The Beowawe Geysers, Nevada, Before Geothermal Development

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The Beowawe Geysers, Nevada, Before Geothermal Development

By DONALD E. WHITE

U.S. GEOLOGICAL SURVEY BULLETIN 1998

U.S. DEPARTMENT OF THE INTERIOR

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The Beowawe Geysers, Nevada, Before Geothermal Development

By Donald E. White

ABSTRACT

The history of natural activity of the Beowawe Geysers in north-central Nevada is documented before geothermal drilling and production, which started in 1959. Previously, the Beowawe Geysers area was second only to Yellowstone National Park in North America for its number of active geysers.

As a basis for this study, 8 reconnaissance visits were made between 1945 and 1957; the number of geysers that were active during the various visits ranged from 12 to 27, erupting to heights of ⅓ to 8 m. Geothermal drilling started in 1959, and subsequent discharge from wells ended the time when completely natural geysers could be observed.

Most geothermal areas are considered "volcanic centered" if the immediate source of heat is a young intrusion (less than approx 3 m.y.). The Beowawe Geysers area is unusual in that no exposed volcanic rocks are younger than about 10 m.y. Its high rate of heat supply is probably through a thinned, stretched crust approximately 30 km thick (the Battle Mountain heat-flow high), in contrast to normal continental crust about 40 km thick. The chemistry of thermal water from Beowawe supports this conclusion. All discharged water is generally dilute and low in chloride (approx 40–69 ppm Cl) and contains less than 1,000 ppm dissolved solids, excluding SiO_2, which depends on temperature and the presence of quartz in the reservoir rocks to equilibrate at reservoir temperatures. Boron content is also low (approx 8 ppm) in comparison with that of waters associated with young silicic volcanic centers, but total combined CO_2 content (as carbonate and bicarbonate) is relatively high. Derivation of heat by thermal conduction through a thin crust is supported by low $^3He/^4He$ ratios, which suggests derivation largely from the Earth's crust with little mantle influence.

Natural upflow in the Beowawe system may have been near 18 L/s, too high to be explained by present recharge from the drainage area alone. Much of the water may be "fossil" meteoric water supplied to a regional aquifer such as the Roberts Mountains thrust fault, possibly 10 ka ago or earlier, when precipitation was higher than at the present time. The stable isotopes of oxygen and deuterium provide some support for this explanation.

Manuscript approved for publication, May 28, 1991.

INTRODUCTION

History

The Beowawe Geysers in north-central Nevada (fig. 1) have drawn little attention over the years, in spite of the fact that the Beowawe sinter terrace is one of the most imposing in North America. Furthermore, Beowawe's active geysers before geothermal exploitation were second in North America only to those of Yellowstone National Park.

Beowawe was mentioned in popular railroad guides soon after construction of the Central Pacific Railroad (for example, Evans, 1869) and briefly in a Federal survey (Hague and Emmons, 1877, p. 618). The area was then largely ignored in geologic accounts until Nolan and Anderson (1934) published the earliest modern study, based on mapping in 1932. Several other popular articles (for example, Murbarger, 1956) were written subsequently, but no detailed descriptions were presented.

Nolan and Anderson (1934) described the sinter terrace as hot-spring deposits of SiO_2 along the front of a southeast-tilted fault block bounded by the Malpais fault zone. Their map of the geyser area shows "old sinter" on both ends of the most conspicuous line of terrace hot springs, geysers, and fumaroles (see White, 1967, for definitions of "geyser," "fumarole," and other terms). Nolan and Anderson (1934) included analyses of the thermal waters and specified that five small natural geysers were then active (excluding a possible sixth at the base of the terrace that had some, but not all, of the characteristics they had expected of a geyser). The volume of sinter in the Beowawe Geysers terrace was estimated by Zoback (1979) at 18×10^6 m^3.

Many changes have resulted from the drilling and discharge from geothermal wells starting in autumn 1959. Because wells were tested intermittently and later vandalized, conditions were always changing. A single producing well can temporarily form new geysers or terminate others, depending on where and how the interference occurs.

The purpose of this report is to document the undisturbed Beowawe Geysers system as it existed during the few years after Nolan and Anderson's (1934) report but before the terrace was disturbed by discharge of geothermal wells early in autumn 1959.

Summary of Geology

The geology of the study area (fig. 1) was mapped by Stewart and Carlson (1974, 1976), and the geology, geophysics, and hydrology were studied by Hose and Taylor (1974), Zoback (1979), and Olmsted and Rush (1987). The relative ages of faults on range-front scarps were mapped by Wallace (1979). The generalized geology is shown in figure 2, and rock units are summarized in table 1. A cross section through the terrace and the Malpais fault zone is shown in figure 3.

Cenozoic igneous activity was intermittent from about 44 to 10 Ma (Stewart and others, 1977). Volcanic and intrusive rocks were intermediate to silicic until about 17 Ma, when bimodal basalt and rhyolite became increasingly abundant. Diabase dike swarms striking generally north-northwest to north were probably feeders for basaltic andesite flows that cap the surrounding ranges. These dike swarms (Zoback and Thompson, 1978) are the probable cause of a magnetic anomaly, called the Oregon-Nevada lineament (Stewart and others, 1975) or the Idaho-Nevada lineament (fig. 1), that is nearly centered beneath the geyser terrace and strikes north-northwest to the western Snake River Plain and the Columbia River basalt flows. The lineament is well defined in north-central Nevada but becomes diffuse near the Oregon-Idaho State line.

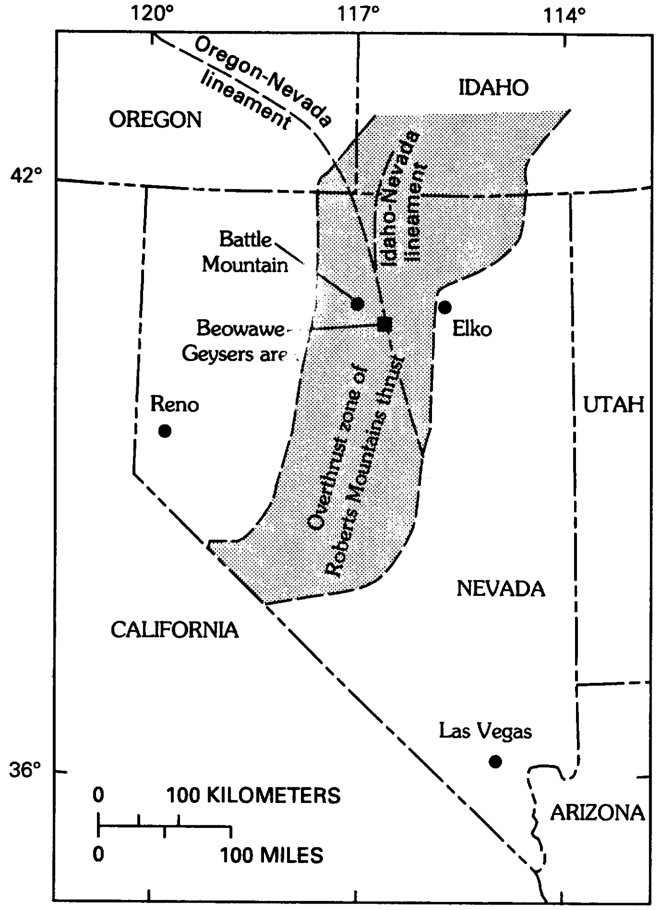


Figure 1. Index map of Beowawe Geysers area, north-central Nevada, showing locations of selected geologic features (modified from Olmsted and Rush, 1987).

Extensional tectonism in the Basin and Range began in mid-Tertiary time and continues to the present. Most ranges of the Great Basin are aligned north-south, but the pattern east of Battle Mountain (fig. 1) is more complex, involving north-northwest-, north-, and east-northeast-striking elements that tilt the fault blocks generally eastward. The ranges near Beowawe mainly strike north to east-northeast, but a subdued, generally older, north-northwest-striking set of faults is clearly evident.

The Malpais fault zone at Beowawe (figs. 2, 4) that controls the thermal activity may have considerable antiquity, possibly more than 100 ka. Faults that separate sinter of two ages are exposed near the east and west ends of the sinter terrace. Old iron-stained opaline and chalcedonic sinter is upfaulted south of the main line of active terrace springs. Two blocks of partially chalcedonized opaline sinter are downdropped north of the eastern springs and rotated, dipping about 70° into the hill. The hillslope above (south of) and adjacent to the line of active springs near the Malpais fault contains some float of chalcedonic sinter, probably indicating an age older than 20 ka if temperatures and pressures increased normally for a near-boiling geothermal system. The most recent sinter is white; older sinter is buff colored.

THE BEOWAWE GEYSERS SYSTEM IN ITS UNDISTURBED STATE BEFORE 1959

On September 22, 1945, P.F. Fix and I made a first inspection of Beowawe and observed eight small geysers actually in eruption, several others that provided positive evidence for recent eruption, a few uncertain ones that could have been categorized with a longer time for observation, and "Beowawe" Geyser, a beautiful geyser with maximum water spurts 8 to 10 m high (fig. 5). The Beowawe geothermal system clearly had the greatest concentration of generally active natural geysers in North America, next to Yellowstone National Park. Steamboat Springs south of Reno, Nev., had fewer active geysers than Beowawe during the 7 years of my continuous monitoring from 1945 to 1952 (White, 1968).

From 1945 to 1957, I made brief inspections of Beowawe, generally once or twice a year. The whole terrace (fig. 6) was mapped at a scale of 1:3,000 (20-ft contour interval), and the crest of the terrace (fig. 7) at a scale of 1:600 (5-ft contour interval) to replace dependence on sketch maps as features and maximum activity changed from place to place. Topographic control for figures 6 and 7 was essentially complete by 1948, and Ozalid copies were available by 1949 for recording activity and observed changes.

Close observation of the active features ended in October 1951; a final check was made in September 1957. When I revisited Beowawe in September 1960, drastic changes had already resulted from discharge of geothermal wells, the drilling of which started in 1959. The geysers at Beowawe were discussed in general terms in some post-1959 reports (Rinehart, 1968, 1980; Zoback, 1979).

Individual Natural Thermal Features, 1945–57

The locations of individual springs, geysers, fumaroles, and inactive vents are shown in figures 6 and 7 and listed with brief observations in table 2. Detailed descriptions of most of the larger and more active features are given below. The general locations of a few numbered springs and geysers shown in figure 6 are for orientation purposes only; similar locations shown in figure 7 are more precisely controlled.

