in the Wendel-Amedee area.

<u>Sample</u>	<u>Salinity (Total meq/l)</u>	<u>T, °C</u>	<u>Type of water source/comments from sampling data</u>
U-1	5.6	22-1/2	Shallow well
U-2	26.5	95-1/2	Wendel H.S.; 250 gpm
U-3	18.3	94-1/2	Shallow well at Wendel H.S.
U-4	5.6	27	Warm Spr.; flow rate not available
U-5	6.1	28	Observation well, probably the same as BR-4 and GP-5 (see table)
U-6	22.3	76	Amedee H.S.-north)
U-7	22.5	92	Amedee H.S.-middle) 700 gpm total flow
U-8	22.2	96	Amedee H.S.-south)
U-9	5.6	15	Artesian well
U-10	4.8	23	Artesian well
U-11	4.4	26-1/2	Artesian well
U-12	4.5	26	Irrigation well
BR-3	27.0	95-1/2	Wendel H.S.; 1,2-0 lpm
BR-4	6.2	28	Southern Pacific RR well. Probably the same as U-5 and GP-5 (see table); 300 lpm pumped, 93 m producing depth
BR-5	23.2	95	Amedee H.S.; 500 lpm
GTS-8	12.7	14-1/2	Irrigation well
GTS-9	8.5	15-1/2	Irrigation well
GTS-10	18.3	22-1/2	Irrigation well
GTS-11	15.0	16-1/2	Irrigation well

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Table 2 (continued)

<u>Sample</u>	<u>Salinity (Total meq/l)</u>	<u>T, °C</u>	<u>Type of water source/comments from sampling data</u>
GTS-12	15.2	17-1/2	Irrigation well
GTS-13	14.1	14-1/2	Irrigation well, H ₂ S odor
GTS-14	34.3	16	Irrigation well, H ₂ S odor, milky dissolved gas , Na-Cl rich.
GTS-15	16.6	13-1/2	Irrigation well, slight H ₂ S odor.
GTS-16	33.3	18-1/2	Irrigation well, strong H ₂ S odor, greenish color, dissolved gas, Na-Cl rich.
GTS-17	17.0	18	Irrigation well, slight H ₂ S odor.
GTS-18	10.9	15	Irrigation well.
GTS-19	14.2	14	Irrigation well.

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Key

Example	Sample no.
.17	U-17
Δ^8	GTS-8
$\square^3$	BR-3

Analyses of U-, GTS-, and BR- series appear in Table

FIGURE 4. Trilinear composition diagram showing sample numbers of waters from springs and wells in the Wendel-Amedee area.

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- 18.3
• Sample composition point with total salinity, meq/l
• = U- series, Δ = GTS-, □ = BR-

○ Line enclosing dilute meteoric recharge waters, salinated 4.4 to 6.2 meq/l

FIGURE 5. Trilinear composition diagram showing salinity of waters from springs and wells in the Wendel-Amedee area.

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The waters of Wendel and Amedee Hot Springs are notable for having nearly the same composition when relative abundances of the major ions are compared, but at different absolute concentrations. Figure 5 shows that ratios of the major ions in each spring are virtually identical. Table 3, on the other hand, presents averaged compositions from several analyses of each spring, and shows that the water of Wendel Hot Spring is, on average, 20% more concentrated than that of Amedee Hot Spring. Individual species are 4% to 44% more concentrated on Wendel, but 7 of 12 parameters fall in the range 17% to 25%. Only F is less concentrated in Wendel than in Amedee, by about 9%. Although table 3 represents only recent analyses of the two hot springs, their composition as reported by White (1963), White and others (1967) and Waring (1915, reproduced in Hardt and others, 1975) is essentially the same as that currently observed.

We believe that the compositional similarities between Wendel and Amedee Hot Springs outweigh the differences and indicate that the two springs are fed by the same reservoir. Reed (1975) reached the same conclusion. The differences can be explained by minor inhomogeneities in reservoir-rock composition and mixing of the Amedee water with about 20% dilute near-surface water.

Table 4 shows rock-water equilibration temperatures calculated for Wendel and Amedee hot springs. Two silica temperatures are shown, one calculated using measured silica concentrations and a second with the measured silica corrected for ionization due to the water's high pH. The pH correction is a relatively new development (Muffler, 1979), and was not considered in previous studies of the geothermal potential of the area. Since the springs are boiling, the measured pH may be higher than pH at depth due to loss of CO₂ from the water during the boiling process. Consequently, the pH corrections of about -9°C to -12°C which appear in table 4 should be regarded as the largest likely to be necessary. True corrections may be smaller, even insignificant.

Previous discussions of the thermal waters of Honey Lake Valley have chosen the quartz, conductive temperature as the most reliable, and this permits estimation of a minimum reservoir temperature of 137°C (279°F) to 149°C (300°F) at Wendel, slightly lower at Amedee probably due to mixing. However, at temperatures below 150°C (302°F) the chalcedony temperature can be in closer agreement than the quartz temperature with directly measured reservoir temperature.

The cation temperatures of the two springs fall in a range from 96°C to 127°C (205°F to 261°F). Both springs have cation compositions which produce a borderline choice between the two possible forms of the cation geothermometer, with the factor $\beta = 1/3$ or $\beta = 4/3$.

Table 3. CHEMICAL ANALYSES OF WENDEL AND AMEDEE HOT SPRINGS

Name	No. in Table 1	T°C	pH	mg/l												meq/l*				Flow, gpm	Wt. Ratio Na/K
				Ca	Mg	Na	K	Li	Total Alk. as HCO ₃	SO ₄	Cl	B	F	SiO ₂	TDS	Σ +	Σ -	Σ+ + Σ-	% Dif.		
WENDEL HOT SPRING	U-2	95.5	8.26	20	<.1	280	8.0	0.11	53	340	185	5.6	4.2	125	1,021	13.38	13.16	26.54	.81	250	
	BR-3	95.5	8.38	18	<.1	280	7.5	0.12	52	360	190	5.5	4.1	120	1,040	13.27	13.71	26.97	-1.63	317	
	Average	95.5	8.32	19	<.1	280	7.75	0.115	52.5	350	187.5	5.55	4.15	122.5	1,031	13.33	13.44	26.76	-.43	-	36.1
AMEDEE HOT SPRING	U-6	76	8.49	16	<.1	235	5.5	0.08	49	280	160	3.7	4.6	100	853	11.16	11.14	22.30	.06	700	
	U-7	92	8.41	16	<.1	235	6.0	0.08	48	290	160	3.8	4.6	100	863	11.17	11.34	22.51	-.73		
	U-8	96	8.36	15	<.1	235	5.7	0.08	57	280	155	3.8	4.6	98	854	11.11	11.13	22.25	-.09		
	BR-5	95	8.43	14	<.1	250	5.5	0.08	48	300	160	4.0	4.4	95	879	11.71	11.48	23.19	1.00	130	
	Average	-	8.42	15.3	<.1	238.8	5.68	0.08	50.5	287.5	158.8	3.83	4.55	98.3	862.3	11.29	11.27	22.56	.08		42.0
RATIO																					
AVE. WENDEL		-	-	1.25	-	1.17	1.37	1.44	1.04	1.22	1.18	1.45	.912	1.25	1.20	-	-	1.19	-		
AVE. AMEDEE																					

Average ratio = 1.22

*Σ- does not include F⁻. % Dif. = [(Σ+)-(Σ-)]/[(Σ+)+(Σ-)]

Table 4. CHEMICAL GEOTHERMOMETRY OF WENDEL AND AMEDEE HOT SPRINGS.

	T°C SiO ₂ ¹						$\sqrt{\text{Ca}/\text{Na}}$	T°C Na-K-Ca ²		
	QTZC	QTZA	β CRIS	α CRIS	CHAL	AMOR		$\beta=4/3$	$\beta=1/3$	Choice
WENDEL HOT SPRING	$\frac{149}{137}$	$\frac{142}{133}$	$\frac{49}{38}$	$\frac{98}{89}$	$\frac{123}{111}$	$\frac{27}{17}$	1.79	104	127	127
AMEDEE HOT SPRING	$\frac{136}{123}$	$\frac{132}{121}$	$\frac{37}{24}$	$\frac{86}{74}$	$\frac{109}{95}$	$\frac{16}{4}$	1.88	96	120	96

Key: QTZC = quartz, conductive
 QTZA = quartz, adiabatic
 β CRIS = β cristobalite
 α CRIS = α cristobalite
 CHAL = chalcedony
 AMOR = amorphous silica

All geothermometers from Fournier (1978).

Note: ¹Upper silica temperature is that calculated from average concentration of SiO₂ in table 3. Lower silica temperature is that calculated after correction of concentration of SiO₂ for high pH, using average pH values in table 3 (see text).

²The cation geothermometer has two forms, with a factor β equal to 1/3 or 4/3. The favored temperature calculation here listed as choice depends upon the temperature for each value of β and the factor $\sqrt{\text{Ca}/\text{Na}}$. Rules for the selection are given by Fournier (1968).

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For this reason, a choice between the two alternatives has a high uncertainty in each case, and the full range of cation temperatures must be regarded as reasonable.

