CONTENTS

ABSTRACT

The Beowawe geothermal system in northern Nevada is a structurally controlled, water dominated resource with a measured temperature of 212°C (414°F). Surface expression of the system consists of large, active opaline sinter terrace that is present along a Tertiary to Quaternary normal fault escarpment. Several companies have explored the area and a considerable volume of surface and subsurface data are now available on the resource. The thermal fluids occur in a 1,220 m (4000 feet) thick section of Tertiary volcanic rocks and in underlying quartzite and argillite of the Ordovician Valmy Formation. The fluids flow to the surface along southwest and northwest trending faults.

Surface alteration associated with the geothermal system is vertically zoned along the Malpais escarpment with hematite stained, argillized rock along the fault trace; silicification, quartz veining and minor sinter zone above the hematite zone; and argillic, acid leach zone above the silicified zone. Subsurface alteration generally increases with depth in the volcanic rocks and is most intense in basaltic-andesite lava flows which are capped by tuffaceous sedimentary rock.

The geothermal fluids contain about 1400 mg/l total dissolved solids. Fluid chemistry suggest a siliceous reservoir rock without significant interchange with carbonate rocks.

INTRODUCTION

The Beowawe Geysers geothermal system is located 80 km southwest of Elko, Nevada, and 10 km southwest of the little town of Beowawe (Fig. 1). The geothermal system is a high-temperature water dominated resource, which appears to be structurally controlled. A large, active opaline sinter mound has formed from springs and geysers issuing from half way up the Malpais fault escarpment (Middleton, 1961). The subsurface measured temperature of 212°C in the Ginn 1-13 well (Chevron Resources Co., 1979) is comparable to the calculated geothermometer temperature of 227°C (Mariner and others, 1974).

Commercial exploration of the Beowawe geothermal system started in 1959 when Magma Power Company, Vulcan Thermal Power Company, and Sierra Pacific Power Company drilled 12 shallow wells between 1959 and 1965 (Garside and Schilling, 1979). Drilling of the exploration holes on the sinter terrace disrupted the natural geyser activity. Since 1974 six deep exploration wells have been drilled, one each by Magma Energy, Inc. and Getty Oil Company, and four by Chevron Resources Company. In general only the wells drilled on or next to the sinter deposit have been successful. Forty-one 150 m deep thermal gradient holes have been drilled in the area and several geophysical surveys have been conducted to help define the thermal system.

Through the Department of Energy's Industry Coupled Program much of the data obtained by industry during exploration of the Beowawe geothermal system has been made public. In addition geologic mapping and geochemical studies have been carried out. The integration and evaluation of these data constitute the present paper.

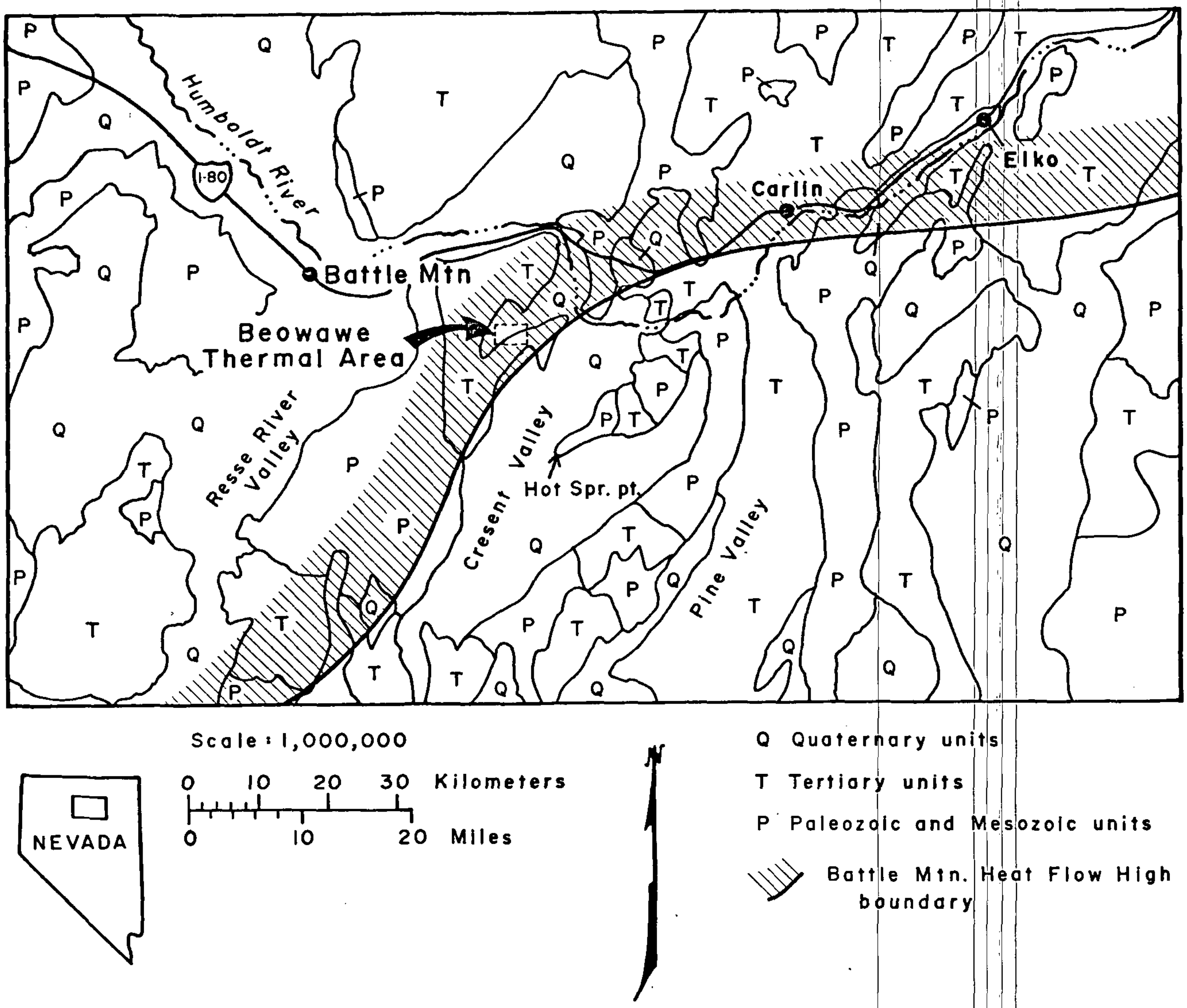


Figure 1. Location map of Beowawe geothermal area. Geology generalized from Stewart and Carlson (1977), Battle Mountain heat flow high boundary from Muffler (1979).

BEOWAWE GEOTHERMAL SYSTEM

Regional Setting

The Beowawe geothermal system is located in the north-central part of the Basin and Range physiographic province. Northeast-trending ranges that represent east-tilted horst or structural blocks bounded by normal faults form the dominate regional structures in the Beowawe area. Another structural trend which lies about 16 km west of the hot springs, is defined by north-northeast trending faults and uplifted Ordovician and Devonian cherts and clastic rocks and is evident on the regional geologic map (Stewart and Carlson, 1976). This stratigraphically uplifted zone parallels the west side of an aeromagnetic high recognized by Stewart and others (1979). The Oregon-Nevada lineament as defined by Stewart and others (1975) would include these north-northwest trending faults and Miocene lava flows on the east side of the uplifted zone.

The Beowawe KGRA lies within the Battle Mountain heat flow high where conductive heat flow is greater than 2.5 HFU (Sass and others, 1971). Heat flow values computed in the Beowawe KGRA average 2.6 HFU (Smith, 1981).

Geology

Stratigraphy

In the Beowawe KGRA a 950 to 1300 m thick section of Miocene dacite to basalt lava flows interbedded with tuffaceous sedimentary rocks overlie and are faulted against Odovician Valmy Formation rocks. The Valmy Formation in the area consist of siltstone, quartzite, chert and argillite and is intensly fractured with pervasive hematite staining in outcrop but is dark gray to black in subsurface drill cuttings. Many diabase and diorite dikes cut the Valmy rocks in some of the deep geothermal wells and possibly Odovician greenstones are present. Over 1700 m of Valmy Formation rocks have been penetrated without reaching the base of the formation.

A conglomerate 76 to 90 m thick and containing clasts of Valmy lithologies and andesite overlies the Valmy Formation (Fig. 2). Above the conglomerate is 230 to 533 m of basaltic to andesitic lava flows. The lower part of the basaltic-andesite lava flows unit thickens to the west (Figs. 2 and 4). The basaltic-andesite unit has not been dated due to its pervasive alteration. The unit (Tba) consists mostly of hematite stained scoria and flow breccia where exposed in Sec. 16, T31N, R48E (Fig. 3).

Tuffaceous sedimentary rocks interbedded with a single lava flow overlie the basaltic-andesite lava flows. The unit consists mainly of mudstone to sandstone, 122 to 183 m thick. The lava flow is andesitic in composition and is located near the top of this sequence (Fig. 2).

