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EARTH POWER PRODUCTION COMPANY  
Geothermal Interpretation of  
Groundwaters, Continental Lake  
Region, Humboldt County, Nev-  
ada, by GeothermEx, Inc.  
December 1977.

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GEOHERMAL INTERPRETATION OF GROUNDWATERS,  
CONTINENTAL LAKE REGION, HUMBOLDT COUNTY, NEVADA

for  
EARTH POWER CORPORATION  
TULSA, OKLAHOMA

by  
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December 1977

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#### CONCLUSIONS

- (1) Three types of groundwater are recognized in the Continental Lake region:
  - a) Calcium-sodium-bicarbonate waters of the basaltic, metamorphic, and intrusive highlands, and in alluvial fans adjacent to these highlands.
  - b) Sodium-bicarbonate waters in the valley fill and highlands composed of silicic volcanics and sediments of volcanic origin. These include several mildly thermal waters and Bog Hot Spring (55°C).
  - c) Sodium-sulfate waters sampled at Balthazor Hot Spring (79-96°C) and a cold well near the McGee Mountain thermal anomaly.
- (2) Balthazor Hot Spring has a maximum subsurface temperature indicated by the silica and Na-K-Ca geothermometers of about 160°C. Significantly higher temperatures seem unlikely, in spite of the presence of old sinter deposits. The spring water probably cools by conduction as it rises to the surface; its surface temperature displays annual fluctuations from about 76°C to boiling, which appear to correlate with flow rate. Temperatures only 100 feet below surface may be more than 20°C hotter than at the surface.
- (3) Balthazor Hot Spring is not likely mixed in any significant degree, as indicated particularly by its very low Mg content and also by the failure of mixing components in hypothetical models to behave consistently with respect to the Na-K-Ca geothermometer. If 50 percent mixing were to occur, reservoir temperatures of 200° to 220°C might be encountered. The deep thermal fluid at Balthazor is probably mild in composition and not a serious corrosion or disposal problem.
- (4) Bog Hot Spring probably has temperatures at depth of no more than 100°C to 125°C, as indicated by the silica and Na-K-Ca geothermometers. It could be a mixed water of about 50 percent cool shallow water and 50 percent deep thermal water. However, even in this case the deep temperature would not exceed 100° to 125°C.
- (5) Neither Gridley Lake warm spring (36°C) nor any of the warm springs of Virgin Valley (23°C to 32°C) is likely to have a temperature at depth more than a few degrees above the surface temperature.

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- (6) Balthazor and Bog Hot Springs, and possibly Gridley Lake warm spring, have artesian-type flow. Their locations probably are controlled by buried faults, which conduct to the surface meteoric water heated by deep circulation along a regional geothermal gradient of 45° to 50°C/km. Thus, flow at Balthazor may reach 3 km and at Bog Hot Spring 2 km. In either case the waters probably enter pre-Tertiary basement at depth. Thermal reservoirs, if they exist, could be in basement rocks or distributed in Tertiary volcanic rocks at higher levels.
- (7) High F in the water of Balthazor Hot Spring may be interpreted to indicate an acidic igneous reservoir host at depth. Either Tertiary dacite-rhyolite or Mesozoic granitics are possible source rocks. Seismicity in the area supports the concept of fractured basement granites serving as a reservoir, perhaps at 1-2 km depth. Tertiary volcanics (basalts) are a likely shallower reservoir.
- (8) To assist in definition of possible reservoirs a determination of depth to basalts and to the Mesozoic basement beneath Continental Lake Valley is needed. A gravity survey to better define buried range-front structure and depth to basement may be worthwhile.
- (9) The warm springs of Virgin Valley occur where water flowing laterally above impermeable strata intersects the ground surface in the canyon of Virgin Creek. None of the Virgin Valley thermal waters is likely to have circulated much below the orifice altitude.
- (10) Two miles northeast of the Painted Hills Mine fumarole (McGee Mountain thermal anomaly) is a stockwell which produces cool, Na-SO<sub>4</sub>-type water strikingly similar in composition to that of Balthazor Hot Spring, only having a lower level of dissolved SiO<sub>2</sub>. This is postulated to be a thermal water which rises along the McGee Mountain fault and flows eastward and downward within gently dipping sediments, cooling and losing silica as it moves. If so, it probably circulates to a similar depth and is stored in similar rocks as the Balthazor water.
- (11) Within the southeast portion of the McGee Mountain thermal anomaly, between the 100° and 125°C/km isotherms, is a cold spring with unusually high SiO<sub>2</sub> (98 mg/l) and relatively high Cl compared to other cool springs of the project area. The Cl may be derived from lacustrine deposits. The SiO<sub>2</sub> may have come from dissolution of tuffaceous volcanic glass; however, it could also be explained as indicating a thermal origin of the water.

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- (12) Na-K-Ca temperatures of *cold* waters in the project area vary according to water type and provenance. In general, the dilute Ca-HCO<sub>3</sub> waters have low temperatures. The Na-HCO<sub>3</sub> waters of Virgin Valley have moderate temperatures, below 100°C, whereas Na-HCO<sub>3</sub> waters from the west side of Continental Lake Valley near McGee Mountain and Bog Hot Spring have temperatures near 200°C. The slightly elevated temperatures of the Virgin Valley waters are probably due to flow of the groundwaters through weathering sodic volcanic rocks and volcanic glass. The highly elevated temperatures along the west side of Continental Lake Valley are probably caused by this effect plus base exchange of Ca for Na on clays in the valley fill and weathered tuffs. A thermal origin for these waters is not necessary to explain their high Na-K-Ca temperatures.
- (13) Estimated perennial yield of the groundwater reservoirs of the area is about 6,000 acre-feet in Virgin Valley, 2,000 acre-feet in Gridley Lake Valley, 11,000 acre-feet in Continental Lake Valley, and 2,000 acre-feet in Pueblo Valley (in Nevada). These yields are small and may place restrictions upon development of geothermal electrification. Annual recharge to the thermal systems alone may be quite small, necessitating reinjection of extracted thermal fluids to sustain production.
- (14) Samples of fluid should be taken from all deeper gradient holes to be drilled in the area.

#### PURPOSE AND SCOPE

GeothermEx, Inc. was asked by Earth Power Corporation to carry out a hydrochemical survey of thermal and cool groundwaters in the Continental Lake region of north-central Nevada as part of a continuing evaluation of thermal anomalies at Balthazor Hot Spring and McGee Mountain. The goals of this survey were to use integrated hydrologic, hydrochemical, and geologic data to describe the region's water-circulation systems and to predict as closely as possible the temperature and composition of deep thermal fluids, characteristics and location of possible aquifer host rocks, volume of recharge to the deep and shallow systems, and potential sustained annual yield. A subsidiary goal was to locate sources of thermal water not previously recognized, including cool groundwaters which arise by slow leakage from thermal systems in areas where surface thermal manifestations are absent.

Altogether, some 27.5 man-days were spent on data collection, analytical interpretation, and report preparation.

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## PROCEDURES

### Review of Existing Data

Sinclair (1963) has appraised the groundwater resources of the Continental Lake region. That report provided much of the basic hydrologic data described below and also included chemical analyses of Bog Hot Spring and three cold well waters. Analyses of numerous thermal waters are also available in Mariner and others (1975) and Cathrall and others (1977). GeothermEx has prepared a photogeologic map of the area which should be used in conjunction with this report.

### Field Methods

Field work consisted of visits to nearly all known or suspected sources of groundwater in the vicinity of Continental Lake. Wherever water was encountered in this region, a sample was taken (plate 1). West of McGee Mountain in Virgin Valley, the sampling was limited to several warm and cool springs and wells believed to represent deep, high-volume flow. Sampling was also selective near and north of Denio. Preferred sample points were those thought to represent the deepest flow available.

Some of the sites visited did not yield useful data. These included dry springs, abandoned wells, and stock wells at which pumps were inactive or inoperative. Such points also are shown on plate 1.

At each sample point the temperature and specific conductance of the water were measured and samples collected after filtration through a 0.45  $\mu\text{m}$  membrane filter. At least three aliquots of each were taken: 250 ml of filtered sample for anion analysis; 250 ml of filtered sample acidified to pH 2 for cation analysis; and a filtered, diluted, and acidified sample for determination of silica. pH was measured at the site with *pHydrion* brand low-range pH paper.  $\text{NH}_3$ , in an unfiltered acidified aliquot, was measured daily at the motel base, using an Orion 407A specific-ion electrode apparatus.

Gas samples were collected at three of the hot springs: Balthazor, Bog, and Gridley Lake. The fumarole at Painted Hills Mine (east side McGee Mountain) was visited; however, its flow was insufficient for gas sampling. Upon return from the field all water and gas samples immediately were delivered to Western Analytical Services, Orinda, California, for laboratory analysis.