Cation temperatures can be biased upwards when applied to thermal waters which lose calcium by precipitation of calcite during flow upwards from a zone of equilibration at depth, or at the surface before a sample is collected. There are tufa mounds near Wendel Hot Springs which indicate some calcium precipitation. Waring (1915, reproduced in Hardt and others, 1975) reported evidence of active deposition at Wendel, and we have received other (verbal) reports that deposition is currently occurring. Calculations of the expected solubility of carbonate in each spring water indicate that both are undersaturated with calcite at 25°C; calcium in each would have to be about twice the detected level for saturation at this temperature. On this basis, it seems unlikely that either hot spring is currently depositing carbonate. However, the waters at depth and reservoir temperatures are most likely saturated with calcite, and there is a pressure effect upon the solubility which makes it possible for calcite deposition to occur when there is a rapid drop in confining pressure with little to no change in temperature. As the springs have rapid flow rates, the difference between orifice temperature and the temperatures at depth may be small enough that this pressure effect is causing some deposition from the waters to occur. Data for quantitative calculations are not available. Whether any deposition occurs in the subsurface is moot, but it seems that if large amounts of calcite were being deposited the cation temperatures of the waters would be anomalously high relative to the silica temperatures, which is not the case.

If the hot spring waters are not currently depositing carbonate, the tufa deposits near the springs may have formed at a time when the spring waters were of a different composition, or when mixing of the hot spring waters with some other ground or lake water produced oversaturated solutions. Alternatively, the tufa could be or have been deposited by an altogether different ground water, not sampled.

The geochemical evidence suggests that temperatures within the Wendel-Amedee system range between 250°F and 270°F and might be as high as 300°F. This estimate is similar to the 259°F ± 13°F estimate of the U. S. Geological Survey (Muffler, 1979) from geochemical data.

The data discussed above suggest a geochemical model for Wendel and Amedee Hot Springs in which the two springs are fed by the same deep reservoir. Waters of meteoric origin have chemically equilibrated with volcanic rocks at a depth of 3,000 to 5,000 feet which overlie granitic basement. The equilibration temperature beneath Wendel and Amedee Hot Springs reflects a gradient of about 4°F per 100 feet which

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probably exceeds the regional conductive gradient; therefore the reservoir must be fed by a hydrothermal circulation system. Such a system very possibly would contain water warmer than 259°F. The lower salinity of the Amedee water relative to Wendel is due to mixing with dilute groundwater in that portion of the reservoir, possibly followed by some degree of chemical re-equilibration. Slight local differences in rock composition and in the composition of the groundwater would be responsible for irregularities in the concentration ratios between Wendel and Amedee, for different species, but different reservoir temperatures may also influence this. Alternatively, the Wendel water may in part owe its greater salinity to subsurface boiling and consequent loss of steam.

There is nothing in this model to require that the reservoir feeding the two springs is a single, hydrologically continuous system. Conceivably, there may exist separate intermediate-level reservoirs, each supplied with water from the same deep hydrothermal source, but the similarities between the waters argues against this and suggests instead that there is a single reservoir. Internal communication may be somewhat limited, but conditions in all parts probably are similar and the average composition of aquifer rocks everywhere about the same.

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GEOPHYSICS

Early Investigations

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

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

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

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

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

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Seismology

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

Investigations Conducted on Behalf of GeoProducts

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

Gravity and Magnetic Surveys

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

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

EXPLANATION

- Station location
- Gravity contour (contour interval = 1 mgal). True value = plotted value + 1,000 mgal.
- Fault (dashed where uncertain). Bar and ball on downthrown side.

FIGURE 6.

Bouguer gravity map and fault interpretation.

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

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

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

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

Evaluation of Electromagnetic Soundings

With regard to the EM data, it is our opinion that too much interpretation has been made of data that inherently contradicts the assumptions used in the interpretation. Specifically, it is clear that there are major electrical inhomogeneities in the area but it is very doubtful that the techniques used could resolve the vertical faults

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hypothesized in this interpretation. This is because the interpretation is based on one dimensional models, whereas the data clearly show that the actual configuration is not one dimensional. To reconcile two different vertical sections that are a few kilometers apart one must, with this approach, insert a fault. There is a fault between almost every receiver station on the N-S profile of soundings from source 5 (Figure 14, Electrodyne Surveys, 1979, Vol. I) and large numbers of faults are located on the basis of the ESP soundings on the EW profile lines (e.g., Figure 46, Electrodyne Surveys, 1979, Vol. I).

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

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

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

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

Error bars are not included on the apparent-resistivity estimates. The data accuracy would have to be very good to allow a section as detailed as that of sounding 5.09 (pages 391-392, Electrodyne Surveys, 1979, Vol. II) to be interpreted from the data shown. Similarly the resolution

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of zones only 2 ohm meters different in resistivity in the ESP profiles would be very difficult without very high instrument accuracy.

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

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

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

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

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TEMPERATURE-GRADIENT DATA

The first study of the subsurface temperature distribution in the Honey Lake area was undertaken by Geothermal Surveys, Inc., on behalf of Gulf Oil Co. Temperatures were measured in the bottoms of some 47 back-filled holes, 10-feet deep, located on approximate one-mile grid centers around Wendel and Amedee Hot Springs. Being well within the depth of the annual temperature fluctuations, temperatures at 10-foot depths yield questionable information about the steady-state temperature conditions at greater depth. Under ideal conditions the shallow temperatures may be sufficient to locate major anomalies, but local surface condition (soil rugosity, vegetation cover, surface orientation, and microclimate effects) and subsurface conditions (porosity, permeability, thermal conductivity, and depth to the water table) greatly affect the shallow temperature distribution.

Temperature data are available from eight drill holes in the Wendel-Amedee area. Locations of these holes are shown on plate 1. Two of the holes, the Magma well (Wendel #1) and Mapes #1, are shallow production wells used to supply thermal water for heating the Geo-Products hydroponics greenhouses. Boiling or near-boiling water is pumped from aquifers at about 100 and 200 feet in depth. Temperature curves for these wells (figure 7) are governed by natural convective processes and by recent pumping, details of which have not been recorded. The data are of little use in understanding the deeper geothermal regime and are not discussed further in this report.

Four temperature-gradient holes were drilled in spring, 1980, by GeoProducts, Inc., to depths of 480, 604, 1,161 and 1,325 feet. Locations are shown on plate 1. The two deeper holes were lined with 4-1/2-inch tubing to total depth. No attempt was made to back-fill the annulus with cement or cuttings. The shallower holes were left open. Later temperature logging could not reach total depth in these, probably because of wall collapse and bridging in the bore hole. Operation logs and lithologic logs were prepared by an on-site geologist. One hole (2-TG) encountered severe lost-circulation problems at several horizons; no such indications of permeability were encountered in the other wells. Temperature logging was performed by Agnew and Sweet Wireline Service on July 1, 1980, using an Amerada-type down-hole recording instrument with an element range of 45° to 232°F. Traverses were made from 20 feet to the total logging depth at a rate of 20 feet/minute. Temperature profiles for the GeoProducts holes are shown in figure 7, lithologic columns in figure 8.

Stabilized temperature data has been supplied by Gulf for its well, Honey Lake No. 2-ST, a 5,056-foot sidetrack of Honey Lake

FIGURE 7. Temperature vs. depth in GeoProducts production wells and temperature gradient holes at Wendel.

FIGURE 8. Lithologic columns for GeoProducts temperature gradient holes.

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No. 2, which was drilled in 1973 a mile southeast of Wendel Hot Springs. Also available for that well were mud, acoustic, and fracture-finder logs. The hole was cased with 9-5/8-inch pipe at 557 feet, leaving 4,500 feet of 7-7/8-inch open hole below. Warm water at 90°F was reported to have flowed into the well at 1,100 feet, though no mention of this is made in the mud log. After a complete circulation loss at 4,171 feet, plugs were set in both permeable intervals. In drilling out the upper plug the hole was accidentally sidetracked, and had to be redrilled to total depth. Circulation was lost at an identical depth in the redrill, but was partially regained with lost-circulation material so that drilling could proceed.

Drilling was suspended on August 10, and temperature logs were acquired on August 29, October 15, October 16, 1973, and November 4, 1975. No flow-test records were kept by Gulf, but a note on the October 16, 1973 temperature log indicates that the well had been flowing for ±20 hours prior to logging. The temperature logs are shown in figure 9 along with mud flow-line temperatures and an interpretation of vague lithologic descriptions in the mud log.

Near Amedee Hot Springs, Gulf drilled another geothermal test, Honey Lake #1-ST, to 5,033 feet. No indications of formation permeability were observed during drilling of this hole. Temperatures measured 8 hours after cessation of drilling ranged as high as 230°F at 5,000 feet. The hole was immediately plugged and abandoned; therefore the stabilized temperatures must be conjectured. Based on experience with similar wells, we estimate conservatively that the bottom-hole equilibrium temperature is at least 20% higher than the measured temperature, or 275°F. The section drilled was similar to that in Honey Lake #2-ST, except that granitic rocks were not penetrated. A radiometric age of 33 m.y. for volcanic cuttings from the bottom of the hole implies, however, "Sierran" volcanic basement was reached.

Temperature profiles for GeoProducts gradient holes and Gulf's Honey Lake #2-ST test show effects of subsurface fluid convection. Shallow flow of warm water must be invoked to explain the high surface-temperature projections of linear gradients below the depth of annual variations (about 70 feet). Under purely conductive heat-flow conditions temperature gradients project to the mean annual air temperature, probably less than 50°F in this area. For all of the GeoProducts holes (and the Gulf well) surface projections are in the range 65° to 80°F. This implies that water in the shallowest ground-water aquifers is being warmed by infiltration of thermal water or by conductive heat transfer elsewhere. Shallow thermal groundwater presence can be deduced also from the 81°F isothermal zone in the upper 100 feet of wells 1-TG and 2-TG.