A 190 m thickness of basalt flows overlies the tuffaceous sedimentary rocks. This unit is best identified by its stratigraphic position and

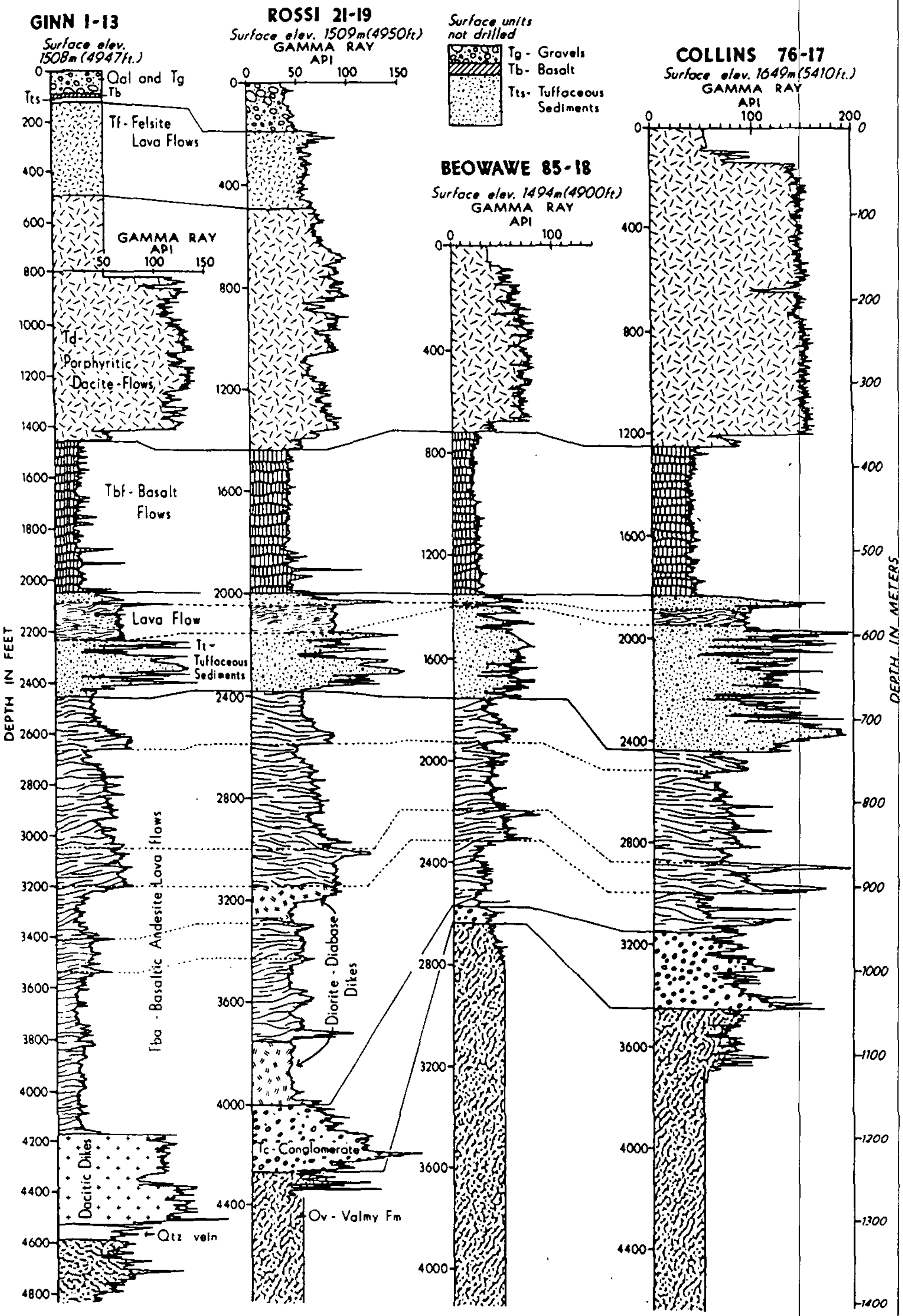


Figure 2. Correlation of lithologic and gamma ray logs for the Tertiary section in four deep drill holes at Beowawe KGRA. The logs are vertically adjusted to align horizontal data plane at the top of the tuffaceous sediments unit (Tt).

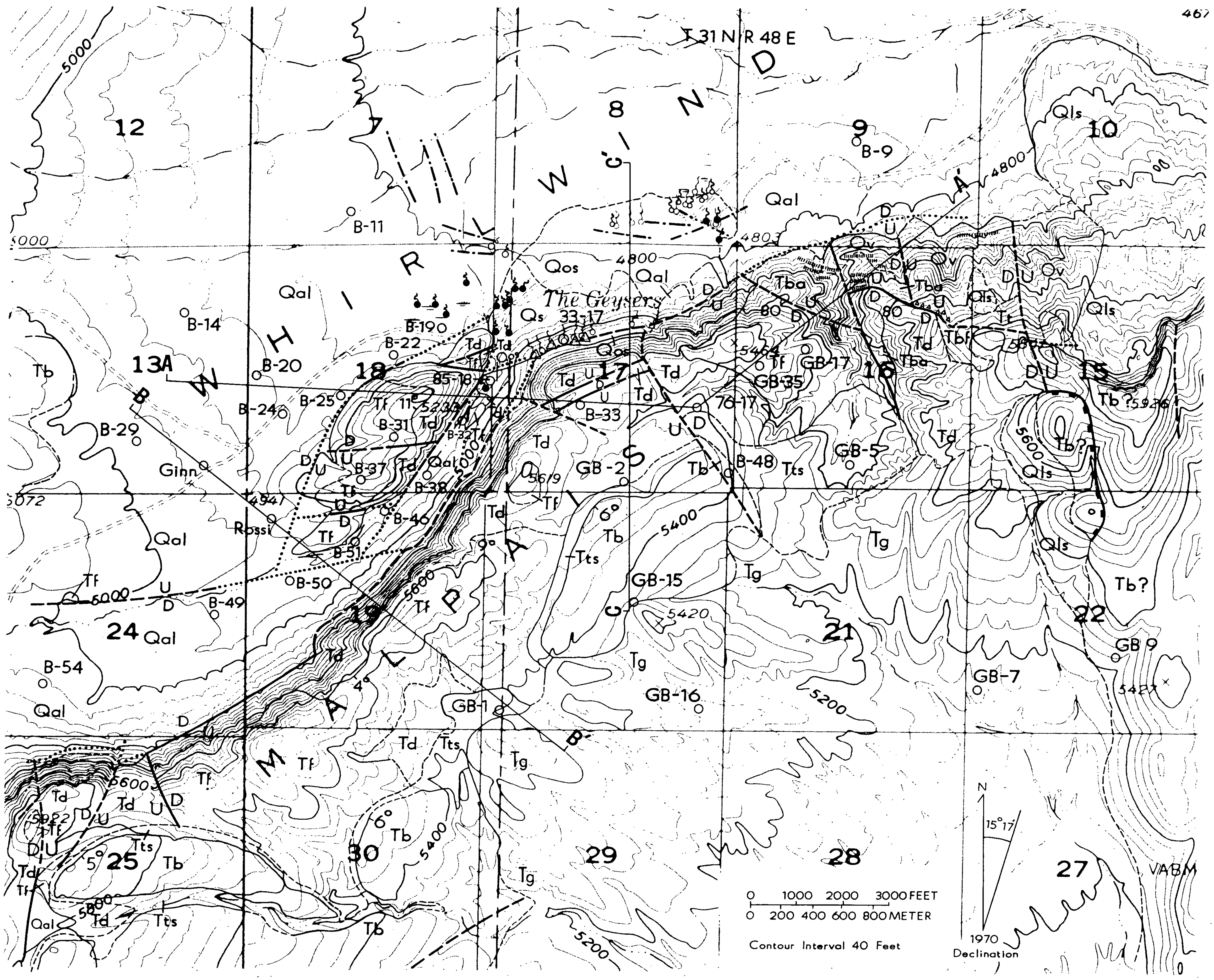
uniformly low gamma log. Correlation of the basalt flows in Sec. 15, T31N, R48E, which seem to be overlain by dacite, with this subsurface unit is tentative. Porphyritic dacite lava flows overlie the basalt in deep drill holes and in outcrop. The dacite unit (Td) is 290 to 366 m thick in drill holes and forms most of the Malpais escarpment (Figs. 3 and 4). The dacite consist of several thick, massive, porphyritic flows with some vitric and scorria zones as well as flow breccia horizons. A felsite lava flow, up to 90 m thick, with only a trace of small feldspar phenocrysts overlies the porphyritic dacite unit. Where present, the non-porphyritic felsite over porphyritic dacite contact is an excellent stratigraphic marker.

A significant unconformity separates the felsite and porphyritic dacite from the overlying tuffaceous sedimentary rocks which are up to 67 m thick and capped by a basalt flow up to 12 m thick (Figs. 2 and 4). Overlying the basalt are thick gravel and mudstone deposits of Tertiary to Quaternary age in Whirlwind Valley and on the south slope of the Malpais ridge.

Structure

The dominant structure in the Beowawe KGRA is the Malpais Fault which trends N75°E from the hot springs east and has about 370 m total displacement, down to the north. West of the sinter terrace the Malpais fault trends S37°W and a 270 m wide graben separates a small horst from the main ridge (Fig. 3). Subsurface data from drill holes indicates another fault is present on the west side of the horst. Using the porphyritic dacite-felsite contact as a marker, the small horst in Sec. 18, T31N, R48E, has dropped 140 m at the high point, relative to the rim, the graben has dropped 230 m from the rim, and the strata west of the horst is 350 m lower than the rim.

The Dunphy Pass fault, as mapped by Zoback (1979) and Struhsacker (1980)