"Teakettle" Geyser (Vent 6)

"Teakettle" geyser (fig. 8) erupted from two related vents approximately 1 m apart; the eruption plume from the western vent was inclined about 40° from vertical to

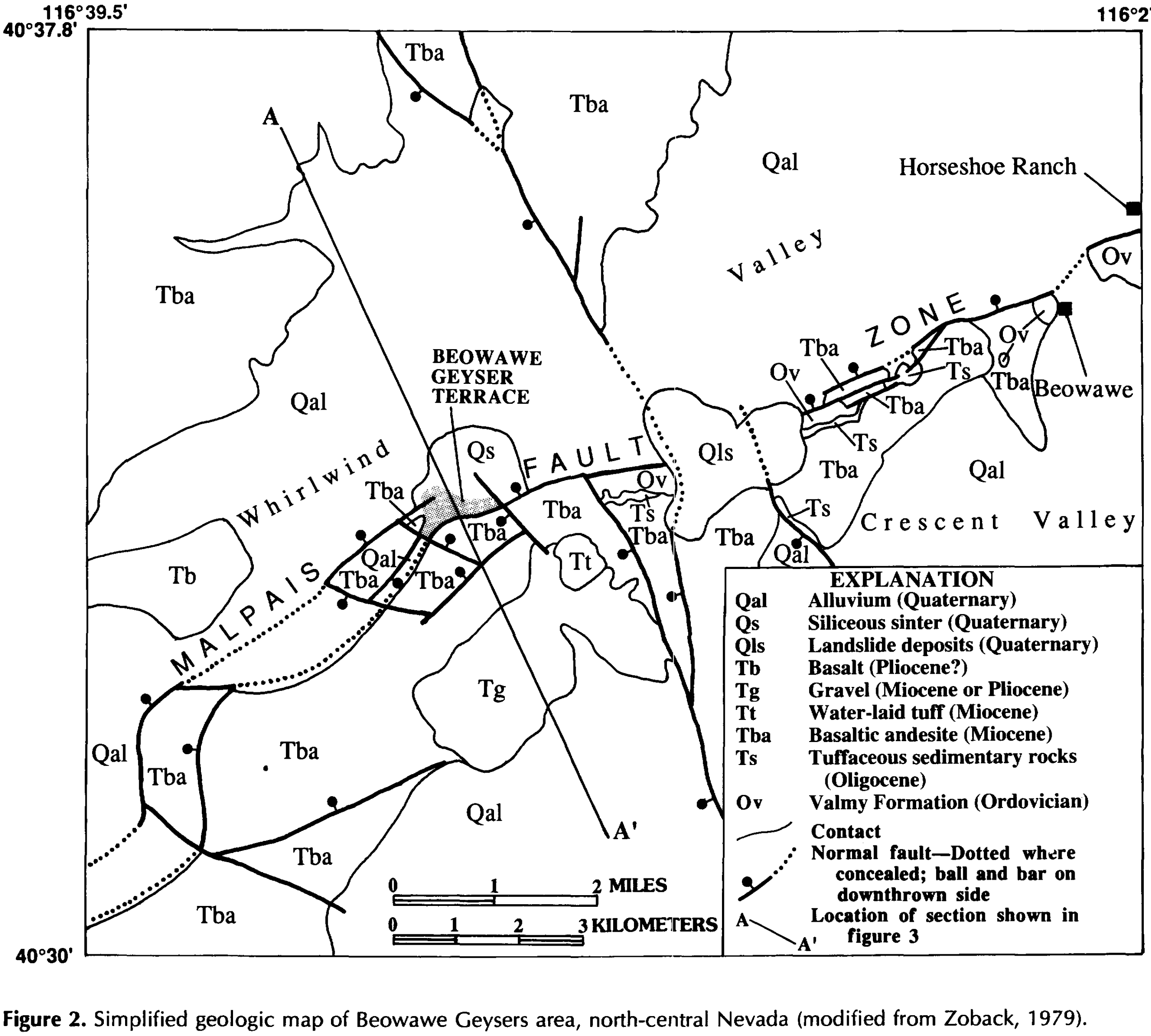


Figure 2. Simplified geologic map of Beowawe Geysers area, north-central Nevada (modified from Zoback, 1979).

Table 1. Stratigraphy of the Beowawe area, north-central Nevada

[Modified from Zoback (1979) and Olmsted and Rush (1987)]

Age	Unit	Thickness (m)	Description
QUATERNARY	Sinter deposits	60±	Mostly opal, but includes some carbonates, sulfates, and silicate minerals. Generally white to light-tan on surface; generally cemented fragments of primary opaline sinter. Forms cones and a terrace, being actively built downslope from and in spring areas
	Younger alluvium and stream deposits	0–50+	Mostly tan silt and sand at land surface; increasing gravel content at depth; underlies nearly horizontal areas of the valley floor.
	Older alluvium and fan deposits	Unknown	Mostly poorly sorted gravel, sand, and silt derived from local rocks. Underlies areas of intermediate slope.
	Landslide deposits	Unknown	Rubble, largely from Valmy Formation, tuffaceous sedimentary rocks, and volcanic rocks that crop out on the scarp of the Malpais fault. Forms hummocky topography; relations to older alluvium unknown.
QUATERNARY AND TERTIARY	Old gravel deposits	0–5	Mostly gravel and sand derived from and underlain by lava flows; underlies part of valley apron.
TERTIARY	Volcanic rocks	?	Lava flows ranging in composition from basalt to dacite; includes small outcrops of other rock types. Forms mountains.
	Tuff and tuffaceous sedimentary rocks	0–75	White to pale-gray, well bedded volcanic ash, interbedded with tuffaceous conglomerate and tuff.
PALEOZOIC (ORDOVICIAN)	Valmy Formation	>1,700	Mostly siliceous siltstone and quartzite; commonly pale-gray.

the west. It erupted to a height of about 4 to 5 m; its duration in 1948 was about 1 minute, and its interval about 6 minutes. The eruption plume from the weaker eastern vent (generally containing water droplets dispersed in steam) erupted to the northeast to a height of about 2 m, nearly always simultaneously with the western vent.

"Spitfire" Geyser (Vent 7)

"Spitfire" geyser (fig. 9; also called "Sputter Pot" geyser) was observed erupting during most, but not all, visits, generally 3 to 5 m high from near the northwest edge of the terrace. Its duration was about 15 minutes, and its interval about 30 minutes.

Unnamed Geyser (Vent 13)

Another major unnamed geyser (fig. 10) commonly had a preliminary overflow and erupted to a maximum height near 5 m. Its possible interconnection to vent 12 and others nearby may have contributed to its irregularity.

"White Flame" Geyser (Vent 17)

A typical eruption of "White Flame" Geyser started with preliminary overflow, at first without gas bubbles breaking the pool's surface. As the rate of upflow and temperature increased, steam bubbles became visible in the bottom of the pool, collapsing almost immediately in the cooler pool with an audible thump. As the pool filled and then overflowed, the bubbles soon became more vigorous, breaking the pool's surface with little noise and erupting about 1⅓ m high as the thumping became much less pronounced. After about 2 minutes of eruption, the thumping ceased, and the pool drained. Water reappeared within about 7 minutes to repeat the cycle.

"Orange Spouter" Geyser (Vent 23)

The vent of "Orange Spouter" was perched 5 to 7 m above the general terrace level, evidently on a southern strand of the Malpais fault. It was frequently inactive, and its color changed to white as the thermophylic organisms dried.

Unnamed Geyser (Vent 25)

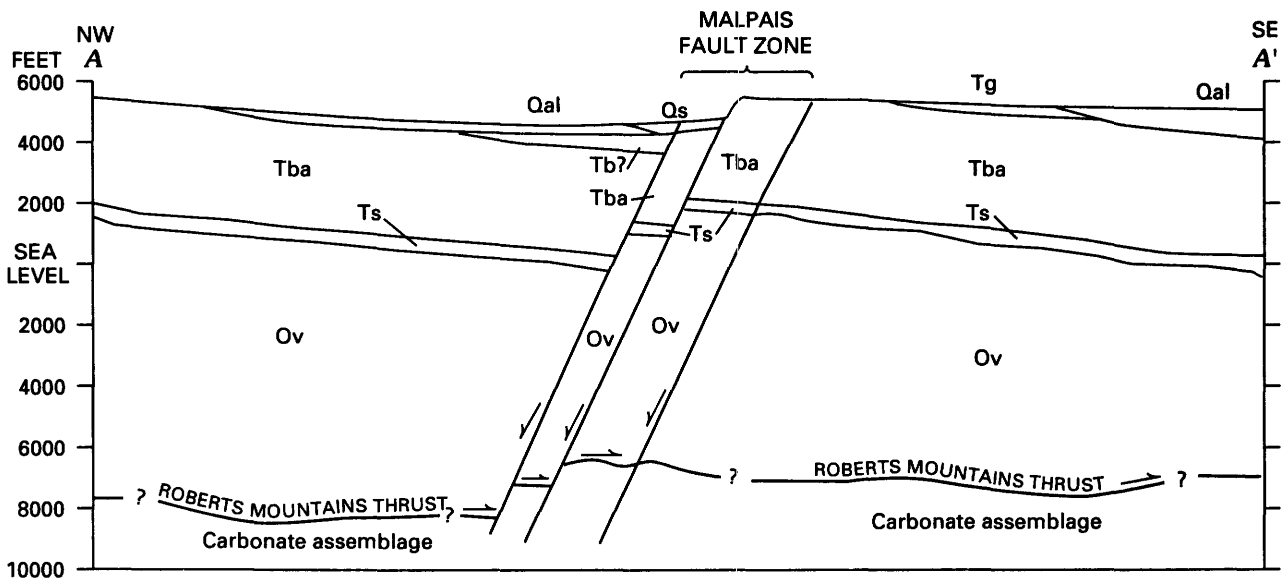
This geyser was active during each visit, typically erupting for at least 10 minutes to a height of about 3 m after a short preliminary overflow. Its interval was generally long, at times more than 30 minutes.

"Pincushion" Geyser (Vent Complex 27)

"Pincushion" Geyser (fig. 11) erupted simultaneously from multiple vents through a pile of sinter-covered basalt boulders, possibly emplaced by Indians. Figure 12 shows at least six vents that are not obviously erupting in figure 11. Figure 13 illustrates the "sugary" opaline sinter zoned in grain size, probably from rapid evaporation of monomeric silica (H_4SiO_4).

"Beowawe" Geyser (Vent 29)

Figure 5 shows "Beowawe" Geyser near its maximum observed eruption height of about 8 m, and figure 14 shows the vent between eruptions. The inner zone of fine-grained "sugary" sinter probably was deposited rapidly as monomeric silica (initially, H_4SiO_4) surrounded by an outer zone of spherulitic or "knobby" sinter, commonly dried, largely or entirely polymerized, that was deposited rapidly as the water films evaporated. Figure 15 shows a subsidiary pool of the same geyser, with white-fringed sinter (when dried) that was deposited above a nearly constant sill level, and darker sinter, presumably from silica polymers that



EXPLANATION

Qal	Alluvium (Quaternary)
Qs	Siliceous sinter (Quaternary)
Tb	Basalt (Tertiary)
Tg	Gravel (Miocene or Pliocene)
Tba	Basaltic andesite (Miocene)
Ts	Tuffaceous sedimentary rocks (Oligocene)
Ov	Valmy Formation (Ordovician)
——	Contact
⇌ ?	Fault — Queried where uncertain; arrow shows relative movement

Figure 3. Cross section through Beowawe Geysers terrace (modified from Zoback, 1979). See figure 2 for location.