The temperature profile for hole 5-TG is clearly not representative of the natural temperature distribution at that location. Sudden

FIGURE 9. Temperature and lithologic log of Gulf well Honey Lake No. 2-ST.

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jumps in temperature may occur where aquifers have only recently become transmissive to fluids. However, in this case the aquifer temperature is in disequilibrium with rocks both above and below, and the aquifer shows up in the profile as a temperature "spike." "Stair-step" gradients are typically caused by vertical movement of groundwater within the well-bore between aquifers whose difference in fluid pressure differs from that due to the normal hydrostatic gradient. This establishes vertical hydraulic gradients which cause the fluid movement. This phenomenon has led heat-flow analysts at the U. S. Geological Survey to adapt a policy of cementing tubing in gradient holes. At the very least, the annulus around the tubing should be back-filled with cuttings.

In the case of hole 5-TG water is moving downward in the well-bore from a volcanic aquifer around 540 feet to another volcanic aquifer between 1,120 and 1,140 feet. Permeability within these aquifers is low enough that no mud losses were noted during drilling. Fluid movement is slow, and some warming takes place during the descent.

Between 540 and 1,140 feet the natural gradient (i.e., undisturbed by wellbore fluid movement) apparently decreases from 6.6 to about 4.1°F/100 feet. The decrease probably is controlled by temperatures in low-permeability thermal aquifers. A 50% increase in thermal conductivity in this interval would have the same effect, but such an increase is not justified by the lithologic column for the hole (figure 8).

Vertical hydraulic gradients probably account also for the less well defined stair-step character of the gradient for hole 2-TG. This is supported by (1) known permeability in the lower aquifer area (demonstrated by mud losses during drilling) and (2) the coincidence of projections of gradient segments from the upper and lower parts of the hole, which implies former continuity.

A large isothermal interval in the temperature logs for Gulf's Honey Lake No. 2-ST test shows that primary permeability for 230°F thermal water is associated with volcanic rocks in the lower one-third of the valley-fill sequence. The hole had nearly equilibrated after five days of stabilization time, but the permeable horizon at 4,175 feet which was cooled by the infiltration of large volumes of mud from both the original hole and the redrill took several months to re-establish equilibrium temperatures. There is no indication of permeability below 4,500 in rocks which, from sketchy descriptions in the mud log, appear to be silicic pyroclastic rocks, possibly "Sierran" volcanics. Beneath these, below 4,800 feet, are granitic rocks of the Sierra Nevada batholith.

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Measured conductive gradients within the impermeable basement rocks (figure 10) cannot be reliably projected to much greater depth for several reasons: (1) the shallow depth of penetration, which does not allow reasonable gradient averaging, (2) lithologic variation within the bedrock interval and consequent variation in thermal conductivity within the bedrock interval, and (3) the likelihood that the upper portion of the granitic rock is weathered or hydrothermally altered and therefore possesses uncharacteristically low thermal conductivity. The equilibrium gradient probably is lower in the granitic rocks than in the overlying tuffs(?), possibly by a factor of 2 as shown in the gradients for October 15 and 16. A reasonable estimate of deeper gradients might be 1.5 to 2.0°F/100 feet, based on the accumulated data from the bottom of Honey Lake No. 2-ST.

Assuming a reasonable thermal conductivity of 7.5 TCU for the granitic rocks, these gradients calculate to heat flows of 2.0 to 2.7 HFU, equal to or slightly higher than regional averages for this part of California (Sass and others, 1976). By projection, a temperature of 250°F would be reached somewhere between 5,350 feet and 5,950 feet, depending on which temperature curve and which deep gradient is used, and a temperature of 300°F between 7,850 and 9,250 feet. The existence of geothermal fluid at these levels is not necessarily implied.

The upper part of the temperature profile for the Gulf well reflects essentially conductive heat flow through the volcanic and sedimentary section, apart from the probable convective disturbance in the very shallow part of the hole which was mentioned earlier. The change in gradient between 600 and 700 feet (figure 9) may be caused by wellbore convection as in gradient hole #5-GT, except that pressurized warm water entering the hole at around 1,100 feet appears to be moving upward to underpressured sand aquifers beneath the casing shoe.

The gradual curvature of the temperature profile between 1,200 feet and the top of the isothermal zone at around 3,000 feet may be controlled by (1) a gradual upward decrease in the temperature of thermal aquifers, (2) progressive lateral retreat of a nearly isothermal, high-angle heat source (such as a fault zone), or (3) a combination of these factors. Because of the demonstrated potential for vertical hydraulic gradients between aquifers it is dangerous to analyze the curve in too much detail.

Because of the widespread permeability in the subsurface and the abundance of fluid movements at numerous levels within the aquifer system, near-surface temperature gradients cannot be modeled quantitatively. This makes it difficult to theorize about the location of major elements of the geothermal system, such as the location of deep conduits.

FIGURE 10. Conductive gradients within impermeable basement rocks, Gulf Honey Lake No. 2-ST.

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The temperature curve for Honey Lake #2-ST demonstrates the existence of a 230°F reservoir within a 1,300-foot section of volcanic rocks. This fluid may be heated (1) by direct conduction from below, (2) by deep circulation at this location, or (3) by deep circulation elsewhere in the system. The first case can be rejected on the basis of the unreasonably high crustal heat flow (about 4 HFU) that would be required to maintain the observed gradients. The second case would imply that the well intersected a deep-circulation conduit, probably a fault. This is possible, but it reduces the potential of finding significantly hotter water at drillable depth in the vicinity of this well; since the gradient within the convecting fluid probably is less than 1/2°F/100 feet, based on the amount of cooling that takes place between the reservoir and the shallow thermal aquifers near Wendel Hot Springs.

The most attractive situation, and the most likely, given the apparent widespread occurrence of 230+°F water within the Tertiary section, is that deep circulation takes place elsewhere and that the fluid flows laterally within the volcanic aquifers. Since some cooling would have taken place en route to the site of Honey Lake #2-ST, it is likely that temperatures near the deep conduits are higher. The exploration problem then is to locate the areas where deep circulation is taking place. Existing data must be carefully integrated with geologic and hydrologic interpretations in the selection of a plausible site for deep drilling.

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FLUID QUALITY

The chemistry of Wendel Hot Springs and Amedee Hot Springs has been discussed in the subsection on geochemistry of the section on geothermal exploration, above. Table 3 presents compositions of the spring waters. The water of each spring appears to have equilibrated, probably in an intermediate-depth reservoir, at a temperature only slightly above the 95°C (boiling) orifice temperature, possibly at no more than about 125°C for Wendel and 115°C for Amedee, although higher temperatures may exist locally, and particularly deeper, within the hydrothermal system or systems. The essential absence of Mg from each spring water implies that neither one mixes with dilute recharge (very likely to contain Mg) after equilibration with surrounding rocks and during ascent to the surface. The good agreement between the silica (chalcedony) and cation temperatures and the high flow rates also suggest that little cooling or chemical re-equilibration has taken place during ascent to the surface. Thus, the compositions listed in Table 3 are a guide to the expected quality of hot water to be encountered in drilling: a Na-SO₄-Cl-HCO₃ fluid of low to moderate salinity (TDS c. 800-1,000 mg/l).

Gases which issue at Wendel and Amedee Hot Springs are mostly nitrogen (N₂) (about 96% and 88%, respectively). At each spring small amounts of methane (CH₄), oxygen (O₂) and carbon dioxide (CO₂) make up the rest, with a trace of hydrogen reported also at Amedee Hot Spring. These gases no doubt entered the spring system dissolved in meteoric recharge, and total non-condensable gases in the reservoir fluid is unlikely to exceed a few percent.

The partial pressure of CO₂ in the spring waters at 25°C is very low, about that in the atmosphere. This fact, plus the relatively low Ca and HCO₃ with high pH results in the waters being undersaturated with calcite (calcium carbonate) at 25°C, by a factor of about two, as discussed in the section on exploration geochemistry. The absence of CO₂ from the waters means that they are unlikely to become oversaturated upon boiling or cooling at atmospheric pressure, but they may become oversaturated as the result of a rapid decrease in pressure with little to no temperature change. Formation of calcite scale is unlikely to be a problem in the production or utilization of these waters, but this is not a certainty, particularly in light of reports of deposition of carbonate at the surface. The question can be treated more definitively only with collection of water samples from deep wells, better knowledge of conditions at depth, and well tests.

Silica in the waters is much lower than concentration levels which are likely to produce silica scale upon cooling. Indeed, the

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spring waters become scarcely saturated with amorphous silica even at temperatures as low as 20°C to 25°C.

Data concerning hazardous trace and minor elements in the spring waters are somewhat scarce. Boron at about 4 to 6 mg/l is not toxic to humans or animals, but exceeds the concentration tolerated by virtually all agricultural crop plants (maximum 1 to 3 mg/l, depending upon the plants). F(luoride) at 4 to 5 mg/l exceeds permissible limits in drinking water (about 1 mg/l). Iron and manganese are present in only trace amounts (table 1, part D). Analyses of arsenic and mercury are not available.

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SUMMARY AND DISCUSSION

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

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

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

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

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

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

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

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

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

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

FIGURE II. NW-SE cross section through the Wendel-Amedee geothermal area, showing proposed well locations.
 (Line of cross section shown on plate I.)

