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A Case History of Injection at the Beowawe, Nevada Geothermal Reservoir

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ABSTRACT

Production of 16.7 MW (gross) from a dual-flash power plant commenced in latest 1985 at the Beowawe geothermal field. Production was initially from two wells with injection into one well. During the next few years, significant changes occurred throughout the geothermal field. The production wells began to cool, the surficial thermal features diminished, the brine chemistry became more dilute, and the noncondensable gas contents declined sharply. These changes are consistent with recharge of cold meteoric water into the geothermal system. Injection at Beowawe has been into a cold aquifer located in close proximity to, but largely unconnected to, the fracture system containing the geothermal reservoir. Efforts are underway to modify the injection program to permit injectate to be returned directly to the geothermal reservoir. It is hoped this will mitigate the problem of cooling production wells.

INTRODUCTION

The Beowawe geothermal field is located in north central Nevada on the Eureka/Lander County line (Fig. 1). Prior to exploratory drilling in 1959 at Beowawe, an imposing silica terrace hosted the second largest number of active geysers in North America (after Yellowstone), and clearly suggested the presence of a high-temperature geothermal system at depth (White, 1992). The only information published on Beowawe since the start of production is by Hoang et. al (1987). This paper was written after approximately one year of production and its timing, in hindsight, is rather unfortunate, as the conclusions were apparently formulated without knowledge of the cooling trend that had either recently started or was about to commence.

Production is located about 1.2 miles west southwest of the silica terrace with injection into a well located at the eastern margin of the terrace (Fig. 2). Currently, about 4,000 gpm of geothermal brine is produced from three production wells and about 3,200 gpm of spent brine is injected into the Batz well. The difference is evaporated through the cooling tower and about 60 gpm are surface discharged as condensate overflowing the cooling tower.

The Beowawe geothermal reservoir is located in a fracture system associated with the normal Malpais Fault (Layman, 1984) where it cuts across a five mile wide Miocene rift zone (Struhsacker, 1980), which defines a portion of the Oregon-Nevada lineament (Fig. 1). Within the rift zone, 4,000 to 4,500' of Miocene volcanic rocks are present. The volcanic rocks are primarily basaltic to dacitic lava flows. Immediately outside the rift, the thickness of the volcanic rocks diminishes to several hundred feet. Underlying the Miocene volcanic rocks is the very thick and intensely deformed Ordovician Valmy Formation which has been

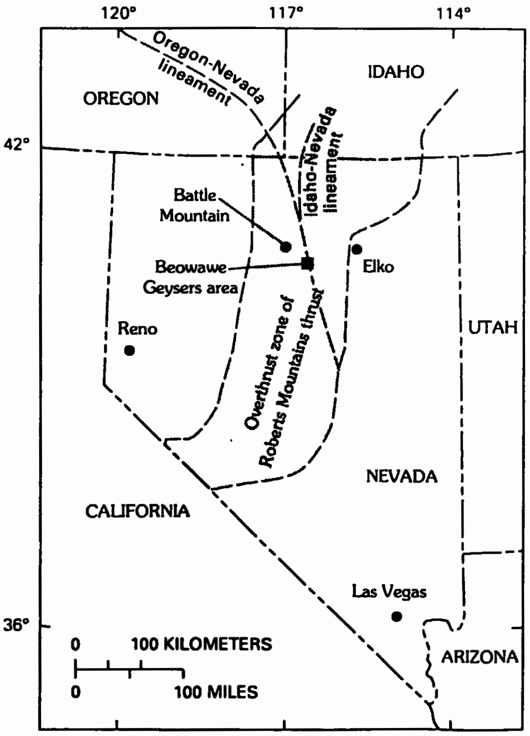

Figure 1. Index map of the Beowawe area, north-central Nevada. (After White, 1992).

thrust over carbonate rocks at great depth on the Roberts Mountain thrust fault. The Valmy Formation consists of variable amounts of chert, shale, quartzite, and basalt dikes or flows which may, in part, represent feeder channels for the Miocene volcanic rocks. Above the Miocene volcanic sequence, only a few hundred feet of unconsolidated alluvium is present near the geothermal field.

The surface trace of the Malpais fault scarp is sharp and sinuous as it meanders across the Miocene rift zone and dips 65 to 70 degrees to the northwest (Layman, 1984). Vertical offset on the Miocene volcanic rocks across the Malpais fault is about 1,100' and there has been some forced folding or draping of the Miocene volcanic rocks over the Malpais fault (Suneson, 1983). Various authors have mapped a variety of subsidiary faults parallel to and along the Malpais fault (eg. Hoang et. al, 1987 Fig. 4). This paper prefers to generally view these lesser features as part of a relatively narrow network of fractures constituting a fractured zone directly above the Malpais fault.