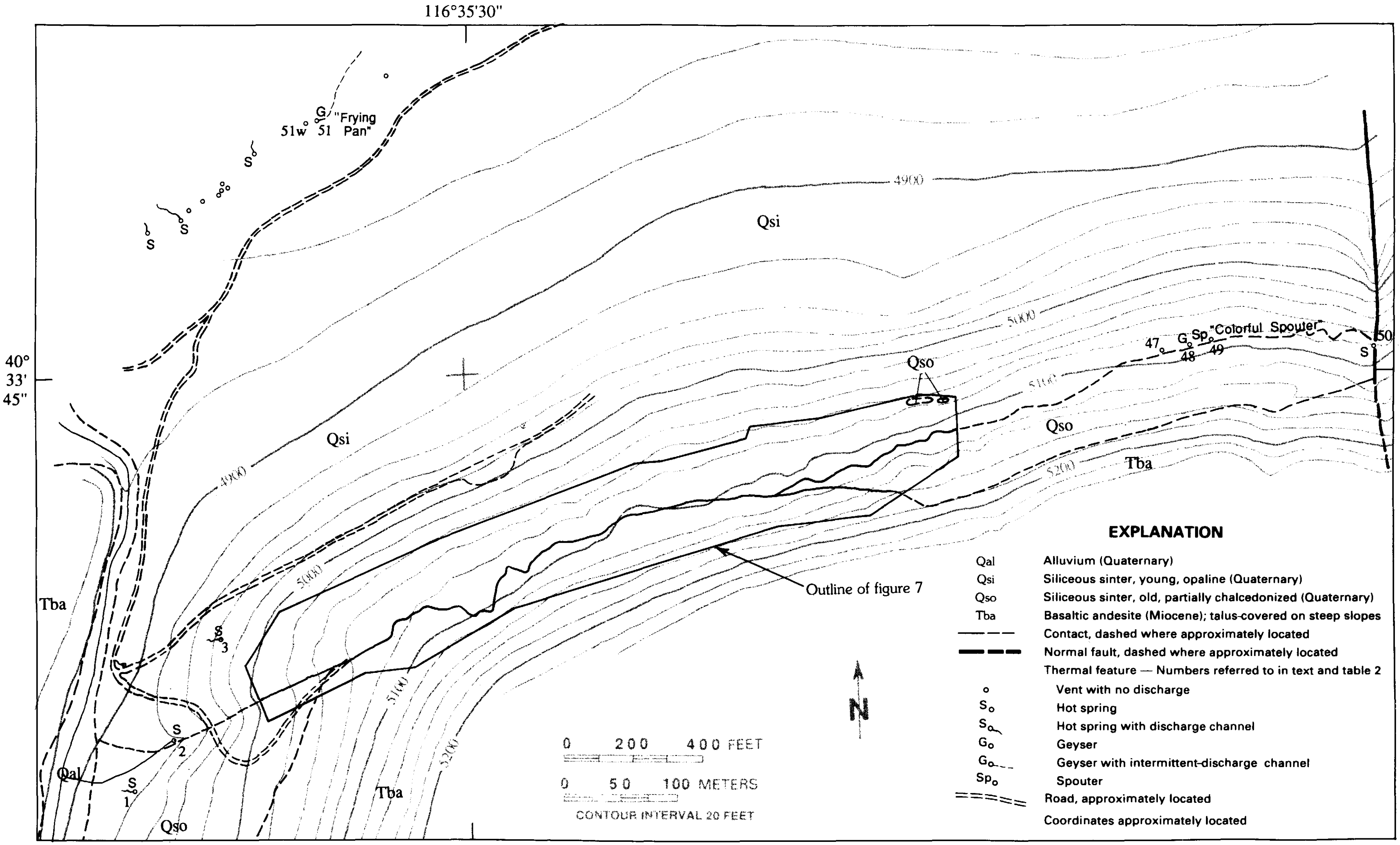


Figure 6. Beowawe Geysers terrace area, largely before 1959. Mapped by R.G. Reeves, Doug Baker, D.E. White, G.A. Thompson, and others, 1948, with later changes (approximate) by D.E. White.

deposited more slowly below water level, probably incorporating some iron oxide as the pool cooled and oxidized between eruptions. This geyser's duration was 1 to 2 minutes, and its interval was half an hour or longer.

Miscellaneous Features on the Terrace

Unnamed vents 33 and 33e are probably interconnected because one tended to be dormant while the other was active. Vent 34 was a mildly acidic spring ranging in pH from 6.0 to 6.4, in contrast to the common 9.0 to 9.5 for erupting geysers and 8 to 9 for discharging springs that retained most of their CO_2 content. Small springs and seeps (vents 40, 41) were the most consistently acidic. The pH of vent 40 ranged from 3.28 to 6.61, whereas the pH of vent 41 was 2.33 to 3.40; Cl content was always lower than in the alkaline springs, most commonly ranging from about 5 to 25 ppm. Discharge was commonly absent but at times was seeping.

A small, unnamed geyser (vent 48) is shown erupting about ⅓ m high in the foreground of figure 16, while "Colorful Spouter" (vent 49) to the southeast is spouting in the background. A closeup view of this spouter is shown in figure 17. The color zonation pattern consists of elemental sulfur in the conspicuous inner ring and different varieties of thermophylic organisms in the outer rings. These organisms show intense colors when the spouter is active but are glaring white when inactive, demonstrating the absence of colored inorganic precipitates.

"Frying Pan" Geyser (Vent 51)

"Frying Pan" Geyser (fig. 18) at the base of the terrace was photographed while looking nearly down its throat. Water is rising into the pool as gas bubbles (largely steam) condense in the cooler water of the pool, already exposed to the atmosphere. As discharge continues and the pool is heated closer to boiling, steam bubbles no longer collapse but surge into mild eruption. Figure 19 shows the same geyser pool in eruption, now boiling in its turbulent center but cooled slightly around the borders of the pool and where discharging (near photographer). Gas bubbles, here mostly steam, break the surface and cause turbulence, which distinguishes a geyser from a spring with intermittent quiet discharge. Figure 20 shows "Frying Pan" Geyser after an eruption (actually photographed in 1962, when its activity was still nearly the same as in 1945; note, however, the aged appearance of vent 51w in the middistance and the great increase in activity in the far distance as compared with figure 19).

A complete eruption of "Frying Pan" Geyser is illustrated by plots of data (fig. 21) for vents 51 and 51w on May 14, 1948; almost identical data were also collected on May 26 and October 15, 1951. Although these 1951 plots are omitted, all show only small differences in duration of the main eruptions and intervals between eruptions, and each plot also shows three preliminary spurts or "false starts" between the main eruptions. These preliminary spurts, like preliminary spurts or overflows of some of Yellowstone's geysers, tend to delay the final eruption time because each expends some stored energy (as steam), with negligible results on discharge. Several workers (for example, Nolan and Anderson, 1934) have described intervals of about 20 minutes for this geyser, but my data show that a full cycle (approx 40 minutes) rather than a half-cycle (approx 20 minutes) was necessary, at least from 1945 to 1957.

Figure 22 shows the geyser terrace from its northwest base, looking southeastward over a local area that was inactive from 1945 to 1957, when the access road to the drilling pad of Sierra Pacific well No. 3 had been constructed more than halfway up the crest of the terrace.

Chemical Analyses of Natural Thermal Waters from Beowawe Geysers

Two chemical analyses of waters from Beowawe Geysers are listed in table 3 for comparison with "volcanic centered" geothermal waters from the west and east edges of the Great Basin, respectively. Steamboat Springs, about 15 km south of Reno, Nev., is associated with rhyolite domes dated at 1.1 and 3.0 Ma (Silberman and others, 1979) and is characterized by boiling springs and small geysers; its maximum recorded subsurface temperature was near 230°C. Roosevelt Hot Springs, Utah, is also associated with young rhyolite domes a few kilometers east of the geothermal field, and its reservoir has a temperature close to 265°C. The area also has an inactive sinter terrace west of the range front and a single hot spring just within the front to the northeast that was rapidly being self-sealed by opaline silica in the 1950's. The temperature of this hot spring was only 85°C in 1950 (H.E. Thomas, written commun., 1955) and had decreased to 55°C at a fraction of its former discharge when I collected this water sample in 1957. When I revisited the area a few years later, the vent was completely self-sealed by glassy opaline sinter.

Most Beowawe geysers were relatively rich in SiO_2 (approx 400–450 ppm), as illustrated by analysis 2 in table 3. "Frying Pan" Geyser (vent 51) at the base of the sinter terrace was an exception (analysis 3, table 3), best explained as a mixture of hot deep water rising along a western strand of the Malpais fault that mixed with near-surface downslope drainage of cooled water from the terrace geysers nearly 350 m to the south. This explanation is supported by the fact that runoff from the terrace partly evaporated as the rest sank below ground along various terrace channels. None of this runoff continued down to the lower line of springs (fig. 6). Much silica was precipitated as the water cooled, thus explaining why "Frying Pan" lacked major eruptions because of insufficient temperature and excess energy. Its SiO_2 content was relatively low, but its Cl content was the highest of the area (69 ppm), owing to partial surface evaporation before sinking underground.

Most of Beowawe's springs and geysers had salinities similar to that of the small terrace geyser analyzed by E.T. Allen (spring 2 of Nolan and Anderson, 1934). Most Cl contents at Beowawe were near 50 to 55 ppm, but a few were enriched slightly by boiling and evaporation; pH was generally near 8 if the waters were unboiled but as high as 9.7 after extensive boiling and consequent escape of CO_2.

Several terrace springs that include vents 40 and 41 had Cl contents at least as low as 16 ppm and pH's that were strongly to slightly acidic (pH=2.3–6.4). Dissolved gases contain some H_2S and CO_2 that boil off below ground level; these gases then escape and may redissolve in lower-temperature condensates of steam. Altitudes of vents ranged from slightly lower to higher than the surrounding ground, and gas pressure was high enough for liquid water to be largely excluded.