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

1. Near-surface thermal activity is concentrated on the northern edge of the basin. Steep faults at the western and south-eastern basin margins and within the basin do not carry thermal fluids to the surface.
2. The potential volcanic heat sources of the Modoc plateau are located entirely to the north and northeast of the basin.
3. The regional pattern of groundwater movement is from the volcanic uplands toward lower elevations in the Honey Lake basin.

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

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

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

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

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the latter difference.

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

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

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

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DRILL-SITE RECOMMENDATIONS

Production Wells

Based on our model for the Wendel-Amedee geothermal system developed in the preceding section, we propose drilling of a deep test in the center of the SE/4 of Section 32, T. 29 N., R. 16 E. (site AM, plate 1), approximately 2 miles north of Amedee Hot Springs. The objective of this well would be to produce 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 significantly higher than those encountered by Honey Lake #2-ST (perhaps 25° to 40°F higher, based on bottom-hole temperature estimates for Honey Lake #1-ST) are likely to be found. Subject to logistic considerations, alternate locations might be permitted on lease blocks immediately to the north or south.

Permitted depth and contracted rig capacity for this hole should be at least 6,000 feet, though production is expected to be from volcanic rocks at a depth of 3,500 to 5,000 feet. Granitic basement is believed to occur between 5,000 and 5,500 feet. The additional drilling capacity is desirable due to the uncertainties in the geologic section and in the subsurface temperature distribution. Provision should be made for a sidetrack if the original hole fails to find adequate permeability.

The drill site has been located in the center of the quarter section to allow for maximum flexibility in directional drilling in case of excessive hole deviation or in the event a sidetrack is necessary. It is situated on relatively flat-lying ground within 1/2 mile of an existing road. Make-up water for drilling can be piped or trucked from existing sources or obtained from a nearby shallow water well drilled specifically for that purpose. In either case, negotiations with surface land owners or users may be necessary.

Selection of a drilling site in the Wendel area hinges on the decision of whether to drill on the east or west side of the Wendel Springs fracture system. Drilling on the east side takes advantage of the higher temperature gradient measured on that side, whereas drilling on the west side offers the possibility of placing the bottom of the hole close to a basement fracture from which high-temperature fluid may be entering the reservoir.

Site WEN-E, located on the east side of the fracture system in the northern part of Section 24, T. 29 W., R. 15 E., takes 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 is chosen so that the hole will approach, or perhaps intersect, the fracture near the planned depth of 5,000 feet.

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Specifications for both wells are identical. Basement is anticipated at about 4,500 feet, as in Honey Lake #2-ST. Good access is provided by the paved road between Wendel and U. S. Highway 395. Water for drilling may be supplied by wells already operated by Geo-Products. Again, rig capacity and permit depths of at least 6,000 feet should be sought in order to accommodate unexpected conditions.

Injection Wells

For the re-injection of spent geothermal fluids it is recommended that the existing Gulf well (#2-ST) be used, if possible. The location in Section 25, T. 29 N., R. 15 E. makes it particularly suitable for injection of fluids produced by either WEN-E or WEN-W, which are located 1 to 1-1/2 miles north and 30 to 35 feet higher in elevation. For site AM, located 3 miles distant and on a separate lease block, it may prove more practical to drill a separate injection well. A possible location (IW) is shown on plate 1, 0.9 mile to the west in the southeast corner of Section 31, T. 29 N., R. 16 E.

The selection of an injection site is as much an engineering problem as it is a geological one. Due to potential artesian conditions within the reservoir, it is problematical whether or not re-injection can be accomplished by gravity feeding alone. Pumping may be necessary. If so, the advantage of a downhill location for the injection well is not as great. However, care should be taken to locate injection wells so that injected fluids are not recycled through the system, as this will certainly tend to long-term cooling of the reservoir. Therefore, considerable attention should be given to determining the direction of fluid movement within the reservoir. This knowledge will also aid in future exploration should it be necessary to locate other wells.

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WELL-DRILLING RECOMMENDATIONS

Lithologic and Temperature Projections

Little difference is expected in the general character of the geologic sections or temperature profiles between the recommended locations and Honey Lake #2-ST (figure 9). Basement depths are expected to be between 4,500 and 5,000 feet for all locations. Basement probably consists of an upper thickness of Miocene to Oligocene volcanic rocks underlain by Mesozoic granitic intrusives. Overlying Plio-Pleistocene volcanic and sedimentary deposits can be expected to have little lateral continuity, making correlation difficult. Based on drilling in the area to date, the upper 1,000 feet probably contain a greater average proportion of clay-rich sediments than the underlying section, which is made up predominantly of volcanic flows and tuffs. However, the details of the section will vary greatly over short distances laterally. Reservoir temperatures may be higher (possibly as high as 300°F), but the reservoir is anticipated at about the same depth as in Honey Lake #2-ST (3,000 feet), and the temperature profile should be similar in shape. Super-hydrostatic pressures may exist within the reservoir.

Primary drilling problems anticipated are lost mud circulation and sloughing of the borehole wall due to structural incompetence in some beds. Mud losses in rocks above the reservoir can be dealt with by using mud additives to reduce formation permeability (lost-circulation material) or, in extreme cases, cementing permeable zones. Within the reservoir, however, care must be taken to insure that permeability is not damaged. In order to continue drilling in the face of massive lost circulation, it may be necessary to change the drilling fluid from mud to water, air, or foam, and/or drill ahead with no returns. Decisions of this type must be tailored to the specific problem at hand, since many variables, such as formation competence, permeability, casing history, and rig capacity must be considered.

Recommendations for Logging and Supervision

Because on-site decisions depend so heavily on estimations of temperature relations in the rock penetrated, a comprehensive program of temperature logging should be planned in advance. This should include:

1. accurate and continuous monitoring of mud temperatures during drilling,
2. measurement of bottom-hole temperatures by means of maximum-reading thermometers attached to down-hole instruments such as those used for directional surveys,

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3. occasional monitoring of temperature build-up within the hole for estimation of equilibrium temperatures,
4. complete temperature logging when total depth has been reached, or at other times when it is deemed necessary. In addition, a complete temperature log should be acquired after a lengthy stabilization period (at least one month), and immediately following any flow test.

We have found in the past that on-site decision making during the drilling of geothermal wells is seriously hampered by the lack of reasonable indications of equilibrium temperature anywhere in the hole. Without some such indication there is no constraint on speculations about what thermal conditions lie ahead. This often leads to unnecessarily protracted drilling at high cost to the operator. It is for this reason that we have recommended that drilling be suspended at strategic depths for 8 to 12 hours to measure temperature build-up. With the build-up curves and good drilling records, equilibrium temperatures can be estimated reasonably well. Tentatively, such suspensions should be scheduled at the 3,000-foot casing point and 4,500 feet, subject to modification in the light of the drilling experience. Lengthy rig down-times can be utilized for this purpose at minimal cost to the operator.

Down-hole geophysical logs, to be run at total depth and, if possible, at the casing depth for the 9-5/8-inch casing, should be compensated for borehole conditions in order to permit quantitative interpretation. The recommended log suite consists of:

1. dual induction laterolog 8 (DIL) or equivalent, with spontaneous potential (SP) log;
2. compensated density-compensated neutron log (FDC-CNL) or equivalent, with gamma-ray (GR) and caliper logs.

(The names given here are trade names of Schlumberger. Equivalent logs are offered under different names by other logging companies.) A borehole-compensated sonic log could also be useful for reservoir analysis and certainly should be run if any seismic exploration work is contemplated in the future.

Minimal on-site drilling records must include (1) mud temperatures in and out of the hole, (2) mud-pit volume, and (3) penetration rate. These functions should be monitored by continuous-recording equipment with both time and depth clearly correlated. Penetration should be monitored by a Geolograph-type recorder. Continuous analysis for gases (preferably CO₂ and H₂S) is also suggested as a potentially useful source of data to help delineate formation changes, fracture zones, and possible production intervals.

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Instruments supplied by the drilling contractor to monitor some of these functions for drilling purposes may not be adequate for use in making technical evaluations while drilling is in progress, due to insensitivity, poor calibration, or unsuitable recording format. It may be advisable to duplicate some of these functions with auxilliary equipment more suited to the needs of the on-site geologist. Recording equipment, whose use is shared by the geologist and drilling personnel, should be located where it can be easily accessed by both without interfering with normal rig operations.

Supervising personnel on location should consist of a drilling engineer and a geologist. The drilling engineer would be responsible for coordinating all drilling activities, formulating drilling strategies, securing necessary supplies and services, keeping well-cost records, and otherwise making sure that the hole is properly drilled, cased, and completed. The geologist would be charged with overseeing the acquisition and compilation of technical data, making detailed lithologic logs and geological interpretations, predicting subsurface conditions, specifying drilling targets, correlating down-hole and surface geology, recommending and analyzing temperature logs, interpreting down-hole geophysical logs, and generally insuring that all technical information is assembled, integrated, and interpreted. The drilling engineer and the geologist would work closely together, in consultation with appropriate executive personnel within GeoProducts and funding government agencies, to formulate drilling strategies which are both technically and operationally sound.

Follow-up work by the geologist should include petrographic analysis of selected cuttings to aid in quantitative well-log interpretation by a reservoir engineer.

Short-term tests will be needed when total depth has been reached but before the well has been completed, in order to determine if and how the well should be completed. Post-completion long-term testing will be required to assess important reservoir parameters and determine if additional wells will be needed to support power plant operations.

