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Geothermal investigation of the Alvord Valley, southeast Oregon

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GEOTHERMAL INVESTIGATION OF THE

ALVORD VALLEY, SOUTHEAST OREGON

By

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ABSTRACT

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The Alvord Valley in southeast Oregon is believed to have geothermal power potential. The purpose of this project was to develop a model for hot water circulation for the three hot spring systems in the valley in order to further the geothermal power evaluation.

The sulfates from four Alvord area hot springs and associated local playa evaporite sediments were sampled and analyzed for their sulfur isotopic ratios. A suite of volcanic rocks from Steens Mountain on the west side of the valley was also analyzed for whole rock sulfur isotopic ratios. Results indicate that sulfur in the hot springs is either leached directly from the volcanic rocks or from nearby playa evaporite deposits as the water circulates up to the surface. No evidence was found to suggest the presence of magmatic sulfur in any of the hot spring waters. This agrees with both deuterium-hydrogen and $^{18}O/^{16}O$ isotope data for the same springs which indicate that the water is meteoric in origin (R.H. Mariner, personal communication, 1975). Gravity surveys were run across two of the three areas containing hot springs in the valley. This information along with structural data already available on Steens Mountain to the east of the valley was used to model the structure of the mountains and the valley-fill. Structural models together with isotopic data, heat flow data, and other geochemical information suggest that the water in the Alvord Valley geothermal systems originates as runoff from Steens Mountain. The waters then circulate down through faults and fractures in the mountains to depths ranging from 1.0 to 1.5 km, become heated, and circulate rapidly back up to the surface along faults at the margins and in the middle of the valley.

It appears that the hot springs in the Alvord Valley look promising for the development of geothermal power. However, it is recommended that consideration should be given to economic factors before undertaking the drilling necessary to study the extent, permeabilities, exact locations, and temperature distributions of the thermal reservoirs associated with the Alvord Valley hot spring systems.

ACKNOWLEDGEMENTS

The author is indebted to Dr. Ian Lange, Dr. David Alt, and Dr. Wayne Van Meter for guidance and advice during this thesis project. Special thanks are due to Dr. Anthony Qamar for invaluable help in the field and discussions concerning gravity data reduction and structure modeling. Thanks are also due to Dr. Roy Krouse and the Stable Isotope Laboratory at the University of Calgary for sulfur isotope analyses. A Grant-in-Aid of Research from the Society of Sigma Xi is gratefully acknowledged.

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CHAPTER 1

INTRODUCTION

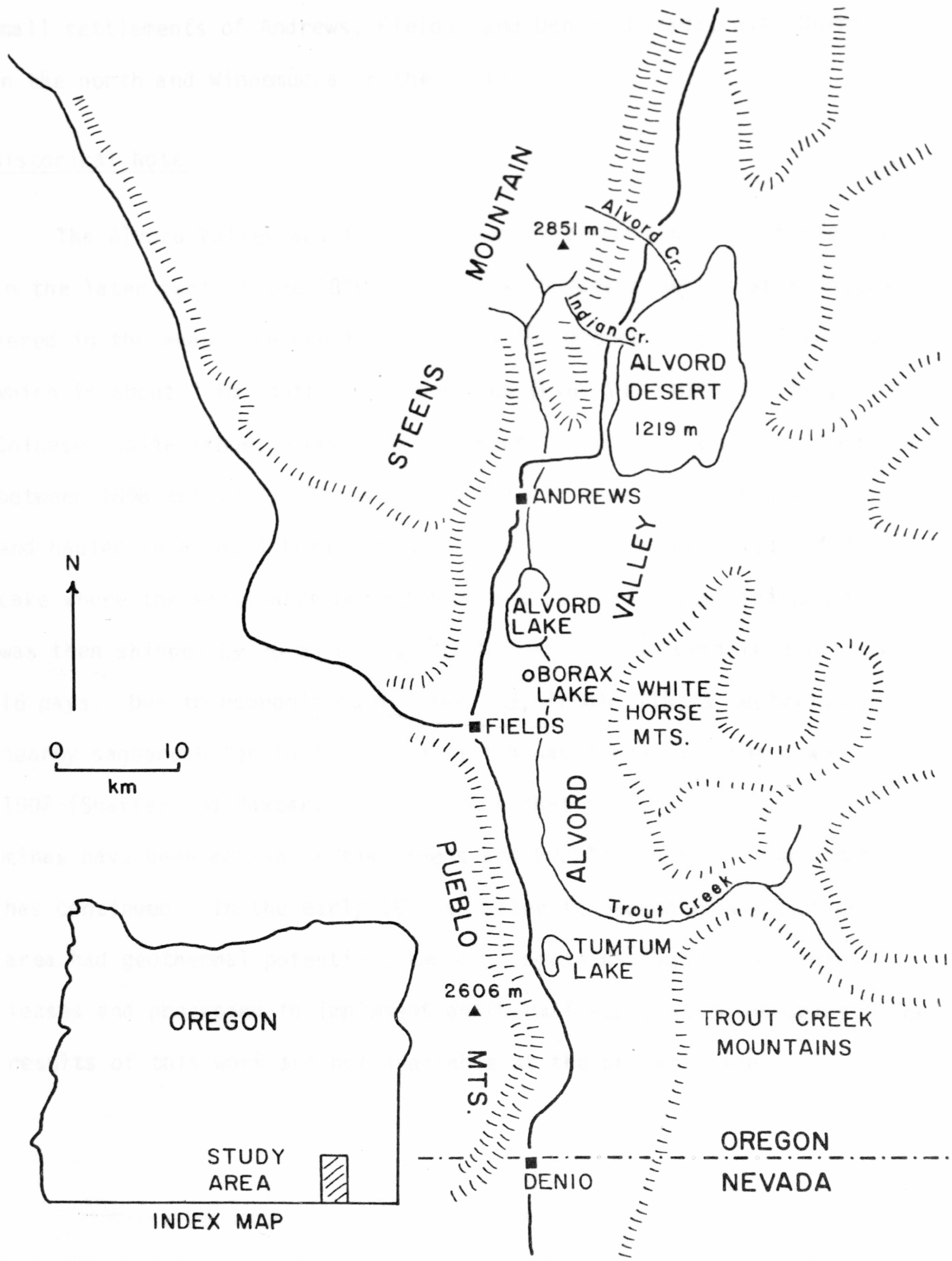
Purpose and Scope

The Alvord Valley in southeast Oregon is believed to have geothermal power potential (Groh, 1966; Godwin, et al., 1971; White and Williams, 1975). Information needed in a geothermal power evaluation includes studies of permeability, heat flow, seismic and gravity surveys, and the origin and circulation of associated thermal waters. The objectives of this project were to: 1) delineate more clearly the structures through which the water is circulating using gravity surveys; and 2) determine the origin and circulation of the thermal waters in the valley through the use of sulfur isotopes and geochemistry. Thus a more complete picture of the Alvord Valley geothermal system will be presented which should be helpful in the evaluation of potential for the development for geothermal power.

Location

The valley, located about 180 km south-southeast of Burns, Oregon, and about 195 km north of Winnemucca, Nevada, is shown on the Adel, Oregon, 1:250,000 scale topographic map (Fig. 1). The valley is about 120 km long and 13 km wide at the widest part near Alvord Lake. The Steens and Pueblo mountains bound the valley on the west while the White Horse or Trout Creek Mountains constitute the eastern boundary.

Figure 1. Location map of the Alvord Valley in southeastern Oregon (Williams and Compton, 1953).



A gravel road along the west side of the valley connects the three small settlements of Andrews, Fields, and Denio, Nevada, with Burns on the north and Winnemucca on the south.

Historical Note

The Alvord Valley was first settled by a small number of stockmen in the later part of the 1800's. In 1898 borate minerals were discovered in the evaporite crusts formed on the ground north of Borax Lake which is about 3 km south of Alvord Lake (Fig. 1). With the help of Chinese coolie labor, a moderately successful borax operation flourished between 1898 and 1907. The evaporite crusts were raked into windrows and hauled to a small borax processing plant on the west side of Borax Lake where the salts were boiled down and refined. The finished product was then shipped by 20 mule teams to Winnemucca, a round trip of some 16 days. Due to economic conditions and, ironically, a depletion of nearby sagebrush for fuel, the operation was forced to shut down in 1907 (Shaffer and Baxter, 1972). Since that time, a few small mercury mines have been active in the Steens and Pueblo mountains and ranching has continued. In the early 1970's, after it became known that the area had geothermal potential, two oil companies signed geothermal leases and proceeded to implement geothermal exploration programs. The results of this work are not available at the present time.

CHAPTER 2

GEOLOGIC SETTING

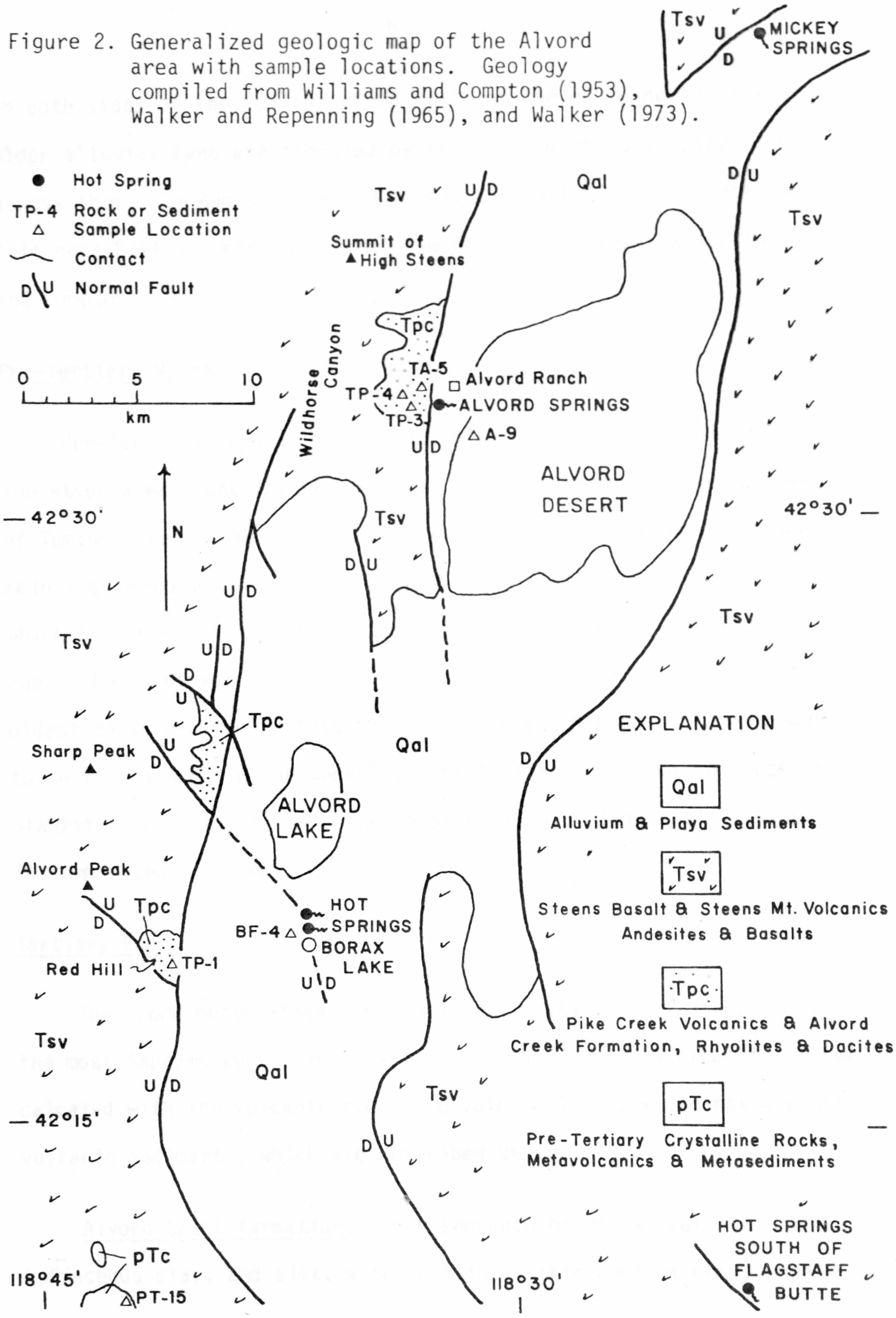
The geology of the Steens-Pueblo Mountains and the Alvord Valley has been described by Waring (1909), Fuller (1931), Williams and Compton (1953), Wilkerson (1958), and Gunn and Watkins (1970). Fuller worked out the impressive volcanic section exposed on the east side of Steens Mountain while Williams and Compton mapped the geology, structure, and mercury deposits of the Steens and Pueblo Mountains. The following summary of the structure and geologic section is taken mostly from Williams and Compton (1953).

Structure

The valley is a graben structure bounded on the east and west by north-trending basin-and-range type normal faults (Fig. 2). On the eastern side displacement is at least 350 meters and may exceed 1,300 meters. Suggested displacements on the Steens-Pueblo Mountain scarp on the west vary from 1,300 meters to 3,300 meters, with the greatest amounts of movement being in Steens Mountain opposite the Alvord Desert.

Dips of volcanic flows exposed by faulting vary from 10° to 30° to the west. Most of the faults which bound the valley on the west in a stair step fashion strike approximately north-south. Another set of transverse faults ranges in trend between N30°W and N60°W with maximum displacements of only a few hundred meters. Recent faults are numerous

Figure 2. Generalized geologic map of the Alvord area with sample locations. Geology compiled from Williams and Compton (1953), Walker and Repenning (1965), and Walker (1973).



on both sides of the valley. From south of Fields to north of Andrews, older alluvial fans are trenched by streams and obvious scarps run across them. On August 9 and 10, 1943, at least 12 small shocks were felt near Fields during Williams' and Compton's investigation (Williams and Compton, 1953).

Pre-Tertiary Rocks

Pre-Tertiary crystalline rocks are exposed in the southern part of the study area along the crest of the Pueblo Mountains from just west of Tumtum Lake southward to the Nevada state line. These rocks are mainly greenstones, argillites, quartzites and marbles of Paleozoic age which are intruded by quartz diorites and monzonites of late Jurassic age. These metavolcanic, metasedimentary and plutonic rocks are the oldest rocks exposed in this part of southeast Oregon and are thought to be the basement which underlies the Tertiary volcanic sequence which blankets the area (Williams and Compton, 1953). This entire sequence is summarized in Figure 3.

Tertiary Rocks

The 1,800 meter Steens and Pueblo Mountain scarp exposes one of the most impressive volcanic sections in the Pacific Northwest. Intercalcated with the volcanic flows are volcanoclastic sediments and non-volcanic sediments, which are described below.

Alvord Creek formation. This sequence of well-stratified tuff, tuffaceous clay, and silt, with occasional interbeds of chert, shale,

Figure 3. Summary of rocks exposed in the Alvord area. Compiled from Fuller (1931), Williams and Compton (1953) and Gunn and Watkins (1970).