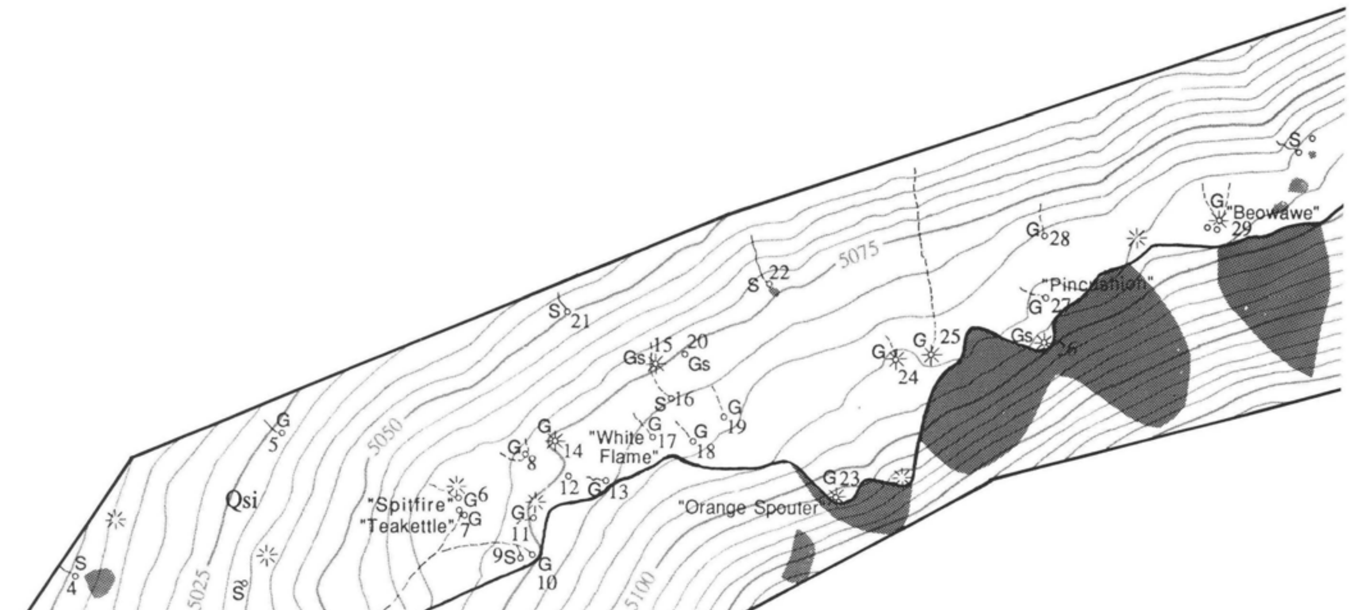
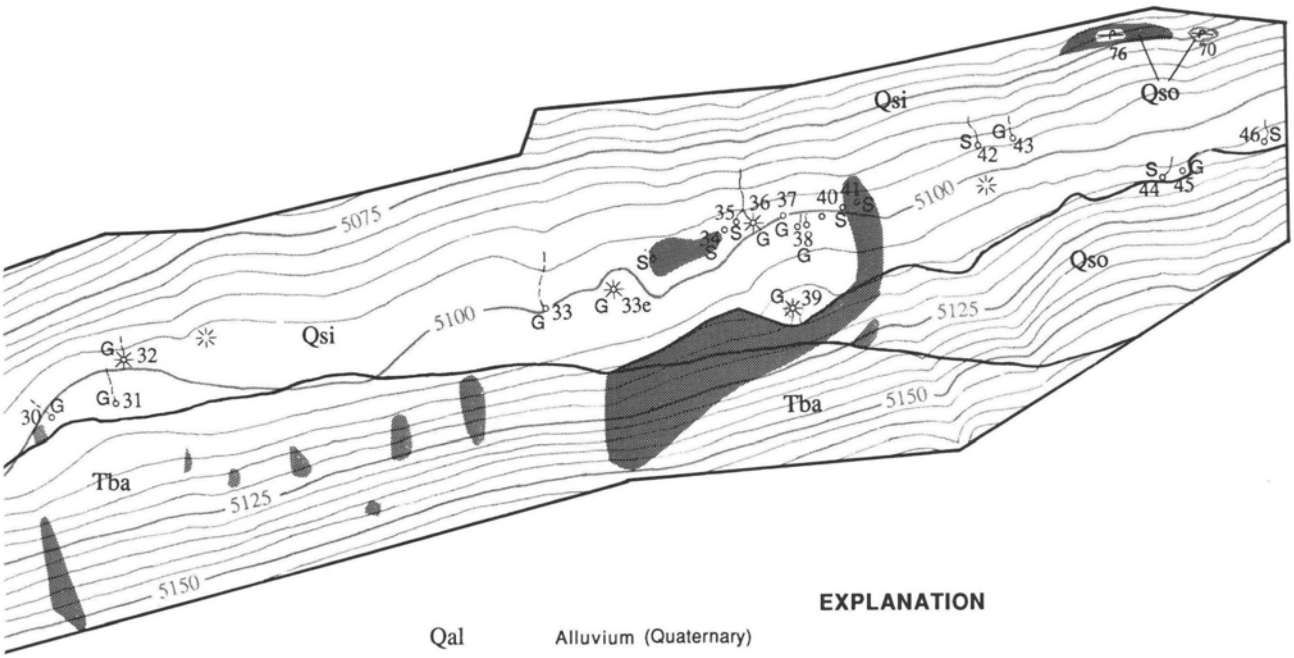


Figure 7. Detailed map of crest of Beowawe Geysers terrace as it appeared before 1959, when many vents were destroyed. Doug Baker, Hale Tognoni, D.E. White, G.A. Thompson, and others, largely in 1948, with a few later additions by D.E. White.

Thermal Waters of the Horseshoe Ranch

Mildly thermal waters discharge near the Horseshoe Ranch, 8 km east-northeast of the geyser terrace and north of Beowawe Station (sec. 32, near northeast corner of fig. 2). Three water samples were collected from the Horseshoe Ranch for analysis of Cl content and pH on September 30, 1950. The first sample (48.2°C) was from an old shallow well that was discharging directly into a pool southeast of the ranch buildings; a second sample (51.4°C) was from a warm spring north of the bunkhouse; the third sample was from a cool well about 1 km east of the ranch.

Water from the old well (48.2°C) contained 30 ppm Cl and had a pH of 7.0. Water from the nearby warm spring (51.4°C) was nearly identical, containing 28 ppm of Cl and having a pH of 7.4. The chemistry of the water from the cool well sample was somewhat surprising—57 ppm Cl and a pH of 7.7. The two thermal waters had more than half the Cl content of typical Beowawe Geysers water, but the temperature of the cool well was too low to record with a maximum-registering thermometer. Total discharge from all three springs was about 200 kg/s. The significant Cl contents of these samples indicate that the use of Cl content for monitoring the total discharge from



EXPLANATION

Qal	Alluvium (Quaternary)
Qsi	Siliceous sinter, young, opaline (Quaternary)
Qso	Siliceous sinter, old, partially chalcedonized (Quaternary)
Tba	Basaltic andesite (Miocene); talus–covered on steep slopes
(line symbol)	Contact
o	Vent with no discharge
So	Hot spring
So~	Hot spring with discharge channel
Go	Geyser
Go---	Geyser with intermittent-discharge channel
Gso	Subsurface geyser
(symbol)	Sinter cone
(symbol)	Area of hydrothermal alteration; boundaries are gradational

Most thermal features are numbered to correspond to table 2, and some are informally named. Mapped by R.G. Reeves, the Beowawe Geysers system is clearly unwarranted (compare White, 1968).

Discharge and Source of Thermal Water

Waring (1965) estimated the natural discharge of the Beowawe Geysers system at 6 L/s, twice his earlier estimate of 3 L/s (Stearns and others, 1937). This uncertainty is understandable because physical measurement of discharge rates is particularly difficult when geysers are present. Either of Waring's estimates, however, is certainly far less than the deep upflow of thermal water, because much thermal water is discharged laterally into near-surface aquifers and cannot be measured at the surface.

This lateral escape of upflowing thermal water is illustrated by the potentiometric surface in the shallow part of the ground-water system of Whirlwind Valley (fig. 23; modified from Olmsted and Rush, 1987). The topographic surface slopes east and then slightly northeast from the terrace to within 4 km of the Humboldt River at a gradient that averages about 5 m/km. However, in the tightly packed contours just north of the Beowawe Geysers terrace (fig. 23), the gradient is greater than 30 m/km (although the 5-m contours are not well constrained because of the absence of detailed data). This gradient is surprisingly high in view of the porous, open-textured sinter debris characteristic of springs on range fronts and of near-surface clastic sinter deposits. The explanation is that the sinter fragments beneath the surface of the Beowawe terrace have been partially cemented and self-sealed by high-silica waters escaping downslope from the main upflow channels. As these waters cool, monomeric silica (H_4SiO_4) polymerizes, cementing any loose fragments and filling most open spaces in opaline sinter with opal or cristobalite (White and others, 1956; Fournier, 1973). Self-sealing is seldom complete; highly permeable rocks become less permeable over time, but even slightly permeable sinter still has some interconnected open spaces.

Measurement of the deep upflow by the chloride-inventory method is inapplicable to such areas as Beowawe that lack a permanent throughflowing stream with low and nearly constant contents of such conservative constituents as Cl or B. Olmsted and Rush (1987), however, developed a hydrologic model that estimates a total deep upflow of 18