Permits

Anticipated permit requirements are listed in table 5. Since the environmental impact report for geothermal development has been completed by GeoProducts, estimated lead times are all less than 2 months. The California Division of Oil and Gas will require a performance bond to be posted before issuing a permit to drill.

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Table 5. Required permits and estimated lead times.

<u>Permitting Agency</u>	<u>Estimated lead time required</u>
County of Lassen (land-use permit)	1 month (with EIR completed)
State Air Pollution Control Board	2 months
State Water Quality Control Board	2 months
State Division of Fish and Game	1 month
State Division of Oil and Gas	1 month

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Water Supply

To support normal drilling operations, a water supply of 400 to 500 barrels per day is needed. Severe lost-circulation problems may force drilling for extended periods of time with no returns. In this case a continuous supply of 200 to 300 gpm (7,000 to 10,000 barrels per day) of water will be needed. Arrangements for a water supply to meet these requirements should be made well in advance of drilling.

Site Preparation

The general shape of the drilling pad is rectangular, with approximate dimensions of 100 feet by 250 feet. The dimensions should be adequate for a rig capable of drilling a well the proposed depth. Adjacent to the pad is the sump, which has a circular or oval shape. The sump capacity should be at least 700,000 gallons, although most of this capacity will not be needed during the drilling phase. To accommodate all phases of well testing, however, this capacity is necessary.

To insure that no sump fluids escape to groundwater systems, an impervious clay liner should be placed on the interior surface of the sump. To construct the sump liner, native materials containing at least 10% clay, or imported materials such as clay and bentonite, will be compacted to 95% of original volume to form a layer approximately two feet thick. The liner will have a maximum permeability of 1×10^{-6} cm/sec.

Typical configurations for the drilling pad and sump and for the deployment of drilling equipment are shown in figures 12 and 13.

Equipment

Rig Specifications. We recommend obtaining a rotary drilling rig with either direct-diesel or diesel-electric power plants. Estimated cost of a rig of this type is approximately \$5,000.00 per day. The exact daily cost depends upon rig availability.

Specifications for major rig components are as follows:

1. Drawworks. Optional manufacturer, with a minimum rated horsepower of 500 to 600.
2. Mast (Derrick). 97 feet minimum height, double mast, with a capacity of up to six lines and a rated load capacity of 350,000 lb.

REVISED	DATE

TSi

ThermaSource Inc.

100 E Street • P.O. Box 1236 • Santa Rosa, California 95402

(707) 523-2960 • Telex 471743 • TWX 510 7446439

FIGURE 12.
TYPICAL WELL SITE AND SUMP CONFIGURATION

DRAWN
FOR: GPW
BY: LEC/ANG
DATE: 11/20/80
SCALE: NTS
DRAWING No. 005

REVISED	DATE	TSI ThermaSource Inc. 100 E Street • P.O. Box 1236 • Santa Rosa, California 95402 (707) 523-2960 • Telex 171743 • TWX 510 7446439	DRAWN
			FOR: GPW
		FIGURE 13. TYPICAL ARRANGEMENT OF DRILLING EQUIPMENT (Actual Arrangement Will Depend on Drilling Rig Used)	BY: LEC/ANG
			DATE: 11/20/80
			SCALE: NTS
			DRAWING No. 004

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3. Mud Pumps. Two pumps required, with liners adequate to discharge 300-350 gpm each. Pumps should have a rating of 500-700 horsepower.
4. Rotary Table. 17-1/2-inch I.D., driven by drawworks.
5. Traveling Equipment. Blocks, four-sheave traveling blocks with 150-ton hook and swivel.
6. Mud System. Minimum 500-barrel circulating system with at least one shale shaker, plus 400-barrel mud-storage capacity.
7. Drill Pipe. 4-1/2-inch 16.60 PPF, grade E, Range 2 drill pipe, minimum 6,000 feet.
8. Substructure. Minimum height 12 feet.

Casing. The casing program recommended for the GeoProducts well is shown on figure 14; casing and cementing specifications are given in table 6. 9-5/8-inch casing is to be set and cemented at a depth of 3,000 feet, the estimated top of the geothermal reservoir. This will block possible water entries from the cool part of the hole and will allow great flexibility in the placement of a down-hole pump with up to 1,000 gpm capacity (maximum size for a stock-built pump). Below this, 7-inch slotted liner will be hung to total depth to protect against caving.

Blow-out Preventers (BOPs). Equipment for blow-out prevention is diagrammed in figures 15 and 16 and specifications are given in table 6. Two BOP configurations are needed for different parts of the hole. For the first 500 feet an annular-type BOP will be welded to the top of the 20-inch conductor pipe and tested to 100 psi. From 500 feet to total depth, the BOP will be a combination annular-type and ram-type mechanism bolted to a casing head valve assembly on top of the 13-3/8-inch casing. It will be tested to 500 psi. All BOPs should be inspected for wear by the manufacturer prior to installation. They must be tested at specified pressures after installation, and should be worked daily.

Inspection of drill pipe and bottom-hole assembly. The initial acceptance of drill pipe should be based on an AAODC-API Class II specification inspection. All subsequent inspections should disregard pipe with 30% wear or greater; that is, use 30% where Class II states 20%.

The drill pipe inspection should include:

Table 6.

CASING, CEMENTING AND BOP PROGRAMS

CASING PROGRAM

SIZE	DEPTH
20"	50'

WELL
GPW

INTERVAL	WEIGHT LB/FT	GRADE	JOINT TYPE	CALCULATED SAFETY FACTORS			
				TOP BURST	BOT. BURST	COLL.	TENSIO
0 - 50'	94	H-40	Welded				

DESIGN CONDITIONS

SURFACE BURST PRESSURE	-	N/A	PSI	OUTSIDE MUD WT. (COLLAPSE)	-	N/A	PP
INSIDE MUD WEIGHT (BURST)	-	N/A	PPG	INSIDE MUD WT. (COLLAPSE)	-	N/A	PP
OUTSIDE MUD WEIGHT (BURST)	-	N/A	PPG	FORM. PRESS. GRAD. AT SHOE (COLLAPSE)	-	N/A	PP
FRAC. GRAD. AT SHOE (BURST)	-	N/A	PPG	BIAXIAL LOAD: COLL. ☐ BURST ☐	BOUANCY: YES ☐ NO ☐		

CEMENTING PROGRAM

SLURRY DESCRIPTION AND PROPERTIES

SLURRY DESCRIPTION (AND NUMBER)

136 cubic feet (5yd³) of Portland Concrete.

Construction Grade Concrete is adequate.

	DESIRED TOP	EXCESS
SLURRY VOL. - CU FT / (SLURRY NO.)	5 yd ³	
SLURRY YIELD - CUBIC FEET/SACK	-	
SLURRY DENSITY - PPG	-	
THICKENING TIME - DEPTH SCH/HRS. MIN.	-	
COMPRESSIVE STRENGTH - PSI/HOURS	-	

RUNNING AND CEMENTING INSTRUCTIONS

SHOE, COLLAR(S) AND JOINT STRENGTHENING

No cementing shoe.

CENTRALIZERS AND SCRATCHERS - NUMBER, TYPE AND SPACING

No centralizers.

PREFLUSH, DISPLACEMENT RATE, PLUGS, RECIPROCATION, ETC.

Cement to be dumped down annulus from ready mix cement truck. Conductor should be installed and cemented prior to large rotary rig moving on location.

PRESSURE TESTING AND LANDING

Weld-on 20" flange for installation of blow out preventer and weld in 3" outlet with flange below the flange.

BOP PROGRAM

API STACK ARRANGEMENT CODE	WORKING PRESSURE PSI	MINIMUM BORE INCHES	TYPE	TEST PRESSURES - PSI		
				RAM TYPE	ANNULAR TYPE	ROTATING ME
-	-	17-1/2"	Annular Preventer		100 psi	

Table 6 (continued)

CASING, CEMENTING AND BOP PROGRAMS

CASING PROGRAM

SIZE	DEPTH	WELL
13-3/8"	500'	GPW

INTERVAL	WEIGHT LB/FT	GRADE	JOINT TYPE	CALCULATED SAFETY FACTORS			
				TOP BURST	BOT. BURST	COLL.	TENS.
0 - 500'	54	K-55	Buttress	8.87	9.99	9.99	9.9

DESIGN CONDITIONS

SURFACE BURST PRESSURE	-	500	PSI	OUTSIDE MUD WT. (COLLAPSE)	-	9.1	P
INSIDE MUD WEIGHT (BURST)	-	9.1	PPG	INSIDE MUD WT. (COLLAPSE)	-	0	P
OUTSIDE MUD WEIGHT (BURST)	-	8.6	PPG	FORM. PRESS. GRAD. AT SHOE (COLLAPSE)	-	9.1	P
FRAC. GRAD. AT SHOE (BURST)	-	9.1	PPG	BIAXIAL LOAD: COLL. ☒ BURST ☒ BOUYANCY: YES ☐ NO ☒			

CEMENTING PROGRAM

SLURRY DESCRIPTION AND PROPERTIES

SLURRY DESCRIPTION (AND NUMBER)

700 cubic feet (432 sacks) of API Class "G" cement blended with 40% by volume of silica flour and 0.5% CFR-2 (friction reducer)

			DESIRED TOP Surface	EXCESS 100%
SLURRY VOL. - CU FT / (SLURRY NO.)	700			
SLURRY YIELD - CUBIC FEET/SACK	1.62			
SLURRY DENSITY - lb/ft ³	116			
THICKENING TIME - DEPTH SCH/HRS, MIN.	2-3 hrs.			
COMPRESSIVE STRENGTH - PSI/HOURS	2895/24 hrs.			