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### Results of Field Work

The field work lasted eight days, including two in transit. During this time 26 water samples were collected plus 3 gas samples. The chemical compositions of these samples are listed in table 1, along with all chemical analyses of waters in the project area found in published sources. Duplicate analyses of several thermal waters show generally good agreement between the work of the several laboratories involved. As the duplicate samples were collected at different times, even years apart, exact agreement is not expected.<sup>1</sup>

Selected chemical parameters for each water are included on plate 1. All samples are numbered by an abbreviation of the sample locality according to Township, Range, Section, to 1/64th-section indicated by a triad of the letters a, b, c, and d (which indicate, respectively, the northeast, northwest, southwest, and southeast quarters of a section, quarter-section, and sixteenth-section). For example, well 45N-27E-1acc is in the SW/4 of the SW/4 of the NE/4 of Sec. 1, T. 45 N., R. 27 E., Mount Diablo base line and meridian.

## GENERAL HYDROLOGIC ENVIRONMENT

### Physiography and Geology

The Balthazor-McGee prospects lie within the Pueblo Valley-Continental Lake watershed, which covers about 1,500 square miles in northern Humboldt County, Nevada (plate 2). An additional 280 square miles drains southward from southern Oregon toward Continental Lake along the west flank of the Pueblo Mountains. The study area includes four principal basins: Virgin Valley, Pueblo Valley, and valleys containing Gridley Lake and Continental Lake. The latter sometimes is called Bog Hot Valley or Thousand Creek Valley but is referred to herein as Continental Lake Valley. It contains the hottest thermal manifestations of the area, Balthazor and Bog Hot Springs, and the Painted Hills Mine fumarole. The valley floor is about 95 square miles in extent and receives drainage

<sup>1</sup>Sample 44N-31E-4aac, Howard Hot Spring, is listed from this study as containing 13.7 mg/l Ca. This value is probably too high and a re-analysis has been requested. Assays of SiO<sub>2</sub> in Balthazor Hot Spring (46N-34E-13bdc) include a 130 mg/l value which is probably too low by about 20 mg/l.

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from Alder and Craine Creeks on the south, Rincon Creek from the north, and from Virgin Valley to the west along Thousand Creek. Alder Creek and Thousand Creek flow perennially but disappear into alluvium before reaching the usually dry Continental Lake playa. Gridley Valley is a southward extension of Continental Lake Valley; the two valleys are separated by a few tens of feet of topographic relief into separate basins. There is similarly low relief across a narrow gap between the Pueblo Mountains to the northwest and the Pine Forest Range to the southeast, which separates Continental Lake and Pueblo Valley. During periods of excessive flow, Continental Lake may spill northeastward through this gap into Pueblo Valley, which is tributary to the Alvord Desert in Oregon.

Gridley Lake, Continental Lake, and Pueblo Valley are structural depressions displaced downwards by faulting relative to surrounding mountain ranges. The mountains comprise pre-Tertiary igneous and metamorphic rocks overlain unconformably by Tertiary volcanics. In the Pueblo Mountains the lower part of the Tertiary section consists of basalts, which may total 4,800 feet thickness (Steens basalt or Pueblo Series). These are overlain by 0 to 500 feet of tuffaceous sediments, tuff, and ignimbrite. On McGee Mountain the total thickness of similar tuffs, volcanic sediments, and rhyolite is probably at least 2,000 to 2,300 feet. The valley floors generally are flat and roughly 2 to 6 miles wide, surfaced by alluvium in the lowest parts. Near some of the mountain borders gentle slopes have been eroded onto flat-lying volcanic sediments which probably underlie the entire basin (Thousand Creek beds). Within gaps between Gridley Lake, Continental Lake, and Pueblo Valley there probably are hydrologic barriers of bedrock uplifted along normal faults and now buried beneath a thin cover of alluvium. These barriers are relatively impermeable and effectively block any interbasin movement of groundwater, as indicated by marshy conditions upgradient.

In the western part of the region the fault-block topography is buried, except for a few relatively recent fault scarps, beneath a thick section of generally flat-lying Tertiary volcanic flow rocks and their sedimentary derivatives. Virgin Valley is a narrow ravine deeply incised in a thick section of volcanic tuff and lake beds and through rhyolite in Thousand Creek Gorge where it connects to Continental Lake Valley. The rhyolite forms a sill which constitutes a base level for drainage in Virgin Valley and impedes groundwater underflow from it.

For detailed descriptions of the geology of the prospect areas, including a geologic map and columnar section, the reader is referred to the GeothermEx report to Earth Power Corporation, January 1978.

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### Climate

The U.S. Weather Bureau has maintained stations at Denio from 1952 to 1961 and at Virgin Valley since 1952. These records are shown graphically in figure 1, reproduced from Sinclair (1963). The slightly lower temperatures at Virgin Valley are presumably due to a station altitude about 600 feet higher than at Denio. The lower precipitation at Virgin Valley is probably caused by the relatively low relief of the desert plateaus in that area and westward, compared to the mountainous relief of the Pueblo Mountains and Pine Forest Range near Denio. Those ranges are the first major barrier to prevailing westerly winds east of California. As Denio is close to the eastern escarpment of the Pueblos, which rises more than 2,000 feet, its precipitation may average slightly more than over the rest of the valley floor.

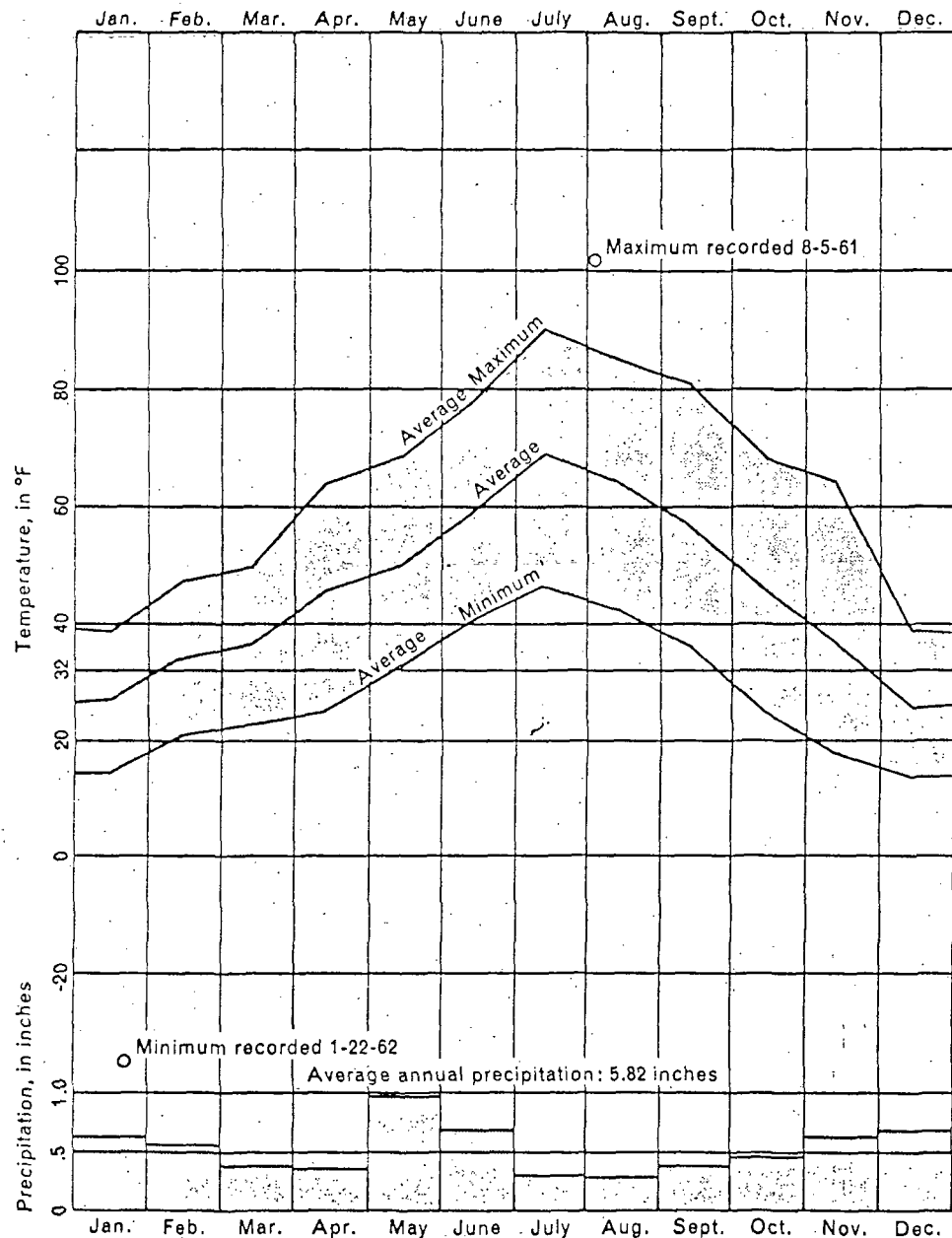
The rate of evaporation from a free water surface in the region is about 48 inches a year or 6 to 8 times the annual precipitation (Sinclair, 1963).