The geothermal system has exceptionally high permeability, up to 800,000 md-ft (Hoang et. al, 1987), in both the Miocene volcanic rocks and the underlying Valmy Formation. The produced portion of the reservoir, with initial temperatures reportedly 415 (Smith, 1983) or 420 °F (Hoang, et. al, 1987), is present in the Valmy Formation at depths below 6,700'. A much shallower subhorizontal aquifer is located at depths of a few hundred feet. This aquifer had pre-exploitation temperatures of 360 to 370 °F in the Miocene volcanic rocks near the silica terrace and is in excellent pressure communication with the deeper reservoir (Epperson, 1983).

The regional geology and structure near the terrace consists of volcanic strata dipping southeast from the top of the Argenta Rim, which defines the north margin of Whirlwind Valley, toward the Malpais fault. These strata can serve as an excellent pathway for allowing flow of meteoric water toward the terrace area at depths up to a few thousand feet. Olmsted and Rush (1987) estimated the entire Whirlwind Valley drainage area to have a meteoric recharge rate of 70 l/sec or 1110 gpm with a thermal water discharge of 18 l/sec or 285 gpm. They concluded "the (water) budget estimate suggests (but does not prove) that recharge within the drainage area tributary to the Geysers could supply all the observed ground-water discharge, both thermal and nonthermal." This interpretation is questioned by White (1992) who prefers a "fossil" water interpretation with recharge from a wider area.

EXPLORATION AND DRILLING RESULTS

Initial drilling to depths of several hundred feet by Magma Power Company in 1959 showed temperatures of 360 to 370 °F to be present beneath the silica terrace. In 1974, Chevron drilled the Ginn 1-13 well about 1.2 miles west southwest of the terrace to 9,507' in an area void of surficial manifestations of geothermal activity. This was, in effect, the discovery well of the Beowawe reservoir, encountering temperatures 415 to 420 °F and extremely high permeability.

Apparently nothing has been published about the rather remarkable and fortunate siting of the Ginn 1-13 well during the early 1970's when industry understanding of geothermal systems was, to put it mildly, primitive. The initial success of Ginn 1-13 was not to be repeated during the drilling of the next five, widely spaced exploratory wells. Geophysical exploration results have been presented by Swift (1979).

Since 1974, seven additional deep wells have been drilled with the intent of producing fluid. Of these, only two have proven commercially viable and both of these, Ginn 2-13 and 77-13, are in the immediate vicinity of the Ginn 1-13 well.

Deep wells, such as the Collins and Batz, drilled in the terrace area (Fig. 2) demonstrated that the source of the fluid supplying the terrace was not beneath the terrace. Temperatures at depths of 6,000 to 8,000' below the terrace are 80 to 150 °F cooler than at equivalent depths in the Ginn wells (Fig. 3). These unproductive terrace area wells also demonstrated that permeability along the Malpais fault was largely confined to a localized fracture network extending perhaps 1,500' above the fault.

Thermal fluid is rising obliquely toward the northeast along the Malpais fault from the vicinity of the Ginn wells. This is at odds with the often published speculation that the intersection of the Malpais fault and the Dunphy Pass fault zone, defining the eastern edge of the margin of the

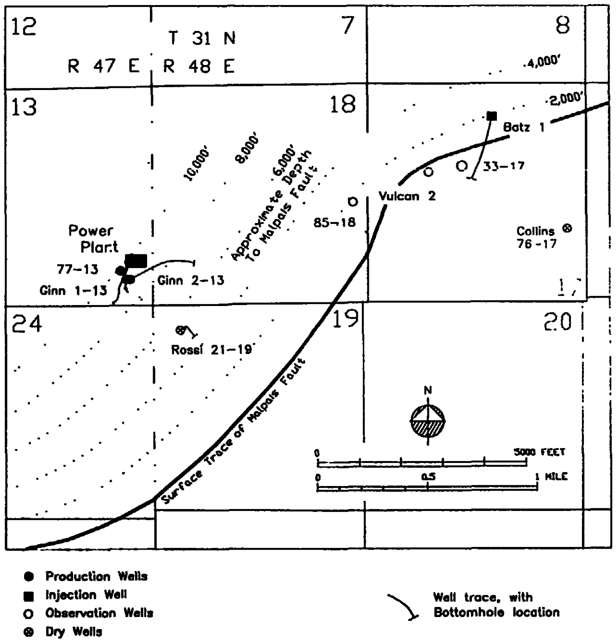

Figure 2. Location map of Beowawe production area. (Modified from GeothermEx, 1991).