RUNNING AND CEMENTING INSTRUCTIONS

SHOE, COLLAR(S) AND JOINT STRENGTHENING

- 1) Use stab-in type cementing shoe.
- 2) Weld-on shoe.
- 3) Thread-lock bottom 3 joints of casing.

CENTRALIZERS AND SCRATCHERS - NUMBER, TYPE AND SPACING

- 1) Centralizer in middle of bottom 2 joints and 1 centralizer on every other tool joint back up to surface.

PREFLUSH, DISPLACEMENT RATE, PLUGS, RECIPROCATION, ETC.

- 1) Circulate bottoms up 2 times before cementing.
- 2) Pump 30 pump viscous geo-gel mud spacer ahead of cement.
- 3) Mix and pump cement until good cement returns appear at flowline.
- 4) Displace cement with mud, leaving 20 lin. ft. of cement in 13-3/8" casing.

PRESSURE TESTING AND LANDING

- 1) Wait 30 minutes before drain cement from blow out preventer.
- Cut and remove 20" casing and blow out preventers.
Weld on 13-3/8" wellhead. Weld internally and externally - Test through port between welds to 1500 psi.

BOP PROGRAM

API STACK ARRANGEMENT CODE	WORKING PRESSURE PSI	MINIMUM BORE INCHES	TYPE	TEST PRESSURES - PSI		
				RAM TYPE	ANNULAR TYPE	ROTATING HI
	960 psi	12-1/4"	See Schedule II	960	960	

Table 6 (continued)

CASING, CEMENTING AND BOP PROGRAMS

CASING PROGRAM				SIZE	DEPTH	WELL	
				9-5/8"	3000'	GPW	
INTERVAL	WEIGHT LB/FT	GRADE	JOINT TYPE	CALCULATED SAFETY FACTORS			
				TOP BURST	BOT. BURST	COLL.	TENSILE
400 - 3000'	36	K-55	L. T. & C.	2.93	4.00	1.42	5.00

DESIGN CONDITIONS

SURFACE BURST PRESSURE	-	960	PSI	OUTSIDE MUD WT. (COLLAPSE)	-	9.1	PP
INSIDE MUD WEIGHT (BURST)	-	9.1	PPG	INSIDE MUD WT. (COLLAPSE)	-	0	PP
OUTSIDE MUD WEIGHT (BURST)	-	8.6	PPG	FORM. PRESS. GRAD. AT SHOE (COLLAPSE)	-	9.1	PP
FRAC. GRAD. AT SHOE (BURST)	-	9.1	PPG	BIAXIAL LOAD: COLL. ☒ BURST ☒	BOUYANCY: YES ☐ NO ☒		

CEMENTING PROGRAM

SLURRY DESCRIPTION AND PROPERTIES

SLURRY DESCRIPTION (AND NUMBER)

1300 cubic feet (613 sacks) of API Class "G" cement blended on a ratio of 1:1 with perlite and 40% by volume of silica flour and 3% gel and 0.5% CFR-2 (friction reducer) followed by 300 cubic feet (185 sacks) of Class "G" cement blended with 40% silica flour and 0.5% CFR-2.

		DESIRED TOP	EXCESS
		400'	100%
SLURRY VOL. - CU FT / (SLURRY NO.)	1300	300	
SLURRY YIELD - CUBIC FEET/SACK	2.12	1.62	
SLURRY DENSITY - lb/ft ³	106	116	
THICKENING TIME - DEPTH SCH/HRS. MIN.	2-3 hrs.	2-3 hrs.	
COMPRESSIVE STRENGTH - PSI/HOURS	1500psi/24 hrs.	2895psi/24 hrs.	

RUNNING AND CEMENTING INSTRUCTIONS

SHOE, COLLAR(S) AND JOINT STRENGTHENING

- 1) Run float collar 2 joints above float shoe.
- 2) Run liner in on midway type liner hanger and hang 100' up into 13-3/8" casing.

CENTRALIZERS AND SCRATCHERS - NUMBER, TYPE AND SPACING

- 1) Run 1 centralizer in the middle of the bottom 2 joints and 1 centralizer every other casing collar except for the top 100' of the 9-5/8" liner string.

PREFLUSH, DISPLACEMENT RATE, PLUGS, RECIPROCATION, ETC.

- 1) Circulate bottoms up 2 times before pumping cement.
- 2) Pump 30 BBLS of viscous Geo-gel mud spacer ahead of cement. No water ahead.
- 3) Liner hanger to be equipped with 2 plugs.
- 4) Displace cement with mud.

PRESSURE TESTING AND LANDING

- 1) Once top plug has bumped, check for flow back then pull out of liner hanger and trip to lay down liner setting tool. Run in open ended and circulate out excess cement down to top of liner.
- 2) Wait 6 hours
- 3) Test lap to 700psi surface pressure
- 4) Squeeze lap if necessary.

BOP PROGRAM

API STACK ARRANGEMENT CODE	WORKING PRESSURE PSI	MINIMUM BORE INCHES	TYPE	TEST PRESSURES - PSI		
				RAM TYPE	ANNULAR TYPE	ROTATING HEAD
	960	12-1/4"	See Schedule 11	960	960	

Table 6 (continued)

CASING, CEMENTING AND BOP PROGRAMS

CASING PROGRAM

SIZE	DEPTH
7"	5000'

WELL
GPW

INTERVAL	WEIGHT LB/FT	GRADE	JOINT TYPE	CALCULATED SAFETY FACTORS			
				TOP BURST	BOT. BURST	COLL.	TENSILE
2800 - 5000'	26	N-80	L. T. & C.	S L O T T E D			9.07
				(2" x 1/8" slots, 90° apart, on 6" centers)			

DESIGN CONDITIONS

SURFACE BURST PRESSURE	-	N/A	PSI	OUTSIDE MUD WT. (COLLAPSE)	-	N/A	PP
INSIDE MUD WEIGHT (BURST)	-	N/A	PPG	INSIDE MUD WT. (COLLAPSE)	-	N/A	PP
OUTSIDE MUD WEIGHT (BURST)	-	N/A	PPG	FORM. PRESS. GRAD. AT SHOE (COLLAPSE)	-	N/A	PP
FRAC. GRAD. AT SHOE (BURST)	-	N/A	PPG	BIAXIAL LOAD: COLL. ☐ BURST ☐	BOUYANCY: YES ☐ NO ☒		

CEMENTING PROGRAM

SLURRY DESCRIPTION AND PROPERTIES

SLURRY DESCRIPTION (AND NUMBER)

Liner to be hung with 200' of lap in the 9-5/8" liner and not cemented.

	DESIRED TOP	EXCESS
SLURRY VOL. - CU FT / (SLURRY NO.)	N/A	
SLURRY YIELD - CUBIC FEET/SACK		
SLURRY DENSITY - PPG		
THICKENING TIME - DEPTH SCH/HRS, MIN.		
COMPRESSIVE STRENGTH - PSI/HOURS		

RUNNING AND CEMENTING INSTRUCTIONS

SHOE, COLLAR(S) AND JOINT STRENGTHENING

- 1) Guide shoe only run on bottom.
- 2) No joints thread-locked or welded except for shoe.

CENTRALIZERS AND SCRATCHERS - NUMBER, TYPE AND SPACING

- 1) No centralizers or scratchers in case liner would require retrieving at a later date.

PREFLUSH, DISPLACEMENT RATE, PLUGS, RECIPROCATATION, ETC.

N/A

PRESSURE TESTING AND LANDING

- 1) Liner hung with Midway type liner hanger.

BOP PROGRAM

API STACK ARRANGEMENT CODE	WORKING PRESSURE PSI	MINIMUM BORE INCHES	TYPE	TEST PRESSURES - PSI		
				RAM TYPE	ANNULAR TYPE	ROTATING HEAD

GROUND LEVEL

1000'

2000'

3000'

4000'

5000'

20' CASING SET IN A 30" HOLE AT 50' WITH 136 FT³ OF CEMENT.

13-3/8" CASING SET IN A 17-1/2" HOLE AT 500' AND CEMENTED WITH 700 FT³ (432 SX) OF CEMENT.

9-5/8" O.D. LINER SET IN A 12-1/4" HOLE FROM 400' - 3000', AND CEMENTED WITH 1600 FT³ (798 SX) CEMENT.

7" SLOTTED LINER HUNG IN A 8-3/4" HOLE FROM 2800' - 5000'± AND NOT CEMENTED.

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			FOR: GPW
			BY: ANG/LEC
			DATE: 11/20/80
			SCALE: TRUE VERTICAL
			DRAWING No.
			003

FIGURE 14. PROPOSED WELL CASING PROGRAM

REVISED	DATE

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FIGURE 15.

BLOW OUT PREVENTER STACK FOR 20" CONDUCTOR

DRAWN

FOR: GPW

BY: WLG/LEC

DATE: 11/20/80

SCALE: NONE

DRAWING No.