### Hydrologic Units

The primary permeability and water-storage capacity of the pre-Tertiary bedrock units exposed in the Pine Forest Range and Pueblo Mountains is generally quite low. Neither the granitic nor the metamorphic rocks are likely to form significant aquifers at depth for either hot or cold groundwaters, unless heavily fractured and jointed. In addition, joints and fractures in such rocks may seal if groundwater temperatures are elevated, due to the formation of low-density alteration deposits. They may be capable of acting as significant thermal aquifers only if repeatedly refractured by continuing seismic activity.

Reports of seismic swarming in the region from north of Denio to McGee Mountain support the possibility of continued tectonic fracturing of basement. Therefore, thermal water storage is postulated tentatively for deep-lying basement sections along or near to Quaternary or historic fault zones.

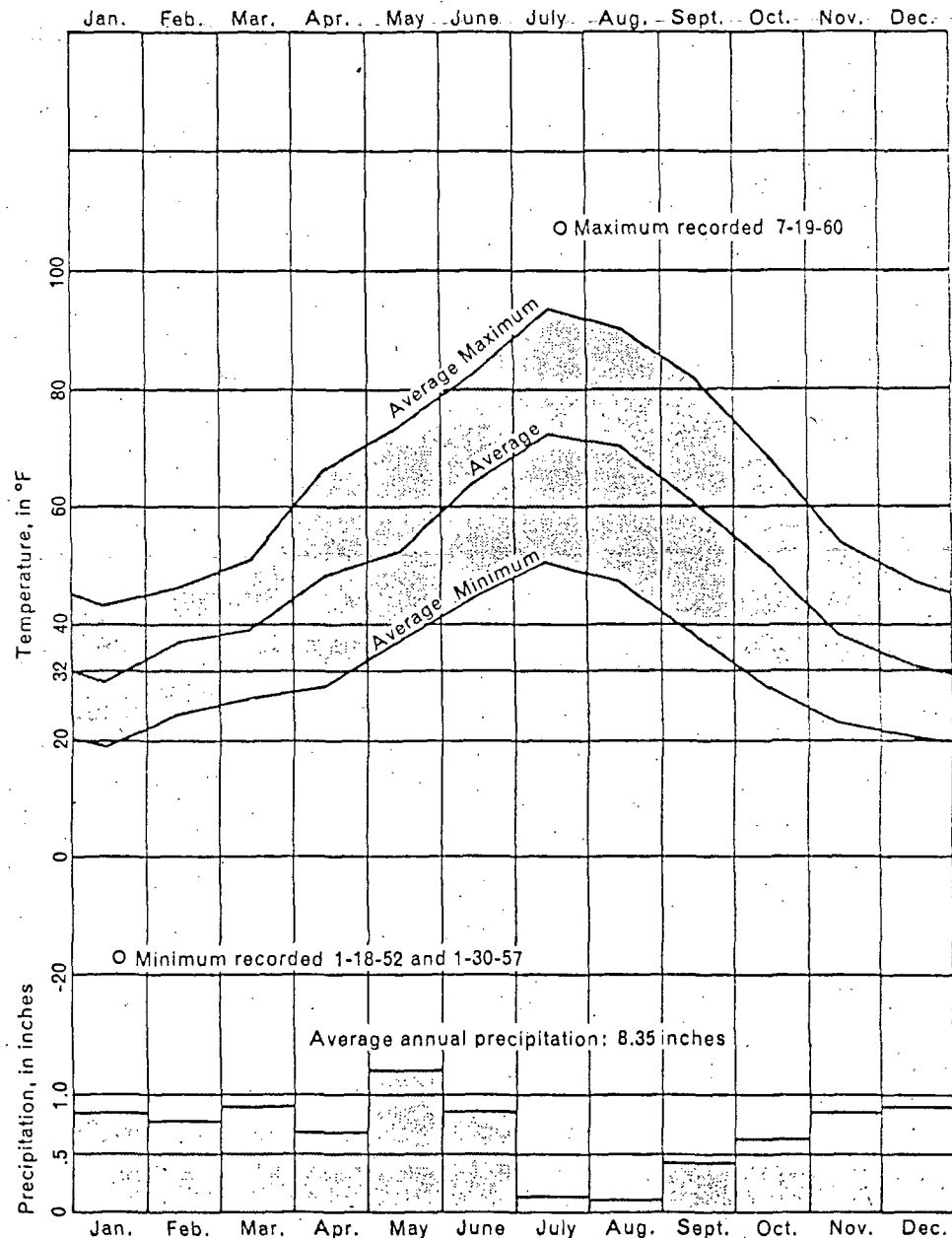
Of the Tertiary volcanic rocks, the greatest aquifer potential probably lies within the basalts of the Pueblo Series, which includes numerous flows of vesicular and nonvesicular character. Groundwaters can occupy fractures, vesicles, and interflow zones in the Series, and as the Series



VIRGIN VALLEY

Altitude 4,805

Average monthly precipitation and temperature data for the period  
1952-1956 and 1960-1962



DENIO

Altitude 4,185

Average monthly precipitation and temperature data for the period 1952-1961

Figure 1. Precipitation and temperature Records, Virgin Valley and Denio, Nevada  
(from Sinclair, 1963)

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may total almost 5,000 feet in thickness, the total storage capacity could be significant. The rhyolite and tuffaceous volcanic and sedimentary rocks above the basalts have lower aquifer potential, particularly for the storage of high-temperature water, as they have relatively low primary porosity, and both the primary and secondary porosities are likely to seal easily with low density alteration products. Rhyolitic flow rocks and welded tuffs may form aquifers, however, where fractured.

The alluvium of the valley fill was described as follows by Sinclair (1963):

[It] is composed of rock debris eroded from the surrounding mountains and deposited largely by mudflow and flood waters because of the flashy nature of the streams. As a result, it is composed of poorly-sorted rock particles ranging in size from clay to boulders.

The permeability of alluvium, although much greater than that of bedrock, is generally low to moderate, depending on the size and degree of sorting of the rock particles. Layers and lenses of well-sorted sand and gravel are found at various levels within the alluvium. These are best developed off the mouths of the canyons where streamflow has sorted the particles according to size and weight, carrying the finest particles farthest out toward the center of the basin. The texture of the source rock is also a controlling factor affecting the permeability of the alluvium. Tuff and lake beds contribute a large proportion of silt and clay to the alluvium, thereby reducing the permeability. Weathered granite is also of generally low permeability due to the angularity of the fragments and the high proportion of mica.

The alluvium mantling the mountainsides has been reworked extensively by wave action in the lakes which have filled the valleys to various levels in the past. The winnowing action of the waves removed much of the fine material from the shores leaving beaches and bars of well-sorted sand and gravel ringing the valleys at several elevations, both above and below the present valley floor. In the central parts of the valleys, the valley floor is underlain by silt and clay deposited in the relatively still, deep parts of the lakes.

Around the margins of the valleys the thick clay and silt sections are interbedded with relatively thin layers and lenses of sand and gravel which are principally stream deposits and reworked alluvium that accumulated during shallow stages of the lakes and periods of desiccation. These sheets of sand and gravel, though thin, may be quite extensive and probably constitute the most important aquifers in

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the area. They are best developed along the edges of the valleys but thin basinward as they interfinger with the silt and clay.

The thickness of the sedimentary fill in Continental Lake Valley is uncertain and probably variable. The oldest alluvium probably grades downward into interbedded and interfingering Tertiary volcanic and sedimentary rocks. The extent and thickness of these over the pre-Tertiary crystalline basement may vary. Most of the Tertiary section may be 4,000 to 7,000 feet thick, but parts may be very much less. In addition, the volcanic sequences and crystalline rocks undoubtedly are broken into uneven relief by normal faults which strike NNE-SSW and others which strike NW-SE. In Alvord Valley, the northern extension of Pueblo Valley, the probable maximum thickness of fill is about 3,300 to 5,000 feet (1,000 to 1,500 meters) beneath the center of the valley, as indicated by gravity studies. However, Alvord Valley is bounded on both the east and west by normal faults.