Miocene graben (located east of the terrace), is the main source of thermal upflow.

No significant permeability has been encountered in the footwall of the Malpais fault despite it being penetrated by four wells for distances between about 2,000' and 8,500'.

Deep subsurface information is concentrated in two clusters of wells near the terrace and about one mile west of the terrace. A number of shallow temperature-gradient holes show a modest sized, shallow thermal anomaly associated with thermal fluid leakage from the terrace area and intruding into cooler groundwater (Smith, 1983). Modestly elevated shallow temperature gradients occur near the Ginn wells.

Static temperature profiles of the wells (Fig. 3) show a variety of shapes characteristic of both upward and lateral flow of thermal water with both gradual and sharp temperature reversals. Most unique and interesting of these is the Batz well, the northeasternmost well drilled in the terrace area and the only injection well utilized during the first seven years of production. The Batz well clearly detected a 290 °F shallow thermal aquifer at a depth of 400' and then a 120 °F aquifer at a depth near 1,500'. The sharp temperature reversals in the Batz static temperature profile argues convincingly that both aquifers are subhorizontal in orientation. (A steeply dipping aquifer would present a more subdued temperature reversal such as is presented by the Batz well near a depth of 2,600' and Rossi well at 4,500' on Figure 3.) This is at odds with the Hoang et. al (1987) interpretation of the cool Batz aquifer being "a range-front fault parallel with and hydrologically unconnected to the Malpais fault zone".

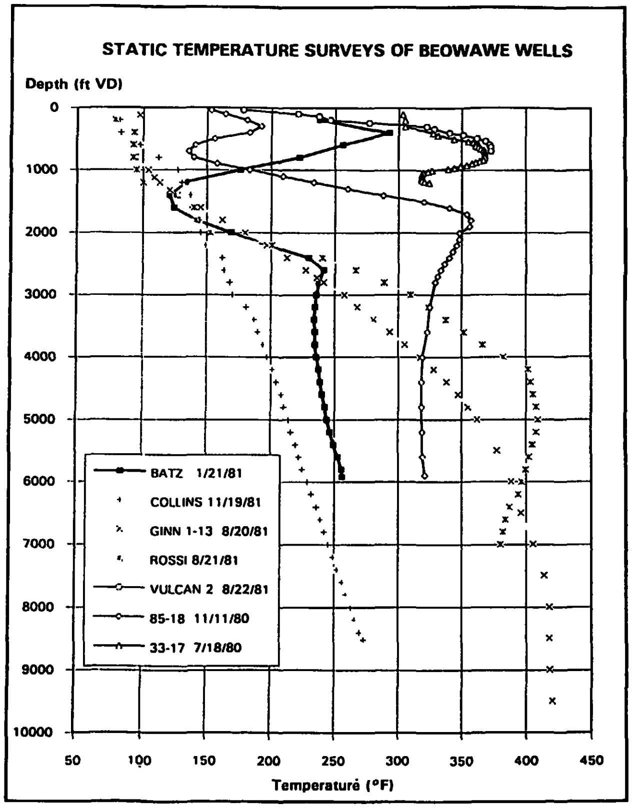

Figure 3. Static temperature surveys of Beowawe wells prior to start of production.

Surprisingly, the highest permeability in the Batz well is associated with the cool aquifer, which has a high reported kh of 850,000 md-ft. Perhaps the most important conceptual feature of the Batz well is that it alone has demonstrated the three dimensional proximity of hot and cold shallow aquifers at the eastern edge of the silica terrace.

INITIAL INJECTION STRATEGY

During extensive reservoir interference testing (Epperson, 1982, Hoang, et.al, 1987), Chevron determined that all wells, except the Batz and Ginn 2-13, had excellent pressure communication with all other wells. Recent interference testing by the Beowawe Geothermal Power Company has shown good communication between Ginn 1-13 and Ginn 2-13, thus further disproving the notion of separated permeable faults close to, and parallel with, the Malpais fault. As the Batz well was located furthest from the Ginn wells, had high permeability, and showed little or no hydrologic connection with the hot reservoir, it was understandably selected as the initial injector.

With benefit of hindsight, injection into the Batz well represents an attempt to inject outside of the geothermal reservoir. This is a rare instance where it has been feasible to inject large volumes of injectate close to, but outside of the reservoir from which it originated. This geology has often been desired during the development stages of geothermal projects and Beowawe offers a unique case history of potential results of such an injection strategy.