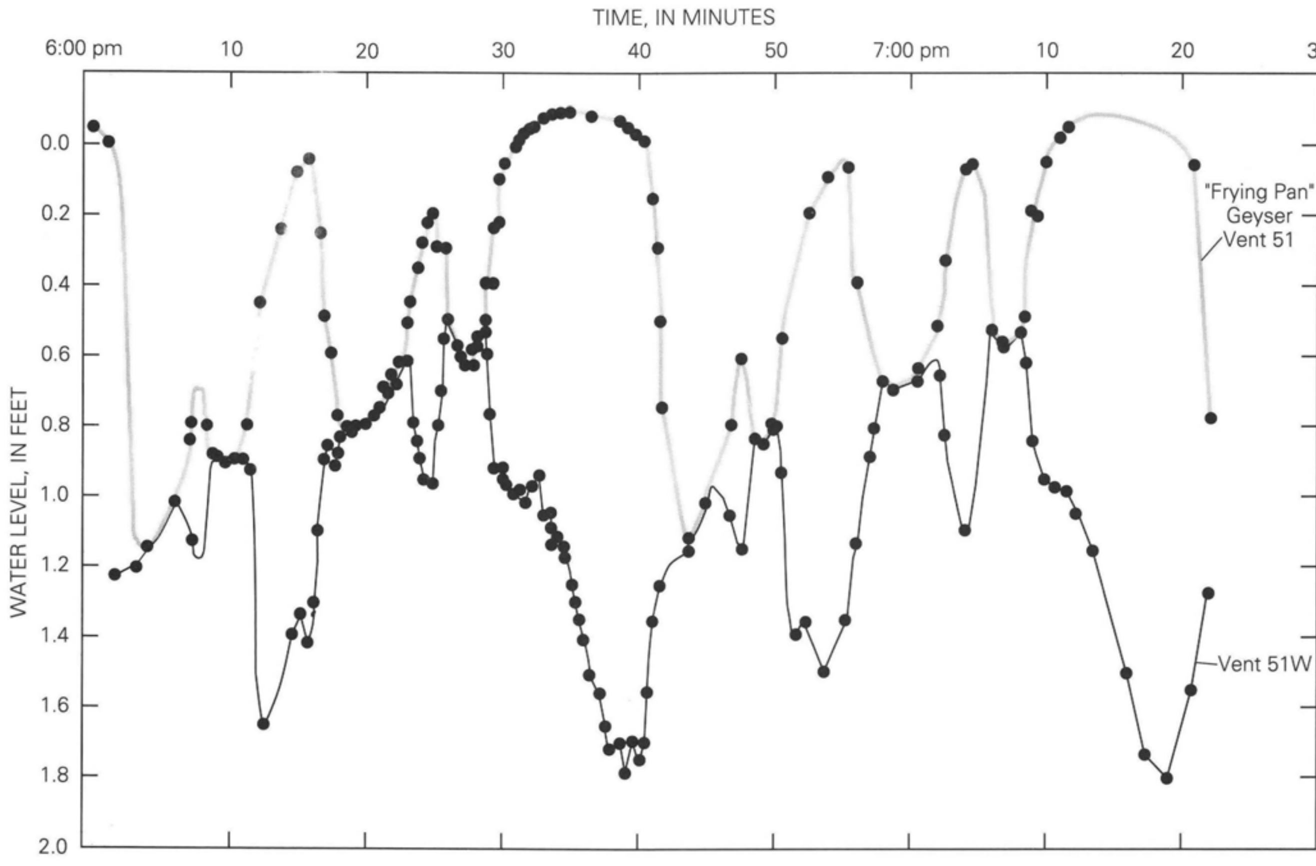


Figure 21. Relative water-level measurements on May 14, 1948, at "Frying Pan" Geyser (vent 51) and related nondischarging vent 51w, less than 5 m to the west.

L/s, with two-thirds of the ascending water leaking laterally from the conduit system before it reaches the surface. This estimate contrasts with the 70 L/s upflow estimated by the Cl-inventory method for Steamboat Springs, Nev., a nearly ideal situation for using the method (White, 1968, p. 82–84, table 40). The terrace area of Steamboat Springs is about 3 times larger than that of Beowawe, but its measured discharge is only approximately 4 L/s, or 6 percent of the total computed upflow, of which geyser discharge is no more than a few percent of the total. The geysers at Beowawe, however, probably account for nearly 50 percent of the total visible discharge, and therefore heat is being conserved to an unusual degree.

The 6- and 3-L/s discharge estimates of Waring (1965) and Stearns and others (1937) are equivalent, respectively, to about 9 and 4.5 percent of the present recharge into the Whirlwind Valley drainage basin (Olmsted and Rush, 1987). More importantly, the upflow estimate of Olmsted and Rush (18 L/s) is 26 percent of the present

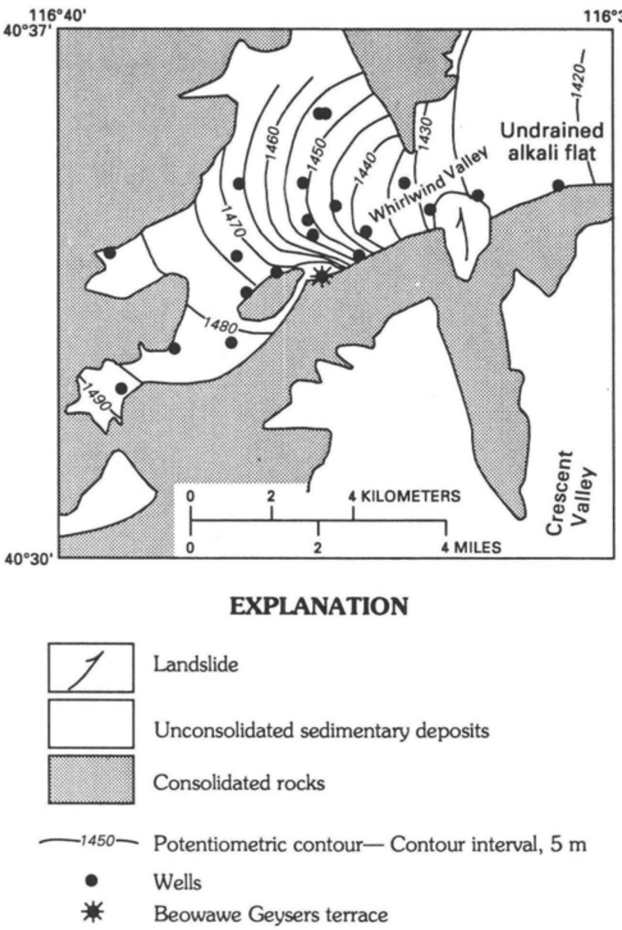


Figure 23. Sketch map of Beowawe Geysers area, showing altitude of potentiometric surface in shallow part of Beowawe ground-water system, as measured in 1973 (modified from Olmsted and Rush, 1987).

recharge into Whirlwind Valley. This proportion seems high, given the gentle local topography and the slight precipitation. Indeed, there is no need to assume that the water supply of the Beowawe Geysers comes entirely from the local basin. Evidence from hydrogen/deuterium ratios indicates that much or most of Beowawe's water is probably "fossil" water from an earlier period of higher precipitation, requiring a recharge area far larger than Whirlwind Valley. This interpretation is supported by the fact that present-day meteoric waters of central Nevada all seem to have higher δD values than the hot springs, in opposition to expected results. A glacial period of higher precipitation, lower atmospheric temperature, and lower δD values would cause this difference (J.R. O'Neil, written commun., 1980; Mariner and others, 1983).

Source of Heat

Most high-temperature hot-spring systems are "volcanic centered" and are enriched in ^3He from the mantle (Craig and others, 1975; Jenkins and others, 1978) relative to the dominant ^4He of the atmosphere and crustal rocks. ^3He is much enriched in "primitive" gases from basalts, the oceanic-ridge systems, and young hotspots, such as the Hawaiian volcanoes and Yellowstone National Park. Such relations support the hypothesis that mantle and core outgassing is still continuing and best accounts for those gases strongly enriched in ^3He.

High-temperature hydrothermal-convection systems that owe their heat primarily to young volcanic rocks generally are enriched in ^3He. Conduction of heat through a stretched thin crust may also result in diffusive enrichment of mantle ^3He, according to Oxburgh and O'Nions (1987). Beowawe is situated on the Battle Mountain heat-flow high that extends from near Steamboat Springs, close to the California-Nevada State line, northeastward to the Snake River Plain in Idaho. Its average width is about 200 km, and its average heat flow is about 50 percent above the crustal average (Lachenbruch and Sass, 1977). Surficial volcanic rocks younger than 10 Ma are not known within about 50 km of Beowawe.

The sparse $^3He/^4He$ data available for Beowawe indicate that the fluids are deficient in mantle ^3He relative to most other high-temperature systems that have abundant geysers and unusually high heat flow. Welhan and others (1988, p. 187) determined an R/R_A ratio (ratio of unknown to atmospheric) of 0.46 for a mixture of liquid and vapor collected from a well erupting freely near the crest of the Beowawe terrace. W.A. Jenkins of the Woods Hole Oceanographic Institute (WHOI) obtained similar results for both water and gas from Beowawe during the early 1980's (Peggy O'Brien, oral commun., 1986).

Table 3. Water analyses from Beowawe Geysers in comparison with analyses from "volcanic centered" waters of Steamboat Springs, Nevada, and Roosevelt Springs, Utah

[All analyses in parts per million; Tr, trace. References: 1, White and others (1963, p. 40); 2, Nolan and Anderson (1934); 3, Mariner and others (1983); 4, White and others (1963, p. 42)]

Analysis	1	2	3	4
	Steamboat Springs No. 8, Washoe County, Nev.	Small geyser, Beowawe Terrace, Eureka County, Nev.	"Frying Pan" geyser, vent 51, Beowawe, Eureka County, Nev.	Roosevelt Springs, Beaver County, Utah
NH_4	<1	4?	0.5	0.0
Li	7.6	—	—	27
Na	653	239	230	2,500
K	71	33	16	488
Mg	.8	—	<1	.0
Ca	5.0	2.0	1	22
Fe	.05	Tr	<.02	<.04
Al	.5	0	.08	<.04
As	2.7	—	.03	2.0
Sb	.4	—	—	—
CO_3	0	173	383	0
HCO_3	305	129		156
SO_4	100	97	130	73
H_2S	4.7	5	—	—
Cl	865	47	69	4,240
F	1.8	11	17	7.5
Br	.2	—	.2	3.5
I	.1	—	.02	.3
B	49	8	—	38
NO_3	—	—	—	11
SiO_2	293	[1]449	320	313
Total, as reported	2,360	1,196	1,165.85	7,880
Temperature (°C)	96	~95	98	55
pH	7.9	—	8.98	7.9

[1]Probably total gravimetric SiO_2; the colorimetric method had not yet been developed.

The source water of the Beowawe system has a maximum recorded temperature of 230°C at depths of about 3,000 m (Hoang and others, 1987). This temperature is exceeded in the Great Basin only by Roosevelt Hot Springs of western Utah, with a maximum recorded temperature near 265°C (Brook and others, 1979). Both Roosevelt Hot Springs on the east and Steamboat Springs near the west margin of the Great Basin, with a maximum recorded temperature near 230°C (Phillips Petroleum Co., oral commun., 1982), are typical "volcanic centered" geothermal systems. The Beowawe system differs from the other two in its absence of recent associated volcanism, its high regional heat flow, and its low content of dissolved solids (excluding SiO_2, which mainly depends on temperature).

I conclude that the Beowawe system differs from most other high-temperature geothermal systems of the world in its absence of young volcanic heat sources, its absence of clearly adequate young meteoric water, and the low salinity of its circulating water (table 3). No explanation is evident for its unusually great abundance of geysers, other than the system's high temperature and the adequate flow rate of its feeding water.

SUMMARY OF GEOTHERMAL DRILLING AND DEVELOPMENT, 1959 TO PRESENT

Four geothermal wells were drilled along the terrace crest by a subsidiary of the Magma Power Co. in late 1959; many more were drilled subsequently. Typically, these wells had very high initial productivity that declined relatively rapidly over time. Three of the four wells were later vandalized by blasting off the wellhead gear, thereby permitting the wells to discharge freely, but no flow data were obtained. Most water and steam from natural springs and geysers on the terrace crest were diverted into uncapped flowing wells, causing the observed decline of 65 to more than 130 m in water levels and cessation of discharge from former springs and geysers. A photograph of the terrace taken about 1963 showed many steam plumes over the upper half of the terrace in places of former discharge of water, indicating general lowering of water levels. The fault zone evidently was penetrated at depths ranging from about -65 to -130 m, where self-sealing had formerly deposited abundant quartz and chalcedony from the high content of dissolved SiO_2 (350–450 ppm at temperatures near 200–220°C). The natural vents had already adjusted to partial self-sealing and reduced permeability; the wells provided a "short circuit" through this zone. Water diverted to the wells could not also supply the springs and geysers. Reduced fluid pressures in former water-saturated sinter then permitted only steam to escape through hot-spring and geyser channels previously filled with water.