T 31 N R 48 E
WHIRLWIND
VALLEY
ALPACA
The Geysers
12
7
8
9
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13A
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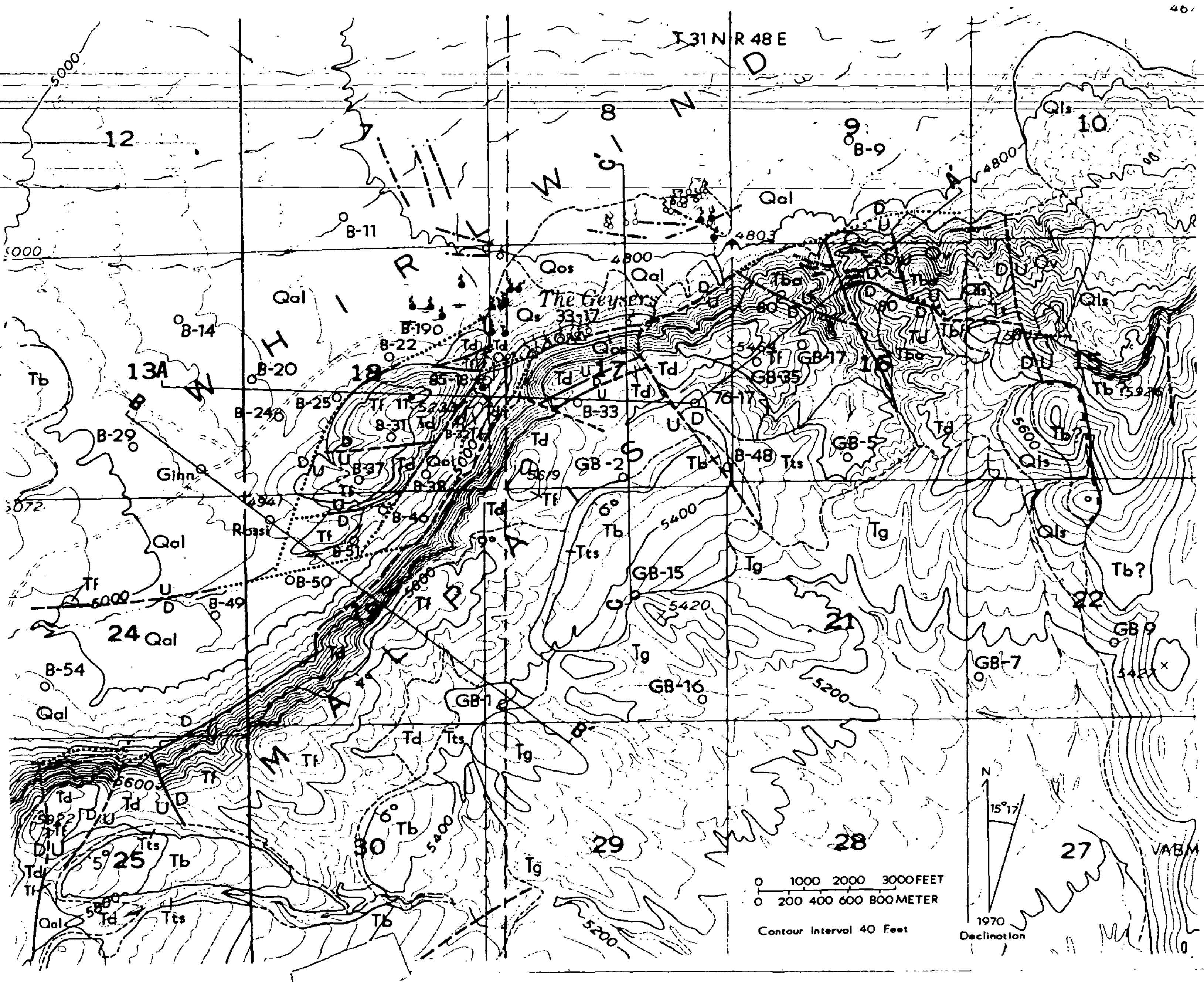


Geologic map of the Beowawe thermal area, by Bruce S. Sibbett.

EXPLANATION

Qs	Active and recent siliceous sinter.
Qos	Inactive siliceous sinter and sinter-cemented alluvium.
Qal	Alluvium, fine gravel and sand.
Qls	Landslides and colluvium below slump areas.
Tg	Uplifted old gravel deposits and tan mudstone.
Tb	Olivine-pyroxene basalt flows with black diktytaxitic texture.
Tts	Tuffaceous sedimentary rocks, white, light gray to buff siltstone, sandstone, porcellanite and non-welded tuff.
Tf	Felsite Lava Flows; dark brown felsite or black vesicular vitric zones with only a trace of 1 mm crystals of feldspar.
Td	Porphyritic Dacite Lava Flows; 5 to 7 percent 2 mm feldspar phenocrysts. The thickness is 290 to 366 m.
Tbf	Basalt Lava Flows; vesicular basalt with 2 mm plagioclase phenocrysts. The unit is 183 to 195 m thick with a uniform low gamma response.
Tt	Tuffaceous Sedimentary Rocks; tuffaceous mudstone, siltstone and sandstone, white to light gray, with an andesitic lava flow interbedded. The unit is 122 to 183 m thick.
Tba	Basaltic-Andesite Lava Flows; basaltic to possibly dacitic lava flows with abundant amygdules of celadonite, calcite and quartz. The flow sequence is 230 to 533 m thick in deep drill holes.
Tc	Conglomerate; clasts of chert, siltstone, quartzite and andesite in a sandstone to siltstone matrix. The unit is 76 to 91 m thick.
Tid, id	Diabase and Diorite Dikes (in subsurface only); olive green to gray fine-grain diabase dikes partly altered to chlorite and calcite and a few diorite, dacite and hornblende andesite dikes.
Ov	Valmy Formation, siltstone, quartzite, chert and argillite, intensely fractured and folded with pervasive hematite staining in some areas.

MAP SYMBOLS

—— - - -	Contact, dashed where approximately located.
—— - - - ···	Fault, dashed where approximate or inferred, dotted where covered.
▲▲▲	Slump block, barbs on upper plate.
—·—·—	Photo linear which may be fault produced.
⫶⫶⫶	Quartz and calcite veins.
⟋ 6°	Dip of contact calculated from contact surface trace or trace to drill hole intercept elevations.
○ B-20	Geothermal exploration bore holes.
●~	Hot or warm spring or seep.
△	Steam vent.

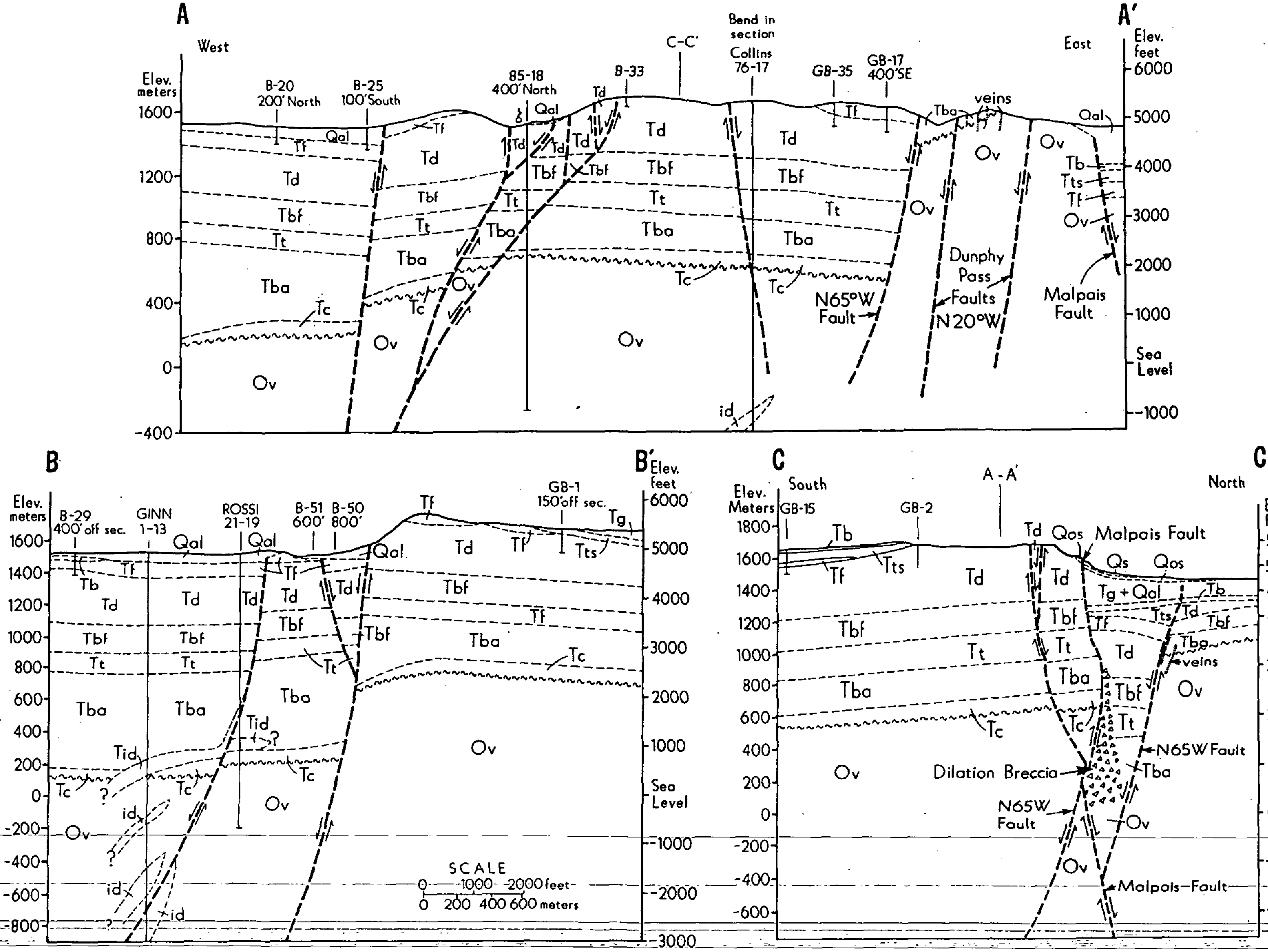


Figure 4. Geologic cross sections. See Figure 3 for description of units.

is a N20°W trending fault zone which passes 2 to 3 km east of the hot springs and displaces rocks down to the west. This fault zone has a significant topographic expression but where it crosses the Malpais rim it offsets the top of the Valmy Formation only about 260 m (Fig. 3).

A major fault trends about N65W from the head of the landslide in section 15, T31N, R48E, to the east limit of hot springs activity (Fig. 3). This fault has a displacement of about 890 m, down to the south, based on the top of the Valmy Formation in the Collins 76-16 hole and Valmy Formation outcrop to the northeast (Fig. 4, AA'). Part of this offset occurs along the west branch of the Dunphy Pass fault south of their intersection. Offset on the Dunphy Pass fault north of their intersection adds another 200 to 260 m of displacement between Valmy Formation outcrops and the Collins hole.

Small grabens indicating extensional faulting are present close to the hot springs. In addition to the 270 m wide graben extending southwest from the sinter terrace, a small wedge-shaped graben with the felsite unit exposed, is present on the north end of the small horst in section 18, T31N, R48E. On the ridge top south of The Geysers sinter terrace a small graben 70 m wide and 650 m long is parallel to, and has about the same extent as the crest of the sinter terrace (Fig. 3).