Major workovers, including perforating and acidizing, were required to prepare the Batz well for injection. Testing has repeatedly demonstrated that the injectate exited the Batz well at depths near 1,500' into the cold aquifer. Unfortunately, no other wells in the terrace area were drilled either far enough to the east and deep enough to penetrate this cool aquifer and serve as potential monitoring sources of the injection program.

The Batz well has been capable of accepting about 3,200 gpm from the power plant on a sustained basis, but this requires injection pump pressures near 500 psi at the power plant. A two-mile long 10" diameter line connects the Batz well to the power plant.

CHEMISTRY

Chemical sampling of deep and shallow production wells as well as the thermal springs at Beowawe, showed the geothermal fluid to be quite homogeneous prior to production (Table 1), with the exception of a few small low chloride, acidic springs high on the terrace (White, 1992). Initial(1985)water samples from the deep Ginn wells were enriched in carbonate relative to waters in the terrace area (Fig. 4). This presumably represents boiling and degassing of the water at shallow depths prior to sampling. This is a logical confirmation of the excellent pressure communication demonstrated throughout the reservoir. The overall chemistry of the brine at Beowawe is a sodium bicarbonate water which is exceptionally dilute for its 415 to 420 °F initial temperature.

TABLE 1
BEOWAWE AREA WATER CHEMISTRY

THERMAL WATERS

Source	Date	Sample Depth	Sample Type	Na	K	Ca	Mg	Si	B	Li	Cl	SO_4	HCO_3	CO_3	F	pH	TDS	Sample Temperature ° F.
Hot Spring	1973			230	16	1.0	<.1	320	2.1	1.3	69	130	321	32	17	8.98	1,139	208
33-17	1981	500′	Bailed	240	20	3.0	0.4	450	1.3	1.45	60	125	280	<2			1,183	±340
85-18	1981	1600′	Bailed	220	40	2.5	.04				55	80	280				677	±330
Ginn 1-13	1985	±9500′	Pre-Flash	197	27	.4	.42	417	1.5	1.25	37	69	253	57	11.4	9.78	1,072	±420
Ginn 2-13	1985	±6700′	Pre-Flash	197	26	.4	0	404	1.6	1.21	39	76	233	63	11.3	9.84	1,052	±420
Injectate	1986		Flashed	245	33	.6	0	528	2.0	1.6	62	94	338	89	14.0	9.57	1,407	±220
Ginn 1-13	1987	±9500′	Pre-Flash	175	22	.5	0	374	1.1	.95	47	69	151	71	11.0	9.66	922	±405
Ginn 2-13	1987	±6700	Pre-Flash	174	21	.4	0	338	1.1	.95	43	71	162	68	10.0	9.67	889	±410
85-18	1988	1700′	Bailed	141	10	10.4	1.6	144	0.7	0.6	59	54	243		7.1	8.0	671	240
85-18	1992	600′	Bailed	112	10.8	8.6	0.5	98	0.5	0.5	42	55	190	0	4.8	7.7	522	±150?
Injectate	1992		Flashed	218	26	1.0	0	359	1.2	1.3	57	87	191	95	11.1	9.92	1,047	±220

BACKGROUND WATERS

Source	Date	Sample Depth	Sample Type	Na	K	Ca	Mg	Si	B	Li	Cl	SO_4	HCO_3	CO_3	F	pH	TDS	Sample Temperature ° F.
31N,48E,4		Shallow	USGS HOLE AH4A	46	12	36	9.3	63	.14	.04	39	38	170		1.0		326	61
31N,48E,5		Shallow	USGS HOLE DH5B	40	9.7	38	9.7	57	.14	.04	33	35	180		1.1		310	61
31N,47E,12		Shallow	USGS HOLE DH16A	46	7.3	31	10	61	.16	.06	32	34	180		1.3		311	50
31N,47E,26		Shallow	STOCK WELL	37	17	35	11	62	.10	.02	49	43	120		.6		303	64
31N,48E,32		Shallow	STOCK WELL	29	6.6	33	7.5	60	.08	.02	21	23	150		1		255	61
31N,47E,16		Shallow	COLD SPRING	38	3.7	61	20	50	.15	.02	64	51	200		.4		386	54
31N,48E,7		Shallow	DRI WELL B-5	40	10.8	36	7.2	89	.18	.03	28	38	161		.7		420	79
31N,48E,7		Shallow	DRI-WELL B-6	47	9.5	34	8.4	72	.32	.03	33	42	165		.8		415	57
Batz	1985	1500′	Bailed	45	12	37	9	101	<.12	.09	64	32	142		4.0	7.1	378	±125