On its west side Continental Lake Valley is clearly bounded by the fault escarpments of the Pueblo Mountains and of McGee Mountain. However, basalt beds exposed at the base of the Pine Forest Range along the east side of the valley dip 25° to 27° westward, and signs of a normal fault between the basalts and the valley are absent. Thus, the Continental Lake valley fill may be wedge shaped, thickening westward. As the valley is about 1.5 miles wide across Continental Lake, just south of Balthazor Hot Spring, the basalts which dip 25° W project to a depth of 3,700 feet below valley surface at the Pueblo Mountains range front. These strata are probably not the top of the basalt unit, which correlates with the Steens-Pueblo Series; and as the basalts probably are overlain beneath the valley by rhyolite, tuff, and tuffaceous sediments at least 800 feet thick, the maximum thickness of fill may easily be one to two thousand feet less than 3,700 feet. The average thickness of fill is probably much less.

The depth of Quaternary valley fill along the McGee Mountain escarpment may be very slight. McGee Mountain is composed of 2,000 to 2,300 feet of tuff, tuffaceous sediments, and rhyolites of Miocene and Pliocene age, which probably overlie several thousand feet of basalts. Vertical displacement on the McGee Mountain fault has been estimated to total about 500 feet, placing the top of the basalts 2,000 feet below the valley surface beneath the 2,000 feet of tuffs and volcanic sediments, with only a very thin veneer of Quaternary alluvium on top.

The only existing deep well in the region is at Knott Creek Ranch (1,150 feet; 43N-27E-4a), south of Gridley Lake in Gridley Valley. Its log lists clay, sand, and gravel overlying granite at 1,148 feet.

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Volcanic rocks are interbedded with the sediments from 369 to 376 feet and in three layers 3 to 13 feet thick between 727 and 788 feet (Sinclair, 1963). It is probable that some of the reported sediments are of volcanic origin, although it is unknown if some actually are tuffs.

INFLOW AND OUTFLOW: WATER BUDGET FOR  
THE BALTHAZOR-McGEE AREA

Groundwater moves from recharge areas in the mountains and alluvial slopes downgradient toward the central parts of the valleys where, under natural conditions, it is discharged by evaporation from bare soil, springs, and seeps and transpired by plants. The ultimate source of recharge to the groundwater reservoirs of Virgin Valley, Gridley Lake Valley, Continental Lake Valley, and Pueblo Valley is precipitation within the watershed. Although the average annual precipitation is probably less than eight inches on the valley floors, it increases with increasing altitude, and the area can be subdivided into precipitation zones, based largely on altitude, exposure, and aspect vegetation. Table 2 presents such a subdivision of the study area, as described by Sinclair (1963).

Only a small part of the total precipitation ever reaches the groundwater reservoirs in the valleys. Most is transpired and evaporated. Part of the rest forms immediate run-off, and part infiltrates into rocks of the mountains and into alluvial fans from which it moves into the valley fill or comes to the surface along streams and at springs. Further loss by evaporation and transpiration then takes place.

A detailed determination of the percentage of precipitation that infiltrates into groundwater aquifers is impossible. The percentage is small and for a given amount of precipitation varies considerably with the terrane. Table 2, however, includes estimates of groundwater recharge based on percentage recharge data determined empirically by hydrologists working in eastern Nevada. These estimates (3 to 15 percent) may be in the proper order of magnitude.

Under natural conditions, groundwater recharge is balanced by discharge at springs and seeps, by transpiration from plants, and by evaporation from the land surface. Some basins may also lose groundwater by underflow through permeable material to adjoining basins. Human activities may modify this balance by well-pumping and irrigation or by alteration of such natural factors as water courses or vegetation patterns.

Table 2. -- Estimated precipitation and recharge to the ground-water reservoirs of the Pueblo Valley-Continental Lake region, Humboldt County, Nevada.

(from Sinclair, 1963)

Drainage area	Precipitation zone (inches)	Altitude of zone (feet)	Area of zone (acres, rounded)	Precipitation (acre-feet per year, rounded)	Percent recharged	Estimated recharge (acre-ft. per year rounded)
<u>Virgin Valley</u>	8-12	5,000-6,000+	280,000	230,000	3	7,000
<u>Gridley Lake Valley</u>						
Western watershed	8-12	4,500-6,000+	64,000	53,000	3	1,600
Eastern watershed	8-12	4,500-6,000	30,700	25,500	3	800
	12-15	6,000-7,000	9,300	10,500	7	700
	15-20	above 7,000	6,100	8,900	15	<u>1,300</u> 4,500
<u>Continental Lake Valley</u>	less than 8	below 4,500	60,000			
Western watershed	8-12	4,500-6,000+	182,000	151,000	3	4,500
Eastern watershed	8-12	4,500-6,000	72,000	60,000	3	1,800
	12-15	6,000-7,000	20,300	23,000	7	1,600
	15-20	above 7,000	13,800	20,200	15	<u>3,000</u> 11,000
<u>Pueblo Valley</u>	less than 8	below 4,500	16,500			
	8-12	4,500-6,000	40,500	33,700	3	1,000
	12-15	6,000-7,000	13,000	14,600	7	<u>1,000</u> 2,000



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Table 3 shows estimated natural discharge from the groundwater reservoirs of the Pueblo Valley-Continental Lake region. The tabulated mechanisms of discharge are as follows.

Springs and seeps are common in the region's mountains. Most are of the gravity type, occurring where the land surface intercepts the water table or where infiltrating groundwater encounters an impermeable rock stratum and flows laterally to the surface. This is common in the Virgin Valley watershed, where water percolates rather easily through basalts capping the mesas, then collects above indurated tuffs and lake beds across which it moves until discharged at canyon walls. The Virgin Valley area includes several warm springs which are probably all of this type: Virgin Valley Ranch warm spring (23°C), Virgin Valley campground warm spring (32°C), and Thousand Creek Spring (26.5°C). All have high flow rates (see table 1), and the warmest is only 20°C above the approximate mean annual air temperature (12°C). If the regional geothermal gradient beneath Virgin Valley is only 40° to 60°C/km, the water issued at the campground warm spring need have circulated to no more than 0.5 km (1,600 feet) or even only 0.3 km (1,000 feet) to be warmed to the observed temperature. These depths are approximately equal to the topographic relief from the altitude at which the spring issues in the valley of Virgin Creek (4,840 feet) to the highest parts of McGee Mountain to the east, beneath which the spring water collects. The summit of McGee Mountain is 6,667 feet, and much of the mountain is above 5,800 feet. Thus, the water at the campground spring, as well as that from the other warm springs of the Valley, probably has not circulated significantly deeper than the altitude at which it issues.

Springs in the central parts of Continental Lake, Pueblo, and Gridley Lake Valleys are more likely fed by upward leakage from underlying artesian aquifers. This is particularly true of Bog and Balthazor Hot Springs, which are associated with probably active fault zones. Sinclair (1963) reported these springs to issue about 1,000 and 200 gallons per minute, respectively. In October 1977, they were flowing about 1,000 and 5 gallons per minute.

As of 1963, the total withdrawal of groundwater from wells for irrigation in Continental Lake Valley was probably 500 to 700 acre-feet at Alder Creek Ranch. At Knott Creek Ranch (Gridley Lake Valley) pumpage may have been 200 to 500 acre-feet per year, and at ranches near Denio (Pueblo Valley), 1,000 acre-feet per year (Sinclair, 1963). Pumpage by 1977 probably was not much greater. The magnitudes of this withdrawal are not sufficient to affect appreciably the hydrologic regimens of the valleys.

Table 3. -- Estimated natural discharge from the ground-water reservoirs of the Pueblo Valley-Continental Lake region.  
(from Sinclair, 1963)

	Area of evapo- transpiration (acres)	Estimated rate of discharge (ft. per year)	Estimated discharge (acre-feet per year) rounded
<u>Virgin Valley</u>			
Ponds, marshes and wet meadows <sup>1/</sup>	3,000	2.0	6,000
<u>Gridley Lake valley</u>			
Greasewood	3,800	0.2	800
Playa and Saltgrass	300	4.0	<u>1,200</u> 2,000
<u>Continental Lake valley</u>			
Greasewood	28,000	0.2	5,500
Playa and Saltgrass <sup>2/</sup>	750	4.0	3,000
Bog Hot Spring <sup>3/</sup>		2.8 cfs	<u>2,000</u> 10,500
<u>Pueblo Valley</u>			
	a 6,000	0.2	1,200

1. Includes phreatophytes supported by discharge from Big Spring (100 gpm<sup>†</sup>) and Thousand Creek Spring (500 gpm<sup>-</sup>).
2. Includes about 100 acres of Saltgrass supported by discharge from Continental Hot Springs (100 gpm<sup>†</sup>).
3. Discharged by evaporation from reservoir, loss to phreatophytes and hydrophytes in reservoir, and by irrigation of about 500 acs. meadowland.
- a. In large part greasewood.