Sinter Deposits

The oval shaped siliceous sinter deposit is 1.9 km wide. The sinter deposit and its mode of formation have been studied in some detail by Rimstidt and Cole (in press). Although hot springs are active at the foot of the sinter terrace (Fig. 3) and probably have been in the past, most of the sinter appears to have been deposited by thermal water issuing from the hillside, more than 60 m above the lower part of the sinter deposit. Currently only steam is issuing from vents on top of the sinter mound, along what is thought to be the trace of the Malpais fault. An older, more eroded sinter terrace stands about 6 m above the crest of the recently active terrace. The older terrace is cut off abruptly on the north side suggesting that movement on the Malpais fault has offset the terrace crest.

Small exposures of sinter, most too small to map, occur along the Malpais fault trace east to the east edge of section 17, T31N, R48E. Along and above this sinter is a band of argillized and hematite stained rock (Fig. 11). Higher on the escarpment above the fault trace, chalcedonic sinter fills open spaces in a less altered flow breccia. Above the zone of silica infilling and the main sinter terrace an argillized, acid leached zone with gypsum present, occurs in the flow breccia. These three zones extend 700 m northeast of the main sinter terrace and terminate abruptly against the N65°W trending fault and the relatively impermeable felsite flow.

Hydrothermal System

Extent and Controls

The surface extent of the hydrothermal system is limited to the area of sinter deposits in the N 1/2 Sec. 17 and the S 1/2 S 1/2 Sec. 8, T31N, R48E, plus hot springs in a swampy area in the NE 1/4 of Sec. 18, T31N, R48E (Fig. 3). The area enclosed by the 20 HFU contour (Fig. 5) corresponds with the extent of surface manifestations. Outside of this area silicified alluvium was penetrated in the center of Sec. 9, T31N, R48E by thermal gradient hole B-9.

The subsurface extent of the system has been partially defined by deep drill holes. Chevron wells Ginn and Rossi, 2 km southwest of the hot springs were hot but did not produce significant thermal fluids (Chevron Resource Co.,

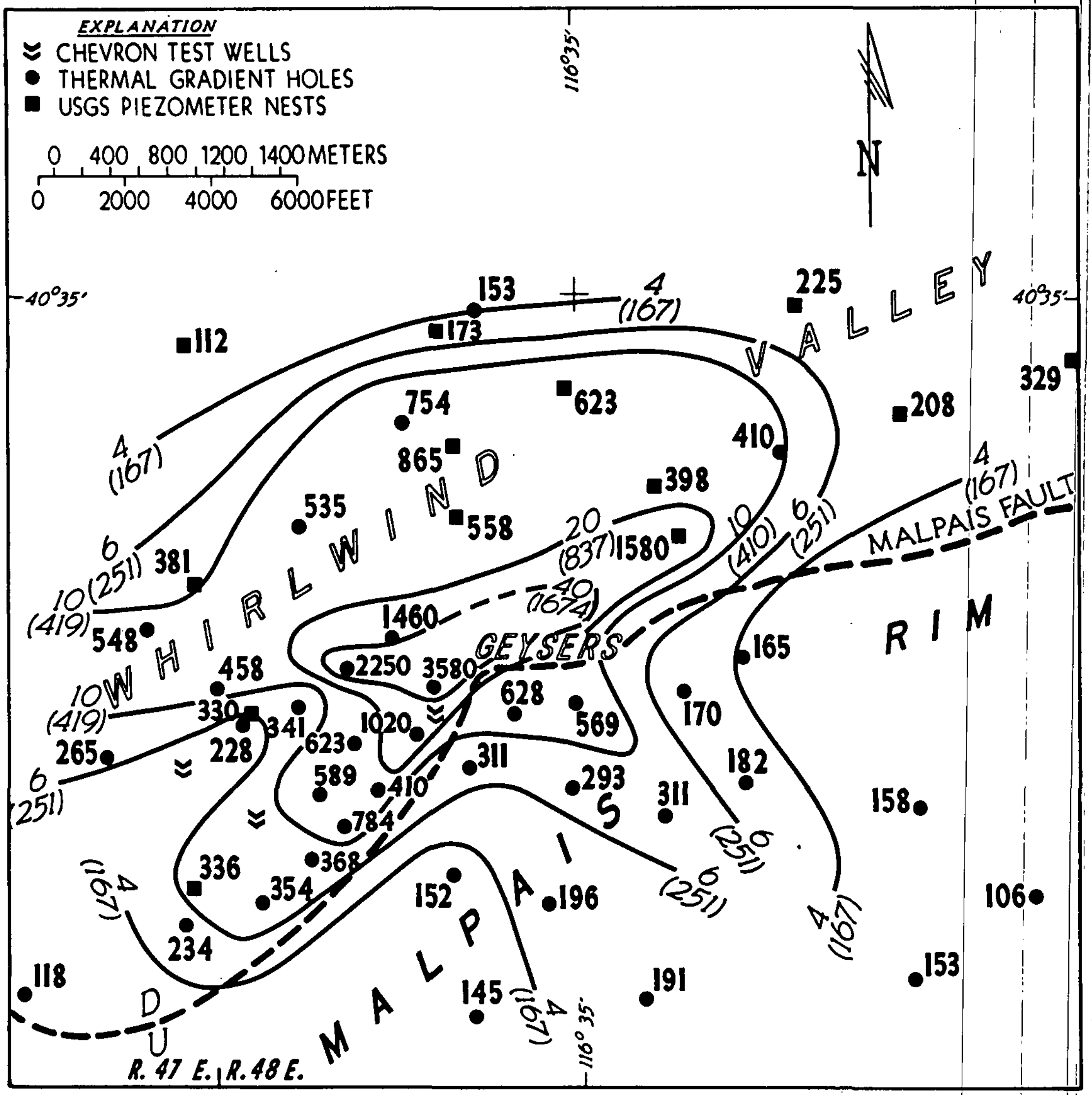


Figure 5. Heat flow at Beowawe from Smith (1981). Contours are 4, 6, 10, 20, 40 heat flow units, with SI units indicated in parentheses.

1979, 1980). Getty's Collins well, 600 m south of the sinter terrace, also failed to penetrate the thermal reservoir (Getty Oil Company, 1980). The Chevron wells 85-18 and 33-17, both collared on the sinter deposit, are reported to be relatively successful. The base of the high thermal gradient which appears to be the top of the thermal system in Chevron 85-18 corresponds with the base of the tuffaceous sedimentary rock unit (Fig. 6). This suggests that the tuffaceous unit (Tt on Figs. 2 and 4) caps thermal fluids in well 85-18. Elevations of stratigraphic units penetrated in well 85-18 are essentially the same as in Collins 76-17 and therefore both are on the same side of the Malpais fault, in the foot wall block (Fig. 4, A-A). Why then is 85-18 a producer and 76-17 not a producer? Beowawe 85-18 is thought to produce from a lost circulation zone in the depth interval 558 to 665 m (1830 to 2150 feet). The upper third of this zone is a subunit which can be correlated in the four deep wells on gamma logs. The lower part of the lost circulation zone in well 85-18 is a subunit (588 to 670 m depth) which correlates very well on gamma logs between the other three deep wells where it is 94 to 113 m thick (Fig. 2). The gamma log for this interval in well 85-18 is quite different, however, and the interval is only 82 m thick. It can therefore be concluded that well 85-18 either penetrated a normal fault which has about 12 to 30 m of displacement and alteration along the fault has changed the rock's radioactive character, or this interval is occupied by a different lithology than in the other deep wells.

Structures, particularly the Malpais Fault, seem to be the dominant control for the Beowawe geothermal system. The hot springs occur at a flexure in the Quaternary Malpais fault where several small grabens are evident, and near the intersection of the Malpais fault with a major N65W trending Tertiary