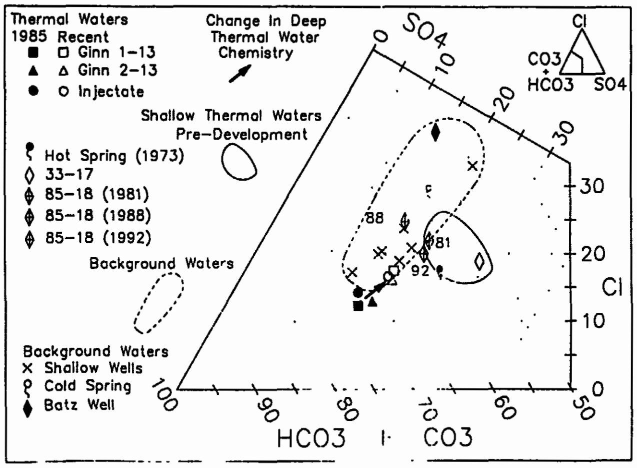

Figure 4. Anion trilinear diagram of Beowawe area water chemistry.

Sampling of shallow cool sources of water in Whirlwind Valley, within a few of miles of the Ginn wells by Iovenitti (1980) and Olmsted and Rush (1987), revealed a fairly homogenous cold dilute bicarbonate groundwater water (Table 1) with a tendency to be slightly enriched in chloride and sulfate relative to the geothermal fluid (Fig 4). The similarity of groundwater to geothermal water in regard to anion ratios is remarkable. Minor element variations and salinity differences are the most obvious way of differentiating the two water populations. Near the terrace there is a localized shallow mixing of the thermal and cold meteoric waters.

Sampling of the cool aquifer penetrated by the Batz well in March 1985, prior to injection, showed a similar dilute groundwater chemistry to be present, albeit, at significantly greater depths than the other available groundwater samples. Differences between the Batz aquifer chemistry and shallow groundwater, in terms of silica, fluoride, and possibly chloride (Table 1), can be explained by the facts that the Batz water was collected from a far greater depth and is hotter than the near-surface waters. Due to its proximity to the shallow thermal aquifer, fluid from the Batz well may contain a component of geothermal fluid. This chemistry is an independent line of evidence that the Batz injection interval is, for practical purposes, outside the geothermal reservoir.

Unfortunately, the stable isotope data base at Beowawe is inadequate to further enhance or restrict any interpretations. No quality analyses were obtained from the Ginn wells prior to 1987 so initial isotopic ratios from the deep and unboiled portion of the reservoir are uncertain. Since 1987 the deuterium data from the deep wells have an inordinate amount of scatter, in part possibly resulting from a variety of labs. The oxygen data show no measurable change since 1987 which is in line with the remainder of the chemistry.

SUMMARY OF THE INITIAL STATE OF THE BEOWAWE RESERVOIR

Prior to production, Whirlwind Valley contained two fluid flow systems: a geothermal system and a much cooler groundwater system which showed only limited amounts of localized shallow mixing near the silica terrace. These concepts are shown on Figure 5, an initial state model of the Beowawe geothermal area. At the eastern end of the silica terrace, the two flow systems were present within several hundred feet of each other and mingled to a minor extent. Hot fluid rose from the southwest along the Malpais fault toward the terrace and a much larger amount of cold meteoric fluid flowed down from the upper portions of Whirlwind Valley in an easterly direction.

POST-PRODUCTION CHANGES TO THE GEOTHERMAL SYSTEM

Within two years of the start of production and injection, major hydrologic changes were obvious both on the surface and underground. On the surface, the thermal activity greatly decreased within a year or two in a manner similar to that described by White (1992) when the first wells were flowed in 1959. Repeated leveling surveys have shown a maximum subsidence of 0.41' between 1985 and 1993 centered near well 85-18. Subsidence is confined to the terrace area.