SCH. I

REVISED	DATE

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FIGURE 16.
BLOW OUT PREVENTER FOR 13-3/8" CASING

DRAWN
FOR: GPW
BY: WLG/LEC
DATE: 11/20/80
SCALE: NONE
DRAWING No.
SCH II

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1. Electromagnetic inspection of tubes (Sonoscope or Scanalog).
2. Wall thickness and cross sectional area (ultrasonic or gamma-ray).
3. End area inspection (electronic or magnetic-particle).
4. Tool-joint O.D. caliper 5-1/4-inch minimum outside diameter for 4-1/2" XH drill pipe.

All drill collar end areas should be magnetic-particle inspected every 14 days. Remind service companies furnishing bottom-hole assemblies that their equipment should be Magna-fluxed prior to delivery.

Auxiliary Equipment. The following auxiliary equipment is recommended and should be supplied by the drilling contractor, if possible:

1. Five-pen drilling recorder with: (a) bit weight, (b) rotary speed, (c) torque, (d) rate of penetration, and (e) inlet pump pressure.
2. 24-hour circular recorder to record mud exit temperature on board scale.
3. Continuous-recording pit-level indications, with totalizer and pump stroke counters.
4. Use square kelly; inspect regularly with same technique used for drill pipe.
5. Use tong torque assembly for making up collars.

The pit-level and mud-temperature indicators must provide continuous records and must be sensitive, well calibrated, and well maintained. If apparatus of high quality cannot be supplied by the drilling contractor, an alternate source should be sought.

Drilling Program

The following is a step-by-step sequence of operations for drilling the Honey Lake well:

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1. Obtain all necessary permits from the various governmental agencies involved.
2. Construct location to accommodate the drilling rig and all related material, estimated size 100 feet wide by 250 feet long. Construct drilling fluid sump with a capacity of 600,000 to 700,000 gallons, or larger if economical. This large size sump is specified to accommodate fluid produced during long-term well tests.
3. Once location is constructed, an auger-type rotary drilling rig could be utilized to set a 20-inch conductor pipe to 50± feet in a 30-inch hole. The conductor should be cemented to surface using Ready Mix cement.
4. A cellar 4 feet deep should be constructed around the conductor pipe, with the dimensions of at least 6 feet by 6 feet. Cellar should be equipped with a drain to the sump.
5. Rig up large drilling rig over conductor pipe (see rig-specification section for details).
6. Install single annular-type blow-out preventer on the conductor and test to 100 psi before spudding well (see figure 15). Notify representatives of State of California Division of Oil and Gas to witness test.
7. Spud well with 17-1/2-inch bit and drill to 500 feet with mud (see table 7 for mud specifications). Take directional surveys every 150 feet, maximum angle to be 5°. Maximum rate of change should be no greater than 1-1/2° per 100 feet.
8. Run logs as per logging program (table 1). Run multi-shot directional survey after hole-conditioning trip.
9. Run 13-3/8-inch casing to total depth and cement same from total depth to surface using stab-in-type cementing shoe (see table 6 for details).
10. Cut off 13-3/8-inch casing and weld-on casinghead. Install blow-out preventers as specified in figure 16. Test blow-out preventers to 500 psi with a representative of the State of California Division of Oil and Gas witnessing the test.
11. Drill 12-1/4-inch hole with mud to 3,000± feet. Take directional surveys every 150 feet, maximum angle to be 8°. Maximum rate of change should be no greater than 1-1/2° per 100 feet.

Table 7.

MUD, LOGGING, WELLHEAD & DIRECTIONAL PROGRAMS					WELL GPW	
DEPTH INTERVAL	MUD TYPE	WEIGHT	API FLUID LOSS	YIELD POINT	PH	Vis.
50 - 500'	Gel & Water	8.8	12	-	10-12	40-45
500 - 3000'	Gel & Water	9.0	10	4-6	10-12	35-37
3000 - T.D.	Gel & Water	9.1	8	4-6	10-12	35-37

REMARKS Lost Circulation - Lost circulation is most likely to be caused by breaking down of formations because of excessive mud weight. This is best controlled by prevention. A mud weight not to exceed 9.1 lbs./gal. is necessary to avoid lost circulation. If a "lost returns" condition is experienced the viscosity should be held in the 36-40 sec./qt. range and the mud weight lowered as much as possible. The addition of fibrous material and graded lost circulation material (LCM) may also be necessary. If lost circulation is caused by large fractures or caverns I would advise drilling ahead blind to a casing point as soon as possible or attempt to cement off the lost circulation zone.

LOGGING

DEPTH INTERVAL	LOG TYPES	LOG SCALES	
50 - 500'	IES & Temperature	5" = 100'	2" = 100'
500 - 3000'	IES, formation density-neutron, temperature	5" = 100'	2" = 100'
3000 - 5000'	IES, formation density-neutron, temperature	5" = 100'	2" = 100'

REMARKS IES and temperature loss are required by the California Division of Oil and Gas for all intervals.

WELLHEAD

API NOMINAL SIZE	WORKING PRESSURE PSI	TYPE	MAKE
20" Flange	100 psi	Weld-on Top Flange	Rental
13-3/8" x 12"	900 psi	13-3/8" Weld-on x 12" 400 ANSI	W-K-M
12" Valve 400 ANSI	900 psi	12" 400 ANSI x 12" 400 ANSI	W-K-M
12" 400 x 8" 300	650 psi	12" x 8" Tubing Spool	W-K-M
* 8" 300 x 8" 300	650 psi	8" 300 ANSI x 8" 300 ANSI	W-K-M

REMARKS These items are required to install tubing and pump in case the well requires pumping and will not flow on its own. These items may be omitted if the well flows.

DIRECTIONAL OR STRAIGHT-HOLE

The proposed hole shall be a straight hole test.

Limits are set on the various hole stages as follows:

50' - 500' Maximum angle to be 5° Maximum rate of change 1-1/2° per 100'

500' - 3000' Maximum angle to be 8° Maximum rate of change 1-1/2° per 100'

3000' - 5000' Maximum angle to be 10° Maximum rate of change 1-1/2° per 100'

Surveys every 150'. Multi-shot survey may or may not be required at casing points.

Side-track may be an alternative for unsuccessful wells.

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12. Log well as per Logging Program (table 1). Run multi-shot directional survey on hole-conditioning trip.
13. Run 9-5/8-inch casing as a liner hung from 100' up inside of the 13-3/8-inch casing to total depth. Hang liner and cement same from top to bottom (see table 6 for details).
14. Drill out all cement from top of liner lap and test casing, lap, and blow out preventers to 600 psi before drilling out 9-5/8-inch casing shoe.
15. Drill out 9-5/8-inch casing with 8-3/4-inch bit and drill 8-3/4-inch hole to total depth, to be specified by operator (nominally 5,000 feet). Take directional surveys every 150 feet, maximum angle to be no greater than 10° . Maximum rate of change should be no greater than $1\text{-}1/2^{\circ}$ per 100 feet.
16. Test well and complete or abandon well, based on short-term tests (see next section).

Completion Procedures

Completion techniques for this well will depend on its potential for production. There are three options or possibilities for completion:

1. Completion with a flowing (artesian) well. If during the testing phases the well flows with commercial temperatures and pressures, the well will be completed with a wellhead design as shown in figure 17 and as specified in table 7.
2. Completion with a downhole pump. If the well will not flow, but the fluid level in the hole recovers, it may be possible to complete the well using a 6-3/4-inch downhole Reda Pump for geothermal services. The pump will be hung on 8-5/8-inch or smaller tubing, and will be capable of pumping approximately 650 GPM. The wellhead design for a pumping well is shown in figure 18; specifications are given in table 7.
3. Abandon or sidetrack well. If the well produces little or no fluids, and fluid level does not recover rapidly, or if temperature is inadequate, it may be necessary to plug and abandon the well. If temperature is adequate but permeability is lacking, sidetracking the well may be an alternative to abandonment.

An outline of the completion sequence is given below:

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FIGURE 17.

WELLHEAD COMPLETION FOR FLOWING WELL

DRAWN

FOR: GPW

BY: WLG/LEC

DATE: 11/20/80

SCALE: NONE

DRAWING No.

001

REVISED	DATE	TSI ThermaSource Inc. 100 E Street • P.O. Box 1236 • Santa Rosa, California 95402 (707) 523-2960 • Telex 171743 • TWX 510 7446439	DRAWN
			FOR: GPW
		FIGURE 18. WELLHEAD COMPLETION FOR PUMPING WELL	BY: WLG/LEC
			DATE: 11/20/80
			SCALE: NONE
			DRAWING No.
			002

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Initial Evaluation

1. Upon reaching total depth the well will be logged.
2. The mud will be displaced with water.
3. The well will then be evacuated using compressed air or nitrogen.
4. If well flows to surface, it will be tested at various rates and pressures.
5. If fluid temperature and production rate appear commercial, the well will be completed as outlined in steps 6 through 10. If the well does not flow adequately to the surface, but commercial production appears possible with pumping (based on recovery rates of fluid level after evacuation), the well will be completed with tubing and pump, as outlined in steps 11 through 19. Additional down-hole temperature logs may be necessary after evacuation in order to establish fluid temperatures. If fluid-level recovery indicates insufficient permeability for commercial production, or if temperature logs indicate that temperatures are inadequate, the well will be abandoned or sidetracked (step 20).

Completion for Flowing Well

6. Run in hole to total depth and clean out any fill.
7. Run slotted liner from 200 feet up in 9-5/8-inch casing to total depth and hang it with Midway-type liner hanger.
8. Displace drilling mud with water if mud was required to clean out the hole.
9. Evacuate the well with compressed air or nitrogen.
10. Lay down drill pipe and move off rig. Well completed as shown in figure 17.