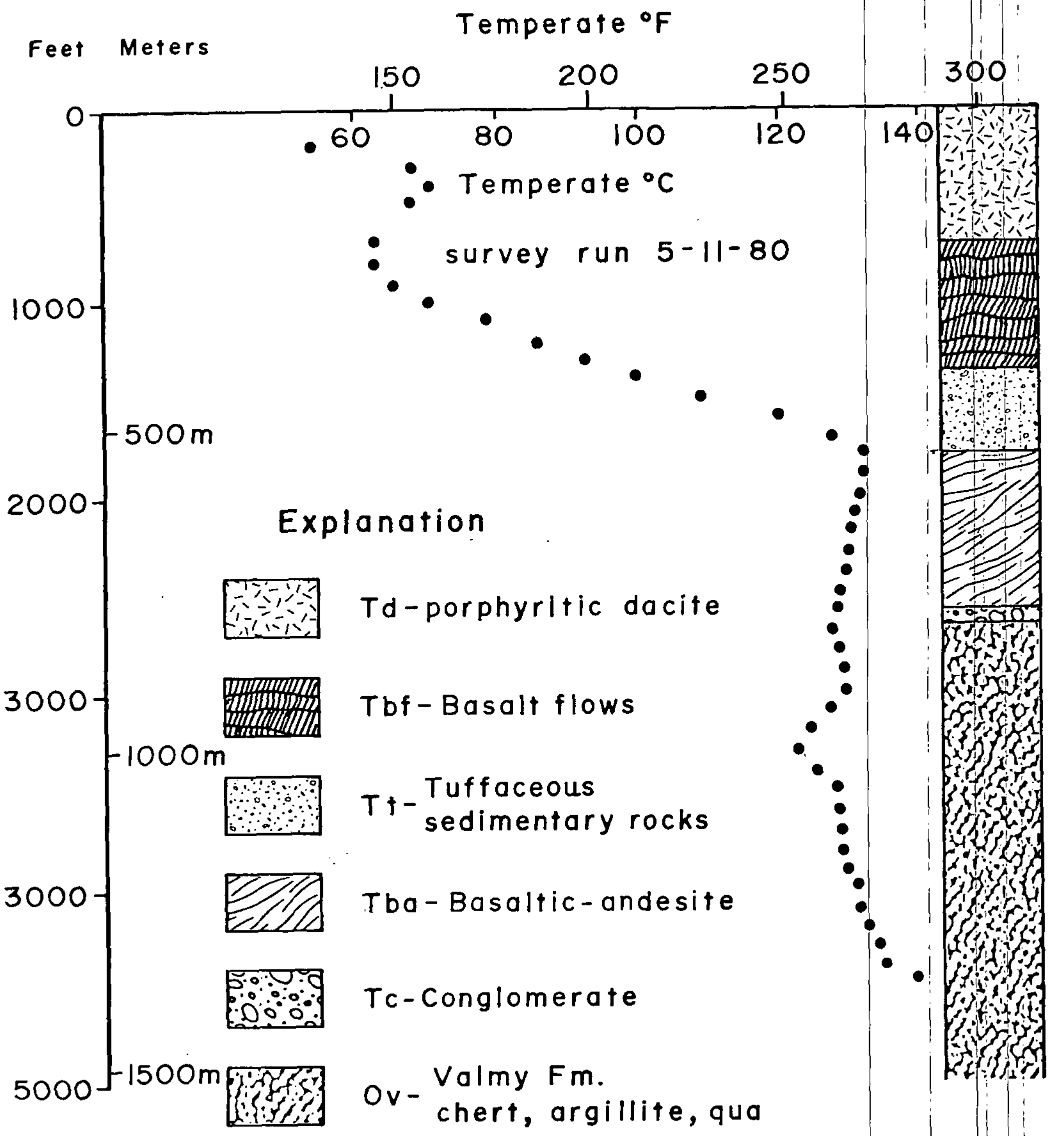


Figure 6. Temperature survey and lithologic log for Beowawe 85-18. Temperature survey from Iovenitti (1981, Fig. 5).

fault. The hot springs in the NW 1/4 NW 1/4 Sec. 17, T31N, R48E, are near the projected intersection of the north-western branch of the Malpais fault and the N65°W trending fault.

There is also evidence for some stratigraphic control of the geothermal system. As noted above, a tuffaceous unit in Beowawe 85-18 seems to cap the reservoir in that well. On the Malpais escarpment, east of the sinter terrace crest, thermal fluids have moved through a flow breccia unit altering the rock and filling original open spaces with chalcedony. Sinter extends from and covers the flow breccia at the east end of the terrace on the escarpment. The flow breccia occurs at about 1,550 m elevation (5080 feet). The Collins 76-17 hole penetrated a limonite-stained silicified zone from 1,610 to 1,570 m elevation. Thermal gradient hole GB-35, 500 m northeast of the Collins hole, penetrated an argillized and silicified flow breccia between 1524 and 1500 m elevation.

Structural Model

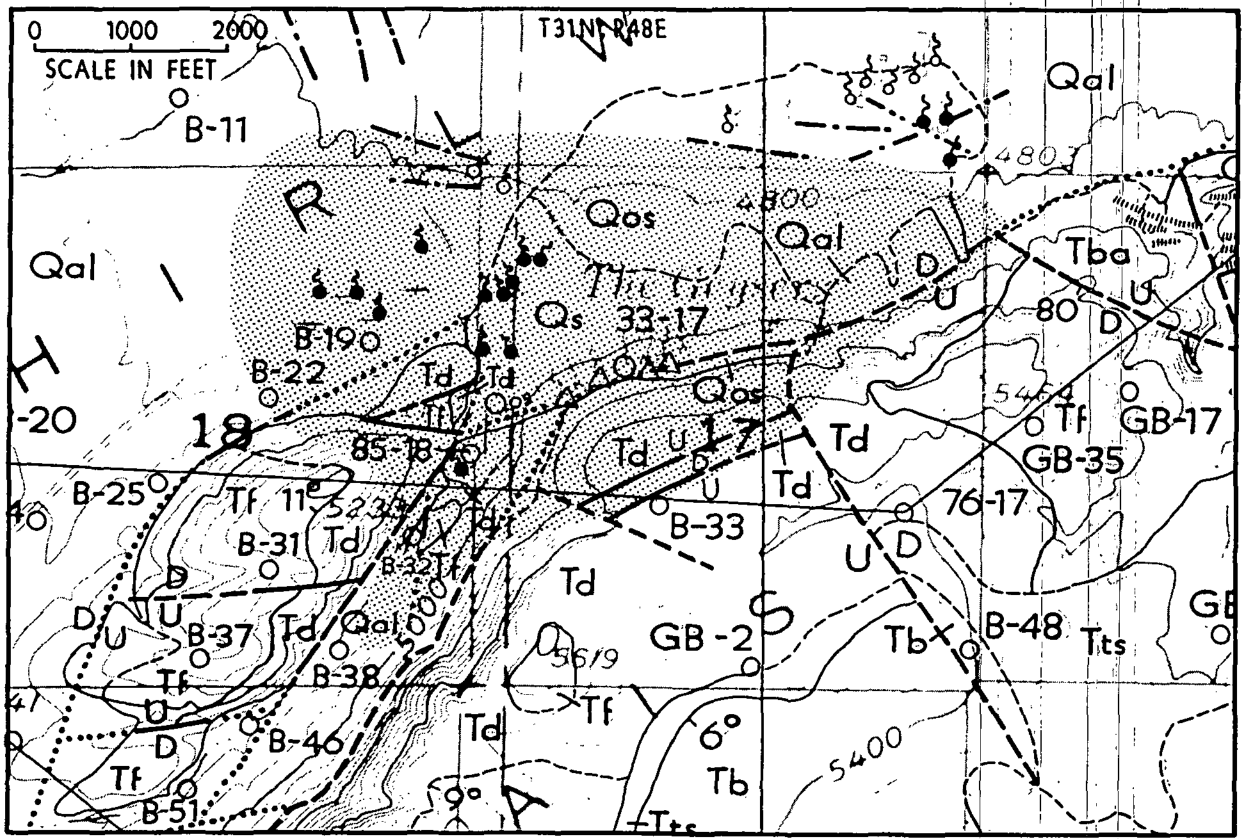
Based on the geologic map (Fig. 3) and subsurface data (Figs. 2 and 4) a conceptual model of the system can be made. Recharge from the west, and possibly north on the Argenta rim moves down faults and southeast to east dipping beds until the water is heated at considerable depth. The hot water rises along open fault breccias formed by the extension faulting along the Malpais fault system near its flexure and intersection with the N65°W trending fault. The northwest trending fault is down to the south and probably dips about 75 to 80 degrees south, similar to the quartz veins which parallel the structure. The intersection of the Malpais fault with the pre-existing, south dipping fault may have produced a steep, irregular and highly brecciated zone (Fig. 4, C-C'). Although the surface trace intersection of these faults is at the east end of the sinter deposition, which has been less active, the faults' intersection would dip west and be under the main terrace at the base of the Tertiary section. The thermal fluids rise along the fault intersection and connected faults within the less permeable Valmy Formation then spread out somewhat in the flow breccias of the basaltic-andesite unit (Tba). In addition to the main flow up the Malpais fault, subsidiary extensional faults, such as the one forming the small graben in the center of Sec. 17, T31N, R48E, transmitted thermal fluids higher in the Tertiary rock. Thermal fluids have in the past spread out within flow breccias in the porphyritic dacite (Td) depositing silica and producing the shallow (60 to 120 m deep) alteration encountered in 76-16, GB-35 and exposed along the Malpais escarpment.

Based on this model the best potential area for production can be defined (Fig. 7). The depth to the base of the potential production zone would be deeper along the east-west axis and toward the west end of the area. This area corresponds well with the area of highest heat flow (Fig. 5).

Chemistry

Geochemical Surveys

Geochemistry can be an effective exploration guide in the geothermal environment. Chemical interaction between rocks and fluids at elevated temperatures results in the development of characteristic chemical compositions of subsurface fluids (Truesdell, 1976) and the imposition of distinctive trace element signatures upon reservoir rocks (Bamford and others, 1980; Christensen and others, 1980). Fluid chemical geothermometers are useful for estimating subsurface temperatures from compositions of surface waters if careful attention is given to the fundamental assumptions (Fournier and others, 1974). Major element fluid chemistry and light stable isotopes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A
Tts
GB

are widely used as tracers of the origin of fluids (Hem, 1970; Taylor, 1975). Trace element signatures developed in rocks preserve the time-integrated record of fluid-rock interaction and thus provide valuable insight into the thermal and convective history of the geothermal system.

Chemistry of Thermal Fluids

The thermal fluids discharging at the surface and obtained from wells in the Beowawe area are notable for their low concentrations of dissolved material. Analyses are listed in Table 1. In general, the fluids are alkaline (ph = 8 - 9) and have less than 1400 mg/l total dissolved solids. Sodium is the principal cation; chloride, sulfate, and carbonate species are all significant anions. Trace elements which are frequently enriched in thermal fluids in other geothermal systems (Ellis, 1979) such as As, Sb, W, B, Li, Rb, Cs, F, and Br, are all present in relatively low concentrations.

Compositions previously reported for fluids drawn from the Ginn and Rossi wells (Christensen, 1980) suggest that these waters were highly contaminated by drilling fluids. These fluids, collected during early drill stem and flow tests, have significantly greater Ca and Mg concentrations and markedly different cation proportions than the springs.

Chemical geothermometers (Truesdell, 1976) calculated for the fluids from the hot springs and the geysering wells indicate temperature of fluid equilibration of approximately 200-210°C. In general, the geothermometers based upon quartz saturation may be more reliable for Beowawe waters than those involving cation ratios due to the low concentrations of Na, K, and Ca. Temperatures predicted from discharge fluids are consistent with measured shut-in well temperatures of approximately 210°C (Chevron Resource Co., 1979, 1980).