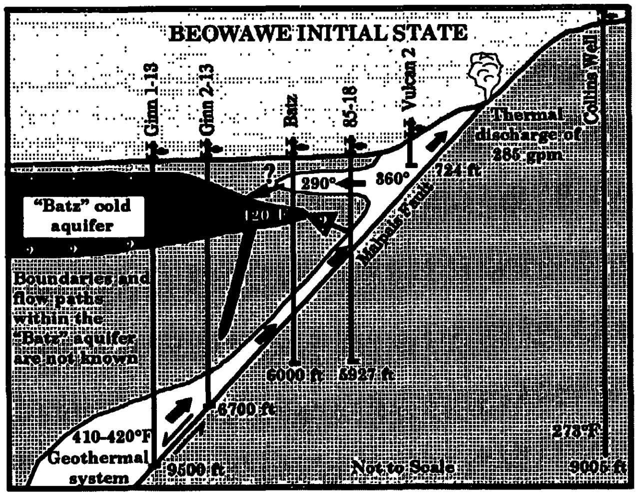

Figure 5. Conceptual model of the initial state of the Beowawe geothermal reservoir.

Since 1986 pressures in Vulcan 2, a 720' deep well located on the top of the terrace, have declined by 175 psi (Fig. 6) which equates to a water level drop of about 415'. This is in spite of up to 3200 gal/min being injected 1500' beneath the eastern portion of the terrace. Clearly, injectate is not easily moving from the cool Batz aquifer into the shallow thermal aquifer or the Malpais Fault Zone near the terrace.

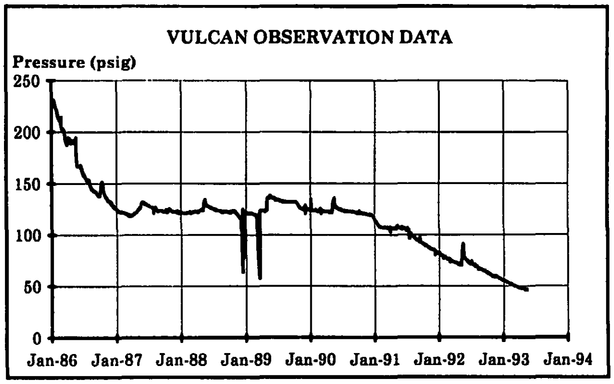

Figure 6. Graph of downhole pressure versus time in the Vulcan 2 observation well.

Beneath the terrace area, maximum static temperatures declined from as high as 360 or 370 °F to as low as 150 to 200 °F (Fig. 7). Currently, temperatures in the shallow thermal aquifer are lower than the 215 °F injectate temperature and therefore must result from an invasion of cooler groundwater.

Downhole samples collected from well 85-18 in 1981 (prior to production), 1988, and 1992 (Table 1) show a major, and increasing, component of meteoric water is now present and a few gallons per minute of cool water could be heard flowing into the wellbore through damaged casing in early 1992.

The deep production wells have also cooled. Ginn 2-13, the shallowest and easternmost well has cooled from as much as 415 or 420 °F to 384 °F between 1986 and 1992, a drop of about 40 °F (Fig. 8). Flowing and static temperature logs from Ginn 2-13 obtained during 1992 have shown that there are now two major fluid entries into the well with temperature differences of perhaps 30 °F between them. It is believed that the cooler feed is connected to the Batz cold aquifer, and is the primary cause of the well's temperature decline. Ginn 1-13 cooled from 410 or 420 °F to below 400 °F by mid 1991.

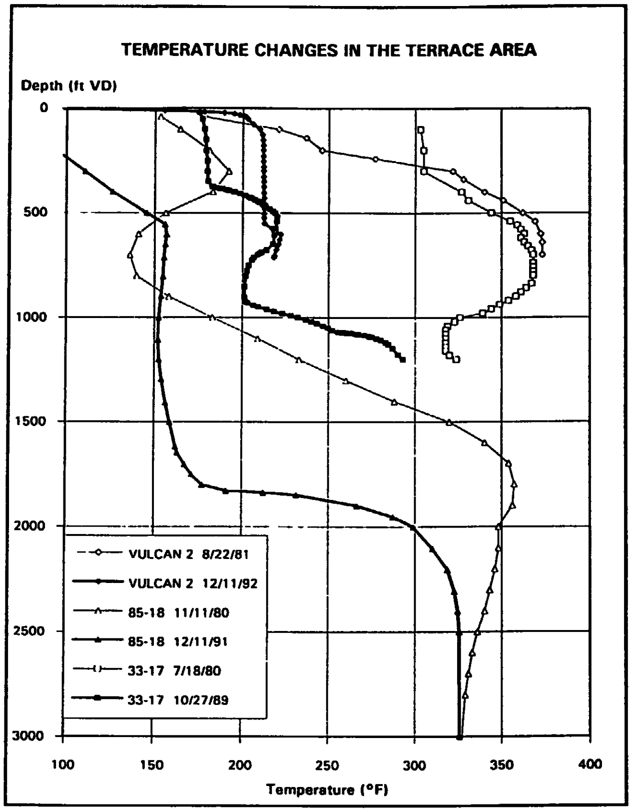

Figure 7. Temperature changes beneath the Beowawe terrace area at shallow depths.

