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FLOW AND PERMEABILITY STRUCTURE OF THE BEOWAWE, NEVADA HYDROTHERMAL SYSTEM

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ABSTRACT

A review of past geologic, geochemical, hydrological, pressure transient, and reservoir engineering studies of Beowawe suggests a different picture of the reservoir than previously presented. The Beowawe hydrothermal contains buoyant thermal fluid dynamically balanced with overlying cold water, as shown by repeated temperature surveys and well test results. Thermal fluid upwells from the west of the currently developed reservoir at the intersection of the Malpais Fault and an older structural feature associated with mid-Miocene rifting. **A** tongue of thermal fluid rises to the east up the high permeability Malpais Fault, discharges at the Geysers area, and is in intimate contact with overlying cooler water. The permeability structure is closely related to the structural setting, with the permeability of the shallow hydrothermal system ranging from 500 to 1,000 D-ft, while the deeper system ranges from 200 to 400 D-ft.

INTRODUCTION

The Beowawe geothermal field has been on production since 1986 supplying steam for a 16.7 MW (gross) power plant. During this time, the temperature of the produced fluid has experienced a decline from 420°F to approximately 360°F. Several causes of cooling may be present and include: injection (thermal) breakthrough, influx of cooler meteoric water in response to reservoir pressure decline, widespread boiling in the shallow thermal system, and temperature stratification in a high permeability fault system. **A** determination of the cause(s) will rely on an understanding of the flow and permeability structure of the Beowawe hydrothermal system.

The INEL and the operator are cooperatively developing a reservoir simulation model of the Beowawe hydrothermal system to investigate the likely cause(s) of the reservoir temperature decline. Insight learned from this study may have practical utility to other Basin and Range geothermal reservoirs experiencing similar cooling.

STRUCTURE

A number of models have been put forth to define structural controls for fluid migration within the Beowawe geothermal system. Faulting initiated in the Beowawe region during the Miocene with Basin and Range extension and continues with current motion. **A** Miocene rift system passes through the Beowawe area establishing an older structural grain oriented N15-25°W. Modern accommodation of Basin and Range extensions has resulted in motion on the younger Malpais Fault zone (MFZ), a major feature of the Beowawe hydrothermal system, oriented N50-70°E. The summaries provided by Zoback (1978, 1979) provide a good overview of the changes of regional stresses and the development of fault systems. The current stress regime of '' E-trending faults produces dip-slip movement. Faults trending NNW to NW exhibit right-lateral components of slip while **NE**- to ENE- trending faults exhibit left-lateral components of slip. Left-lateral motion may create dilatent zones along Malpais Fault segments which deviate from N50-70°E. These open regions in the hanging wall can provide one of the components (permeability) required for a hydrothermal system to develop, see Figure 1.

Benoit (1995) has commented on the marked similarity between the structure of the Malpais Fault and forced folding. Layman (1984) noted that the Malpais Fault could be described as a simple Basin and Range feature with a dip of 65 to 70°. The apparent simplicity of the deep Malpais Fault is masked however by the structural complexity of the shallow geology.

The significance of cross-faults within the terrace area as conduits or as barriers to fluid flow has been the subject of considerable speculation. These faults are of minor displacement and almost certainly do not carry to any depth. The origin of these faults appears to lie in accommodation of shallow stresses associated with changes in direction of the Malpais Fault. While these features affect fluid **flow** at shallow depths, none of these features have been demonstrated to extend to depth as a definable drilling target or to influence fluid flow within the Malpais proper.

In summary, two structural sets are present at Beowawe, one older set oriented N15-25°W associated with rifting and a younger structural set associated with the Malpais Fault oriented N50-70°E. Where the Malpais Fault deviates from this trend, open regions are likely to develop in the hanging wall providing permeability. The Malpais Fault has an average dip of between 65° to 70° but may locally attain a higher dip. The width of this fault zone in terms of open permeability may also vary from negligible to hundreds of feet depending on the stress regime and lithologies present on opposite sides of the fault.

STRATIGRAPHY

The generalized stratigraphy consists of mid-Miocene volcanic rocks which uncomformably overlie Ordovician metasedimentary rocks. The thick section of volcanic rocks (maximum thickness of 3,700 ft) are locally overlain by a thin veneer of surficial alluvium, silcicous sinter, and playa deposits (Comstock, 1984).