Unit	Description
Alluvium	Valley fill consisting of gravel, boulder deposits, sand, silt, and playa lake sediments. Total thickness 1,000 to 1,500 m in the middle of the valley. Age, Pleistocene to Recent.
Steens basalt	Cliff-forming flows of olivine basalt with rare interbeds of tuff. Thickness exceeds 1,000 m on the High Steens. Age, middle Miocene (15.1 $\pm$ 0.3 m.y.).
---------- unconformity ----------	
Steens Mountain volcanic series	Olivine and augite basalts, and amygdaloidal andesites rich in zeolites. Locally thick sheets of dacite and rhyolite cap the basic lavas. Pyroclastic interbeds are rare and thin. Total thickness more than 1,000 m near Sharp Peak and Alvord Peak and in the Pueblo Mountains. Age, early-middle Miocene.
---------- unconformity ----------	
Pike Creek volcanic series	Rhyolite and dacite flows and tuffs. Thickness exceeds 500 m. Age, early Miocene.
Alvord Creek formation	Acidic tuffs and tuffaceous sediments, clays, opaline cherts, and lenses of conglomerate. Exposed thickness, 275 m; base concealed. Age, early Miocene.
---------- unconformity ----------	
Pre-Tertiary crystalline rocks	Greenstones interbedded with argillite, quartzite, marble, sericite phyllite, and chlorite schist. Presumably Paleozoic in age. Intruded by Jurassic granites, Thickness unknown.

and conglomerate is exposed between Pike and Big Alvord Creeks along the base of the scarp just west of the Alvord Desert. The base of this formation is concealed, and the maximum exposed thickness is about 275 meters in the Alvord Creek canyon (Libbey, 1960).

Pike Creek volcanic series. These flows of interbedded rhyolite, dacite, and occasional tuffs conformably overlie the Alvord Creek formation and can be found west of the Alvord Desert, on Red Hill about 3 km north of Fields, and along the scarp about 3 km south of Tumtum Lake. The total thickness is more than 500 meters. Due to the viscous nature of these siliceous rocks, both the flows and the tuffs are quite lenticular in form, making correlation difficult between canyons along the Steens Mountain scarp. The contact of these rocks with the overlying andesites and basalts shows a distinct angular unconformity.

Steens Mountain volcanic series. Following the formation of the rhyolite and dacite lavas there was a long period of inactivity and erosion which was in turn followed by great outpourings of andesitic and basaltic lavas with a few interbeds of sedimentary and pyroclastic rocks. Olivine basalts predominate in this sequence while hornblende andesites are less common. These rocks are exposed along the entire Steens-Pueblo Mountain scarp and have an aggregate thickness exceeding 1,000 meters.

Steens basalt. Lying unconformably above the Steens Mountain volcanics is an impressive sequence of basalt flows reaching a thickness of 1,000 meters near the summit of Steens Mountain. These flows are quite extensive and are known to cover a large part of southeast Oregon. Paleomagnetic evidence indicates that this entire 1,000-meter section accumulated in no more than 50,000 years and possibly as little as 2,000 years. In addition, paleomagnetic evidence and K-Ar age dates indicate that the lavas were extruded 15.1 $\pm$ 0.3 million years ago, making them middle Miocene in age (Gunn and Watkins, 1970). Although Axelrod (1944) and Baldwin (1953) have suggested through fossil evidence that these rocks are early Pliocene or late Miocene, this new evidence appears to show that the rocks from the Alvord Creek formation up through the Steens Mountain volcanics are early to middle Miocene in age.

Alluvium. A belt of old alluvial deposits up to 5 km wide extends for 25 km along the base of the Steens scarp from 3 km north of Fields to Tumtum Lake. Ross (1942) suggested that this older alluvium is probably Pliocene from fossil evidence. Generally the older alluvium is composed of coarse subangular clasts in a matrix of poorly sorted sand. Thicknesses range from 100 to 275 meters. Locally the deposits are well indurated, deformed, and tilted back toward the west since they presumably would originally have had an eastward tilt off the Steens Mountain scarp. Uplift of up to 200 meters has occurred since deposition. Finally, the Alvord Valley itself is filling up with recent alluvial and playa lake deposits since the entire valley is internally drained. Alvord Desert and Alvord Lake are the two largest playas with numerous smaller playas dotting the landscape.

Hot Springs

The hot springs in the Alvord Valley are of course the primary reason for interest in the area as a geothermal prospect. All of the hot springs are shown on Figure 2. Mickey Springs is about 8 km northeast of the Alvord Desert while Alvord Springs is just west of the Alvord Desert about 1 km south of the Alvord Ranch. Borax Lake which is also referred to in the literature as Hot Lake is about 10 km northeast of Fields in the middle of the valley. Several other smaller but hotter springs are aligned along a fracture which runs for about 1 km north from Borax Lake. Another hot spring of interest is an unnamed spring 12 km east of the valley just south of Flagstaff Butte and also just south of the main road.

CHAPTER 3

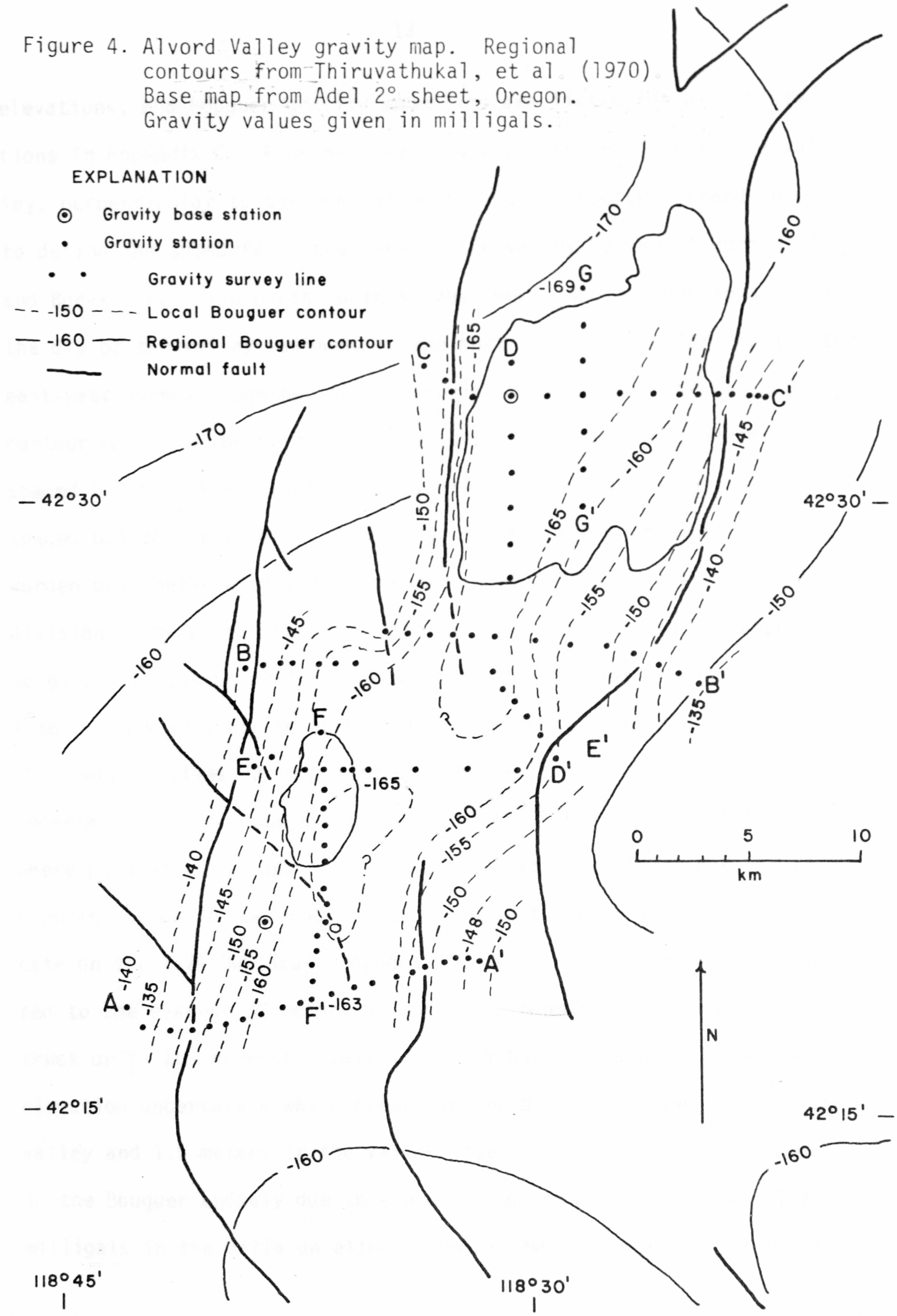
SUBSURFACE STRUCTURE

In order to develop a model for hot water circulation in the hot springs of the Alvord Valley, one must consider the structures through which the waters are circulating (White, Thompson, and Sandberg, 1964). There is little doubt that the hot waters circulate up along faults. In the past, gravity surveys have been found to be quite effective in delineating faults buried by alluvium and in establishing valley fill thicknesses and general subsurface structure in thermal areas located in the Basin-and-Range province (Thompson and Sandberg, 1958; White, Thompson, and Sandberg, 1964). With this in mind, four east-west and two north-south gravity surveys were run in the Alvord Valley. No surveys were done near Mickey Springs or the hot springs south of Flagstaff Butte because of a lack of 1:24,000 scale topographic map coverage in those areas. However, both springs rise along mapped faults (Walker and Repenning, 1965).

Gravity Survey Procedures

The locations of gravity base stations, survey lines, and survey stations are shown in Figure 4. The southern base station was established at a spot elevation beside the road from Fields to Andrews while the northern base station was located on the Alvord Desert which has a uniform elevation of 4,002 feet (1219.8 meters). Coordinates,

Figure 4. Alvord Valley gravity map. Regional contours from Thiruvathukal, et al. (1970). Base map from Adel 2° sheet, Oregon. Gravity values given in milligals.



elevations, and Bouguer gravity anomalies are listed for all 98 stations in Appendix C. Four east-west surveys were run across the valley, perpendicular to the general north-south structural trend in order to define the subsurface structure of the valley between Alvord Springs and Borax Lake. Two north-south surveys were run in order to ascertain the dip of the valley basement in the north-south direction, to tie the east-west surveys together and to provide more control for the gravity contour map. In the hills on either side of the valley stations were spaced 0.4 to 0.8 km apart while stations in the valley were generally spaced 0.8 to 1.6 km apart. Gravity was measured with a portable Worden gravimeter with a dial constant of 0.0877 milligals per dial division. Three readings were taken at each station and averaged to give the station value. One of the base stations was occupied every 2 to 3 hours in order to account for instrumental and diurnal drift.

Uncertainties in this part of the gravity work were mainly due to uncertainty in location and elevation control for gravity stations. Where possible, stations were established at spot elevations, fence corners, bends in the road, or on other spots which were easy to locate on the 1:24,000 scale topographic maps. Some stations were located to the nearest 32 meters by using the odometer on the author's truck or to the nearest 3 meters using a Nikon Theodolite. Maximum elevation uncertainty was 6 meters in the hills on either side of the valley and 1.5 meters in the valley itself. Thus the maximum error in the Bouguer anomaly due to elevation uncertainty would be $\pm$ 1.2 milligals in the hills on either side of the valley and $\pm$ 0.3 milligals in the valley. Errors due to horizontal mislocation of stations are negligible.

Gravity Data Reduction

Standard methods as outlined by Dobrin (1960) were employed in reducing observed gravity values to the Bouguer anomalies (Appendix A). Since there were no points of known absolute gravity within reasonable distance of the valley, the Bouguer anomalies were tied as closely as possible to the regional Bouguer gravity (Appendix A). Maximum error due to all sources (drift, reading errors, elevation, terrain) is estimated to be 1.6 milligals on either side of the valley and 0.6 milligals in the valley. Average errors are estimated to be less than 1.0 milligal and 0.3 milligals respectively.

Structure Modeling Procedure

In order to model the valley fill structure and buried faults in the valley, it was first necessary to calculate the local Bouguer anomaly caused by the less dense valley fill lying above more dense volcanic basement. This was done for each east-west survey by subtracting the local Bouguer gravity from the regional Bouguer trend to give a local Bouguer anomaly which tended toward zero at the valley sides and was negative in the middle. The local Bouguer anomaly should then reflect the basement topography across the valley. Next, the local Bouguer anomaly along with the density contrast between valley fill and basement (assumed to be between 0.4 and 0.6 gm/cc) were used in a computer program to create two 2-dimensional models of the valley structure for each east-west survey. A detailed discussion of the procedures, choice of density contrasts, and assumptions involved in computer modeling is given in Appendix B.

Uncertainty in the structure models originates from four sources: 1) uncertainty in the elevation and position of gravity stations; 2) uncertainty in the reduction of gravity data to Bouguer anomalies; 3) misfit between observed gravity and gravity predicted by the structure models; and 4) uncertainty in the choice of density contrasts. The first two types of uncertainty are compiled in Table 1. Uncertainties in the theoretical gravity generated for each structure model are obviously reflected in the calculated depth to basement for each model. These uncertainties in depth to basement are shown in Table 2. Obviously an error in the choice of density contrasts could cause a drastic error in the depth to basement as shown in the structure models. It is possible to reduce this possibility somewhat by measuring the densities of a large number of samples of rocks thought to make up the basement and valley fill sediments. Unfortunately, one can only sample sediments from the surface, and it is entirely possible that the sediment density changes with depth. As a result, it was necessary to estimate the density contrast from past experience and whatever additional information was available. The choice of density contrasts for these models was based on the following: published average densities of volcanic rocks and valley-fill sediments (Dobrin, 1960; and Clark, 1966); structure modeling of other Tertiary sediment filled valleys

Table 1. Uncertainties in the theoretical gravity anomaly over the structure models caused by uncertainty in station elevations, reduction of gravity data, and uncertainties in the fit of the theoretical Bouguer gravity anomaly to the observed Bouguer anomaly. Uncertainties are given in milligals.

	Maximum Error		Average Error	
	Valley sides	Middle	Valley sides	Middle
Survey + Reduction	± 1.6	± 0.6	± 1.0	± 0.3
Fit of Th. Grav. to Obs. Grav.	± 1.5	± 1.0	± 1.0	± 0.5
Probable Total Error	± 2.2	± 1.2	± 1.4	± 0.6

Table 2. Uncertainties in the depth to basement for structure models caused by errors in Table 1. Errors given in meters. For a density contrast of 0.6 gm/cc, a 1 milligal error causes 40 meters of error in the model. For a density contrast of 0.4 gm/cc, a 1 milligal error causes 60 meters of error.

	Maximum Error		Average Error	
	Valley sides	Middle	Valley sides	Middle
Density Contrast = 0.6 gms/cc.	± 88 m	± 48 m	± 56 m	± 24 m
Density Contrast = 0.4 gms/cc.	± 132 m	± 72 m	± 84 m	± 36 m

(Lankston, 1975); and discussions with Dr. Gary Crosby (1976) who has done gravity and seismic work in the Alvord Valley. In view of this information and the fact that uncertainty in the models themselves is small in the middle of the valley, it is considered unlikely that the valley fill thickness falls outside the range set by the models.

Relationship of Hot Springs to Subsurface Structure

The computer-generated structural models for the east-west gravity surveys are shown in Figures 5 through 8. Survey locations are shown in Figure 4. In looking at the structure models for survey C-C' (Fig. 5), one should notice that Alvord Springs is located directly above the normal fault which bounds the valley on the west (Walker and Repenning, 1965; Walker, 1973). An interesting feature of this survey is the fact that evidence of recent faulting was found on the ground 11.8 km due east of Alvord Springs or about 1 km east of the edge of the Alvord Desert (Figs. 4 and 5). A series of north-south trending fractures were found in the playa sediments directly above this fault as shown on the east side of model C-C'. Mounds of dirt and greasewood which had been ripped apart were found on opposite sides of the fractures. Models C-C' and B-B' (Figs. 5 and 6) show that the average depth to basement ranges between 1.0 and 1.5 kilometers in the western and southern portions of the Alvord Desert and that one of the deepest parts of the valley on the eastern side of survey B-B' has a depth to basement between 1.5 and 2.5 km. The largest gravity anomaly was in this area. Also of interest is the fact that the horst structure which appears on the surface north of survey B-B' (Fig. 2) is expressed in the subsurface in model B-B' (Fig. 6).

The structural configuration across survey E-E' (Fig. 7) appears

Figure 5. Gravity profile and structure model for survey C-C'.
· Calculated Bouguer anomaly for model with 0.4gm/cc density contrast.
∘ Calculated Bouguer anomaly for model with 0.6gm/cc density contrast.