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As mentioned previously, there is probably not any significant underflow between Virgin, Gridley, and Continental Lake Valleys. From the portion of Pueblo Valley in Nevada there may be about 1,000 acre-feet per year underflow into Oregon, calculated as the difference between the recharge and discharge estimates for Pueblo Valley in tables 2 and 3.

The largest discharges are by evaporation and transpiration. Water is lost from Continental Lake and Gridley Lake playas where the land surface intersects the capillary fringe. The areas of perennially standing water or wetted surface were estimated by Sinclair (1963) to be about 750 acres at Continental Lake and 300 acres for Gridley Lake. In October 1977, however, Continental Lake playa appeared to be dry. Transpiration occurs where the roots of plants classified as phreatophytes descend to the water table. Areas of phreatophyte growth in the region are included on plate 2, and the considerable discharge rates estimated for the various types of plants and the areas which they cover are in table 3.

The perennial yield of a groundwater reservoir may be defined as the amount of water that can be pumped or otherwise diverted from the reservoir without causing an excessive depletion of the stored water. This usually means salvaging water from natural discharge, which in turn is limited by natural recharge. As a preliminary estimate, the perennial yield of each sub-basin of the Pueblo Valley-Continental Lake area can be taken as within an order of magnitude of the estimates of recharge and discharge in tables 2 and 3: 6,000 acre-feet in Virgin Valley, 3,000 acre-feet in Gridley Lake Valley, 11,000 acre-feet in Continental Lake Valley, and 2,000 acre-feet in Pueblo Valley in Nevada.

Total groundwater in storage in the alluvium of each valley can be obtained from the estimated amount of water, by volume, which will drain from the deposits for each foot of lowering of the water level. The average specific yield is probably about 10 percent. As the floor of Continental Lake Valley covers about 60,000 acres, its alluvium probably would yield about 6,000 acre-feet per foot of lowering of the water table. This is to be regarded as a maximum. Due to variations in permeability of the sediments, and because of the possibilities of narrowing of the valley with depth and of finding chemically poor (saline) water in some areas, the potentially usable reservoir is probably much smaller.

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### Geothermal Water Demand

The above estimates of perennial yield are relatively small and may place restrictions upon geothermal development for electric-power generation at the anomalies in Continental Lake Valley. Water demand for geothermal operations varies with the size of the field and the type of power plant used. Assuming the use of an isobutane power plant, estimated minimum make-up demand per plant of 55-mW capacity would be approximately 3,100 acre-feet per year. Thus, a 500-mW total generating capacity would require approximately 30,000 acre-feet per year. These cooling-water requirements need not necessarily come from local surface reservoirs or water wells but may be obtained instead, all or in part, from produced geothermal waters. Blow-down water produced by the cooling cycle, approximately 100 acre-feet per year per plant, probably would be injected, as its high concentration of dissolved solids precludes recycling or its use as make-up water. The difference between make-up water and blow-down, about 3,000 acre-feet per year per plant, is lost through evaporation.

Only a small percentage of the estimated 11,000 acre-feet annual recharge to the groundwater systems of Continental Lake Valley is likely to enter the deep thermal regimes. The present influx is probably close to the natural flow rates of the springs. This rate might be increased, but only very slightly, by extraction of hot water from wells. If development proceeds, reinjection of the extracted hot water will certainly be necessary. For example, a single 55-mW isobutane plant may require heat from 11,000 acre-feet per year (3,300,000 pounds per hour) of 210°C (405°F) water.<sup>1</sup>

### WATER TEMPERATURE AND GEOTHERMAL GRADIENT MEASUREMENTS

Known sources of thermal groundwater in the area include Balthazor (or Continental Lake) Hot Spring, 76-100°C; Bog Hot Spring, 55°C; a fumarole at Painted Hills Mine on the east side of McGee Mountain; Gridley Lake warm spring, 36°C; and several warm springs in Virgin Creek Valley (see table 1). In contrast to these, cool groundwaters of the area range from 10°C to 18°C.

<sup>1</sup>Note that a 6,400-acre geothermal field (10 square miles) with a reservoir in valley fill of 10 percent specific yield would suffer a 17-foot drawdown per year if the hot water were simply pumped out and not reinjected. Such drawdown would probably quickly "mine" the reservoir and lead to problems of ground subsidence.

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Earth Power Corporation has carried out temperature-gradient drilling and defined the anomalies around Balthazor Hot Spring and the Painted Hills Mine fumarole (McGee Mountain).

#### WATER CHEMISTRY

##### General Chemical Character of the Groundwaters

Groundwaters of the Continental Lake area fall into several chemical groups:

1. Calcium-sodium-bicarbonate waters of the mountain highlands composed of Tertiary basalts and Mesozoic intrusive and metamorphic rocks, and in alluvial fans adjacent to these highlands.
2. Sodium-bicarbonate waters in the valley fill and silicic volcanic highlands. These include several mildly thermal waters and Bog Hot Spring (55°C).
3. Sodium-sulfate waters sampled at Balthazor Hot Spring and at a well about two miles from the Painted Hills Mine thermal anomaly (14°C, 45N-27E-13bdd).

These will be discussed in the sections on thermal groundwaters and anomalous cool groundwaters.

The calcium-sodium-bicarbonate (Ca-Na-HCO<sub>3</sub>) waters are typical of highland recharge throughout much of the western United States. They are dilute to very dilute (TDS 165 to 440 mg/l). Though Ca is the dominant cation by weight, it rarely is more than three times as abundant as the next most concentrated, usually Na. Their composition is the result primarily of the dissolution of calcic silicates, particularly feldspars and pyroxenes, by rainfall made weakly acidic from dissolving atmospheric carbon dioxide. The Ca-Na-HCO<sub>3</sub> waters are found in the Pueblo Mountains and Pine Forest Range, each comprised of basalts and Mesozoic metamorphic and intrusive rocks.<sup>1</sup> They form surface runoff as well as groundwaters,

<sup>1</sup>Groundwaters in some granites carry more Na than Ca, reflecting the abundance of alkali feldspars in such rocks. This effect was not seen in the Pueblo and Pine Forest waters sampled, except perhaps as the Na-HCO<sub>3</sub>

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so that they enter alluvial fans and adjacent valley sediments by infiltration through alluvial deposits as well as by subsurface flow. Thus, for example, Ca-Na-HCO<sub>3</sub> waters are produced by valley wells near Alder Creek, which perennially flows from the Pine Forest Range (samples in T. 45 N., R. 28 E.), and by valley irrigation wells around Denio adjacent to the Pueblo Mountains (samples 47N-30E-4b and 41S-35E-17dd).

Cool sodium-bicarbonate (Na-HCO<sub>3</sub>) groundwaters occur in silicic volcanic rocks of McGee Mountain and adjacent highlands in the western half of the project area (plate 1) and in alluvial fans adjacent to these highlands. These waters are usually dilute to very dilute (TDS about 90 to 350 mg/l). Their compositions are determined by the dissolution both of alkali feldspars in the silicic volcanics and (to lesser extent) volcanic glass. Similar waters can occur in valley deposits where groundwaters originally of Ca-HCO<sub>3</sub> composition have lost Ca and gained Na by cation exchange with clays. Mud Spring (47N-30E-14dbc) east of Denio issues a NaHCO<sub>3</sub> water from valley deposits. Its composition may be controlled by such base exchange on clay particles. However, the adjacent highlands are granitic and also may be a source of the Na. Mud Spring has notably high F (5.9 mg/l), which likely is derived from weathering of the granite and granitic detritus.

#### Thermal Groundwaters

The several mildly thermal groundwaters of the Virgin Valley area (23° to 32.5°C), the warm spring at Gridley Lake (36°C), and Bog Hot Spring (55°C) all issue Na-HCO<sub>3</sub> waters of unremarkable character. TDS are approximately 120 to 300 mg/l. All are associated with silicic volcanic rocks and volcanoclastic sediments at the surface. They probably have been heated by rapid circulation of meteoric waters to moderate depths within similar rocks, although the water of Bog Hot Spring may have penetrated into underlying earlier Tertiary volcanics, including basalts. Its water is hot enough to show a characteristic depression of Ca and Mg due to the retrograde solubility of Ca and Ca-Mg carbonates and sulfates.

Dyke Hot Spring (61-66°C) and Howard Hot Spring (55°C), in Pine Forest Valley, were sampled to monitor any temporal changes in composition which these waters might show and to provide a check on laboratory

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water of spring 41S-35E-8dba which issues from diorite or greenstone in the Pueblo Mountains, close to a contact with Mesozoic quartz diorite, granodiorite, and quartz albitite.