Stratigraphy plays a minor role in the movement of thermal fluids. The chill zones in the thick volcanic sections and minor interbeds may host cold aquifers that are in contact with the MFZ. These aquifers supply cold water to the MFZ and play a larger role in the dynamic balance of thermal and cold fluids.

GEOCHEMISTRY

The geochemistry of the Beowawe system has suffered from several problems in interpretation during the exploration and development phase. The primary problem has been a persistent adherence to the requirement for carbonate source rocks for a reservoir host and the second has been the quality of the brine samples in early production and operation tests.

Source **Rocks**

The most persistent problem has been published statements attributing the ***gross*** character **of** the waters to a long residence within carbonate formations (Epperson, 1983; Layman, 1984). Carbonate rocks were considered to be a logical low-chloride source rock. With the nearest carbonate rocks at Beowawe being beneath the Robert's Mountain thrust at depths in excess of 20,000 ft, the reservoir source rock and the deep Beowawe reservoir found a home at **an** inaccessible drilling depth.

The origin of sodium bicarbonate-type waters includes a combination of softening in which calcium and magnesium is exchanged for sodium and by reduction in which sulfate present is reduced to sulfide. The likely origin for Beowawe reservoir water is within the thick shale and quartzite units such as the Valmy. Long residence time within such formations produces a low-chloride water due to lack of chloride in the formation. **A** low-calcium and magnesium water results due to softening reactions which precipitate and/or exchange these metals for sodium and a low sulfate water due to reduction of sulfate which is either precipitated as metal sulfides or remains present as dissolved hydrogen sulfide gas.

Water types and End-members

The water types present at Beowawe do not cover a wide range. Some of the contrasts were discussed by Benoit and Stock (1993). The few shallow waters sampled within the Whirlwind Valley are similar to thermal waters in terms of ratios of major anions. The cation ratios for shallow waters and thermal waters are dissimilar in terms of higher calcium and magnesium present in shallow waters. The main differences between the two water types is salinity with **TDS** averaging near 350 ppm in ground waters and near 1050 ppm in deep thermal waters. The main problem in identifying mixing trends of ground water with thermal waters in production fluids at Beowawe is the lack of specific tags for ground water showing up in the production waters. The best evidence for mixing is a decline in TDS associated with the lower salinity ground water.

HYDROLOGY

The Beowawe hydrothermal system is one component of the hydrology of Whirlwind Valley. An understanding of the hydrology of Whirlwind Valley and the Beowawe hydrothermal system is crucial to evaluating the interaction of the two. One of the hypothesized sources of cool water invading into the deep production zone is from a shallow meteoric source.

Regional Hydrology

The regional hydrology **of** the Whirlwind Valley, Reese River Valley, and Boulder Valley has been previously studied, with primary focus on the Whirlwind Valley (Shepherd Miller, Inc. and Baker Consultants, Inc., (SMI & BCI), 1995). This study relied on a database of over 100 wells, water level elevations, geochemistry, aquifer pump tests, local and regional stratigraphy and structural geology to develop a conceptual hydrologic model of the Whirlwind Valley. The conceptual hydrologic model envisions water flowing from the crest of the northern Shoshone Mountains through bedrock aquifers to lower elevations in the surrounding valleys and basins. Water flows eastward into the Whirlwind Valley in bedrock hydrostratigraphic units and discharges into alluvial aquifer units. As the water flows eastward through the Narrows, the water is unable to move laterally out of the confined aquifer and is discharged from bedrock units into the confined alluvial aquifer and leakage upward into the overlying unconfined alluvial aquifer. Water continues eastward into the eastern Whirlwind Valley sub-basin and discharges into the Humboldt River. The potentiometric surface of the Whirlwind Valley is presented in Figure **2.** It is extremely interesting to note a pronounced feature in the potentiometric surface oriented NNW and on trend with the abrupt change in direction of the MFZ in the Horse Heaven area. This feature was informally designated the Boundary Fault by SMI & BCI (1995). This feature may be the western boundary of the Miocene graben.

Water budgets for the Whirlwind Valley have been calculated by SMI & BCI (1995) and Olmstead and Rush (1987). **A** comparison of the two water budgets for the Whirlwind Valley is presented in Table 1. The two water budgets are similar except for estimates of the thermal contribution to recharge to the shallow hydrology of the Whirlwind Valley. Olmstead and Rush (1987) include a component of thermal recharge from the Beowawe geothermal system based on heat discharge considerations. They estimated the total convective heat discharge above a shallow heat flow of 250 mW/m^2 at 17 MW,. Assuming a deep source temperature of 444°F, they calculated a discharge rate from the thermal system of 18 kg/s (143 K lbm/hr). Approximately two-thirds leaks laterally into the shallow hydrologic system.