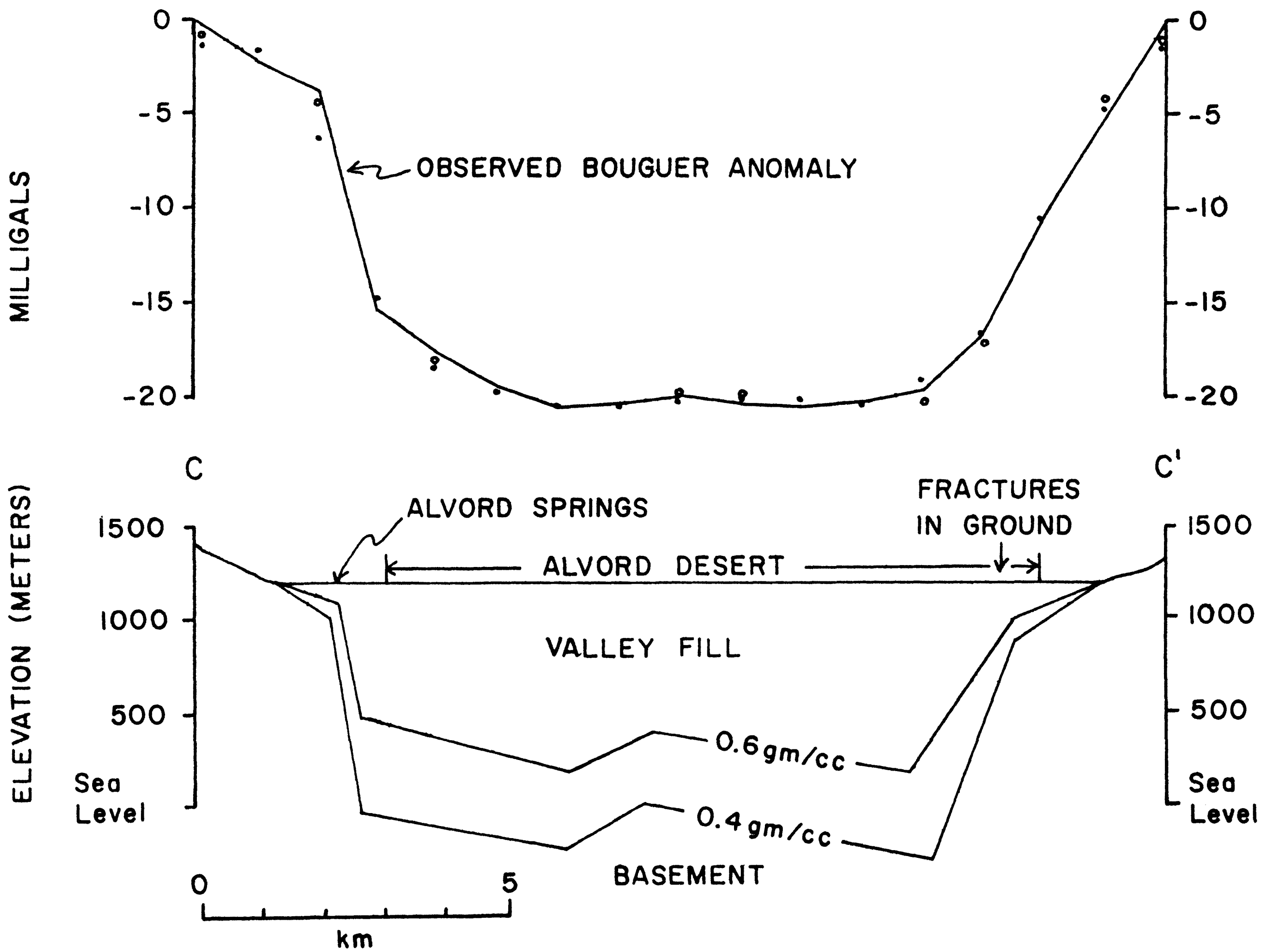


Figure 6. Gravity profile and structure model for survey B-B'.
• Calculated Bouguer anomaly for model with 0.4gm/cc density contrast.
∘ Calculated Bouguer anomaly for model with 0.6gm/cc density contrast.

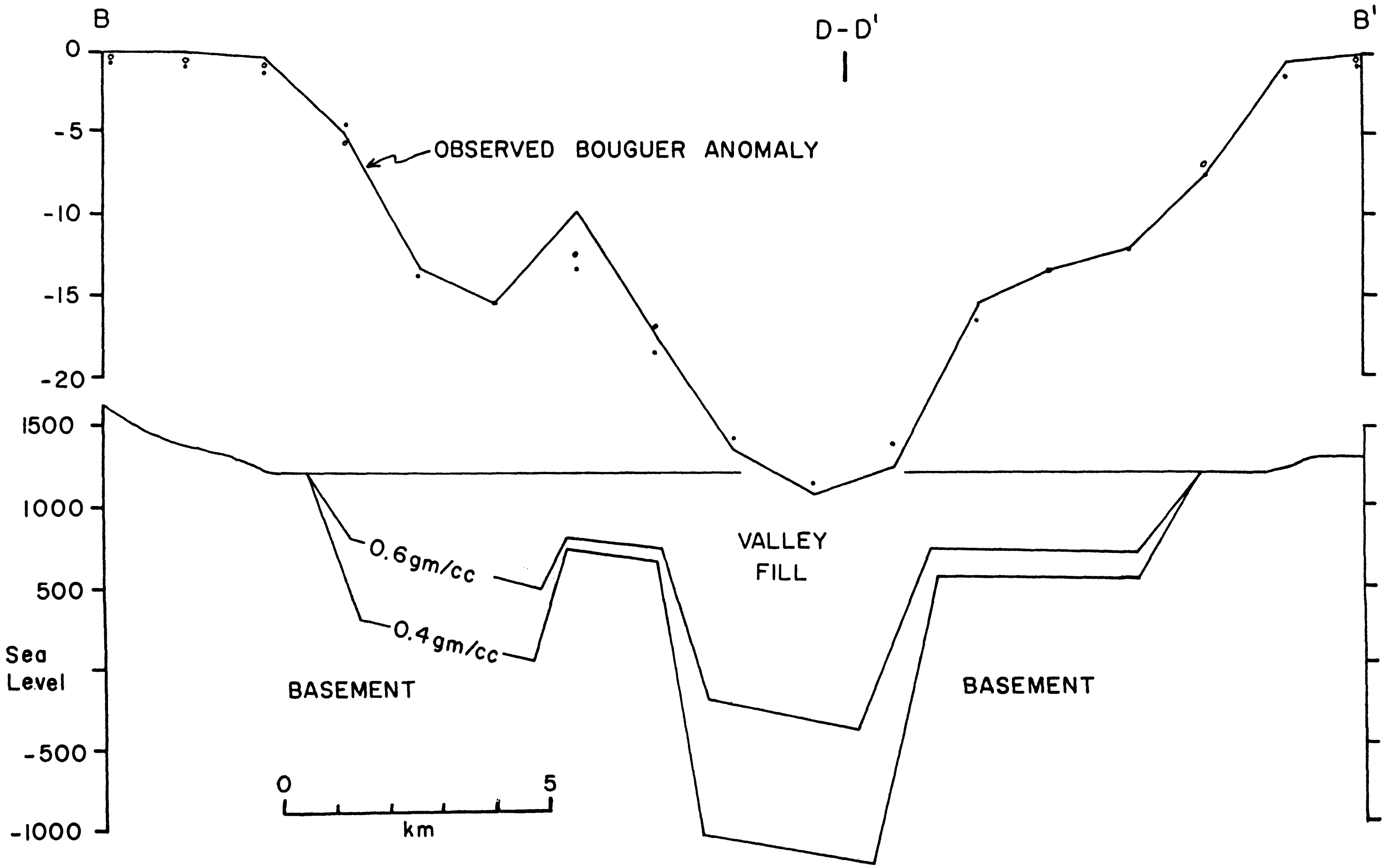
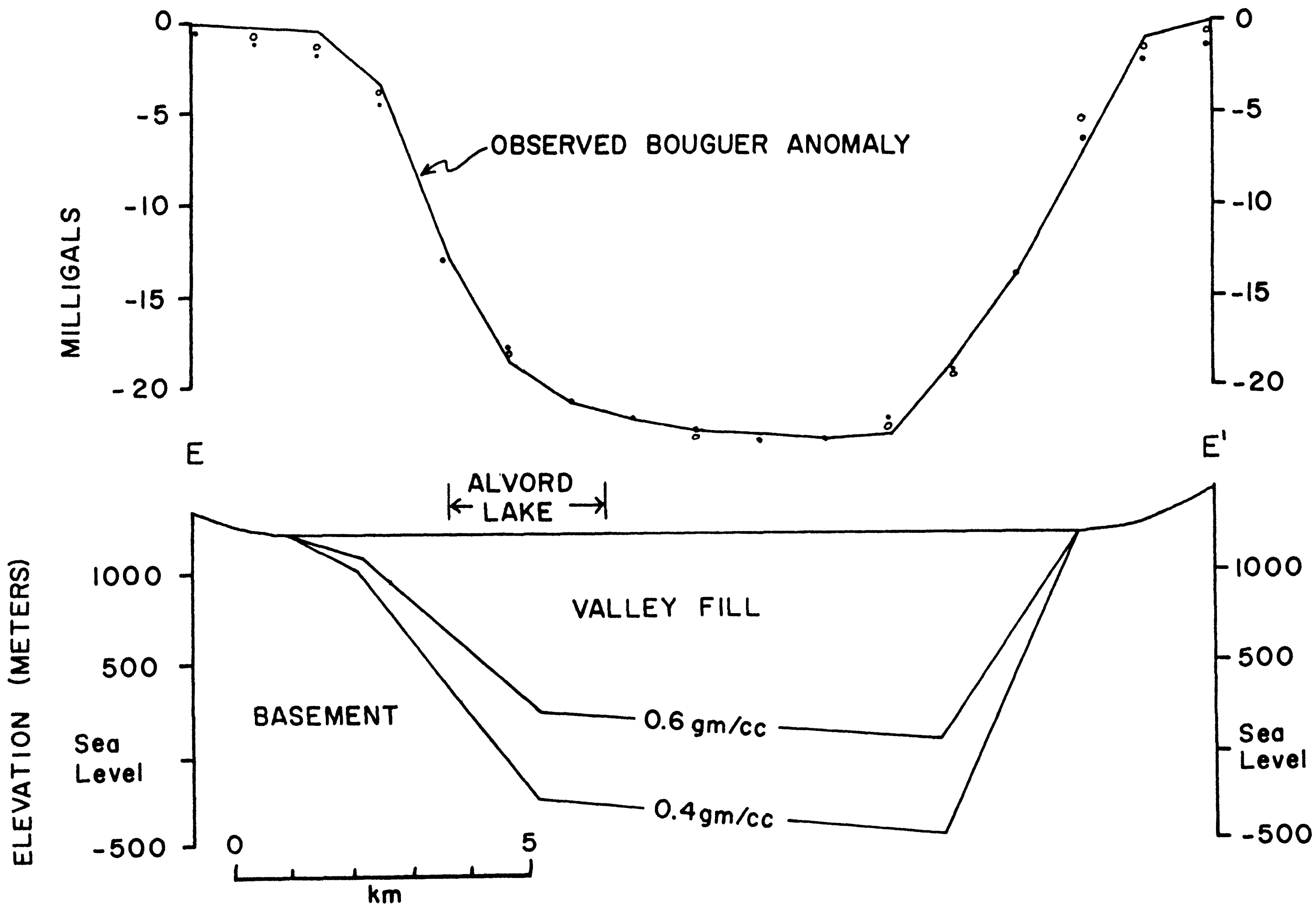


Figure 7. Gravity profile and structure model for survey E-E'.
• Calculated Bouguer anomaly for model with 0.4gm/cc density contrast.
∘ Calculated Bouguer anomaly for model with 0.6gm/cc density contrast.



to be that of a simple downthrown block while the structure is more complicated across survey A-A' (Fig. 8). The west side of the graben-like structure in model A-A' is located directly south of Borax Lake and in line with the series of hot springs north of the lake. Survey F-F' (Fig. 9) also traverses this structure. The anomaly increases directly under Borax Lake and the associated hot springs to the north suggesting that a fault with moderate displacement (100-200 meters) is under the springs. A series of northwest-southeast (transverse) faults with moderate displacements mapped directly west of Alvord Lake (Williams and Compton, 1953) have trends (S35°E) which intersect Borax Lake and the springs to the north (Fig. 2). In 1918 residents living just west of Alvord Lake within 1 km of these faults felt a swarm of several small earthquakes. Tremors were not felt by residents living in Fields or Andrews (Fig. 1) only a few kilometers away. Shortly after these small, local quakes, the flow from Borax Lake and the associated hot springs to the north was observed to increase significantly (Williams and Compton, 1953). Presumably then, these are the faults or fault which acts as a conduit for thermal waters in the Borax Lake area and is shown dotted on Figure 2.

The 5 milligal Bouguer contours drawn on Figure 4 show that Bouguer gravity in the valley reflects the general north-south structural trend and that gravity drops off sharply near the valley sides where normal faults are located. All of the hydrothermal areas in the valley seem to be associated with faults and not with local gravity highs or lows which has been shown to be the case in other Known Geothermal

Figure 8. Gravity profile and structure model for survey A-A'.
• Calculated Bouguer anomaly for model with 0.4gm/cc density contrast.
∘ Calculated Bouguer anomaly for model with 0.6gm/cc density contrast.