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performance. Both of these also are Na-HCO<sub>3</sub> waters, similar to Bog Hot Spring, although chemical geothermometry (see below) suggests that Dyke Hot Spring is hotter at depth.

Balthazor Hot Spring is distinctly different from all the above. It is a Na-SO<sub>4</sub> (or Na-SO<sub>4</sub>-HCO<sub>3</sub>) water of low to moderate TDS (about 700 mg/l) and moderate silica (approximately 150 mg/l) and contains relatively high B (about 2 mg/l) and F (7 mg/l) compared to most of the other thermal and cool groundwaters of the region. Its composition is generally similar to other Na-SO<sub>4</sub>-type thermal waters of Nevada and the lava plateaus of southern Oregon and northeastern California, although its Cl content is atypically low. Borax Hot Spring, in Alvord Valley some 30 miles to the north, is like Balthazor but for higher TDS, an unusually high level of B, and relatively higher chloride (SO<sub>4</sub> = 434 mg/l, HCO<sub>3</sub> = 378 mg/l, B = 16 mg/l, Cl = 250 mg/l).

Balthazor Hot Spring issues from depth into a single overflowing pool some 15 feet in diameter on the flat floor of Continental Lake Valley some distance from the eastern front of the Pueblo Mountains. Two reported estimates of its flow rate have varied by a factor of 4 (28 and 104 lpm), and records of its temperature made between 1970 and 1977 have ranged from a low of 76°C (measured during this study, October 1977) to a high of 96-98°C (by David Langenkamp, May 1977). Three of the four available measurements fall between 76° and 83°C. A well about one-quarter mile west of the spring has been known to flow water as hot as 96°C at about 25 lpm from an unknown depth. In October 1977 this well was not flowing; although cool at the surface, its temperature at a depth of 90 feet was 98°C. In December 1977 Murray Gardner of GeothermEx found the well flowing about 6 lpm at 97°C. This reactivation of flow was probably a response to rainfall in mid-November.

Three different chemical assays of Balthazor Spring taken at 76°C to 83°C and one of the well taken at 90°C all show an identical composition. These various records suggest that Balthazor's temperature fluctuations are most probably due to variable conductive heat loss from the water as it rises to the surface. The two estimates of its flow rate support this, as the higher flow was coincident with a higher temperature. Another possible source of temperature fluctuations is variable subsurface mixing of deep-hot and shallow-cool groundwaters. However, as discussed below, Balthazor probably is not of mixed origin.

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Cool Groundwaters of  
Anomalous Character

Near the north end of Gridley Lake is a spring which issues a Na-HCO<sub>3</sub> water with slightly greater TDS than other Na-HCO<sub>3</sub> waters in the study area (sample 44N-27E-1c; TDS = 885 mg/l). This water is also notably enriched in chloride (Cl = 177 mg/l) relative to all other waters sampled, including those of thermal origin. The spring flows about 2 lpm from salt-encrusted alluvium in a small alkali flat. A small (fault?) scarplet strikes N-S about 100 feet west of the spring, which suggests that its origin may be controlled by a fault-originated weakness zone in underlying sediments.

Most probably, the water has been relatively enriched in Cl (and Na) by flow through or storage in buried lacustrine deposits. The water is also enriched in silica, containing 98 mg/l. By comparison, most of the cool Na-HCO<sub>3</sub> waters contain 32 to 65 mg/l of silica, with only scattered samples showing more: 81 mg/l at Bog Cold Spring (46N-28E-7cbc), 76 mg/l at Bog Hot Ranch well (46N-28E-17cca), and 82 mg/l at Mud Spring (47N-30E-14dbc).

By comparison, the Ca-HCO<sub>3</sub> groundwaters carry about 25 to 30 mg/l of SiO<sub>2</sub> in the mountains, 31 to 43 mg/l in alluvial fans, and 52 to 57 mg/l where found in the valleys. The 98 mg/l silica anomaly at spring 44N-27E-1c could be due to its origin as a deep or mixed thermal fluid which has cooled to its 12°C surface temperature by conduction during slow ascent. Notably, the spring is located about two and a half miles from the center of the McGee Mountain (Painted Hills Mine) thermal anomaly, falls between the 125°C/km and 100°C/km isogradient contours determined from temperature-gradient drilling, and is near a 118°C/km gradient hole.

Alternatively, the high silica could be due to low-temperature dissolution of SiO<sub>2</sub> from glassy tuffaceous sediments. Such rocks are common in this area, and it thus might be expected that high SiO<sub>2</sub> concentrations would be more commonly encountered in cool groundwaters. The lack of evidence of former hot-spring activity at the spring site may weaken the thermal hypothesis.

However, 98 mg/l silica is more than found in any known thermal water of the area, except Balthazor. The warm spring at Gridley Lake (36°C), for example, contains only 66 mg/l of SiO<sub>2</sub>. Although the hypothesis of a thermal origin for this water probably is not essential to explain its character, it should be borne in mind.



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Three miles northeast of the McGee Mountain (Painted Hills Mine) thermal anomaly is a stockwell which produces a 14°C water strikingly similar in character to the water of Balthazor Hot Spring (see sample 45N-27E-13bdd). This is the only cool, Na-SO<sub>4</sub>-HCO<sub>3</sub> water sampled. It differs from Balthazor water only in having much lower SiO<sub>2</sub> (65 mg/l) compared to 154 mg/l), slightly higher Ca, Mg, K, and HCO<sub>3</sub>, and slightly lower SO<sub>4</sub> and F. Only the difference in SiO<sub>2</sub> is large compared to the otherwise very similar characteristics. Both waters contain the highest levels of boron (B) in the project area and ammonia (NH<sub>3</sub>) detected at 0.2 mg/l as N. Ammonia at 0.2 to 2.0 mg/l as N occurs also in Bog, Dyke, and Howard Hot Springs but is absent from all mildly thermal and cold waters with the one exception here considered.

Earth Power Corporation has drilled a temperature-gradient hole to a depth of 80 meters adjacent to well 43N-27E-13bdd, encountering a gradient of 58°C/km (hole number 147, bottom temperature 16.8°C). The probability that the well produces a water of thermal origin seems high. The well is located on a gentle slope underlain by alluvium and Tertiary sediments about two miles east of the fault escarpment of McGee Mountain. The low temperature at the site suggests that thermal water rises along the McGee escarpment fault and travels eastward and downward within the alluvium and unconsolidated sediments, the well tapping this flow. During this travel the water probably cools conductively and may precipitate excess silica.

To test the hypothesis of a thermal region, and in consideration of the presence of cinnabar deposits at Painted Hills Mine, mercury was sought in the cool sulfate water and in samples from Bog and Balthazor Hot Springs plus two other cool waters (table 1). Unfortunately, all samples contained less than the laboratory's detection limit of 0.0005 mg/l Hg. As the samples were not treated in the field with a preservative for Hg, small amounts near the detection limit could have escaped measurement. Cathrall and others (1970) reported 0.0007 mg/l Hg in Balthazor Hot Spring.

The possibility that the thermal water is leaking into other cool waters near well 45N-27E-13bdd has been investigated by plotting on plate 1 the ratio (SO<sub>4</sub>/TDS) x 100 as an indicator of relative sulfate content and drawing a few contour lines, which help to visually emphasize geographic patterns shown by the ratio in the eastern half of the project area.<sup>1</sup> As

<sup>1</sup>Relative sulfate is also indicated by the ratio of equivalents sulfate to total anion equivalents in each sample. Plotting of the ratios of equivalents gives the same general conclusions as the ratio of weight sulfate to TDS, even though in detail the resulting contours are slightly different in shape.

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the sample density is low, it should not be assumed that all unsampled groundwaters within each contour interval will have corresponding sulfate levels; the contours represent only those waters plotted.

The  $\text{SO}_4/\text{TDS}$  ratio is highest at Balthazor Hot Spring and the cool well 45N-27E-13bdd. A relative high extends from Balthazor northward into Pueblo Valley, where groundwaters contain about two-thirds the (relative)  $\text{SO}_4$  content of the hot spring. Another region of similarly high values surrounds the cool well, to several miles distance. Each region (within contours 20 on plate 1) may be one where the cool bicarbonate groundwaters contain a component of cooled deep thermal sulfate water. This mixing is only hypothetical, as the sulfate could well have come instead from valley sediments in a relatively shallow nonthermal flow regime, as, for example, from the oxidation of sulfide released by decaying, buried plant debris.

The relative amounts of sulfate in valley sediment groundwaters may depend in part on the source and character of active recharge mixing with older valley water. The sulfate ratios of Alder and Thousand Creeks are unknown but may be assumed to be low. The lowest ratios in valley sediments are found along the paths of each creek, where creekwater probably is infiltrating into the valley sediments and moving down-gradient towards Continental Lake.