TABLE 1

FLUID COMPOSITIONS FROM THE BEOWAWE AREA

	1	2	3
SiO_2	265*	357*	329*
Na	234	261	214
K	15	27	9
Ca	<.25	<.25	---**
Mg	<.5	<.5	---
Li	1.3	1.5	tr.
B	2.0	2.2	1
Cl	4	10	50
F	1.2	1.2	6
SO_4	100	103	89
H_2S	---	---	6.1
HCO_3	---	---	41
CO_2	---	---	168
TDS	906	1120	855
pH (20°C)	8.4±.2	9.0±.2	9.3
T, °C, collection	95°	95°	132°

* all analytical values in mg/l

** (---) indicates value not determined

1. Hot spring below sinter terrace (Christensen, 1980)
2. Blowing well brine (Christensen, 1980)
3. Vulcan 2A well brine (Cosner and Apps, 1978)

Although the salinities and trace element concentrations are low, silica concentrations are high. This suggests that the sampled fluids would not be in equilibrium at elevated tempertures with feldspar or mica-bearing lithologies. Several conditions could result in this particular chemistry. If reservoir lithologies are volcanic or sedimentary units containing feldspars or other alkali-bearing minerals, fluids must have had short effective residence times within the system and consequently have undergone relatively little chemical interaction with the reservoir rocks. This may be a consequence either of rapid fluid transport through the system or of fluid flow through a low-surface-area environment. Alternatively, fluids may simply have equilibrated with siliceous reservoir rock, such as the Valmy Formation, or may have become depleted in alkali elements due to mineral precipitation or the formation of alteration minerals. The unusually low concentration of Ca indicates that direct movement of fluids to the surface from a carbonate reservoir at depth does not occur and suggests that the carbonate-reservoir model (Edmiston, 1979; Swift, 1979; Zoback, 1979) may not be realistic.

Trace Element Geochemical Zoning

The chemistry of a number of surface rock samples from the Beowawe area which have clearly been affected by interaction with thermal fluids is summarized in Table 2. Samples from NE 1/4 NW 1/4 , Sec. 16, numbers 1, 2, and 5, document the trace element signature associated with the chalcedonic veining present along the N65°W trending fault in that area. Arsenic is consistently enriched and relatively high concentrations of Ag occur in sample 2. Samples from the active geothermal area are relatively enriched in Hg (sample 4), and Mn (sample 3), compared to the concentrations of altered rocks from White Canyon, probably reflecting the dilute chemistry of the thermal fluids at Beowawe. The concentrations in drill cuttings of these elements and Li from

TABLE 2

TRACE ELEMENT GEOCHEMISTRY OF SELECTED SURFACE SAMPLES

	1	2	3	4	5	6
Ti*	2530	2790	2640	212	7100	2060
P	458	903	468	28	2760	440
Sr	81	136	202	158	934	98
Ba	1090	1390	971	1~~2~~49	1790	210
Mn	42	60	123	10	20	60
Co	<1	2	2	15	31	82
Cu	6	9	7	53	<5	20
Pb	15	22	17	<10	12	<10
Zn	<5	39	22	21	<5	6
Ag	<2	4	<2	<2	0.8	0.96
As	145	65	7	45	32	<25
Li	36	15	42	18	11	17
Be	5.4	4.4	3.4	2.9	2.6	0.9
Zr	250	314	219	173	314	97
La	34	50	40	31	38	5
Ce	59	96	64	40	55	<10
Hg	---	---	---	5.3	19.8	1.4

* all analytical values in mg/kg

1. Silicified, argillized volcanic breccia, White Canyon
2. Argillized volcanic breccia, White Canyon
3. Opaline sinter from sinter terrace
4. Argillized volcanic from sinter terrace
5. Altered basaltic-andesite at the mouth of White Canyon
6. Altered Valmy rocks from near the Barite mine, 3 miles east of the hot springs.

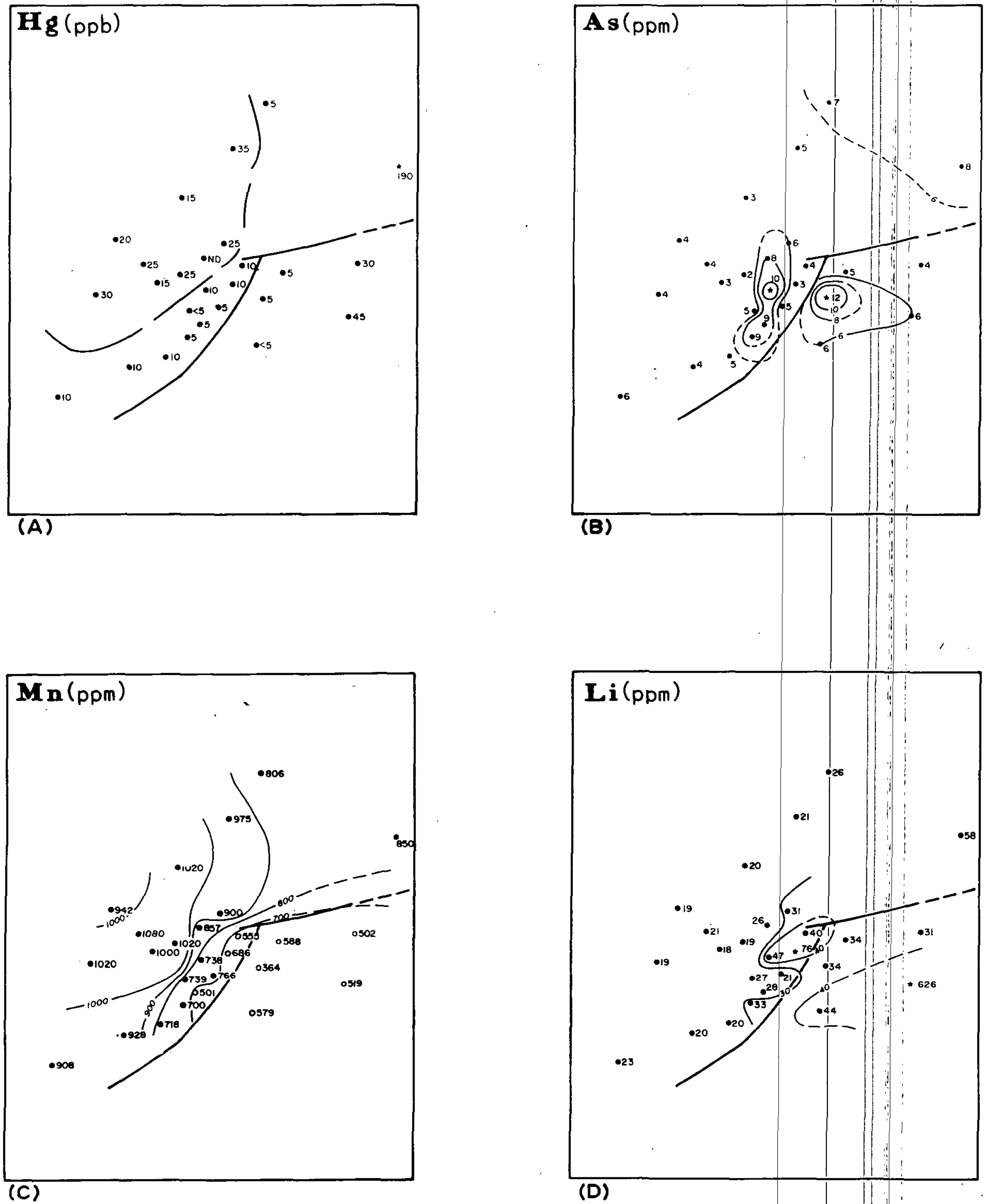


Figure 8. Concentrations of four elements in drill cuttings from the depth interval 0-30 meters in 26 shallow gradient holes.

the depth interval 0-30 meters in 26 shallow gradient wells are presented in map section in Figure 8. Distributions at other depth intervals to 150 meters are presented in Christensen (1980). These four elements have been found to be readily remobilized by thermal fluids in other systems and their concentrations in thermal gradient holes has proven to be a useful exploration guide where near-surface movement of thermal fluids has occurred (Christensen, 1980).

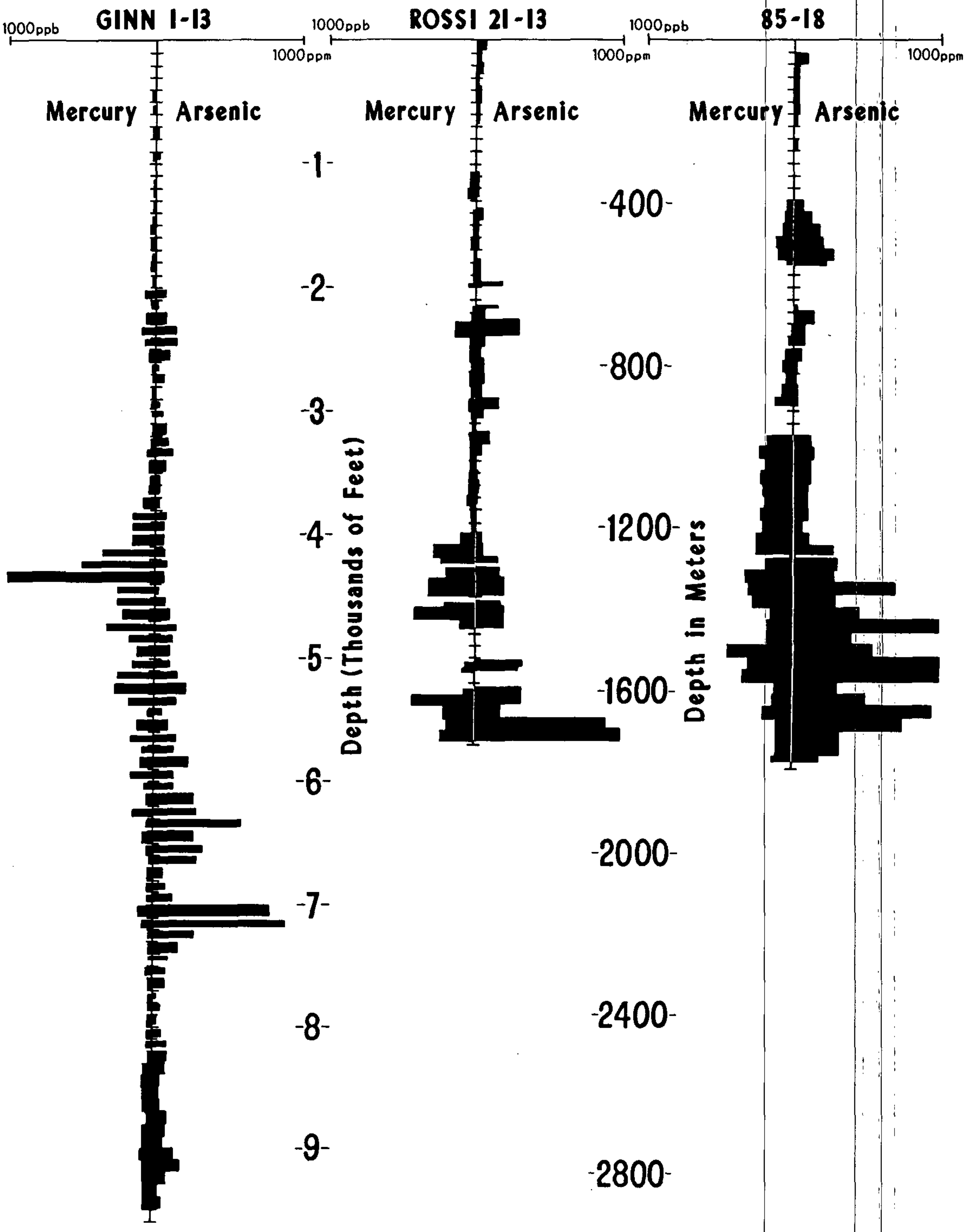
The coherent near-surface enrichment of As and Li immediately to the west of the active system and the peripheral Mn enrichment to the north are in context consistent with a system in which the fluids slightly enriched in Mn, As and Li discharge from along the Malpais Fault and flow downslope within alluvium or permeable bedrock. As the fluids cool, As and Li were deposited near the discharge point and Mn more distally.