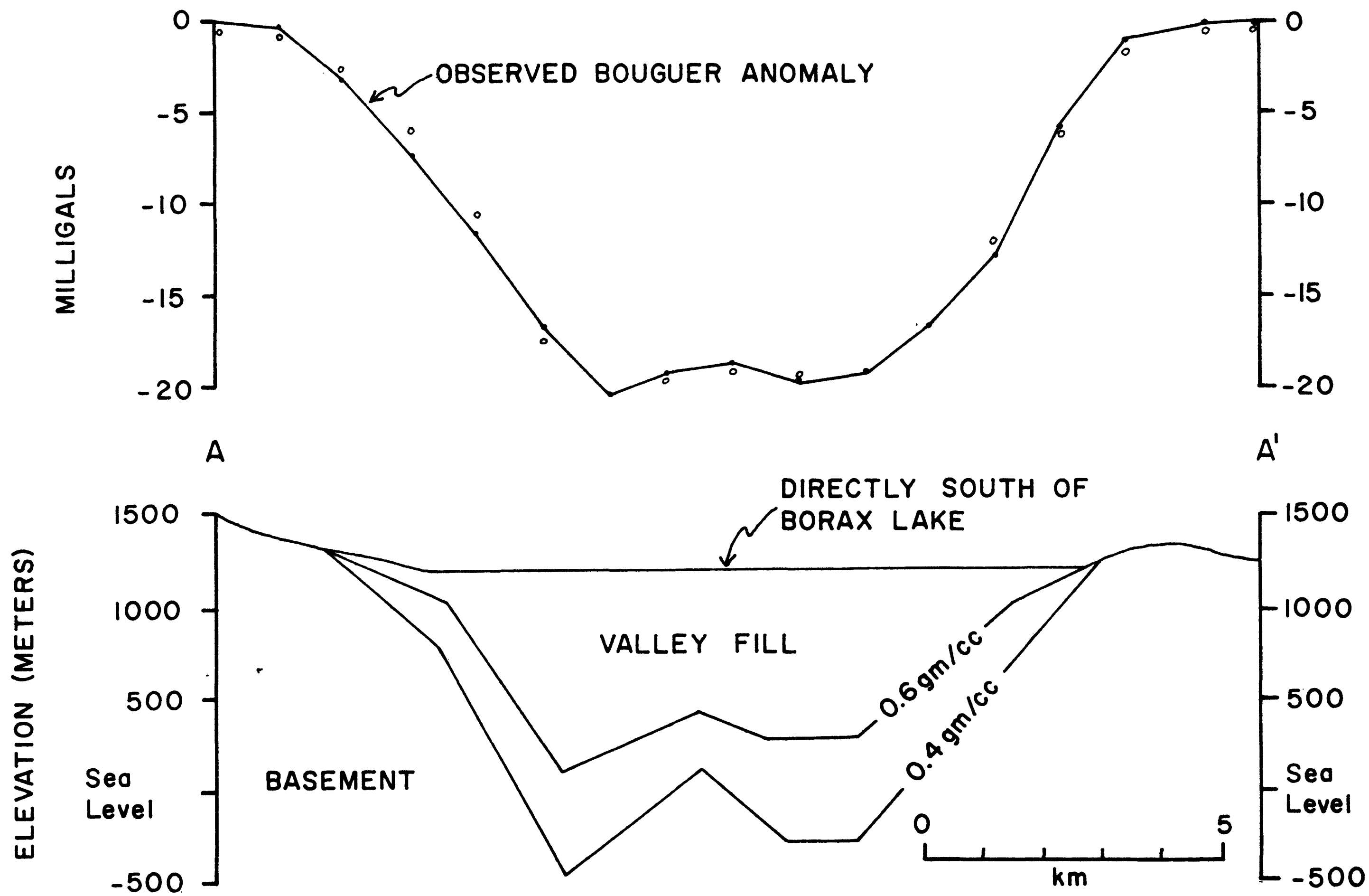
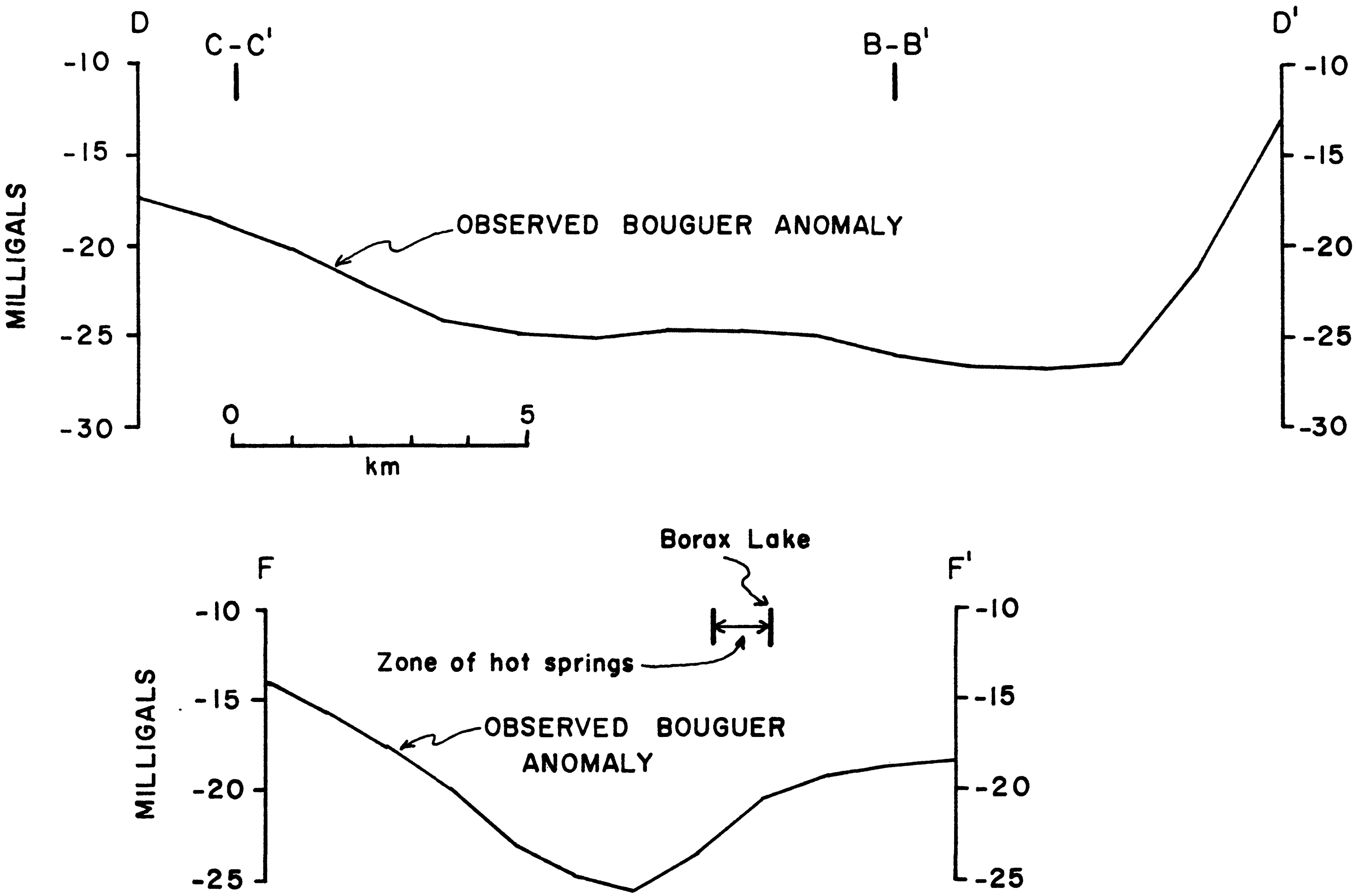


Figure 9. Plot of Bouguer anomalies for north - south surveys D-D' and F-F'.



Resource Areas. Detailed gravity surveys in the Imperial Valley, California, have shown that gravity highs correlate with high heat flow areas. Presumably the gravity highs are due to increased density caused by silica deposition and low-grade metamorphism from plumes of hot water in unconsolidated sediments (Combs and Muffler, 1973). Conversely a gravity low situated under The Geysers, California, is thought to be suggestive of a magma chamber or still molten intrusive body at depth (Chapman, 1975).

CHAPTER 4

ORIGIN OF THERMAL WATERS IN THE ALVORD VALLEY

Having located the most probable avenues for thermal water circulation in the valley, the next goal of the study was to establish the most likely origin of the hot spring waters. The two most reasonable alternatives for the origin of these thermal waters are that the waters are either entirely meteoric or are predominantly meteoric with a small magmatic component. Three approaches were used to select the better of the two alternatives. First, consideration was given to the high boron content of the waters and associated borate deposits of the Alvord Valley. Following that was an analysis of recently completed but unpublished work done by the U.S.G.S. involving analyses of deuterium/hydrogen and $^{18}O/^{16}O$ isotope ratios of the thermal and surface meteoric waters of the Alvord Valley. Finally, the origin of the sulfur in the hot spring waters was evaluated in the light of analyses done for this study of sulfur isotope ratios ($^{34}S/^{32}S$) of spring water sulfate, sulfates from playa sediments in the valley and whole rock sulfur from the volcanics exposed on the east side of Steens Mountain.

Origin of the Boron in Alvord Area Hot Springs

All of the hot springs in the Alvord Valley have anomalous concentrations of boron while the hot spring south of Flatstaff Butte, located outside the valley, has a very low concentration as is shown in Table 3.

Table 3. Comparison of the chemistry of Alvord area hot springs with hot springs in other known thermal areas. Concentrations given in parts per million.

	Surface Temp°C	pH	SiO_2	Na	HCO_3	SO_4	H_2S[2]	Cl	B	B/Cl[3]
Alvord Area Springs[1]										
Mickey Springs	73	8.05	200	500	774	230	<0.5	240	10.5	0.043
Alvord Springs	76	6.73	120	960	196	220	1.2	780	30	0.038
Borax Lake	36	7.28	190	500	420	350	<0.5	300	16.6	0.55
Hot Springs N. of Borax Lake	96	7.30	160	450	374	434	<0.5	250	15	0.06
Flagstaff Butte Springs	52	6.77	105	270	439	204	-	24	0.89	0.37
Thermal Waters from Geyser Areas in Volcanic Environments[4]										
Upper Basin, Yellowstone Park, Wyoming	94	9.6	363	352	0	23	2.6	405	4.4	0.011
Norris Basin, Yellowstone Park, Wyoming	85	7.5	529	439	27	38	0	744	12	0.015
Steamboat Springs, Washoe Co., Nevada	89	7.9	293	653	305	100	4.7	865	49	0.057
Thermal Waters from Nongeyser Areas Associated with Volcanism[4]										
Hot Creek, Mono Co., Calif.	93	8.3	131	350	497	90	0.2	200	10	0.05
Niland, Imperial Co., Calif.	40	6.4	75	7,280	1,600	384	-	12,900	53	0.004
Roosevelt Beaver Co., Utah[5]	55	7.9	313	2,500	156	73	-	4,240	38	0.009

1. After Mariner, et al., 1974.
2. H_2S analyses for Alvord Area Springs are courtesy of R.H. Mariner, written communication of unpublished data.
3. Ratios greater than 0.001 are considered to be high.
4. After White, Hem, and Waring, 1963.
5. This is a Known Geothermal Resource Area being developed at the present time.

Sixteen other hot springs sampled by the U.S.G.S. in southeastern Oregon (Malheur, Lake, and Harney Counties) have boron concentrations ranging from 0.11 to 13.6 ppm with an average of 5.18 ppm. These are significantly lower than the boron concentrations in springs located in the Alvord Valley (Mariner, et al., 1974). Boron has been shown to to a constituent of condensates of fumarolic gasses from active volcanoes (White and Waring, 1963) and has also been shown to occur in anomalous amounts in thermal waters associated with recent volcanic activity (White, Hem, and Waring, 1963). The chemistry of thermal waters in the Alvord area is quite similar to the chemistry of thermal waters associated with volcanic activity. They are predominantly sodium chloride waters high in silica, bicarbonate and boron having moderately high ratios of boron to chloride as is shown in Table 3.

One important difference between the Alvord area springs and the other springs listed in Table 3 is that the Alvord area springs are not directly associated with any recent volcanic activity while all of the other springs are in areas where there has been eruptive activity at least as recently as the Pleistocene (White, Hem, and Waring, 1963). The last volcanic activity in the Alvord area occurred in the mid to late Miocene and the nearest volcanics of Recent age are 175 km to the east near Jordan Valley, Oregon (Gunn and Watkins, 1970).

The presence of boron in thermal waters and proximity to areas of recent volcanic activity does not necessarily imply that the thermal waters are partly of magmatic origin. In fact, Goldschmidt (1954) pointed out that marine sediments, especially argillites and carbonates, are much more enriched in boron (100-1,000 ppm) than are igneous rocks. Flood basalts of Oregon and Washington have been shown to average only about 5 ppm boron while intrusives and extrusives of granitic composition average about 15 ppm boron (Parker, 1967). Goldschmidt (1954) also suggested that the widely held theory of the magmatic origin of boron in volcanic emanations is erroneous. He proposed that anomalous boron in volcanic emanations, thermal waters, and marginal zones of igneous rocks, probably originates by remobilization from intruded marine sediments.

Paleozoic low-grade metavolcanics and marine argillites, quartzites, and marbles are known to outcrop in the Pueblo Mountains adjacent to the southern portion of the Alvord Valley as has been previously mentioned (Fig. 2). Presumably these rocks are the basement which underlies the blanket of Tertiary volcanics which covers southeast Oregon and would have been intruded by the volcanics. The oldest volcanics in the area are the Alvord Creek formation and the Pike Creek volcanics which are all of rhyolitic and dacitic composition. If these rocks intruded through the Paleozoic metavolcanics and metasediments, it is certainly possible that they could have become enriched in boron by leaching it out of the slightly metamorphosed marine sediments. Furthermore, these siliceous volcanics would probably be much more enriched in boron than the overlying basalts and andesites because of the high water content and leaching capacity of granitic magmas compared to dry basaltic magmas.

There are exposures of siliceous volcanic rocks in the Alvord area adjacent to the springs with the highest boron concentrations. Alvord Springs is located directly east of a 13 square km exposure of the Pike Creek volcanics and the Alvord Creek formation. The fault zone which is probably the conduit for thermal waters feeding Borax Lake and the hot springs north of there traverses a slightly smaller exposure of the Pike Creek volcanics 2 km west of Alvord Lake (Fig. 2). Mickey Springs has a moderately high boron concentration but is not located adjacent to exposures of siliceous volcanics. However, Mickey Springs is located just east of an extensive exposure of the Steens Mountain volcanic series which is known to overlie the Pike Creek volcanics farther to the south.

Samples were taken from the pre-Tertiary crystalline rocks in the Pueblo Mountains, from the Alvord Creek beds and the Pike Creek volcanics west of Alvord Springs and from the Steens Mountain volcanic series along the road running west out of Fields through the mountains. A total of 38 specimens were examined, both in hand sample and in thin section, for the presence of tourmaline, a boro-silicate. No tourmaline or any other boron-bearing minerals were found. All of the rocks which were examined have already been described petrographically, in abundant detail, by Fuller (1931) and thus the petrographic descriptions have been omitted from this report. However, borates are known to occur in significant quantities in playa sediments between Borax Lake and Alvord Lake. These sediments were derived by erosion of the volcanics exposed on the east side of Steens Mountain. It is known that boron is easily leached at moderate temperatures (150°-300°C) from volcanic rocks in the laboratory (Ellis and Mahon, 1964) and that the boron content in hydrothermally altered rock in other geothermal areas is only a small percentage of the content in nearby unaltered rocks (Ellis and Sewell, 1963; Ellis, 1967). Although the evidence here is entirely circumstantial, it seems probable that borates in Alvord Valley playa sediments are derived from weathering of volcanics exposed on Steens Mountain and probably in greatest quantity from the more felsic Pike Creek volcanics and Alvord Creek formation. It also seems clear that the anomalous boron in the hot springs is probably derived either from leaching of felsic volcanics or is dissolved directly from playa sediments as the thermal waters circulate back up to the surface.

Deuterium/Hydrogen and $^{18}O/^{16}O$ Isotope Ratios of Alvord Area Waters

In the literature isotope ratios are generally reported as δ°/₀₀ values which are per mil (part per thousand) deviations of the isotope ratio of the sample to that of the standard for that element

$$\text{where } \delta D ‰ = \left[\frac{D/H \text{ sample}}{D/H \text{ std (SMOW)}} - 1\right] \times 10^3$$

and

$$\delta^{18}O ‰ = \left[\frac{^{18}O/^{16}O \text{ sample}}{^{18}O/^{16}O \text{ std (SMOW)}} - 1\right] \times 10^3$$

For example, δD of -13‰ for a sample would indicate that the sample was depleted by 13 parts per thousand in its ratio of deuterium to hydrogen relative to the D/H ratio for the standard. The standard used for D/H and $^{18}O/^{16}O$ isotope ratios is standard mean ocean water (SMOW) which has been shown to have very constant isotopic ratios.

It is well known that D/H and $^{18}O/^{16}O$ ratios can be helpful in determining the origin of thermal waters (Taylor, 1967). Metamorphic waters have been shown to be high in both deuterium and ^{18}O (Taylor and Epstein, 1962) (Fig. 10). Magmatic waters are generally high in ^{18}O but have a lower and wider range of deuterium ratios (White, 1974) (Fig. 10). Waters of meteoric origin are quite distinctive due to the fact that for these waters a well established linear relationship exists between D/H and $^{18}O/^{16}O$. Even though meteoric waters have a wide range of isotopic compositions (Fig. 10), the relationship $\delta D = 8\delta^{18}O + 10$ (in per mil) has been shown to hold in almost all cases (Craig, 1961) (Fig. 11). In part, this is due to the fact that the deuterium and ^{18}O contents of most meteoric waters decrease with latitude, altitude, and distance from the ocean (Craig, 1961). Craig (1963) has also observed that although the $^{18}O/^{16}O$ ratio of thermal waters may increase while the waters are in contact with crustal rocks, the D/H ratio should change only a small amount. This has been very helpful in determining the origin of thermal waters in geothermal areas throughout the world. Waters emanating from geothermal areas are generally thought to be of meteoric origin since the D/H ratios are usually the same as local meteoric water and the $^{18}O/^{16}O$ ratios are slightly higher due to isotopic exchange with heavier oxygen contents in wallrock silicates and carbonates (Craig, 1963) (Fig. 11).