Table 1: Comparison of Whirlwind Valley Water Budgets

Source	Regions	Recharge (ft^3/day)	Discharge (ft^3/day)	Comments
SMI & BCI	Above 6000 ft	127,000		
	5000 to 6000 ft	111,000		
	4800 to 5000 ft	10,000		total 33,000 ft^3/day below 5000 ft
	4700 to 4800	23,000		
	Other Non-specific Lowlands	0		
	Phreatophyte Areas		232,000	independent of Olmstead & Rush (1987)
	Estimated Well Pumping		69,000	est. as 10% of permitted water rights
	Discharge to Humboldt River		22,000	
	Discharge to Boulder Valley		1,000	
	Total	**271,000**	**324,000**	**Variance 20%**
Olmstead & Rush (1987)	Above 7000 **ft**	29,026		
	6000 to 7000 ft	114,168		total 143,194 ft^3/day above 6000 ft
	5000 to 6000 ft	70,629		
	Below 5000 ft	0		
	Geothermal System	54,921		est. from heat discharge considerations
	Phreatophyte Areas		232,206	
	Total	**268,744**	**232,206**	**Variance 14%**

A synthesis of the two water budget estimates including the geothermal recharge of Olmstead and Rush (1987) into the SMI & BCI (1995) water budget is proposed. This change would result in recharge and discharge almost exactly in balance with a variance of 0.6%, implying that approximately 17% of the total recharge into the shallow hydrology of the Whirlwind Valley is due to thermal water. SMI & BCI (1995) explicitly assumed thermal recharge to the Whirlwind Valley was non-existent after 1986. This assumption is probably incorrect, due to injection into the Batz 1 outside of the geothermal reservoir. However, the hydrology of the Whirlwind Valley was disrupted by the relocation of thermal recharge (by injection). Disruption of the shallow thermal system at the Geysers area by exploitation created the potential for a reversal of shallow aquifer flow direction into the geothermal reservoir.

Thermal Hydrology

Prior to exploitation and disturbance of the Beowawe hydrothermal system, the presence of geysers in the sinter terrace area (White, 1992) was clear evidence that steam was being produced locally by the heating of ground water above its boiling point or boiling of reservoir fluid discharging to the shallow ground water.

Temperature surveys for wells Vulcan 1, Vulcan 2, Vulcan 3 approach a boiling point with depth behavior below depths from 50 to 330 ft. Maximum temperatures measured were 408-410°F at depths ranging from 590 to 660 ft (Oesterling, 1962). As the top sinter terrace is approximately 250 ft above the base of the valley, these wells clearly demonstrated boiling water was present at or very near the elevation of the adjacent valley floor. The early extended flow testing, bulldozing of thermal features by Magma Power in an effort to maximize well flow rates, and vandalism of wellheads disturbed the native state of the shallow Beowawe hydrothermal system several decades prior to the eventual installation of a geothermal power plant in 1986, (White, 1992).

Smith (1983) utilized temperature-depth profiles from 30 thermal gradient wells and concluded there was vertical and west to east movement of cold water above the thermal flow system, consistent with the shallow hydrology of the Whirlwind Valley. This information was further used to delineate zones of downward or upward fluid movement based on the character of the temperature with depth surveys. Abrupt inflections in temperature in regions of downward flow were interpreted to indicate the level where the buoyant thermal water maintains a dynamic equilibrium with the denser, overlying colder water, Figure 3. This delicate balance of rising thermal waters and overlying cold waters is a key feature in understanding the Beowawe hydrothermal system.

RESERVOIR ENGINEERING

An extensive set of pressure transient tests and temperature measurements have been made at Beowawe covering over 15 years of reservoir evaluation and exploitation. These tests have been used to identify regions of high and low permeability, quantify well production characteristics, develop wellhead performance curves, and estimate the reservoir volume. Epperson (1982, 1983, 1984) and Hoang et al. (1987) have reported the results of a series of pressure transient, interference, and reservoir limits tests. The information is summarized in Table 2 and discussed below.