The spatial distributions of these elements are , however, neither laterally nor vertically continuous. This suggests that there is not now, nor has there been in the past, pervasive movement of thermal fluid throughout the sampled rock, but rather that isolated chemical anomalies represent the intersection of the drill holes with fractured zones or permeable horizons through which fluids have coursed. The relatively weak geochemical signatures in rock associated with the present system as compared to the more pronounced enrichments in the exhumed chalcedonic veins suggest that the present fluids are more dilute than the older fluids.

The distribution of Hg is broadly similiar to Mn and may also reflect deposition from relatively cool fluids that have moved downslope from a source along the Malpais fault. The highest concentrations of Hg occur in well B-9-79, located on the eastern edge of Fig. 8. Details of the Hg distributions in this well are shown in Fig. 9 along with a lithologic log. Comparison of the lithologic and geochemical log indicate that zones of intense Hg deposition are associated with silicified alluvium.

The downhole distributions of As and Hg in the Ginn, Rossi, and 85-18 geothermal test wells are shown in Figure 10. The concentrations here of both elements are significantly greater than in the shallower gradient holes.

The observed enrichments of As and Hg in these wells (Figure 10) are generally coincident with zones of hydrothermal fluid flow through fractured rocks as inferred from the temperature-depth logs. For example, in Ginn 1-13 arsenic is enriched in the interval from the top of the zone of convective flow, 1600 m (5250 ft), to 2440 m where a major structure is intersected (Struhsacker, 1980). Similarly, the temperatures reported for the Rossi well indicate that convective heat transfer is dominant at depths below about 1200 m; As and Hg are enriched within the same interval (Figure 10). In well 85-18, the concentrations of these elements are again greatest within the lower portions of the well. ~~In~~ constant enrichments of Hg occur at higher elevation than those of As in Ginn 1-13, reflecting the greater mobility of Hg at lower temperatures. One possible explanation for these relationships has been provided by the recent studies of Christensen and others (1980). They recognized a similiar pattern of Hg and As enrichment in wells at Roosevelt Hot springs, Utah and demonstrated that at temperatures near 250°C As is actively being deposited without Hg. On the other hand, Hg without associated As was deposited only on the margins of the thermal field. While both elements could be deposited in the central portions of the geothermal field at temperatures below about 225°C, these relationships suggest that temperatures in Ginn 1-13 between about 5000 and 7000 feet may have been above 250°C in the past.


GINN 1-13
ROSSI 21-13
85-18
1000ppb
1000ppm
Mercury
Arsenic
-1-
-2-
-3-
-4-
-5-
-6-
-7-
-8-
-9-
Depth (Thousands of Feet)
-400-
-800-
-1200-
-1600-
-2000-
-2400-
-2800-
Depth in Meters

Locally coincident concentrations of As and Hg near 5200 feet in Ginn 1-13, in Rossi 21-13 and in 85-18 may have been deposited at slightly lower temperatures. Continued upward migration of As depleted thermal fluids in rocks penetrated by Ginn 1-13 and in alluvium in B-9-79 may account for the relatively high concentration of Hg in these rocks.

The observed distributions of As and Hg in these drill holes suggest that these elements have been remobilized by thermal fluids which have traveled along permeable structural breaks and permeated the fractured rocks. The general absence of both Hg and As enrichments in the upper portions of both Ginn 1-13 and Rossi 21-13 suggests that the near surface parts of the thermal field to depth of several thousand feet have been relatively impermeable.

Hydrothermal Alteration

Surface Alteration

The present geothermal system and previous thermal activity have produced alteration in the Beowawe KGRA. The general distribution of argillic alteration, hematite staining, silicifiction and veins is indicated on Figure 11. Most and possibly all of the alteration and veining in the Valmy Formation is from older activity. The best evidence for this conclusion is exposed at the barite mine in Sec. 12, T31N, R48E, three miles east of the hot springs. The Valmy Formation rocks are eugeosynclinal sediments (Roberts and others, 1967) and the disseminated barite mineralization at the mine, which is restricted to the Ordovidan rocks, may be volcanogenic in origin. The Ordovician rocks are hematite stained at the barite mine and some of the hematite staining extends into overlying Tertiary conglomerate which is present in channels cut into the Valmy Formation. The hematite staining is truncated by the angular unconformity which cuts the conglomerate and Valmy

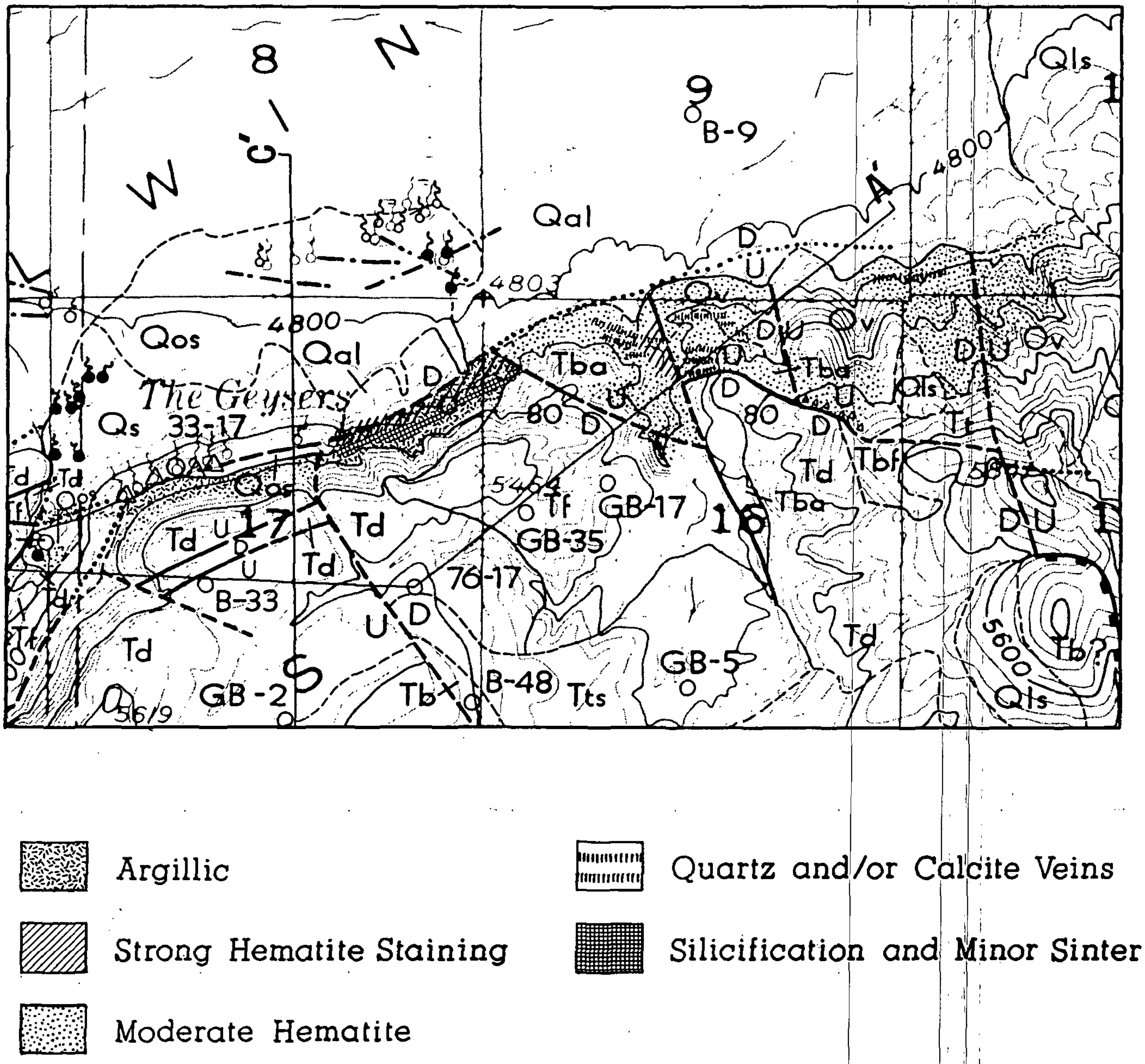


Figure 10. Distribution of alteration along the Malpais escarpment.

Formation rocks. The tuffaceous sedimentary rocks above the unconformity are overlain by basaltic-andesite lava flows. Closer to the hot springs, in the north half of Sec. 16, T31N, R48E (Fig. 11), hematite staining and quartz veins are restricted to the Ordovician rocks and the Tertiary basaltic-andesite lava flows (Tba). The younger porphyritic dacite is relatively unaltered.