Alvord area waters also fit the pattern (Fig. 11). Table 4 shows that the isotopic ratios of thermal waters from Mickey and Alvord

Figure 10. D/H and $^{18}O/^{16}O$ ratios of various waters in nature. Data for Alvord Valley waters from R. H. Mariner, personal communication (1975). Data for other waters from Taylor (1967), White (1974), and Sheppard and Taylor (1974).

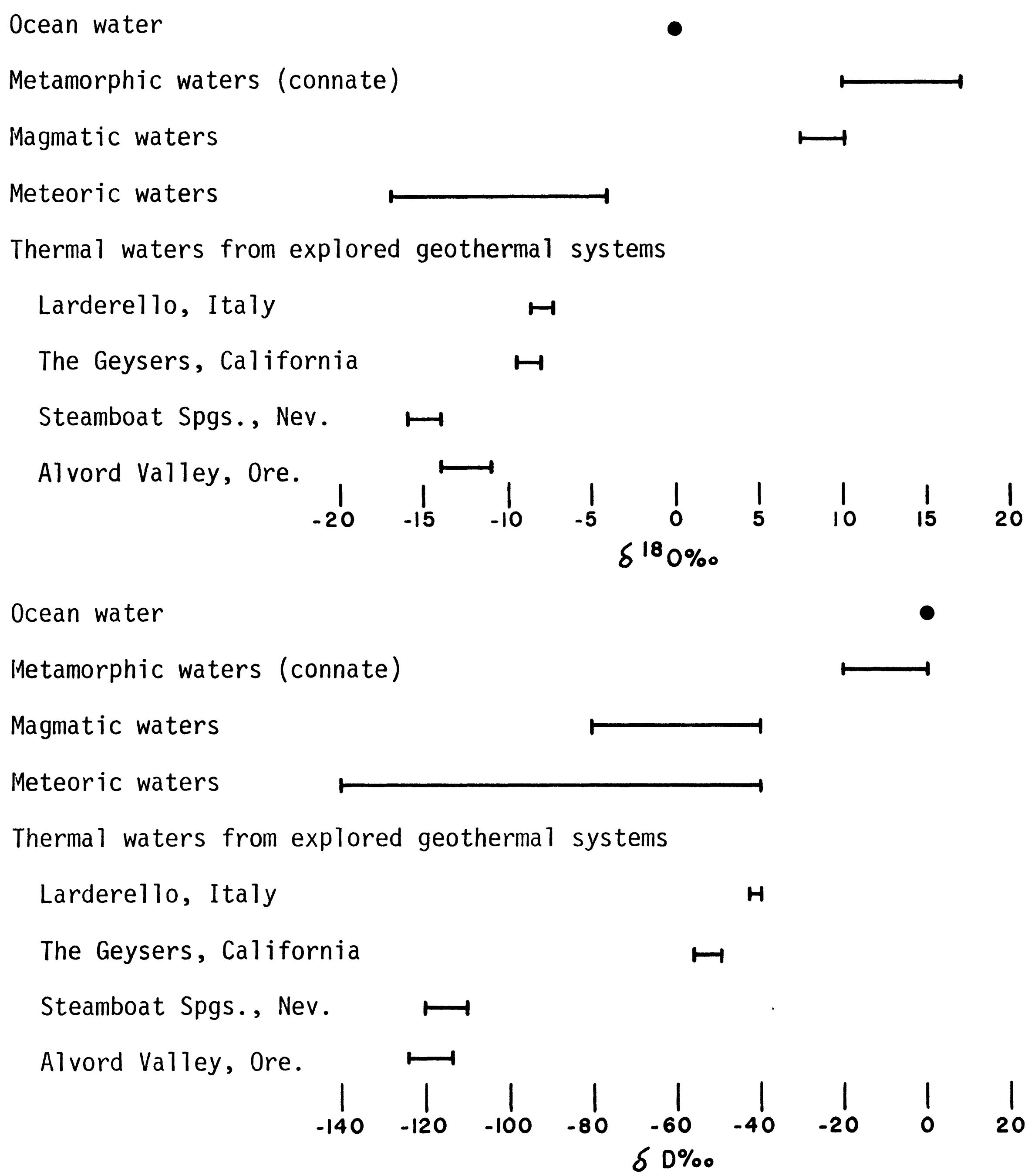


Table 4. D/H and $^{18}O/^{16}O$ isotope ratios for Alvord area waters. (R. H. Mariner, personal communication, 1975)

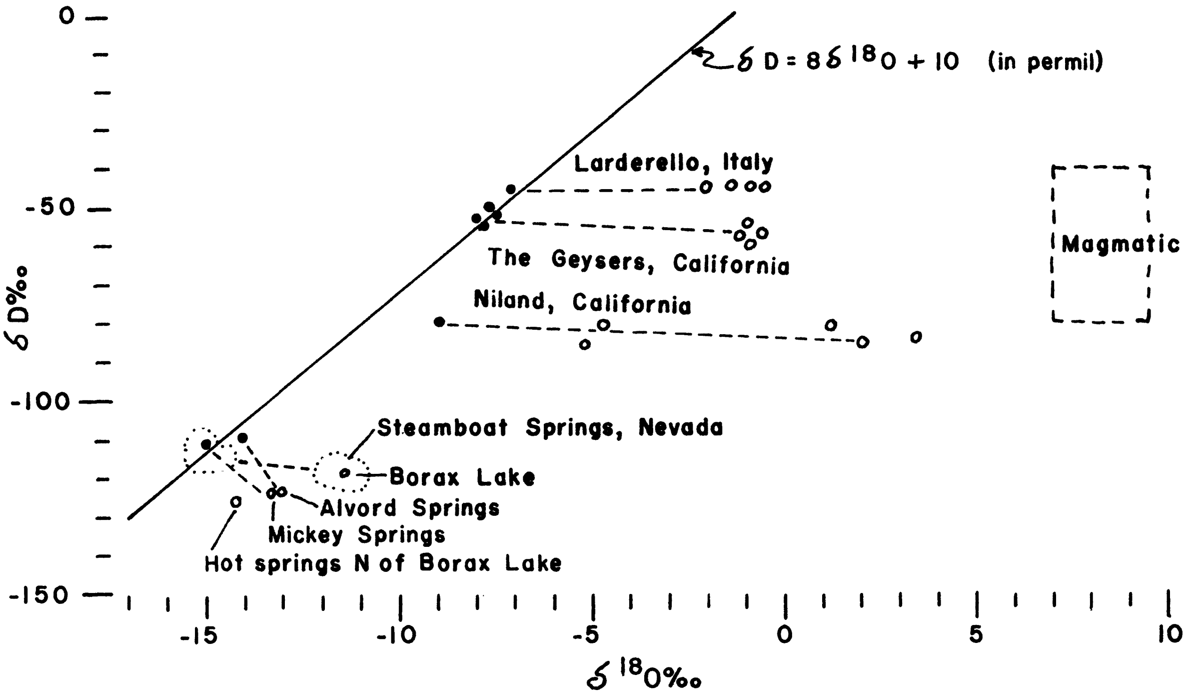
	$\delta^{18}O$°/oo	δD°/oo
Mickey Springs	-13.4	-124.3
Local meteoric water	-15.1	-111.5
Alvord Springs	-13.2	-123.6
Local meteoric water	-14.1	-108.4
Hot Springs (N of Borax Lake)	-14.4	-125.4
Borax Lake	-11.5	-115.8

Springs are quite close to the isotopic ratios of the respective local meteoric waters. Thermal waters from Borax Lake and Hot Springs north of the lake are also in the same range. Thus it is highly probable that the thermal waters are mostly, if not all, meteoric (R. H. Mariner, personal communication, 1975). One difference between Alvord area waters and waters from other geothermal systems (Fig. 11) is that the D/H ratios of Alvord area thernal waters are lower than local meteoric waters. The reason for this is not immediately clear, but in any case, the thermal waters have lower D/H ratios which shifts them away from the higher D/H ratios of magmatic waters. The range for D/H and $^{18}O/^{16}O$ ratios of magmatic waters is shown on the right side of Figure 11.

It is possible that due to the long circulation time in the hot spring systems (thousands of years), present-day thermal waters were precipitated as meteoric waters thousands of years ago when Alvord area meteoric waters had lower D/H ratios. This could have been caused by a

Figure 11. Comparison of D/H and $^{18}O/^{16}O$ isotope ratios of Alvord Valley waters with waters from other geothermal systems. Data for Alvord Valley waters from R. H. Mariner, personal communication (1975). Data for other waters from Craig (1963).

- ∘ Thermal water
- • Associated meteoric water



change in weather patterns in the last few thousand years.

Origin of Sulfur in Alvord Valley Thermal Waters

The problem remains, however, that uncertainties in sampling, analysis, interpretation, and models are such that a component of, say, 5% magmatic water which would not significantly affect the D/H and $^{18}O/^{16}O$ isotopic ratios of thermal waters could go unnoticed (White, 1974). There is also a problem with the fact that most of the hot water geothermal systems, including the Alvord, have waters which are high in soluble elements of low crustal abundance such as Li, B, As, Sb, and Cs. Although these elements do occur in trace amounts in igneous rocks, especially silicic igneous rocks (Turekian and Wedepohl, 1961), and are quite leachable, the long life of these geothermal systems (probably hundreds of thousands of years, if not millions) presents a problem in maintaining a supply of these elements for the life of the system. This would seem to favor the presence of a continuous supply of magmatic water enriched in these elements (White, 1974). One might point out, however, that it has yet to be demonstrated that geothermal systems remain enriched in these elements for the life of the system. Furthermore, it is easy to find examples of thermal waters from geyser areas and areas associated with recent volcanism which are indeed low in these elements. Beowawe Geysers, Eureka County, Nevada, Huakadalur Geysers near Reykiavik, Iceland, and Nalachevskie, Kamchatha, U.S.S.R. all fit into this category (White, Hem, and Waring, 1963). Finally, it is likely that these elements could be recycled in an internally drained basin such as the Alvord Valley where they could be leached from valley fill sediments and find their way back to the hot spring reservoirs by subsurface circulation.

In any case, one approach to the solution of this problem would be to conduct isotopic studies of these elements to get an idea of their origin. Unfortunately, isotopes of Li, B, As, Sb, and Cs do not fractionate significantly in nature making them of little use for isotopic studies. However, isotopes of sulfur fractionate extensively in nature, and much is known about the abundances and distribution of sulfur isotopes, and the presence of sulfur of magmatic origin in thermal waters would be permissive evidence for the presence of a small component of magmatic water in a geothermal system. One of the purposes of this study was to test this hypothesis and thus an investigation of sulfur isotopes in the Alvord Valley geothermal system was undertaken.

<u>Sampling and analytical procedure</u>. The exact locations of samples for sulfur isotope analysis are given in Table 5 and in Figure 2. A four liter water sample was taken from each hot spring in the Alvord Valley and from the hot springs just south of Flagstaff Butte. Dissolved sulfate was precipitated at the site by the addition of a $BaCl_2$ solution to precipitate $BaSO_4$. An unsuccessful attempt was made at each spring to precipitate dissolved and gaseous sulfide (H_2S, HS^-, and $S^=$) using a $Cd(OH)_2$ suspension. These sampling techniques are described in detail in Rafter and Wilson (1963). It was not possible to precipitate any dissolved sulfides because of their extremely low concentrations in the springs (less than 1.2 ppm) as is shown in Table

Table 5. Alvord area sulfur isotope results. Mean values are underlined.

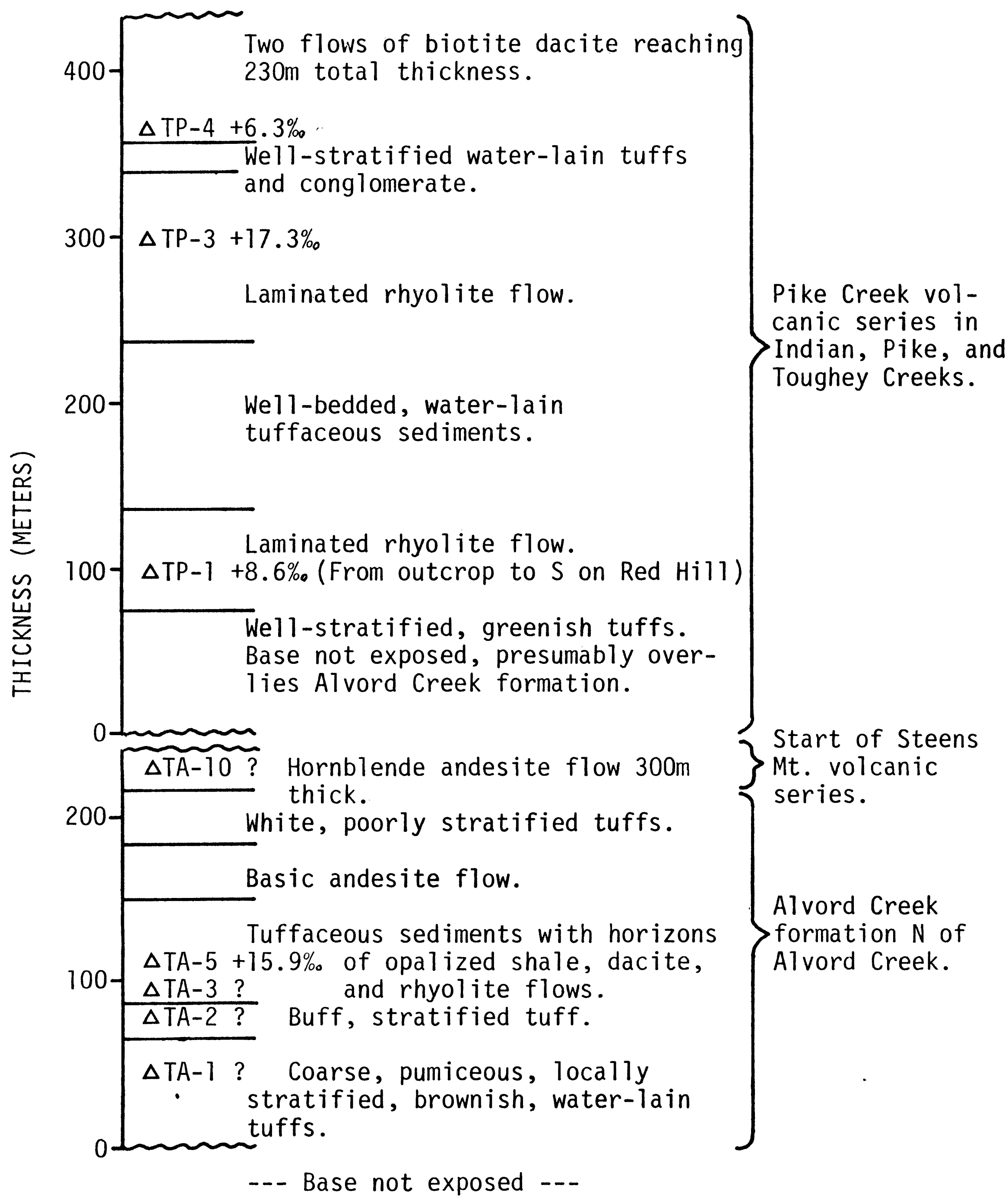
Sample	$\delta^{34}S$ °/oo	Location/Remarks
Hot Spring Sulfates		
M-1	+12.8	Mickey Springs lower pool.
A-1	+13.3	Alvord Springs.
BL-1	+ 9.7	Borax Lake.
BF-1	+ 9.9	Hot spring ½ km N of Borax Lake.
FB-1	+20.3	Located on Defenbaugh's ranch.
Average except FB-1	<u>+11.2</u>	
Soil & Playa Sulfates		
A-5	+10.7	Crust from orifice of Alvord Springs.
A-6	+12.3	Soil sample 50m E of Alvord Springs.
A-9	+11.0	Playa sample from Alvord Desert 1.5 km SE of Alvord Springs.
BF-4	+ 9.7	Borax crust from ground 0.5 km NW of Borax Lake.
Average	<u>+10.9</u>	Mean for Alvord Valley playa & soil sulfates.
Whole Rock Sulfur		
TA-5	+15.9	Biotite dacite flow from the Alvord Creek fm. exposed on N side of Alvord Creek.
TP-1	+ 8.6	Rhyolite flow from Pike Creek volcanics exposed on Red Hill SW of Alvord Lake.
TP-3	+17.3	Rhyolite flow from Pike Creek volcanics exposed at the Alexander Mine on the N side of Indian Creek.
TP-4	+ 6.3	Biotite dacite from Pike Creek volcanics exposed at the Alexander Mine.
Average	<u>+12.0</u>	Mean for whole rock sulfur in the Alvord Creek fm. and Pike Creek volcanics.
FB-5	+ 1.8	Highly silicified material found near mouth of hot springs S of Flagstaff Butte.
PT-15	+ 0.7	Quartz muscovite talc schist (metarhyolite) from N side of Denio Creek in the Pueblo Mountains. From the pre-Tertiary crystalline rocks.