Intermittent study of Beowawe as a natural undisturbed system thus ended with my 1957 observations (table 2). Sinter and other debris were bulldozed into former spring and geyser vents as activity declined, under the mistaken notion that declining well productivity was caused by a loss of steam rather than a declining water table. Essentially all natural spring and geyser activity on the terrace had ceased by September 1960. Water levels in the four repaired wells were measured on March 31, 1962, when nonerupting depths to water ranged from about 87 m to 93 m below local land surface, in comparison with former geysers and springs that had discharged at the surface. All natural vents near the terrace crest were drained of their water supply. Many new steam vents, however, became temporarily active near the terrace crest and were generally more prominent in cold weather.

After drilling by several private interests, Chevron Resources, a subsidiary of the Chevron Oil Co., became interested in the area (Hoang and others, 1987); by January 1986, electricity was being produced from a dual-flash electric powerplant designed to generate 16 MW from two wells, Ginn 2–13 (1,733 m deep) and Ginn 1–13 (2,915 m deep; Hoang and others, 1987). The powerplant is located about 1½ km southwest of the sinter terrace (not visible from the terrace). Its rated capacity was attained by October 1986. The minimum electric-power potential of the Malpais fault zone was considered to be 200 MW. The two producing wells were located in different strands of the Malpais fault zone, and fluids from each strand were interpreted to be independent. According to Hoang and others (1987), neither well has shown any change in temperature (approx 220°C) or pressure with production.

SUMMARY AND CONCLUSIONS

The Beowawe Geysers was a spectacular but little-known area of small geysers in north-central Nevada, second only to Yellowstone on the North American Continent. During my 8 visits to Beowawe between 1945 and 1957, the total number of observed geysers ranged from 12 to 27; at least 28 features had been geysers at one time or another during the 12 years of sporadic observation. The maximum observed height was almost 8 m. For its small area, this may have been the largest natural concentration of geysers in North America. Subsurface eruptions, aquifer eruptions, variable-discharge springs, perpetual spouters, and drilled wells are excluded.

Many manmade changes to the Beowawe system resulted from the geothermal drilling and production that extended from 1959 to the present. Depending on details of subsurface plumbing and localized pressure release, discharge of geothermal wells can cause vents to change temporarily into geysers or geysers to cease erupting. Over an extended period of time, cessation of eruption is much more likely to occur than eruption of a previously non-geysering vent.

The rate of upflow of thermal water from Beowawe's reservoir was estimated by Olmsted and Rush (1987) at 18 L/s, much of which may be "fossil" water from an earlier period of higher precipitation.

Although the source of heat at Beowawe geysers is not yet certain, high regional heat conduction to a deep aquifer, such as the Roberts Mountains thrust fault, is favored in the absence of adequate "volcanic centered" heat sources. Although the age of the Beowawe system is not yet known, fault displacement of older sinter suggests that the system may have been active for at least 100 ka.

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FIGURES 4, 5, 8–20, 22; TABLE 2

Figure 4. Malpais fault zone and Beowawe Geysers terrace. View eastward; photograph by G.A. Thompson, taken October 18, 1951.

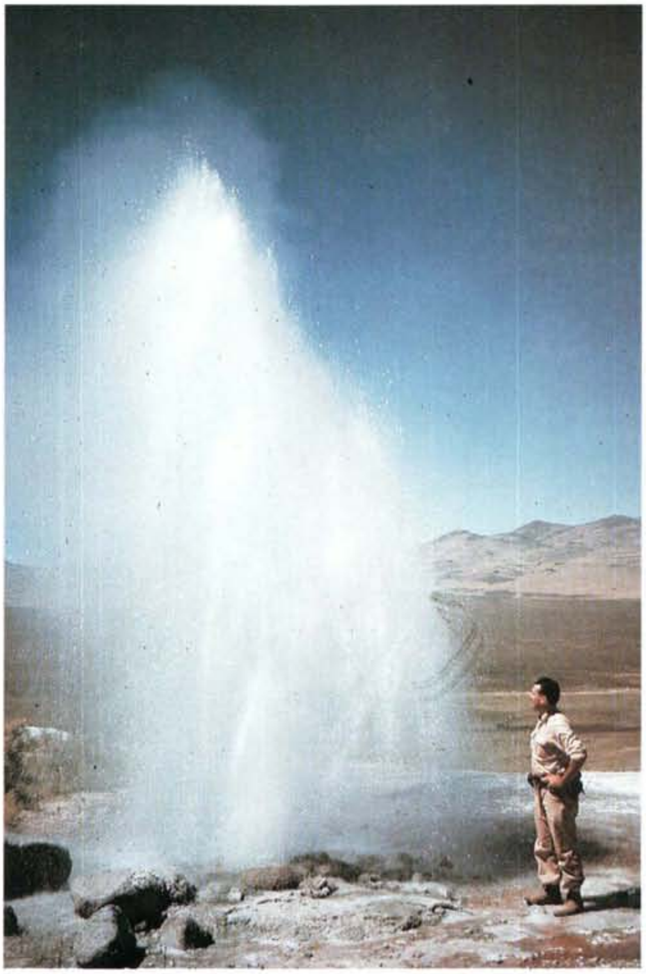

Figure 5. "Beowawe" Geyser erupting from vent 29 to a height of about 8 m on September 22, 1945.

Figure 8. "Teakettle" Geyser (vent 6) erupting from its double vent, October 1, 1950. Stronger plume, 3 to 4½ m high, is inclined about 40° from vertical to the southwest. Weaker plume, largely of mist, is about 2 to 3½ m high and inclined about 50° from vertical to the northeast.

Figure 9. "Spitfire" Geyser (vent 7; also called "Sputter Pot" Geyser), near northwest edge of Beowawe terrace. Eruption plume is nearly vertical to a height of about 4 m. View northward.

Figure 10. Unnamed geyser (vent 13) near centerline of Beowawe terrace erupting nearly vertically to about 5 m on October 1, 1950. Regular pattern of boulder distribution may be due to early settlers or Indians. View northward.

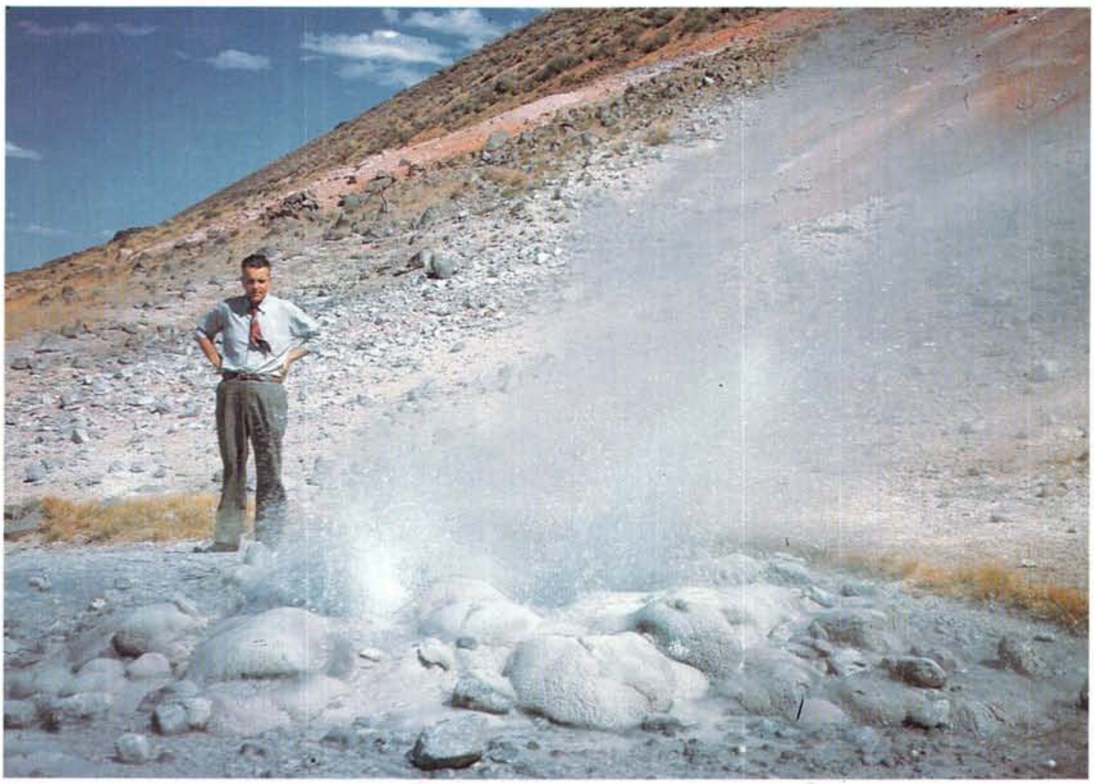

Figure 11. "Pincushion" Geyser (vent complex 27) erupting in August 1945 from many vents through a pile of sinter-covered basalt boulders, possibly emplaced by early settlers or Indians. Plumes from only two or three vents are distinguishable in this photograph. More distinct plume on left is dispersed and about 1 m high; second, less conspicuous plume is inclined to right and about 1½ m high.