Three groundwater samples from the Pueblo Mountains have very low sulfate ratios. Two samples from the Pine Forest Range have higher sulfate ratios, although one is from fan deposits (45N-28E-35abb). Giliotti well (45N-28E-32caa) and spring 44N-27E-1c may also represent Pine Forest recharge and also have relatively high sulfate. However, these two sources are both also within the slight sulfate anomaly around the McGee Mountain area cool sulfate well 45N-27E-13bdd. Two samples of McGee Mountain recharge have relatively low to moderate sulfate ratios (West Spring, McGee Mountain Spring). As mentioned above, the sulfate water of the cool well may be of thermal origin. Two miles northeast of it is a cool well (Bog Hot Well, 45N-27E-1acc) which may produce a mix of McGee Mountain recharge and the thermal water.

#### Gas Samples

The gases which escape at Balthazor Hot Spring, Bog Hot Spring, and Gridley Lake Warm Spring are primarily nitrogen with about 4 percent to 17 percent oxygen (table 4). Balthazor gases also include 0.8 percent methane. Ar was detected in the Balthazar gas but not in the remaining

TABLE 4

COMPOSITION OF GASES ESCAPING FROM HOT SPRINGS,  
CONTINENTAL LAKE REGION<sup>1,2</sup>

Spring Name	Oxygen (O <sub>2</sub> ) + Argon (Ar)	Nitrogen (N <sub>2</sub> )	Methane (CH <sub>4</sub> )	Carbon Dioxide (CO <sub>2</sub> ) <sup>3</sup>	Source <sup>4</sup>
Balthazor Hot Spring	4.2 <sup>5</sup>	95.0	0.8	<2	A
Bog Hot Spring	7.6	92.4	<0.05	<2	A
Bog Hot Spring	9	91	<1	<1	B
Gridley Lake Warm Spring <sup>6</sup>	17.2	82.7	<0.05	<2	A

<sup>1</sup>Compositions are in volume percentages.

<sup>2</sup>All samples lack detectable H<sub>2</sub> and H<sub>2</sub>S.

<sup>3</sup>CO<sub>2</sub> determined by difference.

<sup>4</sup>Source A: this study; source B: Mariner and others (1975).

<sup>5</sup>Argon detected as doublet peak this sample only.

<sup>6</sup>Average of three samples; range in O<sub>2</sub> + Ar = 16.5 to 18.1 percent;  
in N = 83.5 to 81.9 percent.

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samples. However, the chromatographic techniques employed for the analysis were not designed to quantitatively separate  $O_2$  and Ar.

In studies of hydrothermal gases at Yellowstone National Park, Gunter and Musgrave (1966) concluded that both  $N_2$  and Ar were of atmospheric origin, on the basis of isotopic evidence and ratios of the gases to each other and to other components. The origin of the oxygen is probably also atmospheric. Consistency of results in duplicate sampling suggests that the oxygen is truly evolving from the hydrothermal systems and is not merely a contaminant introduced during sampling.

However, because conditions at depth in hydrothermal systems are believed to be reducing, it is uncertain whether the oxygen has circulated to the deepest parts of each spring system or whether it may have been carried down locally by descending surface water. Similar amounts of oxygen have been measured in spring gases at Yellowstone National Park and in New Zealand (Gunter and Musgrave, 1966; Hulston and McCabe, 1962). In each set of cases, the circulation history of the oxygen has been regarded as uncertain.

The methane at Balthazor Hot Spring may have come from a reaction between carbon dioxide and hydrogen or from decay of organic matter.

Gases from alkaline springs at Yellowstone have been found to be predominantly nitrogen (Gunter and Musgrave, 1966) and are very similar to these Continental Lake region spring gases. However, the alkaline springs at Yellowstone, whose gases are greater than 80 percent  $N_2$ , almost always have a pH of 8.0 to 9.2. The aqueous pH's at Balthazor and Gridley range from 7.0 to 8.0, and the pH at Bog is 7.8 to 9.1. The Yellowstone gases with approximately neutral pH's usually contained variable amounts of both  $CO_2$  and  $N_2$ , the  $CO_2$  having come from alteration and decomposition of the country rock, from the atmosphere, and/or from organic decay.

The total lack of  $H_2S$  in the gas analyses precludes the use of  $CO_2$ : $H_2S$  ratios, which are used occasionally to determine the direction toward the highest-temperature portion of a field.

It is concluded, therefore, that gas analyses for the Continental Lake region added essentially nothing to our understanding of the deep thermal system.

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Geothermometer and Mixing  
Calculations

Table 1 includes equilibrium temperatures of the hot and cold groundwaters calculated with the various silica (quartz, conductive) and sodium-potassium-calcium (Na-K-Ca) geothermometers. Equations used for the calculations are from Truesdell (1977). The silica equation is based upon solubility data above 125°C (82 mg/l SiO<sub>2</sub>) and therefore has not been applied to waters with lower silica levels. Graphical representations of the solubility are available for the range 20°C to 125°C.

The solubility of SiO<sub>2</sub> (quartz, cristobalite, glass) always increases as temperature increases, but in comparing a group of cold or only mildly thermal groundwaters the measured SiO<sub>2</sub> levels cannot be assumed directly proportional to aquifer temperature, even as an approximation. This is because the sources of SiO<sub>2</sub> in such waters may vary. First, the rates of dissolution and equilibration of the various forms of silica are very slow at low temperatures, so that the amounts present in cool waters may not represent chemical equilibrium. This is particularly true wherever low-temperature weathering reactions also contribute silica to natural waters.

For example, the conversion of two moles of sodium feldspar to one mole of kaolinite by reaction with water and hydrogen ions releases four moles of silica, and ferromagnesian minerals may also release silica during weathering or other low-temperature alterations, such as serpentinization. (In contrast to the release of silica by weathering of sodium feldspars, plagioclase weathers to kaolinite without silica loss.) In the direct dissolution of silica, amorphous silica such as volcanic glass is much more soluble than quartz. For example, at 40°C, amorphous silica equilibrates with about 160 mg/l dissolved SiO<sub>2</sub>, whereas quartz equilibrates with only about 20 mg/l dissolved SiO<sub>2</sub>. Thus, anomalously high silica in a cool or mildly thermal (20°-30°C) groundwater may totally or in part be due to weathering reactions and solution of amorphous silica, particularly where siliceous volcanic or intrusive rocks are abundant.

Amorphous silica is unstable relative to crystalline silica and generally is absent from rocks in thermal systems where the kinetics of recrystallization are accelerated by high temperature. A temperature above which amorphous silica in rocks is not to be found cannot be specified. However, amorphous silica appears rarely to be present above 100°C to 150°C, and there are thermal systems below 100°C in which quartz probably controls the level of dissolved silica and amorphous silica is absent, either because it has recrystallized or because it never was present.

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The silica contents of the hot spring waters of the project area are lower than the solubilities of amorphous silica at their surface pool temperatures. It is thus possible that amorphous silica is dissolved by the hot waters from near-surface rocks or sediments, causing an anomalously high estimate of subsurface temperature with the quartz geothermometer. At Balthazor Hot Spring the quartz and Na-K-Ca geothermometers are in close agreement. Thus, the amorphous silica effect may be minimal and the SiO<sub>2</sub> quartz temperature correct. At Howard Hot Spring, in contrast, the quartz temperature (124°C) far exceeds the Na-K-Ca temperature (81°C), and the amorphous silica effect may be substantial. This is particularly likely as surrounding Howard Hot Springs are abundant old deposits of opal and sinter.

Bog Hot Spring contains 57 mg/l SiO<sub>2</sub>, no more than in many cool waters of the area and equivalent to the solubility of quartz at about 100°C. The Na-K-Ca geothermometer applied to Bog gives a temperature of 100°C to 125°C in four of five analyses; the fifth gives 87°C.

Considering the two geothermometers, a temperature at depth in the Bog system of greater than 100° to 125°C seems unlikely. It could be a mixed water of about 50 percent cool shallow water and 50 percent deeper thermal water. However, even in this case the aquifer temperature of the deep component is not likely to be above 100° to 125°C. In fact, if the cool component were similar to Bog Cold Spring (sample 46N-28E-7cbc), which carries more silica and has a higher Na-K-Ca temperature than the hot spring, the temperature of the hot Bog component could be less than 100°C!