3. It is well known that the average human nose can detect concentrations of H_2S as low as 1 ppm in the air. Gasses emanating from each hot spring were tested in this manner and no H_2S could be detected nor could any CdS be precipitated by bubbling gasses through a $Cd(OH)_2$ suspension. However, all of the springs had between 200 and 450 ppm sulfate (Table 3) and thus the overall sulfur isotopic ratio for any spring would not be significantly affected by failure to collect such a minute amount of sulfide.

Samples of soil or playa sediments were taken from near Alvord Springs, the Alvord Desert, and from the flats 1 km north of Borax Lake (Table 5). A suite of rock samples was taken from the section of volcanics exposed directly west of Alvord Springs and another suite was taken from the pre-Tertiary crystalline rocks exposed to the south in the Pueblo Mountains. One sample of hydrothermally altered material was taken from the rocks exposed near the hot springs south of Flagstaff Butte.

All sulfur isotope analyses were carried out at the University of Calgary's Stable Isotope Laboratory under the direction of Dr. H. Roy Krouse. Samples of $BaSO_4$ precipitated from hot springs, soils and playa sediments were reduced to H_2S in a mixture of hot HI, H_3PO_2, and HCl which was bubbled through a $Cd(C_2H_3O_2)_2$ solution to precipitate CdS. $AgNO_3$ was added to the CdS to precipitate Ag_2S which was subsequently oxidized at 1000°C to yield SO_2 for analysis on a mass spectrometer. Isotopic analyses of whole rock sulfur were carried out at a later date by Dr. Krouse using a procedure described by I. R. Kaplan,

Figure 12. Stratigraphic locations of samples taken from the east side of Steens Mt. just west of Alvord Springs. Sulfur isotopic values are shown for samples which were successfully analyzed. Samples which were not successfully analyzed are followed by a question mark. Stratigraphy is after Fuller (1931).



et al. (1970). Detailed descriptions of these procedures can also be found in Ryznar (1965) and Jensen (1957). Unfortunately, none of the andesite or basalt samples contained a sufficient amount of sulfur for an isotopic analysis (10 milligrams). Only the rhyolites and dacites contained enough sulfur for an analysis. The exact stratigraphic location of each sample from Steens Mountain for which an isotopic analysis was obtained is shown in Figure 12.

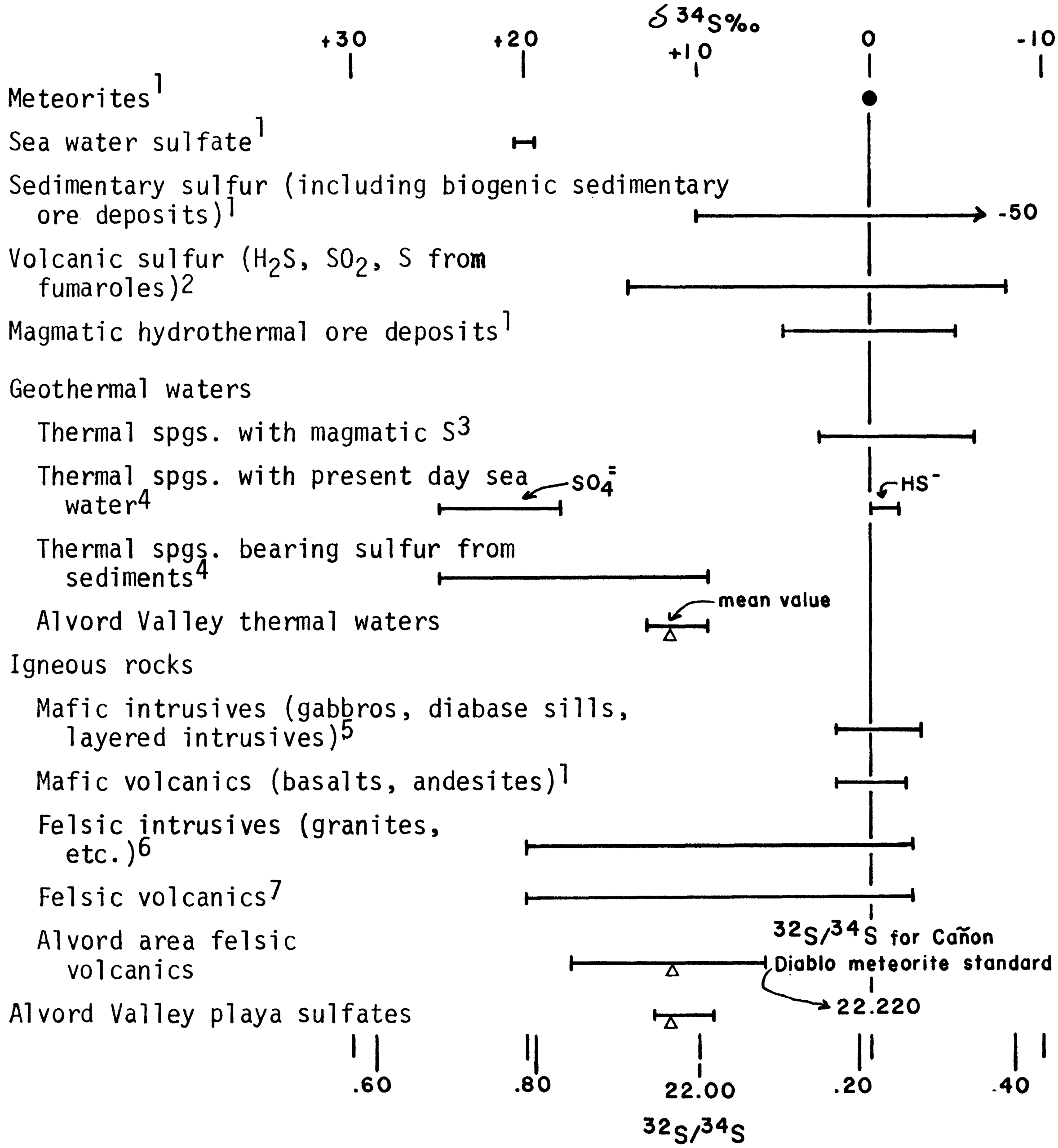
Results. Sulfur isotope ratios are reported as $\delta ^\circ/_{\circ\circ}$ values or part per thousand (per mil) deviations of the isotopic ratio of the sample from the standard where:

$$\delta^{34}S ^\circ/_{\circ\circ} = \left[\frac{^{34}S/^{32}S \text{ sample}}{^{34}S/^{32}S \text{ std (Cañon Diablo meteorite)}} - 1 \right] X\ 10^3$$

The standard used for sulfur isotope ratios is the troilite phase of the Canon Diablo meteorite which has an absolute $^{32}S/^{34}S$ ratio of 22.220 (Fig. 13).

The results of sulfur isotopic analyses of all Alvord area samples are shown in Table 5 along with sample locations and descriptions. The overall range for samples from the Alvord Valley itself and nearby felsic volcanics on the east side of Steens Mountain is +6.3 to +17.3$^\circ/_{\circ\circ}$. Samples taken from the Flagstaff Butte area and from the pre-Tertiary crystalline rocks (PT-15) exposed in the Pueblo Mountains fall outside of the range for Alvord Valley samples. No explanation is immediately apparent for the fact that sulfate from the hot springs south of Flagstaff Butte (FB-1) has a value of +20.3$^\circ/_{\circ\circ}$ while sulfur from highly silicified rock (FB-5) found near the mouth of the springs

Figure 13. Comparison of isotopic ratios of sulfur from various occurrences including sulfur in the Alvord Valley.



1. Jensen, 1967.
2. Jensen, et al., 1971.
3. Schoen and Rye, 1970.
4. Krouse, 1974.
5. Kaplan, et al., 1970; Shima, et al., 1963.
6. Sasaki, 1969; Shima, et al., 1963.
7. Sasaki, 1969; Jensen, 1967.

has a value of +1.8°/₀₀. It is possible that the hot spring sulfur could be contaminated if the thermal waters flow through Cretaceous sediments which may underlie this area (Dr. David Alt, personal communication, 1975). The value of 0.7°/₀₀ for a sample of metarhyolite (PT-15) from the Pueblo Mountains suggests that the sulfur in the rock is of magmatic origin. The large difference between the value for this rock and values from samples from the Alvord Valley farther north suggests that this particular rock unit did not contribute sulfur to the Alvord Valley geothermal systems.

Discussion and interpretation. Sulfur from a particular environment usually has a characteristic isotopic ratio or range of ratios (Fig. 13). Present-day sea water sulfate always has values close to +20 per mil while sulfur from sediments can have a wide range of values from approximately +10 to -40 or -50 per mil (Jensen, 1967). This is generally due to the preferential reduction of ^{32}S by sulfate reducing bacteria (Jensen, 1967). Sulfur from fumaroles associated with active volcanoes also has a wide range of values. However, the mean is closer to zero per mil, presumably because the sulfur is from a magma but has undergone homogenization or various exchange reactions between sulfate and sulfide phases causing fractionation of ^{34}S among the various sulfur species (Jensen, et al., 1971). Sulfur which is derived directly from the earth's mantle is thought to have values within $\pm$ 5 per mil of those of the meteorite standard (Jensen, 1967). Thus many magmatic hydrothermal ore deposits have sulfur with values clustering near zero per mil (Jensen, 1967) as do mafic igneous rocks (Kaplan, et al., 1970;

Shima, et al., 1963). Curiously, felsic igneous rocks often have wide ranges of sulfur isotope ratios as is shown on Figure 13. Some granitic rocks do indeed have values clustering near zero per mil while others have sulfur with various positive ratios up to +20 per mil (Sasaki, 1969). It has been suggested that felsic igneous rocks having widely scattered positive values originated from the melting of sediments or were contaminated by assimilation or hydrothermal leaching of sedimentary sulfur before solidification (Shima, et al., 1963). One can speculate that basaltic rocks have a narrow range of values near zero because of their deep crustal or mantle origin and the fact that they are relatively dry, while granitic rocks can be of lower crustal or melted sedimentary origin. Granitic rocks are also wetter which allows for greater contamination.

Geothermal waters are known to have sulfur of various origins. A number of thermal springs in Jamaica and Vancouver Island, B.C. with sulfur isotopic values near +20 per mil are thought to be circulating present-day sea water (Krouse, 1974). Many thermal springs in western Canada have water which is apparently entirely of meteoric origin and sulfate sulfur having values between +15 and +25 per mil. It is theorized that the sulfur has been leached from buried marine sediments (Krouse, 1974). There are a few geothermal systems which contain sulfur of deep-seated mantle origin derived either from a body of degassing magma or from leaching of igneous rocks containing uncontaminated and unfractionated sulfur. The acid hot spring areas at Yellowstone Park are an example. All sulfur species from thermal waters, fumaroles, and nearby soils have isotopic values which vary only between +3.3 and -5.5 per mil (Schoen and Rye, 1970). This area is also associated with very recent volcanic rocks and other geophysical evidence suggests that a degassing body of magma may in fact exist at depth (Eaton, et al., 1975). A cooling body of magma is also thought to exist beneath The Geysers in California (Chapman, 1975) and the geothermal area at Larderello, Italy (McNitt, 1965).

Results of sulfur isotope analyses from the Alvord Valley show that the isotopic values for valley hot spring sulfates are strikingly similar to values for nearby playa and soil sulfates (Table 5). Samples A-5 and A-6 probably contain some sulfate derived from evaporation of thermal water from Alvord Springs, but the other soil and playa samples (A-9 and BF-4) have sulfate clearly derived from weathering of rock on Steens Mountain and subsequent deposition and evaporation in the middle of the Alvord Valley. Isotopic values of sulfur in felsic volcanic rocks have a wide range from +6.3 to +17.3 per mil but have a mean of +12.0 per mil (Table 5), very close to the means for soil, playa and hot spring sulfates. Presumably these varied, but heavy values (high ratios) indicate that sulfur in the volcanics is not entirely of deep seated origin but may in part be derived from contamination of the magma before solidification as has been previously discussed. It is evident on Figure 13 that values for Alvord area felsic volcanics fall within the range shown for felsic volcanic rocks in general. In addition, the rocks with the heaviest values (TA-5 and TP-3) are from flows which are adjacent to water laid tuffs and tuffaceous sediments (Fig. 12). It is possible that sulfur in these rocks was in part derived from these volcanic sediments.

The close agreement of the mean isotopic values for sulfur from soil and playa sediments, volcanic rocks, and hot springs suggests that the soil, playa and hot spring sulfates are derived from leaching and/or weathering of volcanic rocks on Steens Mountain. In general, basalts and more silicic volcanic rocks contain an average of about 300 ppm sulfur (Ricke, 1960). However, the older rhyolites and dacites in Steens Mountain probably contain more sulfur than the basalts and andesites since none of the andesites or basalts contained enough sulfur for an isotopic analysis. Calculations show that they contained less than 100 ppm sulfur. Thus the contribution of sulfate from the older silicic volcanics to the thermal waters and sediments is probably greater than their smaller outcrop area would suggest. The fact that the rocks have varied isotopic ratios while the hot springs and sediments do not is easily explained if one considers that sulfur leached or weathered out of the rocks would become homogenized during transport and deposition. Sulfate in Alvord Valley thermal waters may either be derived directly from leaching of volcanic rocks or from leaching of playa sediments as the thermal waters circulate back up to the surface. The probability that the sulfur in the hot springs is of direct magmatic origin is extremely small.