Completion for Pumping Well

11. Run in hole to total depth and clean out any fill.
12. Run slotted liner from 200 feet up in 9-5/8-inch casing to total depth and hang it with Midway-type liner hanger.

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13. Displace drilling mud with water if mud was required to clean out the hole.
14. Evacuate the well with compressed air or nitrogen.
15. Pick up 6-3/4-inch O.D. pump (Reda Model #675 or equivalent) on 8-5/8-inch or smaller tubing (if required to enter 9-5/8-inch casing). Run in hole with pump and tubing to approximately 200 feet below the static fluid level.
16. Install W-K-M tubing hanger spool with control-line port as shown in figure 18.
17. Flow well with pump and test at a minimum of 3 different flow rates, measuring drawdown.
18. Adjust pump depth, if necessary, based on drawdown tests.
19. Lay down drill pipe. Move rig off location.

Abandonment or Sidetrack

20. Abandonment will be according to the State of California Division of Oil and Gas Regulations. Depth and direction of a possible sidetrack will be determined by the geologist in consultation with GeoProducts and funding government agencies.

Well Costs

Estimated well costs are broken down in table 8 for three possible completion arrangements. These costs cover only those operations which relate directly to the drilling of the well up to the time the rig is released. They therefore include expenses related to initial short-term testing, but do not cover long-term reservoir analysis, geologic follow-up work, or the compilation of final reports. Costs for a possible sidetrack have not been computed. Communications costs have been omitted because of their great variability at the discretion of the operator.

WELL COST ESTIMATE

DATE

11/20/80

LEASE AND WELL NUMBER

GeoProducts Corp.

☒ NEW WELL☐ REDRILL

PROPOSED TOTAL DEPTH

5000' +

DIVISION

Geothermal

FIELD, COUNTY & STATE (OR COUNTRY)

Lassen County, California

PROJECT DESCRIPTION

Drill and complete an exploration geothermal well to 5000'± in the Honey Lake area of California.

SUMMARY OF ESTIMATED COST

Flowing

Pumping

Dry Hole

ACCOUNT
CODE

(30 DAYS)

(32 DAYS)

(30 days)

TANGIBLE WELL COSTS

021

CASING

\$ 84,000

\$ 84,000

\$ 50,000

022

TUBING

-

10,000

-

023/024

WELLHEAD ASSEMBLY (MATERIAL ONLY)

40,000

60,000

20,000

SURFACE PUMP, EQUIP. (MATERIAL ONLY)

SUBSURFACE PUMP, EQUIP. (MATERIAL ONLY)

85,000

025

OTHER WELL EQUIPMENT (MATERIAL ONLY)

INSTALLATION OF SURFACE EQUIPMENT

Liner Hangers

15,000

15,000

-

TOTAL TANGIBLES

\$ 139,000

\$ 254,000

\$ 70,000

LEASE DEVELOPMENT COSTS

SEPARATION FACILITIES

STORAGE TANKS & SHIPPING FACILITIES

FLOWLINES

OTHER LEASE EQUIPMENT (MATERIAL ONLY)

INSTALLATION COSTS

TOTAL LEASE DEVELOPMENT

\$

\$

\$

INTANGIBLE WELL COSTS

PERMITS, SURVEYS & LOCATIONS (INCLUDING CONDUCTOR)

20,000

20,000

20,000

046

RIG MOBILIZATION

20,000

20,000

20,000

049

CONTRACT DRILLING

155,000

165,000

155,000

051

DIRECT SUPERVISION

30,000

30,000

30,000

052

BITS, STABILIZERS, HOLE OPENERS & REAMERS

60,000

60,000

60,000

025

OTHER EQUIPMENT

-

-

-

053

ROTARY MUD & CHEMICALS

12,000

12,000

12,000

055

OTHER DRILLING TOOLS

10,000

10,000

10,000

056

CEMENT & CEMENTING SERVICES

38,000

38,000

38,000

059

TESTING, SAMPLING & CORING

5,000

5,000

5,000

061

ELECTRICAL LOGGING

30,000

30,000

30,000

057

MUD LOGGING

9,000

9,000

9,000

062

WELDING & INSPECTION

8,000

8,000

8,000

063

WHIPSTOCKING & DIRECTIONAL SURVEYS

3,000

3,000

3,000

064

FISHING TOOLS & EXP.

-

-

-

066

DRILLING EQUIPMENT RENTAL

6,000

6,000

6,000

068

SMALL TOOLS & SUPPLIES

3,000

3,000

3,000

069

TRANSPORTATION

10,000

10,000

10,000

072

FUEL, WATER & POWER

10,000

10,000

10,000

073

COMMUNICATIONS

-

-

-

074

WELL INSURANCE

3,000

3,000

3,000

077

PERFORATING

-

-

-

078

OTHER COMPLETION COSTS

5,000

5,000

5,000

084

MISC. EXPENSE

5,000

5,000

5,000

085

ABANDONMENT COSTS

-

-

5,000

091

DISTRICT EXPENSES

3,000

3,000

3,000

092

ADMINISTRATIVE OVERHEAD

3,000

3,000

3,000

TOTAL INTANGIBLES

\$ 428,000

\$ 438,000

\$ 433,000

TOTAL WELL COSTS

\$ 587,000

\$ 712,000

\$ 523,000

ESTIMATED BY

L.E. Capuano, Jr.

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APPENDIX A
LIST OF MATERIALS SUBMITTED BY
GEOPRODUCTS FOR REVIEW

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Materials Submitted by GeoProducts for Review

1. Water Quality Analysis, Inferred Geothermal Reservoir Temperatures and Reservoir Evaluation Test, September 1976, U.S. Dept. of Interior, Bureau of Reclamation.
2. Susanville Geothermal Investigation, Special Report, June 1976, U.S. Dept. of Interior, Bureau of Reclamation.
3. Susanville Geothermal Investigation, Supplemental Technical Data, June, 1976, *ibid*.
4. Chemical Analysis, Morse Labs, March 15, 1978; June 16, 1978, conducted by GeoProducts on HLHF springs/wells.
5. Water Analyses: Flow Rates of Various Wells and Springs On and Near Wendel Hot Springs, GeoProducts inhouse.
6. California Streamflow Characteristics, June 7, 1971, U.S. Geological Survey.
7. Hydrologic Data 1973, Northeastern California, December 1974, Dept. of Water Resources.
8. Water Resources Data for California Water Year 1975, U.S. Geological Survey.
9. Dowsing - distance map, June 1978, GeoProducts Corporation.
10. Environmental Analysis, September 30, 1976, GeoProducts Corporation.
11. Gulf Report on Honey Lake #2, August 15, 1973.
12. Glenn Pump and Drilling Test Results, November 9, 1978, GeoProducts Corporation.
13. Preliminary Report All Geophysical Surveys, Wendel Hot Springs, September 15, 1978, Electrodyne Surveys.
14. Revised Preliminary Report, All Geophysical Surveys, Wendel Hot Springs, September 29, 1978, Electrodyne Surveys.
15. Status Report, Wendel Hot Springs Geophysical Surveys, May 15, 1978, Electrodyne Surveys.
16. Pre-analysis Geothermal Temperatures at Depth in Wendel Hot Springs, April 20, 1978, Electrodyne Surveys.

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17. Correspondance re: Honey Lake Project, April 7, 1977, George Zebal.
18. Progress Report, Honey Lake Geothermal Prospect, March 12, 1976, GeothermEx.
19. The Honey Lake Geothermal Area, March 14, 1975, George Zebal.
20. The Potential for Geothermal Energy Resources Honey Lake Area, December 26, 1975, GeothermEx.
21. Electric Log, Magma Well.
22. Electric Res. Log, Wendel Well #2.
23. Temperature Logs, GeoProducts Well #2.
24. Temperature Logs, Mapes #1.
25. Temperature Logs, Magma Well.
26. Gulf Mineral Resources, Apparent Resistivity Map.
27. Gulf Mineral Resources, Micro seismic Anomaly Map.
28. Gulf Mineral Resources, Shallow Ground Temperature Map.
29. Gulf Mineral Resources, Honey Lake - 2ST Well Log.
30. Gulf Mineral Resources, Static Temp. Survey, Honey Lake 2ST Well.
31. Gulf Mineral Resources, Honey Lake 2ST Sidetrack well log.
32. Gulf Mineral Resources, Compensated Acoustic Velocity Log, 2ST sidetrack.
33. Gulf Mineral Resources, Fracture Finder Micro-Seismogram.
34. Gulf Mineral Resources, Subsurface Temperature Survey, Honey Lake 2ST.
35. Gulf Mineral Resources, Bouger Gravity Map.
36. Gulf Mineral Resources, Static Thermal Data Log, 2ST.
37. Gulf Mineral Resources, Dynamic Thermal Data Log, 2ST.
38. Geothermal Exploration Surveys at Honey Lake, Wendel, California, January 11, 1973, Geothermal Surveys, Inc.

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39. Draft Environmental Assessment Record, Honey Lake Valley, January 1977, Bureau of Land Management.
40. A Geophysical Evaluation of the Wendel Hot Springs Area, Electrodyne Survey Services.
41. Geophysical Survey Evaluation Honey Lake Prospect, Wendel-Amedee, CA, Vols. I & II, October 1979, Electrodyne Surveys Services.
42. Electric Logs for Thermal Gradient Wells.