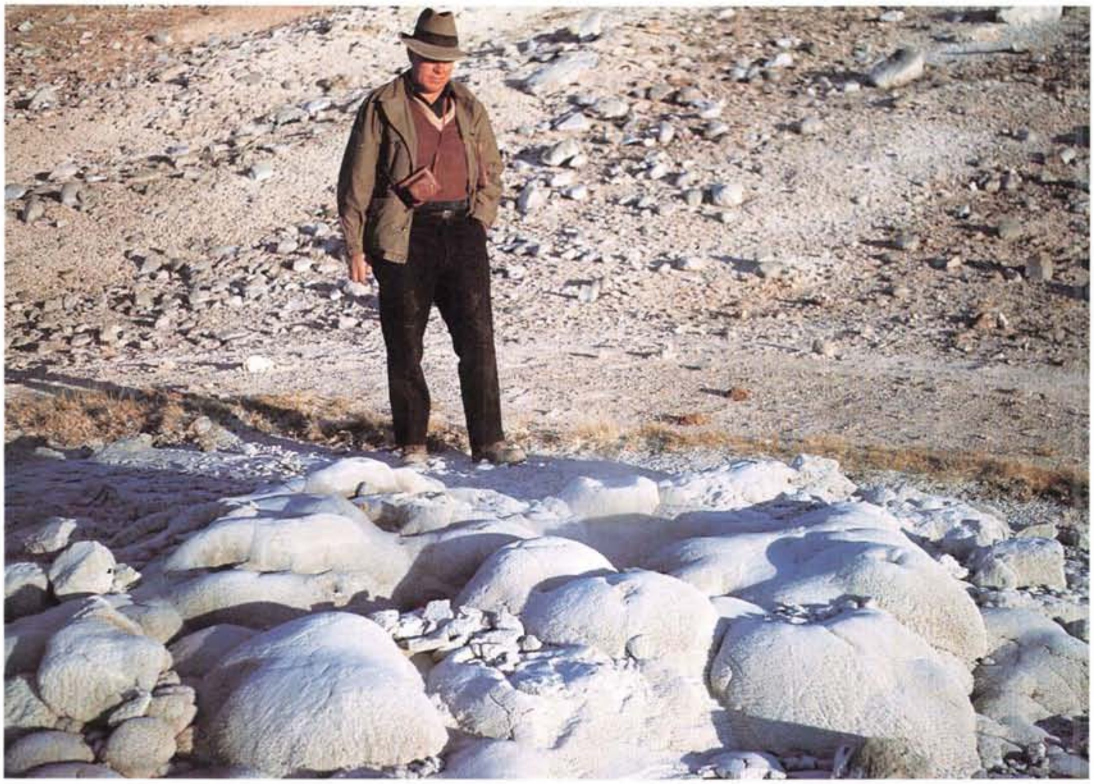

Figure 12. "Pincushion" Geyser (vent complex 27) on September 20, 1950, between eruptions, showing some of 8 to 10 vents nested among basalt boulders that may have been emplaced by early settlers or Indians. Geyser is steaming slightly, but no water is visible.

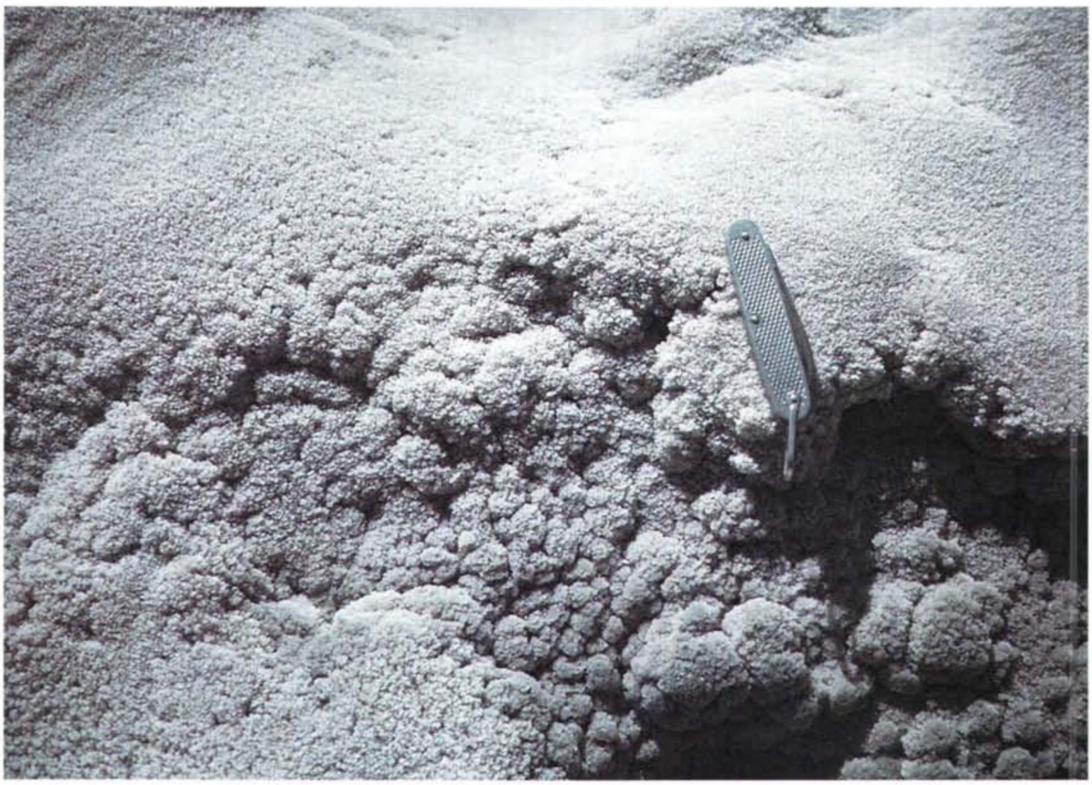

Figure 13. "Pincushion" Geyser (vent complex 27), showing "sugary" opaline sinter zoned in grain size from direct evaporation of silica (initially, monomeric H_4SiO_4).

Figure 14. Opaline sinter texturally zoned around main vent of "Beowawe" Geyser (vent 29) between eruptions (center) on October 1, 1950. Inner zone of fine-grained "sugar" is nearly always wet, probably deposited as monomeric silica; outer zone of spherulitic sinter is commonly dry and results from complete rapid evaporation of polymerized silica. Vent of this geyser was photographed by Nolan and Anderson (1934, pl. 6, right center).

Figure 15. Subsidiary pool of "Beowawe" Geyser, probably in 1947, showing white-fringed sinter deposited above a nearly constant sill level and dark, more slowly deposited sinter as small polymeric molecules of silica (with Fe?) precipitating as water cools between eruptions.

Figure 16. Unnamed small geyser (vent 48) erupting about ⅓ m high in foreground on October 1, 1950, while "Colorful Spouter" (vent 49 to the east) is spouting in background.

Figure 17. Closeup view of "Colorful Spouter" (vent 49) on September 2, 1947. This spouter was active during all visits except September 9, 1949, when it was dormant. When active, color zonation seems constant; inner yellowish-white zone is elemental sulfur; darker outer zones when wet are thermophylic algae and bacteria. View westward.

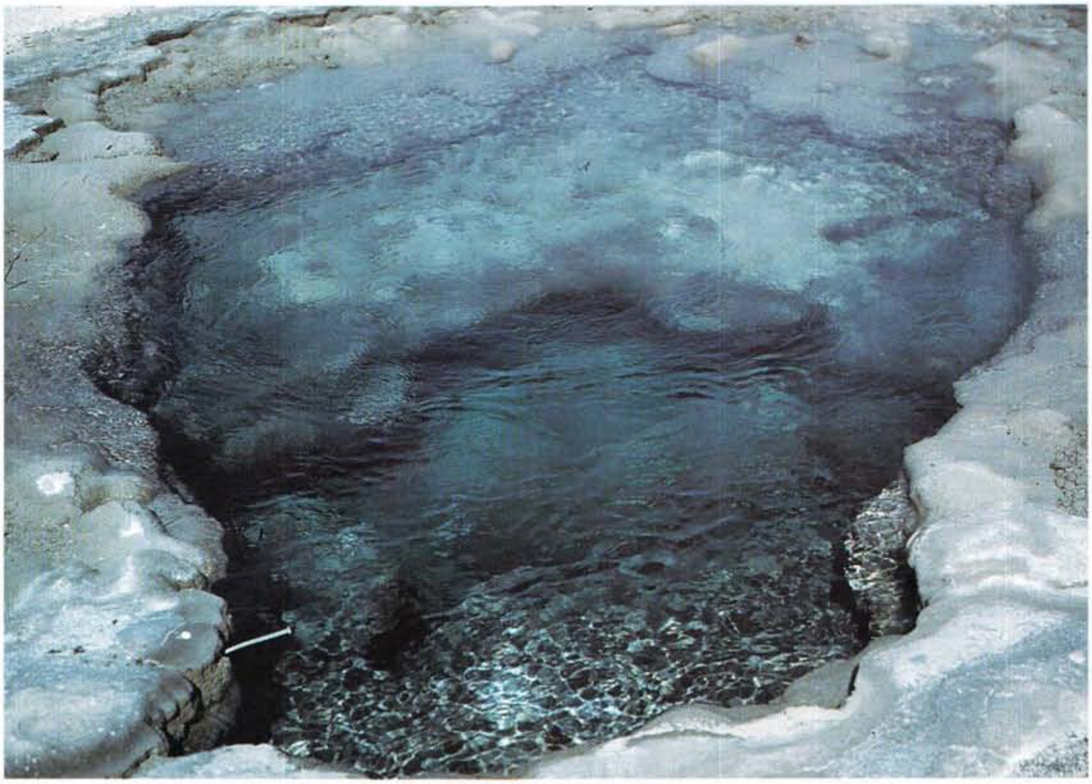

Figure 18. "Frying Pan" Geyser (vent 51), looking nearly down its throat on October 1, 1950, before eruption, in flat area north of base of terrace. Water is rising in the throat as gas bubbles (largely steam) become more prominent and, at first, condense in cooler water of pool. As pool heats up, bubbles no longer condense but break the surface. Nail at near left was used as reference for measuring depth to water.

Figure 19. "Frying Pan" Geyser in eruption on September 22, 1945. Water rises until it fills pool and discharges through old constructed channel next to photographer, who is facing west (for view northeastward, see Nolan and Anderson, 1934, pl. 8).

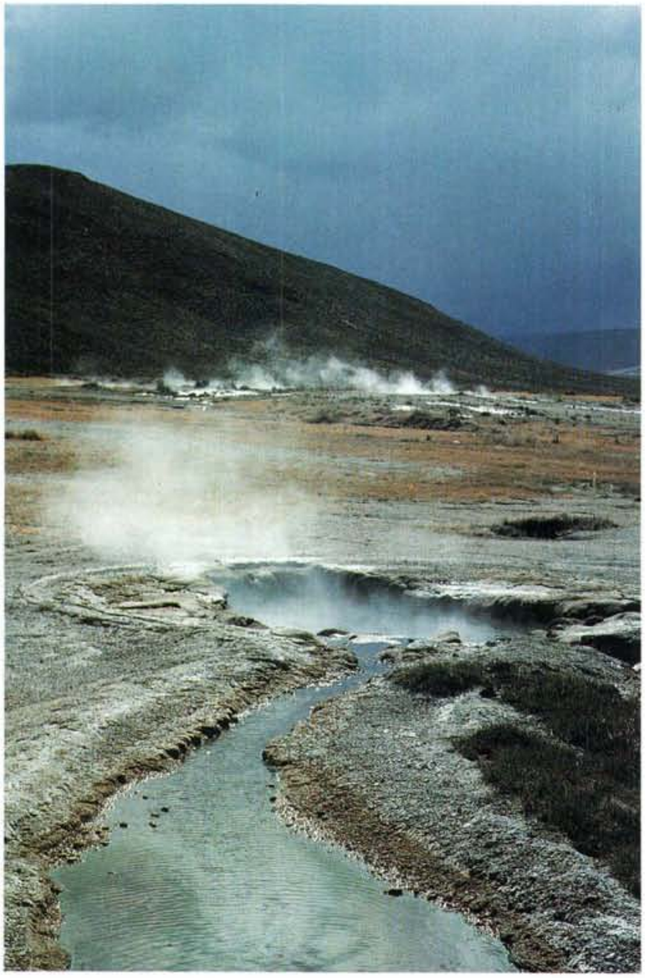

Figure 20. "Frying Pan" Geyser pool after eruption. View west-southwestward; photograph taken in 1962 after reactivation of northwestern group of springs steaming in background.