Conclusion

The presence of magmatic water in the hot springs of the Alvord

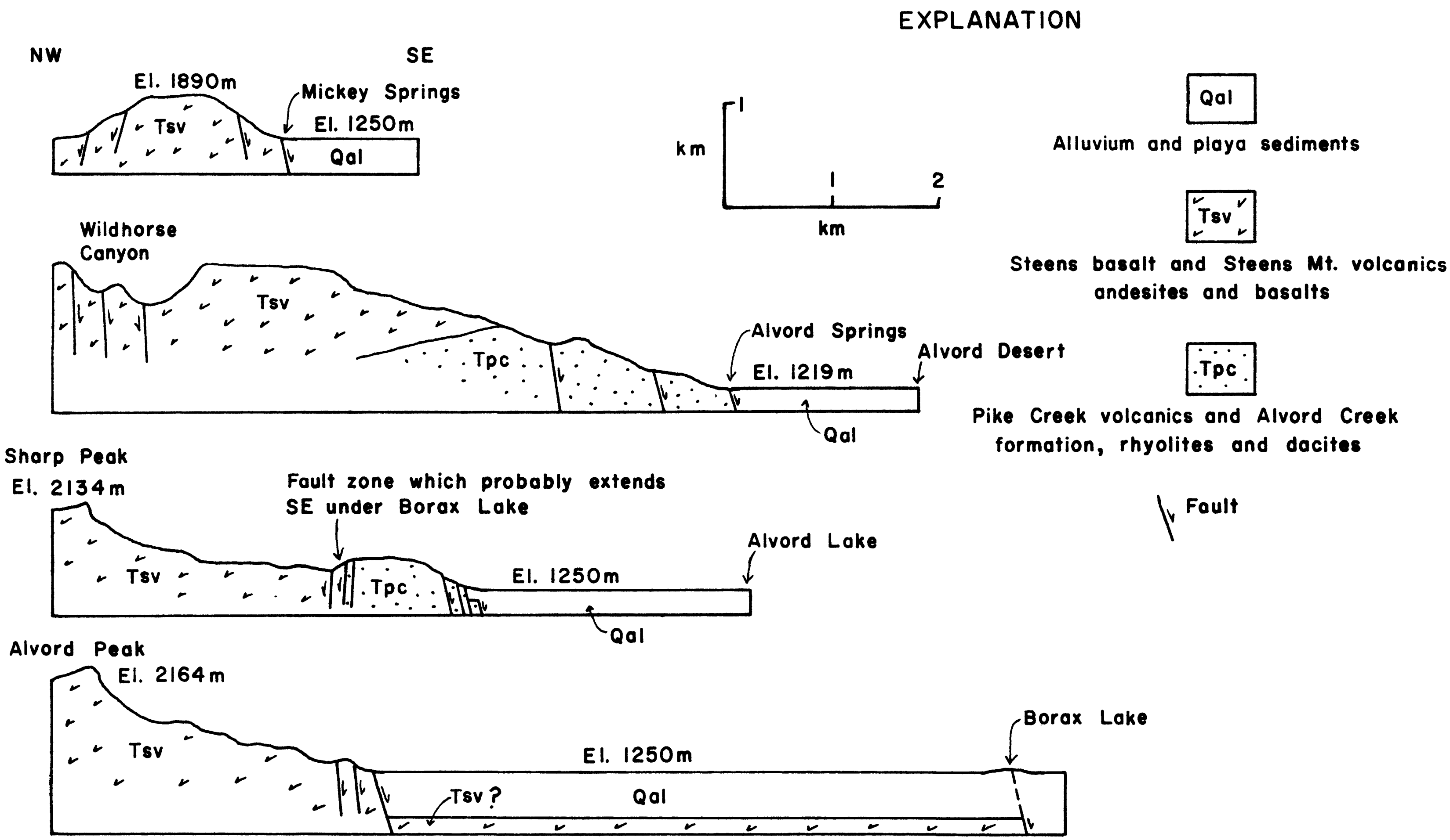
Valley appears to be unlikely. Evidence which supports this conclusion includes: 1) the fact that the most recent volcanic activity in the area occurred 15 million years ago; 2) D/H and $^{18}O/^{16}O$ ratios of thermal waters indicate that the waters are at least 95% meteoric; and 3) the fact that anomalous boron and sulfate in the thermal waters are probably derived from nearby volcanic rocks. Therefore, thermal waters in the Alvord Valley appear to be entirely of meteoric origin.

CHAPTER 5

MODEL AND DISCUSSION

In addition to the valley structure and origin of thermal water, one needs to consider the following points in order to develop a circulation model for a particular geothermal system: 1) the recharge area for water in the system; 2) the permeability and structure of the rocks enclosing the system; 3) the probable depth of circulation of thermal waters; 4) the heat source and driving force for water circulation; and 5) whether the system is dominated by vapor or hot water (White, 1968). The thermal springs of the Alvord Valley have been classified as hot water convection systems by the U.S. Geological Survey (White and Williams, 1975). This implies that the system is circulating mainly hot water with very little vapor being involved in the transfer of heat through the system (White, Muffler, and Truesdell, 1971). The U.S. Geological Survey also suggests that due to the 23 to 25 km distances between springs, Mickey Springs, Alvord Springs, and Borax Lake are three separate systems and thus not connected at depth to form one very large geothermal system (White and Williams, 1975). A generalized model which could represent any of these three systems is presented in Figure 15 and will be discussed in the following paragraphs.

Figure 14. Structure sections for Alvord Valley hot springs showing major faults. Section for Mickey Springs is from reconnaissance mapping by Walker and Repenning (1965) and Walker (1973). Other sections are generalized from detailed cross sections by Williams and Compton (1953). Section locations are shown on Figure 2.



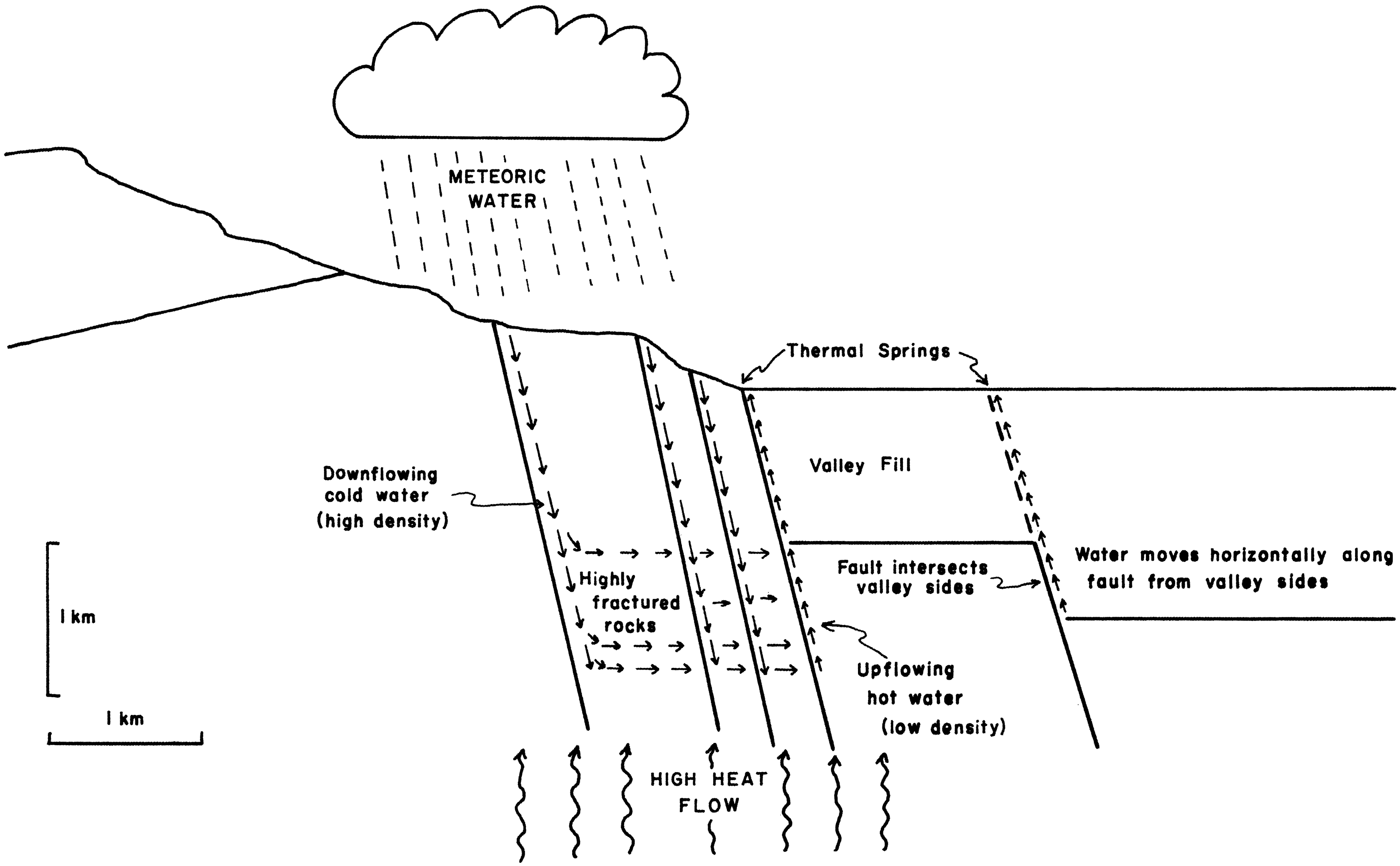
Recharge Areas

Steens Mountain is considered to be the recharge area for Alvord Springs and Borax Lake due to its areal extent, height, proximity to all the springs, and the fact that it is covered with considerably more vegetation than the low and dry hills on the east side of the valley. The recharge area for Mickey Springs is probably the adjacent mountain to the west. Mickey Springs issues from a fault at the base of this mountain (Walker and Repenning, 1965).

Permeability and Structure

In general, the boundaries between the valleys and hills in the Basin-and-Range province are defined by numerous parallel or en echelon normal faults which give the appearance of stair steps in cross section. The Alvord Valley is no exception. There are of course many lesser faults and fractures throughout the eastern side of Steens Mountain (Williams and Compton, 1953) which can also catch meteoric water flowing down the mountains. The appearance of the topography and the observation of recent earthquakes in the area makes it clear that these faults and fractures are quite recent and presumably highly permeable zones for the inflow of cold meteoric water. Structure sections for the three Alvord Valley hot spring areas are shown in Figure 14. They are compiled from detailed mapping and cross sections done by Williams and Compton (1953), regional mapping from Walker and Repenning (1965), and Walker (1973), and information from this report. Major faults which probably control most water circulation to nearby

Figure 15. Thermal water circulation model for Alvord Valley hot springs.



springs are shown on each section. Two sections are shown for the Borax Lake area since the northern section through Alvord Lake shows the faults which are likely conduits for water in the recharge area west of Alvord Lake, while the other section shows the structure directly under Borax Lake. Faults, steeply dipping fractures and fractures connecting adjacent faults are shown diagrammatically but more or less to scale in Figure 15. Structures shown on this model represent the plumbing system for Alvord area hot spring systems.

Depth of Circulation

If one knows or can estimate the underground reservoir temperatures of each hot spring system, the thermal conductivity of the associated rocks, and the local average heat flow, it is possible to get an approximate idea of the minimum circulation depth for each hot spring system through the following relationship (Clark, 1966):

$$D_{min} = \frac{Tr}{Hf/Tc} \times 10^{-5} \quad \text{where}$$

D_{min} = minimum circulation depth (kilometers)

Tr = estimated thermal reservoir temperature - average surface temperature (°C)

Hf = heat flow (cal/cm^2-sec)

Tc = thermal conductivity of associated rocks (cal/cm-sec-°C).

All of this data along with the calculated minimum circulation depths are shown in Table 6. One should remember, however, that these are minimum circulation depths, and it is possible that the waters could

Table 6. Estimation of minimum circulation depths for Alvord Valley hot springs.

	Mickey Springs	Alvord Springs	Borax Lake
Estimated thermal reservoir temperature[1] (°C)	193	174	171
Thermal conductivity of assoc. rocks[2] (10^{-3} cal/cm sec °C)	4.5 ± 1.5	4.5 ± 1.5	4.5 ± 1.5
Heat flow[3] (10^{-6} cal/cm^2 sec)	5.5 ± 0.5	4.5 ± 0.5	4.5 ± 0.5
Calculate minimum circulation depth (km)	1.3 ± 0.3	1.4 ± 0.3	1.4 ± 0.3

[1] Averaged from values reported by Mariner, et al. (1974) using SiO_2, Na-K, and Na-K-Ca geothermometry. For method, see Fournier and Rowe (1966) and Fournier and Truesdell (1973).
[2] Averaged from values for volcanic rocks and recent sediments reported by White (1968) and Clark (1966).
[3] Heat flow measurements were done by Phillips Petroleum Company (1975). Values are from Dr. Gary Crosby, personal communication (1976). Average heat flow for the Basin-and-Range province is about 2.0 X 10^{-6} cal/cm^2 sec (Lee And Uyeda, 1965).

late much deeper. Information from deep drilling in other well-explored hot water geothermal systems has shown that temperatures tend to change very little with depth after the average reservoir temperature is reached and that circulation depths of up to 3 km are possible (White, 1968; White, Muffler and Truesdell, 1971). In any case, the depth of interest for drilling in any Alvord Valley hot spring system would probably not exceed 1.5 km as is shown in Table 6. The model in Figure 15 shows water in the thermal reservoir at depths between 1.0 and 2.0 km.

Heat Source, Driving Force

In view of the fact that no evidence has been found in this study to suggest the presence of any magmatic component in the thermal waters of the Alvord Valley, it is reasonable to conclude that there is probably no cooling magma chamber at depth under the valley. This, of course, does not rule out the presence of a deep-seated magma chamber, but suggests that the possibility is remote. It is well known that the Basin-and-Range province as a whole has high heat flow, usually between 2.0 and 2.5 X 10^{-6} cal/cm^2 sec (Lee and Uyeda, 1965). With high heat flow in an area having rocks of relatively low thermal conductivity such as valley fill sediments and volcanic rocks (Clark, 1966; White, 1968), it is possible to have temperatures well above the surface boiling point of water at relatively shallow depths (as low as 1 km). This was shown in Table 6. Next, if there are highly permeable areas nearby such as recent faults, it is possible for hot water to circulate down to hot rocks at shallow depth, gain heat by conduction from the rocks, and circulate rapidly back up to the surface to appear as hot springs with surface temperatures near boiling. The anomalous heat flow found in hot spring areas is probably due to the fact that hot waters are circulating nearby but could be due to local hot spots caused by anomalous concentrations of radioactive elements or hot spots in the mantle. However, investigations have not been made into any of these theories and further speculation is unwarranted.

The driving force for thermal water circulation is caused by the hydrostatic head developed by waters in the recharge areas which are at least 300 to 600 meters above the valley floor as is shown in Figures 14 and 15. In addition, White (1968) has shown that density differences between cold, descending water and hot, ascending water also contribute to the driving force. The density of pure water is 1.00 at 4°C, 0.958 at 100°C, 0.917 at 150°C, and 0.863 at 200°C. Thus descending water at a temperature of 50°C is roughly 6% more dense than ascending water at 150°C. Density differences due to increased salinity of heated waters were shown to be insignificant. Other factors which promote circulation at depth are: 1) the fact that the viscosity of downflowing water at 50°C is 0.0060 poise while upflowing water at 150°C has a viscosity of only 0.0020 poise; and 2) the increased solubility of silica at the temperatures estimated for this geothermal system. As the temperature increases, the water can dissolve increasing amounts of silica and increase the permeability of channels through which the water is flowing (White, 1968).

Electrical Generating Potential

The U.S. Geological Survey has estimated the electrical generating potential of the most promising geothermal systems in the United States (White and Williams, 1975). Alvord area hot springs were included in this category. The Mickey Springs system was estimated to have a power generating potential of 46 megawatts for a life of 100 years while Alvord Springs and Borax Lake were estimated to have 17 and 32 megawatts respectively. The Geysers in California, the only producing thermal area for which estimates were given, was shown to have a potential of

477 megawatts for a life of 100 years. Although the power generating potential of the Alvord area hot springs was lower than the other thermal systems listed, it appears that potential for the development of significant amounts power from Alvord Valley hot springs does exist.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The purpose of this project was to delineate structures through which hot spring waters are circulating in the Alvord Valley and to determine the probable origin of thermal waters in order to develop a model for water circulation in the thermal springs and thus further the evaluation of potential for geothermal power in the valley.