Interestingly, both flowing and static downhole pressures in both Ginn wells have increased while the temperatures have cooled (Fig. 8). To compliment this, flash point depths in the Ginn wells have risen over time. This is in spite of the fact that about 4000 gpm is being removed from this portion of the reservoir. A likely explanation for this is the increased density of cooler water now entering the reservoir.

In addition to the cooling, the chemistry in Ginn 1-13 and 2-13 showed a significant and sharp decline in salinity and carbon dioxide (Fig. 9) during 1986 and 1987. Since late 1987, the chemistry of the production wells has remained quite constant, but the temperature decline has continued. There has been no indication of increasing salinity of the produced fluid as has occurred at nearby Dixie Valley where injectate is being recycled in significant quantities (Benoit, 1992).

The anion ratios of the deep production fluid have shown modest enrichment in both chloride and sulfate (Fig. 4). The detailed direction of the trend is between that of the shallow thermal water and the meteoric background water, which suggests the deep production fluid now contains a component of both shallow fluids.

The shallow terrace area and deeper production wells seem to be impacted by the same thermal and chemical trends.

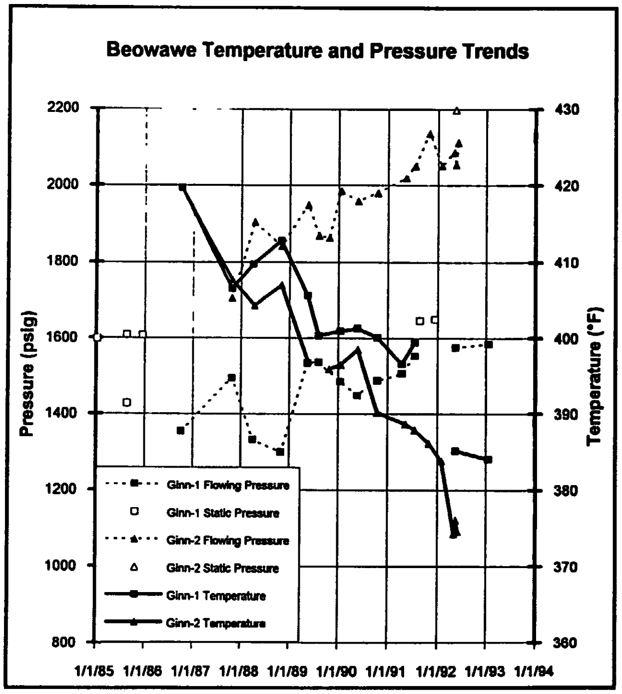

Figure 8. Temperature and pressure changes versus time for the Ginn 1-13 and 2-13 production wells.

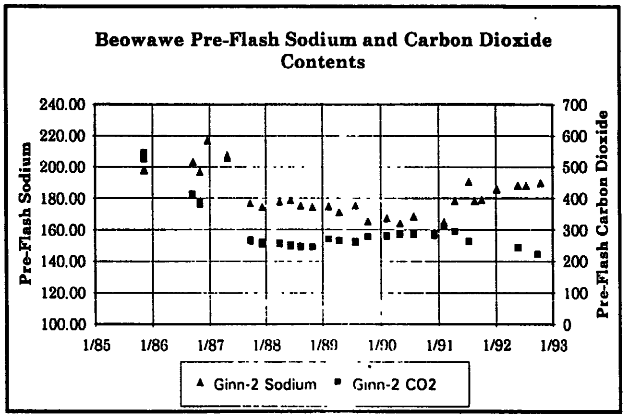

Figure 9. Concentration of sodium and carbon dioxide in the pre-flash fluid at Beowawe versus time.

As the terrace area has suffered by far the greater impact in a shorter time, it is logical to suspect that the process is working its way down, with time, through the Malpais fault zone.

TRACER TEST

In 1990, fluorescein was injected into the Batz well. Fluorescein returned to both Ginn wells and conclusively proved some communication between the Batz and the Ginn wells. First returns to Ginn 2-13 moved at a minimum velocity of 26.8 ft/hr during 14 days. It took another six days for the tracer to travel the minimum 3,200' to Ginn 1-13 at a minimum velocity of 22.2 ft/hr. Peak return times were 99 days for Ginn 2-13, and 115 days for Ginn 1-13, giving a fairly flat return curve. About 8% of the tracer was recovered.