All cool groundwaters in T. 46 N., R. 28 E, and two of three sampled in T. 45 N., R. 27 E., have Na-K-Ca temperatures of 190° to 200°C. This could be due to origin of the waters by leakage from a deep thermal aquifer. Much more likely, however, the assumption of equilibrium with feldspars does not apply to these waters, and their high Na-K-Ca temperatures are due to the effects of weathering of silicic volcanic glasses and base exchange of Ca for Na on clays in the valley sediments in which the waters reside. At Bog Hot Spring the Na-K-Ca thermometer is more likely valid because the real temperature of the water at the surface (55°C) indicates that it must have circulated to a moderate depth, at the least below the valley fill, and perhaps into the Tertiary basalts of the Pueblo Series and perhaps into underlying metamorphic rocks.

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At Balthazor Hot Spring the quartz (conductive) geothermometer indicates a 160°C aquifer,<sup>1</sup> and the Na-K-Ca geothermometer suggests equilibration with feldspars at 135° to 155°C. These are compatible results. An assumption of an aquifer temperature significantly higher than 150° to 160°C seems risky, and less than 135°C is probably equally unlikely.

Because Balthazor issues at a sub-boiling temperature, it is tempting to regard it as a mixed water with a deep component hotter than 160°C. However, neither considerations of surface temperature nor water chemistry clearly supports a mixed origin.

Evidence for conductive cooling of the Balthazor water has been discussed; temperatures at the spring may be as much as 20°C hotter only 100 feet below the surface (see section on Thermal Groundwaters). Chemical data, also, do not combine to present a consistent model of the water as mixed. Considerations of mixing based solely upon the temperature and silica content of the hot spring, and a range of probable temperatures and silica levels in hypothetical and cool components, suggest the existence of a deep, hot component at about 200°C to 220°C which has mixed with perhaps 50 to 60 percent of a cool groundwater before issuing at the spring.<sup>2</sup> However, when this mixing ratio is applied to all the major solutes in the Balthazor water, in combination with the composition of the various cool groundwaters in table 1, it is not possible to find a suitable cool component for the model.

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<sup>1</sup>Three of four silica measurements of Balthazor are from 150 to 160 mg/l. The fourth, 130 mg/l, was made on a sample not preserved by dilution when collected and (apparently) not analyzed by a laboratory which routinely processes geothermal waters. That analysis probably is in error.

<sup>2</sup>This mixing prediction uses the most conservative estimate of the spring's "mixed" temperature, which is the hottest known water: 96-98°C measured at 100 feet depth in the Balthazor well in October 1977 and measured at the surface in May 1977 and December 1977. This assumes, then, that mixing produces a water of approximately 100°C, which then cools conductively to about 80°C at the spring orifice. The possibility of mixing at a still higher temperature, followed by correspondingly more conductive cooling, remains. However, the general result of this consideration applied to mixing models is that the higher the initial temperature of the mixture (before conductive cooling), the lower the temperature of the hypothetical deep component. Thus, the 200° to 220°C estimate for the deep temperature should be considered a maximum.

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The Balthazor water contains very little Mg, so little that the Ca-HCO<sub>3</sub> recharge waters would constitute less than 10 percent of it. Even most of the Na-HCO<sub>3</sub> valley and highland waters contain too much Mg to serve as the cool fraction. When the uncommon examples of those that do not (Giliotti well; 45N-28E-32caa; Mud Spring, 47N-30E-14dbc) are used in the model, this conflict is avoided. However, the deep fluid compositions that are then calculated have alkali concentrations such that Na-K-Ca temperatures remain about 150°C, instead of rising to the 200°C to 220°C suggested by silica.

Thus, acceptance of a mixed origin for Balthazor water requires assuming that the silica geothermometer is valid, whereas the Na-K-Ca geothermometer is not. Since both types of geothermometer jointly predict an aquifer temperature of 150°C to 160°C without mixing, it seems safest to accept that temperature as the reservoir base temperature and conclude that mixing has not occurred. At an outside limit, SiO<sub>2</sub> (but not Na-K-Ca) geothermometry permits assumption of 200° to 220°C in a deep reservoir.

The remaining thermal waters of the Continental Lake area (Gridley warm spring, the Virgin Valley area warm springs) all have silica and Na-K-Ca temperatures slightly to well below 100°C. The only exception is a 214°C Na-K-Ca temperature at Gridley Lake warm spring. However, its silica content is so low (66 mg/l) that the Na-K-Ca temperature is highly suspect. None of the warm springs can safely be assumed to have an aquifer temperature more than a few degrees above the surface temperature.

No estimate of reservoir temperature can be derived geochemically for the fumarole at McGee Mountain (Painted Hills Mine). However, it is not unreasonable to assume that temperatures there will parallel those at Balthazor, based upon temperature-gradient data.

#### SUMMARY AND MODEL OF GEOTHERMAL SYSTEMS AT BALTHAZOR HOT SPRING AND MCGEE MOUNTAIN

From the chemical composition of Balthazor Hot Spring, a reservoir temperature of about 160°C is inferred. Sharply higher temperatures seem unlikely, and the water probably does not mix with more than a small percentage of cool recharge as it ascends to the surface. Thus, the deep fluid is probably much like that at the surface, mild in composition (TDS about 700 mg/l) and unlikely to present problems of corrosion or disposal if tapped by deep wells.

The chemical composition gives some indication of the rock compositions encountered by the water at depth. First, a carbonate reservoir can



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be discounted. The water is of sodium-sulfate character which is like many thermal waters in Nevada, Oregon, and California, particularly in the lava plateaus region of south-central Oregon, northeast California, and northwest Nevada. This suggests storage in, or at least circulation through, volcanic rocks at depth.

Balthazor Hot Spring contains relatively high F. Its absolute concentration of F is about the same as in Howard and Dyke Hot Springs, and its ratio F/TDS is about one-half of theirs. The ratio F/TDS at Balthazor is greater than at any cool groundwater source in the area, except for Mud Spring. It is also similar to F/TDS of the water at Mickey Hot Spring in the Alvord Desert but higher than F/TDS of Alvord Hot Spring. Mud Spring probably derives its high F from sedimentary detritus eroded from granitic rocks of the Pine Forest Range. We infer that the source of high F in Dyke, Howard, and Balthazor Hot Springs is acidic igneous rocks. These may be Tertiary rhyolite or dacite or, more likely, Mesozoic granite. It is assumed, therefore, that granitic basement at depth beneath the southern Pueblo Mountains, the Pueblo Valley, and the Pine Forest Range serves as host for circulation and possible storage of fluid, at depths perhaps of more than a kilometer.

Waters circulating below the McGee Mountain thermal anomaly may be of a sodium-sulfate character similar to Balthazor Hot Spring in temperature and source rock, but hot water does not erupt at the surface. The indication of water composition is provided by a cool sodium-sulfate well outside the temperature anomaly. We hypothesize that the well produces thermal water which has moved down-gradient from beneath the anomaly to the well-site. Notably, it has the highest F concentration in that sub-area. Samples of fluid should be taken from all deeper (>500 feet) gradient holes to be drilled in the area.

Regional heat flow probably results in an average geothermal gradient beneath the Continental Lake area of 40° to 50°C/km. Thus, the Balthazor water may circulate to about three kilometers in the absence of an external heat source. Thermal reservoirs, if they exist, could lie at various and much shallower depths. Possible aquifer host materials are basalts of the Steens-Pueblo Series and fractured Mesozoic basement. At the McGee Mountain anomaly the basalts may lie 2,000 feet below the valley surface, beneath Tertiary volcanic sediments and tuffs, and at 1,500 to 2,000 feet below the easternmost mountain uplands. A well in the valley at the mountain escarpment may pass through the normal bounding fault and penetrate basalt beneath the upland at about 1,000 feet depth. At Balthazor Hot Spring the basalts may underlie perhaps 2,500 to 3,500 feet of younger Tertiary materials and valley fill.

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Seismicity in the area supports a concept of fractured basement granites acting as a reservoir. Quaternary valley fill, especially in its deeper sections, may be too indurated or clay-rich to serve as an aquifer. To help in evaluation of hypothetical reservoirs in basalts and granitic basement beneath the valley at Balthazor Hot Spring, it may be worthwhile to perform a gravity survey. Estimates of the depth to these units would be useful for comparison with known temperature gradients to place bounds on possible aquifer temperatures.

The thermal anomaly at Balthazor apparently extends beneath the Pueblo Mountains as well as Continental Lake Valley. The gradient hole density is too low to show in detail whether there are discontinuities in heat flow passing from the valley to the mountains. Although a single deep reservoir may underlie both, it would be intersected by the normal fault bounding the Pueblo Mountains and might occupy different rock types on each side.

Alternatively, there may be separate reservoirs beneath valley and mountains, at different depths and temperatures and in different rock suites: for example, a deeper and hotter reservoir in Tertiary volcanic beneath the valley and a shallower, cooler reservoir in the same unit of rocks across the fault under the mountains, or reservoir in basement on one side of the fault and in Tertiary volcanic rock on the other.

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