Studies of the D/H and $^{18}O/^{16}O$ isotopic ratios of meteoric and thermal waters from the valley and sulfur isotopic ratios from whole rock, playa, and hot spring sulfates have uncovered no evidence for the presence of a magmatic component in any of the valley's thermal waters. To the contrary, isotopic data and data concerning the origin of anomalous boron in thermal waters suggest that the waters are entirely of meteoric origin. Gravity surveys done for this project and compilation of published structural data for Steens Mountain have located the main basin and range type faults in the valley and in Steens Mountain to the west. These faults and associated fractures are thought to be the plumbing system for each of three hot springs in the valley. Probable recharge areas for Mickey Springs, Alvord Springs and Borax Lake have been located in the mountains to the west of each spring.

Estimates of subsurface temperatures by the U.S. Geological Survey for each of the three hot spring areas has shown that the subsurface reservoir temperatures are relatively high - between 170 and 200°C. This information along with heat flow data from the Phillips Petroleum Company has been used to calculate that the minimum circulation depth for thermal waters in all of the valley hot springs is about 1.3 ± 0.3 km. The generalized model for water circulation (Figure 15) for Mickey Springs, Alvord Springs, and Borax Lake shows cold, dense, meteoric water circulating down through faults and fractures in the mountains, becoming heated in a thermal reservoir at depth and circulating rapidly back up to the surface along faults at the sides or in the middle of the Alvord Valley.

In conclusion, it appears that the hot springs in the Alvord Valley look promising for the development of geothermal power. Although the presence of a magmatic heat source at depth could not be established, all of the hot springs have been shown to have reservoirs with temperatures high enough for power generation at reasonable depths. Mickey Springs is the most promising since it has the highest estimated reservoir temperature and the highest heat flow. Mickey Springs and Alvord Springs issue from faults at the west side of the Alvord Valley and probably have thermal reservoirs located in highly fractured volcanic rocks. Borax Lake and the associated hot springs to the north may have a thermal reservoir located in valley fill sediments at depth or in the underlying volcanic rocks. Further studies of the extent, permeabilities, exact locations, and temperature distributions of the thermal reservoirs associated with the Alvord Valley hot springs would require drilling. However, the estimated potential for power generation from all three of the Alvord Valley hot spring systems is low compared to the estimated power potential for other producing geothermal systems such as The Geysers in California. Obviously consideration of economic factors will be necessary before a project so risky and expensive as drilling can be undertaken.

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APPENDIX A

GRAVITY DATA REDUCTION

Observed gravity values were corrected for drift and latitude and then reduced to the Bouguer anomaly using the following formula:

B.A. = corrected grav. + elev. corr. + terr. corr. - K,

where K is a constant relating the observed relative Bouguer gravity to the absolute regional Bouguer gravity. The elevation correction combines both the free air correction and the Bouguer correction. The free air correction reduces all values to an arbitrary datum plane with an elevation of 4133 feet (1259.7 meters) which was the elevation of the southern base station (Fig. 4). The Bouguer correction removes the gravitational effect of a presumed infinite horizontal slab of rock between the plane of each station and the datum plane (Dobrin, 1960). The density of the infinite slab was assumed to be 2.67 gms/cc. Stations above the datum plane had a positive elevation correction while stations below the plane had a negative correction.

Terrain corrections are necessary to account for the upward influence on gravity caused by hills and valleys which have vertical dimensions similar to the distance from the station. Corrections were carried out for 47 stations to zone K on the charts (a distance of 9,903 meters) published by Hammer (1939) using the extended tables published by Douglas and Prahl (1972). Most of the corrections were done for stations located in mountainous terrain at the ends of the gravity surveys. Since the valley itself is extremely flat, few corrections were done for stations in the valley. In fact, there are many places in the valley where elevations vary by no more than 2 or 3 meters over distances of several kilometers. Corrections were interpolated for stations for which no correction was worked out manually. Maximum error for terrain corrections in or adjacent to mountainous areas is ± 0.2 milligals while maximum error for stations in the valley ± 0.2 milligals.

Normally, it is possible to relate the observed gravity in the area being surveyed to absolute gravity. This is done by measuring gravity at a base station and at a point of known absolute gravity, usually an airport, within three to four hours. The Alvord Valley is so remote that this was not possible. However, it was possible to relate the Bouguer gravity anomaly in the valley to the absolute regional Bouguer anomaly. This was done by finding a gravity station (C10) located on one of the regional Bouguer contours (Thiruvathukal, et al., 1970) and computing the difference between the arbitrary Bouguer gravity at that station and the absolute Bouguer gravity for that contour. This number, K (305 milligals), was then subtracted from the arbitrary Bouguer gravity for all stations. Due to the fact that the regional Bouguer trend is not parallel to the trend in the valley, all of the absolute Bouguer anomaly values in the valley could be in error by ±10 milligals. However, this in no way affects the internal consistency or precision of the gravity data or the configuration of the structure models presented in Chapter 3 since all values would be in error by exactly the same amount.

APPENDIX B

COMPUTER MODELING PROCEDURE AND DISCUSSION

The computer program used to model valley structure was written by Bronson Hawley of the University of Montana using a method described by Bott (1960). The program was run on a Digital GT 40 TV screen plotter. The theory and assumptions involved in the computer modeling are somewhat complex. The program divides the cross section of the valley, as set up by the user, into a series of vertical slabs which have infinite length perpendicular to the survey (north-south for the Alvord Valley) and calculates the Bouguer anomaly over each slab and displays this information. The program assumes that the topographic surface of the valley is flat and that the model is 2-dimensional, e.g. that the valley is infinitely long and homogeneous perpendicular to the survey line. The first assumption posed no significant problem because the valley is extremely flat and elevation and terrain corrections reduced the gravity data to a datum plane. Surveys A-A', B-B', C-C' and E-E' did extend up into the hills on the west side of the valley as much as 600 feet (183 meters) above the valley floor. However, in each survey, the edge of the valley fill was at least 2 to 3 km from the stations at higher elevations and there was no significant effect on the fit of the valley fill model to the observed Bouguer gravity anomaly. The second assumption also posed no significant problem. There is a well-known gravity program by Talwani and Ewing (1960) which creates 3-dimensional gravity models. In modeling the valley fill in the Bitterroot Valley of western Montana, Lankston (1975) compared results from both the

Bott (1960) and Talwani and Ewing (1960) programs. He found that differences in results between the 2-dimensional and 3-dimensional models were negligible if the perpendicular extent of the valley on each side of the survey was at least as great as the width of the valley across the survey line This requirement was met for all of the east-west gravity surveys in the Alvord Valley.

The choice of a correct density contrast is another problem in gravity modeling. Assuming that the basement under the valley fill is Miocene volcanic rock with an overall density ranging from 2.6 to 2.8 gms/cc (Dobrin, 1960) and that the valley fill has a density ranging from 1.9 to 2.3 gms/cc (Dobrin, 1960; Clark, 1966), the maximum density contrast is 0.9 gms/cc while the minimum contrast is 0.3 gms/cc. Lankston (1975) chose a density contrast of 0.5 gm/cc for structural models of the Bitterroot Valley in western Montana. This valley is filled with Tertiary to Quaternary alluvium and lake deposits, sediment similar to that found in the Alvord Valley. During 1974 a detailed, 500-station gravity survey was run in the Alvord Valley between Fields and Mickey Springs by the Geothermal Operations branch of the Phillips Petroleum Company under the direction of Dr. Gary Crosby. From this information and studies of telluric currents done by Phillips in the area, it was concluded that the average valley fill thickness is about 1 km (Dr. Gary Crosby, personal communication, 1976). Experimentation has shown that if two structural models are constructed from each survey using density contrasts of 0.4 gm/cc and 0.6 gm/cc, the average valley fill thickness is bracketed between about 0.7 and 1.3 km. This is also consistent with the density contrast chosen by Lankston (1975). Structural models using these density contrasts are shown in Figures 5 through 8.

APPENDIX C

BOUGUER ANOMALY VALUES

Values are relative to the regional Bouguer anomaly as explained in Appendix A. Locations are accurate to ± 0.5 seconds of arc for both latitude and longitude. Stations are grouped by survey going from north to south or from west to east. * denotes stations for which terrain corrections were computed.

Station	Latitude	Longitude	Elevation (meters)	Bouguer Anomaly (mgals)
N. Base (C5)	N42°32'27"	W118°30'10"	1219.8	-167.64
S. Base *	42°20'02"	118°39'00"	1259.7	-155.14
A1*	42°17'54"	118°42'29"	1468.2	-137.07
A2*	42°17'21"	118°41'55"	1380.7	-135.75
A3*	42°17'07"	118°41'08"	1329.5	-142.11
A4*	42°17'16"	118°40'20"	1303.6	-146.73
A5*	42°17'22"	118°39'51"	1292.3	-150.41
A6	42°17'28"	118°39'22"	1272.5	-154.59
A7	42°17'35"	118°38'48"	1272.5	-157.42
A8*	42°17'42"	118°38'12"	1256.1	-161.42
A9	42°17'52"	118°37'27"	1246.9	-160.70
A10	42°17'57"	118°37'01"	1239.6	-161.00
A11*	42°18'03"	118°36'36"	1238.1	-161.27
A12	42°18'13"	118°35'47"	1236.6	-163.01
A13	42°18'21"	118°35'05"	1234.4	-162.97
A14*	42°18'28"	118°34'29"	1235.4	-161.14
A15	42°18'36"	118°33'54"	1235.9	-159.07
A16	42°18'41"	118°33'27"	1237.8	-154.88
A17*	42°18'48"	118°32'54"	1243.6	-151.78
A18*	42°18'52"	118°32'21"	1286.3	-147.73
A19*	42°19'00"	118°31'54"	1287.2	-147.91
A20*	42°18'58"	118°31'22"	1281.7	-147.24
A21*	42°18'55"	118°30'40"	1251.8	-148.81
B1*	42°25'55"	118°38'31"	1416.1	-140.85
B2*	42°26'02"	118°38'04"	1276.5	-142.50
B3	42°26'00"	118°37'33"	1250.6	-144.36
B4*	42°26'09"	118°36'59"	1236.9	-147.83
B5	42°26'08"	118°36'04"	1237.8	-154.74
B6*	42°26'08"	118°35'24"	1238.1	-157.08
B7	42°26'08"	118°35'00"	1238.4	-157.31
B8*	42°26'48"	118°33'12"	1240.2	-157.04

Station	Latitude	Longitude	Elevation (meters)	Bouguer Anomaly (mgals)
B9	N42°26'48"	W118°33'12"	1240.2	-157.04
B10	42°26'44"	118°32'36"	1230.5	-162.90
B11*	42°26'45"	118°31'56"	1223.5	-164.94
B12	42°26'44"	118°31'14"	1223.2	-166.78
B13	42°26'43"	118°30'27"	1222.2	-167.00
B14*	42°26'38"	118°29'28"	1222.1	-158.45
B15	42°26'27"	118°28'05"	1221.1	-152.88
B16*	42°26'15"	118°26'56"	1221.2	-151.00
B17	42°26'07"	118°25'58"	1234.6	-148.32
B18	42°25'54"	118°25'04"	1257.0	-140.24
B19*	42°25'34"	118°24'36"	1305.9	-138.27
B20	42°25'18"	118°24'08"	1319.5	-138.50
C1*	42°33'10"	118°33'05"	1426.5	-152.36
C2*	42°32'50"	118°32'12"	1291.1	-154.30
C3*	42°32'34"	118°32'02"	1240.8	-155.51
C4*	42°32'27"	118°31'34"	1222.2	-164.67
C5	42°32'27"	118°30'10"	1219.8	-167.64
C6*	42°32'22"	118°29'02"	1219.8	-168.74
C7	42°32'18"	118°27'52"	1219.8	-167.09
C8*	42°32'14"	118°26'43"	1219.8	-166.56
C9*	42°32'10"	118°25'33"	1219.8	-165.00
C10*	42°32'05"	118°24'42"	1219.8	-163.30
C11	42°32'02"	118°24'08"	1219.6	-159.84
C12*	42°32'00"	118°23'33"	1223.2	-153.72
C13	42°31'59"	118°23'07"	1225.9	-150.19
C14	42°31'56"	118°22'33"	1241.1	-146.09
C15	42°31'56"	118°22'24"	1259.7	-143.68
C16*	42°31'55"	118°22'14"	1286.6	-141.96
D1*	42°33'20"	118°30'10"	1219.8	-167.26
C5	42°32'27"	118°30'10"	1219.8	-167.64
D2*	42°31'35"	118°30'10"	1219.8	-169.12
D3	42°30'43"	118°30'10"	1219.8	-170.63
D4*	42°29'51"	118°30'10"	1219.8	-170.08
D5	42°28'59"	118°30'10"	1219.8	-169.08
D6*	42°28'06"	118°30'10"	1219.8	-167.40
B13	42°26'43"	118°30'27"	1222.2	-167.00
D7	42°25'46"	118°30'56"	1223.2	-168.16
D8*	42°25'16"	118°30'42"	1223.5	-166.27
D9	42°24'53"	118°30'35"	1223.5	-164.70
D10*	42°24'26"	118°30'24"	1224.1	-162.53
D11	42°24'00"	118°30'12"	1224.7	-159.59

Station	Latitude	Longitude	Elevation (meters)	Bouguer Anomaly (mgals)
E11*	N42°23'35"	W118°30'05"	1225.9	-154.60
E1*	42°23'34"	118°38'22"	1265.8	-142.89
E2	42°23'52"	118°37'48"	1242.1	-147.18
E3*	42°23'30"	118°36'52"	1226.5	-157.08
E4	42°23'30"	118°36'16"	1226.5	-160.68
E5	42°23'30"	118°35'40"	1226.5	-162.49
E6*	42°23'30"	118°35'08"	1226.8	-163.29
E7	42°23'30"	118°34'47"	1227.7	-163.48
E8	42°23'30"	118°33'18"	1226.2	-163.87
E9*	42°23'32"	118°31'40"	1225.0	-163.81
E10	42°23'31"	118°30'56"	1226.5	-161.05
E11*	42°23'35"	118°30'05"	1226.2	-154.54
F1*	42°24'27"	118°36'08"	1226.5	-157.85
E4	42°23'30"	118°36'16"	1226.5	-160.68
F2	42°23'05"	118°36'16"	1226.5	-162.60
F3	42°22'39"	118°36'15"	1226.5	-164.18
F4*	42°22'14"	118°36'14"	1226.5	-166.04
F5	42°21'47"	118°36'14"	1226.5	-167.91
F6	42°21'21"	118°36'14"	1226.5	-169.02
F7*	42°20'40"	118°36'14"	1229.6	-167.74
F8	42°20'15"	118°36'10"	1234.7	-165.88
F9	42°19'52"	118°36'11"	1237.2	-163.96
F10	42°19'37"	118°36'36"	1238.1	-163.30
F11*	42°19'16"	118°36'28"	1238.7	-162.42
F12	42°18'53"	118°36'35"	1238.7	-161.74
F13	42°18'27"	118°36'38"	1238.4	-161.69
A11*	42°18'03"	118°36'36"	1238.1	-161.27
G1	42°34'50"	118°26'43"	1219.8	-168.65
G2*	42°33'06"	118°26'43"	1219.8	-167.53
G3	42°33'59"	118°26'43"	1219.8	-167.07
C8*	42°32'14"	118°26'43"	1219.8	-166.56
G4	42°31'22"	118°26'43"	1219.8	-165.26
G5*	42°30'29"	118°26'43"	1219.8	-163.39
G6	42°29'38"	118°26'43"	1219.8	-161.71