The surface alteration associated with the geothermal system exhibits a vertical zonation. The lowest exposed zone consists of strongly hematitically stained, argillized rock exposed along and just above the Malpais fault east of the main sinter terrace (Fig. 11). The matrix and phenocrysts of the dacitic rock are altered to clay but relic texture remains with white altered feldspar crystals in hematite stained matrix. Alteration is most complete in flow breccia but less altered blocks remain. Minor botryoidal quartz is present and small areas of sinter are present at the surface.

A zone of silica deposition occurs above the hematitically stained zone. The flow breccia is unaltered to argillized along block surfaces and chalcedonic material fills open spaces and forms small veins. Some of the chalcedony is horizontally banded. The silica zone merges with the top of the sinter terrace to the west and slopes slightly down hill to the east and ends against the N65°W trending fault shown in Figure 11 and cross section AA', Figure 4.

The third and highest alteration zone is one of complete argillization and acid leaching. The dacite, both flow breccia and massive rock, is altered to clays, probably kaolinite. Gypsum and minor botryoidal quartz are present in this zone. The alteration is generally thicker and more complete in flow breccias, but some massive rock has been altered. This argillized and bleached zone extends for 1.5 km, occurring just above the main sinter terrace where alteration is the strongest and extends east where it ends against a felsite lava flow (Fig. 11).

Subsurface Alteration

The fine grained felsite (Tf) is unaltered in the drill holes. The porphyritic dacite which extends to a depth of 710 to 1460 feet (216 to 445 m) depending on the drill hole, is generally unaltered except for the flow breccia exposed east of the sinter terrace and encountered in the Collins 76-17 well, which was discussed with surface alteration. In Beowawe 85-18 there is minor hematite staining in the dacite, pyroxenes are partly altered to chlorite and there is minor sericite in the glass matrix.

Alteration is stronger in the basalt flows (Tbf, Fig. 2) probably because of higher permeability and greater susceptibility to alteration. The extent of alteration is variable within the unit but generally pyroxene and matrix is partially altered to chlorite, celadonite, saponite and calcite. There is minor alteration of plagioclase to sericite and chlorite and moderate hematite staining is present.

The tuffaceous sedimentary rocks (Tt) are weakly altered to sericite, chlorite, calcite and clay with some secondary quartz and traces of pyrite. The pyroxene and plagioclase crystals are unaltered. Moderate to strong hydrothermal alteration is present in the basaltic-andesite lava flows (Tba) which are capped by the tuffaceous sedimentary rocks. Quartz and calcite veins are present, especially in Beowawe 85-18, and pyrite is present. Pyroxene is generally altered to calcite and celadonite and the matrix is altered to sericite, calcite, chlorite and saponite. Plagioclase is fresh or altered to sericite, chlorite and quartz.

Dacite and diabase dikes cut the unit in the Ginn and Rossi holes. Some of the dikes are strongly altered but others are unaltered suggesting the alteration predates some of the dikes.

The metamorphic lithologies of the Valmy Formation are not very susceptible to alteration and can not be directly compared to the volcanic rocks. Quartz and calcite veinlets are present with minor pyrite. The dikes in the Valmy rocks generally have mafic minerals altered but the plagioclase is fresh.

The data from available holes is not sufficient to determine how much of the alteration is related to the current geothermal system. Alteration is a little stronger in Beowawe 85-18 where it is most intense in the basaltic-andesite lava flows unit.

EXPLORATION METHODS

Exploration efforts for an electrical power resource have been conducted in the Beowawe KGRA for over twenty years with most of the activity in the past ten years (Struhsacker, 1980). During this time various methods including drilling, thermal studies, chemical studies, geologic mapping and geophysical surveys have been employed to gain an understanding of the thermal system and select drill sites. This study will attempt to evaluate what each exploration method contributed toward these two goals.

Geologic Mapping

The Beowawe KGRA has been mapped by Zoback (1979), Struhsacker (1980), Chevron Resources Company (unpublished data), and the current author has remapped the central area (Fig. 3). As part of the geologic study, available cuttings from drill holes have been logged and rock samples age dated. The mapping has defined the major faults which may be controlling the near surface flow of the thermal system. The lithologic logs have defined the Tertiary stratigraphy and in combination with the surface geology have allowed determination of structural offset, dip of beds, better definition of fault locations and their dips. The age dating has determined the youngest surface igneous activity and placed a minimum age on some of the alteration. However, because all the age dates were about 16 m.y., the dates did not distinguish between igneous events. The geologic mapping has defined a limited favorable area (Fig. 7) which coincides with the high heat flow area (Fig. 5), and encloses Beowawe 85-18 and 33-17. The geologic mapping does not account for the silicified alluvium found in thermal gradient hole B-9, Sec. 9, T31N, R48E.

Thermal Studies

The 41 thermal gradient holes at Beowawe have defined the near surface thermal anomaly (Fig. 5) and provided valuable information on geologic structure and distribution of elements mobilized by the thermal fluids. Although drilling a near surface thermal anomaly does not ensure success, it should be noted that the two deep wells drilled before the thermal gradient holes failed to produce adequate thermal fluid flow, but two of the three deep wells drilled after the study were relatively successful. It should be remembered that of all the surface or near surface exploration methods only thermal studies directly measures the resource in a spacial distribution since.

Drilling

Drilling as an exploration method is the most direct but also the most costly. Shallow thermal gradient holes are a necessary phase in most exploration programs. To be most effective the thermal gradient drilling should be done after the water geochemistry, the geologic mapping and preliminary geophysical surveys as appropriate for the area, and before any deep exploration holes. Based of the geologic mapping and surface heat flow studies, more attention should have been given to the area north, northwest and northeast of the hot springs during thermal gradient drilling. Also holes drilled in deep alluvium should be extended to bedrock where possible to reach below surface water affects and add to the structural control.

Deep exploration drilling, when all factors are favorable, is necessary to confirm a resource. The two deep exploration wells drilled close to each other early in the exploration cycle but far from the surface expression of the thermal system provided very interesting structural and stratigraphic data but failed to produce from the thermal system. When adequate data from drill holes, such as wire line logs, cuttings and fluid samples are not collected and saved, such as from the Vulcan wells, then little value is saved from the exploration cost.

Chemistry

Fluid chemistry studies have provided data which can be used to predict scaling and corrosion problems during production. Reservoir equilibrium temperatures can be predicted with geothermometer calculations. Fluid chemistry studies can also give an indication of the type of reservoir rock and the rate of turnover in the system.

Trace element geochemical zoning appears to be inconclusive in the near surface at Beowawe but generally agrees with the concept of major discharge along the Malpais fault. The deep trace element zoning suggest both structural and lithologic control of thermal fluid movement. The zoning does not appear significantly different between the producing and non-producing wells for the available data base. A larger data base, particularly from other producing wells is needed before it can be determined if the zoning can be used to define the current system at Beowawe.

RESTROSPECTIVE EXPLORATION STRATEGY

The first exploration step at a geothermal occurrence such as Beowawe would be to sample all of the flowing springs around the sinter terrace, including the springs in the swampy area to the west. This geochemical survey would give information on the reservoir temperature, fluid chemistry, types of reservoir rocks to be expected and some indication of the systems size and turnover rate.

The second step should be geologic mapping of the area. The mapping would define the structures and type of alteration associated with the system, providing a data base on which to select and locate geophysical surveys to better define structures and look for indications of the extent of subsurface alteration and thermal fluids.

The third step would include geophysical and geochemical surveys. Heat flow, electrical resistivity and self-potential surveys would use the surface expression of the system as a reference point and be interpreted in light of the known structures. Geochemical soil and outcrop sampling should use the exposed alteration zoning and fluid chemistry as a reference. Unfortunately geochemical characterization of the alteration zones at the surface has not yet been done. The water sampling from springs and wells may extend to a regional bases during this phase to determine mixing and possible recharge areas and thereby flow path of the thermal fluids.

The fourth step would be thermal gradient hole drilling. These holes should be sited based on a combination of the geologic and geophysical data base with some consideration given to locations that will provide critical geologic and geochemical data in addition to temperatures. Study of the cuttings will greatly add to the geologic and geochemical data base plus help refine interpretation of the geophysical data. The results of the thermal gradient drilling may point out the need for additional studies in one or more of the methods previously employed.

At this point in the exploration program the near surface extent and character of the thermal system and its history should be fairly well defined. Total expenditures to this point should be under a million dollars. Reservoir target models should be well formulated.

The fifth step is drilling a deep exploration well which given the data base generated above would have a good chance of being successfully sited.

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FIGURE CAPTIONS

Figure 1. Location map of Beowawe geothermal area. Geology generalized from Stewart and Carlson (1977), Battle Mountain heat flow high boundary from Muffler (1979).

Figure 2. Correlation of lithologic and gamma ray logs for the Tertiary section in four deep drill holes at Beowawe KGRA. The logs are vertically adjusted to align horizontal data plane at the top of the tuffaceous sediments unit (Tt).

Figure 3. Geologic map of the Beowawe thermal area, by Bruce S. Sibbett.

Figure 4. Geologic cross sections. See Figure 3 for description of units.

Figure 5. Heat flow at Beowawe from Smith (1981). Contours are 4, 6, 10, 20, 40 heat flow units, with SI units indicated in parentheses.

Figure 6. Temperature survey and lithologic log for Beowawe 85-18. Temperature survey from Iovenitti (1981, Fig. 5).

Figure 7. Pattern indicates the area of best potential for geothermal production based on reservoir conceptual model. See Figure 3 for explanation of geologic symbols.

Figure 8. Concentrations of four elements in drill cuttings from the depth interval 0-30 meters in 26 shallow gradient holes.

Figure 9. Mercury concentrations and lithologic log for well B-9-79, center of section 9, T.31N.,R48E.

Figure 10. Downhole distributions of arsenic and mercury in cuttings from three deep drill holes at Beowawe KGRA.

Figure 11. Distribution of alteration along the Malpais escarpment.