1980 Test Program

Epperson (1982) presented the results of a series of pressure transient tests conducted in 1980. These tests showed the ***kh*** **at** Beowawe ranged from 200 to 800 D-ft. It was noted that interference response times were less than one hour irrespective of the distances between the wells, diagnostic of a high permeability, low volume system.

1981 Test Program

Additional flow tests were conducted on wells 33-17, 85-18, and Vulcan 2 during January through March, 1981, (Davenport, 1981). Pressures were recorded in these three wells at various times during the test program. Two flow tests were conducted on well 33-17, located on the sinter terrace. A continual decline in James Tube stagnation enthalpy was observed during both flow tests. The stagnation enthalpy ranged from a high of 294 BTU/lbm to 253 BTU/lbm, for a change in temperature of 40°F (324°F to 284°F). The cooling was attributed to an influx of cooler waters down the Malpais Fault into the production zone. In retrospect, this was an early indication of the dramatic potential for production induced cooling demonstrating the sensitivity of the dynamic balance between buoyant thermal water and overlying cooler, dense water. The large interference storativity is suggestive of boiling occurring during the test program. The apparent compressibility of boiling water is very large and results in a large storativity for regions investigated by pressure transient testing.

Epperson (1984) conducted a flow test program on wells 85-18, Ginn 1-13 and Rossi 21-19 (lower interval) in December 1981. This testing program was conducted to confirm aspects of the January through

March, 1980 program. The inactive wells were used as observation wells for the flowing well. This testing program clearly demonstrated that the Rossi well was in excellent pressure communication with the deeper Ginn 1-13 and the shallow 85-18. Hoang et al. (1987) state the reservoir around the Rossi well is a region of low permeability because the well was unable to flow upon testing. It is more likely the Rossi well is in excellent communication with overlying cold water and the well was never able to flow unassisted.

September 1985 Ginn 1-13 & Ginn 2-13 Flow Tests

Production well Ginn 1-13 was recompleted by pulling a 7 in liner out at +/- 2000 ft and replacing with a 9-5/8 in liner. New production well Ginn 2-13 was drilled as an offset to Ginn 1-13 and completed September 1985. Ginn 2-13 achieved a flowrate of 520 K lbm/hr at a FWHP of 89 psig. The kh from the pressure buildup was 345 D-ft and a skin of +118. The high wellbore skin was attributed to drilling mud damage despite the observation of rapid pressure recovery in the wellbore (Hoang, 1985). Radial flow analysis was used to define a large wellbore skin; a finite conductivity fracture analysis would likely result in a skin factor in agreement with the observed rapid pressure recovery in the wellbore.

March 1987 Batz 1 Fall-off and Interference Test

The reservoir pressure response around the Batz well has been poorly understood since the start of testing at Beowawe. The well was completed in the interval from 1443-1693 ft in December 1981, an interval corresponding to the coldest portion of the temperature survey. An injection fall-off test was performed on the Batz 1 well March 17-19 (Smith, 1987) to quantify the current reservoir properties around this well and to check for pressure interference with three observation wells, Rossi 21-19, 85-18, and Vulcan 2. The Batz 1 was shut-in March 17 and injection was resumed March 19, for approximately 52 hour shut-in period. The power plant maintained full operations and injection fluid was surface discharged for the duration of the testing program. The only pressure transient introduced in the reservoir would be associated with the Batz 1 well and the cessation of injection for the test duration. One of the more intriguing aspects of this testing program was the clear interference response to Batz 1 in wells Vulcan 2 and 85-18. The interference response in these two wells clearly shows that the Batz well is in excellent pressure communication with wells in the sinter terrace but not to the Rossi well. Note the very good agreement for both the interference conductivity and storativity. No interference was noted in the Rossi 21-19 well. The large storativity is again diagnostic of boiling and a two-phase region. This testing program was the first to clearly document that Batz 1 was in pressure communication with the wells in the shallow terrace area. The lack of response in the Rossi which is in good pressure communication with Ginn 1-13 confirmed poor communication from Batz 1 with the deep Malpais feed zone. Repeated acid stimulations have been performed to remove the calculated high skin factor, without success. The high skin factor and the lack of success in removal is an artifact of an inappropriate flow model for pressure transient analysis.