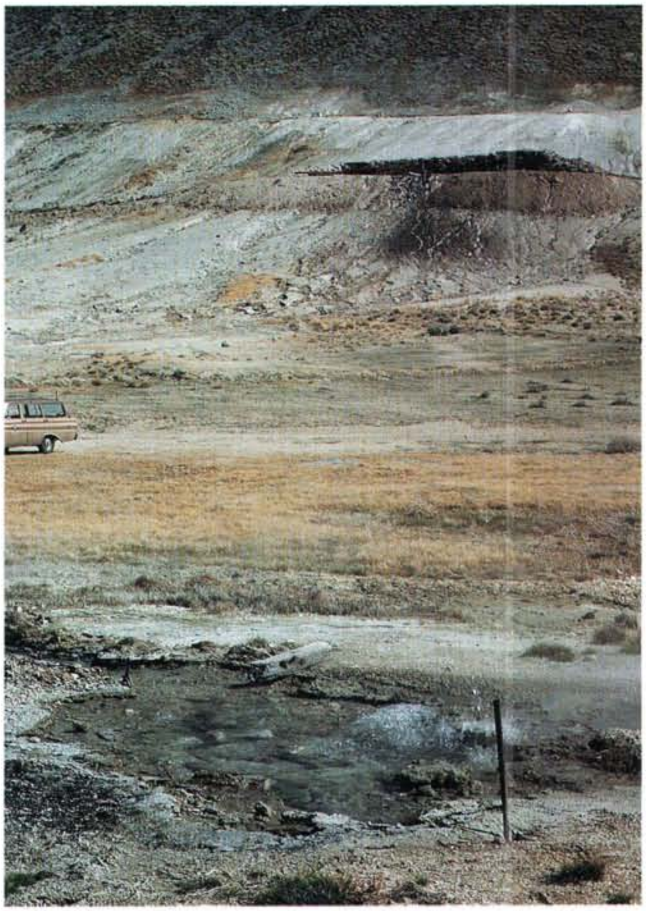

Figure 22. Sinter terrace of Beowawe Geysers on April 5, 1965, overlooking reactivated area in foreground. View southeastward.

Table 2. Selected characteristics of hot-spring activity observed in the Beowawe Geysers area, Nevada, 1945–57

[See figures 6 and 7 for locations. G, geyser observed or considered definitely active; G?, geyser, probably active during observation period; Gs, geyser, subterranean; S, active hot spring; Si, vent, showing varying water level. S?, spring, probably active; Sp, perpetual spouter; Sv, spring, showing varying discharge rate; dashes, no data.]

Map No. (vent)	Name	Date: Sept. 22, 1945	Sept. 1–2, 1947	May 14, 1948	Sept. 8–9 1949	Sept. 30–Oct. 1, 1950	May 25, 1951	Oct. 15, 1951	Sept. 1, 1957	Summary
1	Hot spring	S	S	S?	S?	S?	S, 58°C, ~18 L/m	S, 57.5°C, ~40 L/m	---	S
2	Hot spring	S	S	S?	S?	S?	S, 57°C	S, ~12 L/m	---	S
3	Hot spring	S	S	S?	S?	S?	S, 98°C, 30 L/m	S, 98.1°C, 8 L/m	S	S
4	Hot spring	S	S	S, 6 L/m	S?	S?	S	S, 90.8°C	S	S
5	Hot spring or geyser.	S	S	S?	S?	G, small	S	S, 90°C, 8 L/m	G, small	G, small.
6	"Tea Kettle" Geyser.	G, 2 vents	G	G, 1-min eruption.	G	G, 2 vents to 5 m.	G, 6-min interval	G, 6-min interval	G, >2 m	G, 2 m, 3-min. eruption, ~60-min interval.
7	"Spitfire" Geyser.	G?	G?	G, 40-min eruption.	G	G, steam phase.	G, long interval.	G, long interval.	G	G, ~40-min. eruption.
8	Unnamed geyser	G?	G?	G	G?	G	G?	Inactive?	S?	G at times.
9	Variable spring	---	Sv	No recent eruption.	---	---	Sv, variable	Sv, variable	---	Sv
10	Unnamed geyser	---	G, ~0.3 m	G, ~0.5 m	G, ~0.8 m	G	G	G	G, <1 m	G, 0.3 m for 1 min, 30-min interval.
11	Unnamed geyser	G	G?	G?	G	Sv?	---	Surging to surface, no discharge.	---	G
12	Vent	---	---	Inactive	Si	---	---	Si, no discharge	---	Si
13	Unnamed geyser	G?	G?	G	G, erupting	G, to 5 m	G	Gs?	---	G, at times to ~5 m
14	Unnamed geyser	---	G, 2 vents	Inactive?	G	G, to 2 m	Surging, no net discharge.	G, ~6 L/m	---	G, active to ~2 m.
15	Vent, subsurface geyser.	---	Gs?	Gs	Gs	---	Gs?	Inactive?	Inactive?	Gs
16	Intermittent spring	---	Si	Si	---	---	---	S, seeping	S, seeping	Si
17	"White Flame" Geyser.	G	G	G	G	G, mild	G, 2-min duration, ~10-min interval.	G, bubbles collapsing.	G	G, >1 m.
18	Unnamed geyser	G?	G?	G, active	G	G, >1 m	G	G	G	G
19	Unnamed geyser	---	G?	G?, no very recent eruption.	G	G	Active	S, cooled by vent 23 discharge.	S, cooled by vent 23.	G at times.
20	Subsurface geyser	---	---	Gs	---	---	---	Inactive	Gs	Gs
21	Hot spring	S	---	---	S	---	---	S, 3 L/m	Inactive	S
22	Hot spring	---	---	S, ~1 L/m	S	---	---	S, 20 L/m	Inactive	S
23	"Orange Spouter"	Sp	---	No activity	---	---	Inactive	Sp, 97.6°C, ~10 L/m	Inactive	Sp
24	Small geyser	---	Sp?	G, small	G	G	G	G	G	G, small, 1 m or less.
25	Unnamed geyser, disintegrating.	G	G, to 3 m	G, to 3 m	G, preliminary discharge.	G	G, ~30-min discharge.	G, >12-min eruption.	G	G, erupting, 3-min overflow, erupts 3 m for ~13 min.

26	Subsurface geyser.	---	Gs	G?	---	---	Inactive	Gs	Si	Gs, commonly subterranean.
27	"Pincushion" Geyser.	G	G?	G	G, multiple vents.	G	Inactive(?), no recent eruptions.	G, multiple vents to 2 m.	G	G, multiple vents to 2 m.
28	Small geyser	---	G?	G, surging to ⅓ m.	G	---	S?	Sv, variable, ~2 L/m	G	G
29	"Beowawe" Geyser.	G, to 8 m	G	G	G	G	G, 2-min duration, interval ~150 min.	G, 2-min duration.	G	G, to 7–9 m.
30	Unnamed geyser	---	G	G	---	---	2 bubbling pools, no discharge.	S, seeping discharge.	G, inactive	G
31	Unnamed geyser	---	---	G	---	---	Sp, ⅓ to >1 m	Sp, 12–20 L/m	G, inactive	Small G or spouter at times.
32	Unnamed small geyser.	S	---	G, small	S	---	S, ~10 L/m	S, variable discharge.	G, inactive	Small G at times.
33, 33e	Geyser, alternating.	G?	---	G	---	G	Inactive	G	G	G, one of two vents, alternating.
34	Spring, slightly acidic.	---	---	Acidic	pH 6.4	pH 6.1, seeping.	Seeping	pH 6.03, seeping.	Active	S, commonly slightly acidic.
35	Variable spring	---	---	---	S	Sv	S	Sv, ~2 L/m	Sv	Variable spring.
36	Unnamed geyser	G, to 2 m	Sv	G, 40–100 L/m	S	Sv	Sv, ~50 L/m	G, ~30 L/m	G	G, high discharge to 2 m or more.
37	Unnamed small geyser.	---	S	G, small	---	---	Inactive	Inactive	G, small	G, small.
38	Unnamed geyser-spouter.	---	G	G, 2 vents	---	---	G, small	G	G, small	G, small.
39	Unnamed geyser	G, to 1⅓ m	G?	G, splashing?	G	---	Inactive	Inactive	G, >1⅓ m	G, >1⅓ m
40	Acidic spring	pH 3.40	pH 6.61	pH 5.85	pH 3.28	---	No discharge	Seeping, variable	S, acidic	Acidic spring.
41	Acidic spring	pH 3.40	pH 2.61	pH 2.59	pH 2.33	pH 2.84	No discharge(?)	pH 2.59, seeping	S, acidic, 3–5 L/m	Acidic spring.
42	Small spring	---	---	Inactive	---	---	Inactive	Inactive	S, ~3 L/m	S
43	Small geyser	---	---	Inactive G?	G	Inactive	Inactive	Inactive	G, at times active.	G, active at times.
44	Small spring	S	S	S, 2 L/m	S	S	Inactive	Inactive	S, discharging	S, generally active.
45	Small geyser(?)	S	G?	G?, not recently active.	G?	G?, recent	Inactive	Inactive	G?	Small G?
46	Small spring	S	S	S, 6 L/m	S	---	Inactive	Inactive	S?	Spring.
47	Vent, inactive	---	---	Inactive for ~1 yr	---	---	Inactive	Inactive	Not seen active	Dormant.
48	Unnamed geyser	---	Inactive	G, ~⅓ L/m	G	G	Inactive	Inactive	Gs	G, ~⅓ m.
49	"Colorful Spouter"	Sp	Sp	Sp	Inactive	Sp	Sp, 20–36 L/m	Sp, ~24–36 L/m	Sp	Spouter.
50	Small spring	S	S?	Inactive	S?	S	S, ½ L/m	Sv, 1–4 L/m	S?	S, generally discharging.
51	"Frying Pan" Geyser.	G	G	G	G	G	G, ~10-min eruption, 40-min interval.	G, normal	G	G, ~⅓ m.
51w	Vent, varying water level.	---	Si	Si	Si	Si	Si	Si	Si	Si
Total number of geysers, active and probably active (G and G?).		14	19	27	20	18	12	14	19	28

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