A fraction of the injectate is returning to the production wells, but it is apparently masked, in terms of its higher salinity, by a larger component of more dilute meteoric water.

POST-PRODUCTION MODEL

A current conceptual model of the reservoir (Fig. 10) shows an invasion of cold meteoric water into the shallow and deeper portions of the Beowawe geothermal reservoir. For practical purposes, the shallow thermal aquifer beneath the terrace has ceased to exist and there is no flow of liquid water onto the surface.

Pressures in the Beowawe reservoir have dropped to the point that cool groundwater is able to enter the shallow thermal aquifer and migrate deeper into the reservoir. After one year of production Hoang, et. al, (1987) reported no pressure depletion and interpreted this to mean the reservoir was capable of producing 200 MW. In light of more recent data, the lack of pressure depletion now appears to represent an ominous invasion of cold water into the reservoir and not a constant pressure boundary and its associated infinite reservoir.

The tracer test suggests a better connection between the Batz aquifer now than could be detected through interference testing in the early 1980's. This is shown on Figure 10 as a fairly direct connection between the Batz cold aquifer and the lower part of Ginn 2-13 where abnormally cold entries were verified by detailed temperature logging in 1992.

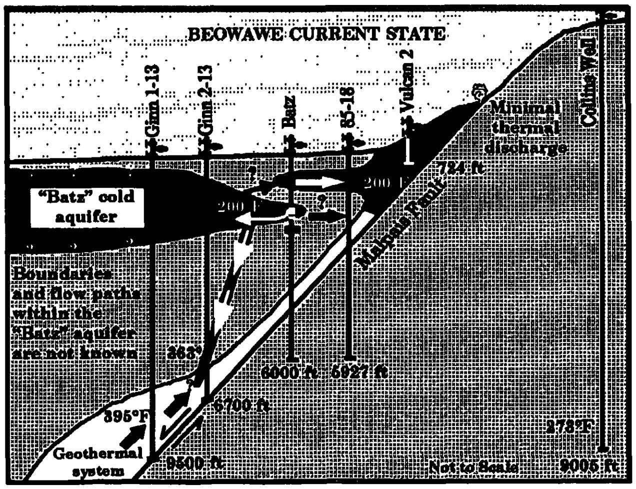

Figure 10. Conceptual model of the current state of the Beowawe geothermal reservoir.

THE FUTURE

Additional cooling of the three existing production wells will result in a plant output below the design rating of 16.7 MW. Options available for maintaining plant output in the future are drilling additional production wells, reducing fluid and megawatt output, pumping the existing wells, and/or modifying the injection program to return injectate to the reservoir.

Drilling additional hotter wells some distance from the power plant will be very costly, but can result in a near-term turnaround in the production temperature and has the advantage of resulting in a lower fluid removal rate (due to higher steam fractions) from the reservoir. However, over the long-term this may actually be a temporary solution and involves stepout drilling risk. Reducing plant output is not a desirable course of action. Pumping the wells can also be viewed as a temporary fix if the cooling trend continues and results in higher fluid removal rates which might further exacerbate the inflow of cold water.

The last option of modifying the injection strategy has the objective of removing injection from the cool aquifer interpreted to be responsible for the influx of cool water into the reservoir, and instead injecting into the shallow Malpais fault zone near the terrace. This is expected to increase the temperature of recharge fluid moving down the Malpais fault zone, while simultaneously reducing the recharge from the Batz cold aquifer.

This is perhaps the least costly option, but is likely to be the slowest course of action in having an impact on the cooling trend. The least costly choice within this option is to shift injection to existing well 85-18. Well 85-18 has very high permeability, and appears ideally located near the intersection of the shallow Malpais fault zone and the shallow thermal aquifer and is in excellent pressure communication with both features. It is recognized that the cooling took a period of years to be detected and it may take a period of years to detect and confirm positive changes. The redistribution of pressure and consequent changes in recharge to the reservoir should take place quickly, however, and this offers some hope for a relatively quick improvement to the temperature declines in the production wells.

CONCLUSIONS

Placement of up to 3,200 gpm of injectate, largely outside the geothermal reservoir at Beowawe, appears to have locally lowered pressures in the reservoir and increased pressures in a nearby cold aquifer to the point that cold meteoric water is entering the reservoir in quantities sufficient to result in a major cooling of the production wells. To attempt to reverse this cooling trend, well 85-18 will be reworked and placed in service as an injector to attempt to increase the pressure of the shallow reservoir to the point that the entry of cold, meteoric water is either reduced or eliminated.

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