May 1988 Plant Shut-Down Monitoring Program

An extensive pressure monitoring and temperature/pressure survey was conducted in May 1988, when the power plant was shut-down for inspection and maintenance. This extended shut-down was used as an opportunity to collect a large amount of pressure transient information (Smith, 1988). A build-up test was conducted on Ginn 2-13, an injection fall-off on Batz 1, and interference monitoring was conducted in wells Beowawe 85-18, Vulcan 2, and Rossi 21-19. Perhaps the most interesting item in this analysis is the very consistent interference kh between the two production wells and 85-18 and Vulcan 2. The interference storativity has increased by approximately an order of magnitude since the 1981 test program. This increase is due to the initiation of boiling and the development of a vapor region in the shallower portions of the reservoir. As the compressibility of a boiling water is very high, even a small region of boiling can exhibit a large interference storativity. All of the wells exhibited a rapid increase in pressure at late times in excess of a line source solution. Two explanations are offered: 1. the impact of well testing in a bounded system with, 2. a constant pressure boundary, such as fluid recharge, acting on the developed reservoir.

May 1989 Plant Shut-Down Monitoring Program

One year later a similar pressure monitoring program was conducted to further investigate the pressure response of the reservoir and quantify pressure interference between the two Ginn wells (Smith, 1989). The reservoir pressure, based in direct measurements and extrapolated infinite shut-in pressure, p^*, indicated about a 100 psi decline in deep reservoir pressure from the start of production operations in 1985. Reservoir pressures from 1988 to 1989 had appeared to stabilized. This test program noted that the pressure build-up response in Ginn 2-13 began to decline after 10 hours into the build-up. This was attributed to a temperature decline in the well and in retrospect, the first indication of cold water intrusion into Ginn 2-13.

This behavior was not noted in the prior year's testing program. **A** comparison of p^* for Ginn **2-**13 for the 1985, 1988, and 1989 test programs indicate a 102 psi decline in pressure from 1985 to 1988, but a **22** psi increase in pressure from 1988 to 1989 again suggestive of cooling temperature in the fluid column above the well.

Table 2:Summary of Beowawe Pressure Transient Testing

Well	Analysis Method	kh ,D-fi	$\phi c_t h$,ft/psi	Comments
33-17	semi-log build-up	800		1980 Test Program
85-18	semi-log build-up	550		
Vulcan 2	semi-log build-up	780		
33-17	interference from 85-18	190	7.75E-4	March 1981 Test Program
Vulcan 2	interference from 85-18	233	2.50E-3	
85-18	interference from Ginn 1-13	446	3.55E-5	December 1981 Test Program
Rossi 21-19	interference from Ginn 1-13	423	6.69E-5	
Rossi 21-19	interference from 85-18	443	2.76E-5	
Ginn 1-13	interference from 85-18	128	1.23E-6	
Ginn 2-13	semi-log build-up	345 skin =+118		September 1985 Test Program
Vulcan 2	interference from Batz 1	1,086	3.2E-2	March 1987 Test Program
85-18	interference from Batz 1	700	3.5E-2	
Batzl	semi-log fall-off	435 skin = +18.2		
Ginn 2-13	semi-log, build-up	232 skin =+48.6		May 1988 Test Program
Batz 1	semi-log, fall-off	531 skin =+37.1		
85-18	interference from Ginn 2-13	297	1.845E-4	
85-18	interference from Ginn 1-13	294	1.048E-4	
Vulcan 2	interference from Ginn 2-13	381	1.171E-4	
Vulcan 2	interference from Ginn 1-13	404	5.656E-5	
Ginn 2-13	semi-log build-up	320 skin =+52		May 1989 Test Program
Batz 1	semi-log fall-off	591 skin =+41		
85-18	interference to plant shut down	721	1.59E-4	
Vulcan 2	interference to plant shut down	558	1.08E-4	
Vulcan 2	interference to Ginn 2-13	617	1.34E-4	
Ginn 2-13	interference to Ginn 1-13	473	5.78E-5	

Sxploitation Response

The commercially exploited reservoir is of limited volume, suggested by tracer return data on the order of 57 million barrels (Rose et al., 1995). This volume s dramatically less than that inferred by Epperson 1982) from reservoir limits testing, of 10 to 100 bil-ion barrels. It is difficult to construct a plausible reservoir geometry and porosity to contain such a large volume in a simple fault model. Instead, the reservoir imits test was being influenced by fluid recharge into and along the **MFZ.** The estimated reservoir volume of Rose et al. (1995) would imply at typical field production and reinjection rates a recycling of the entire reservoir volume approximately every 800 days. This time approximately corresponds to the time period after the start of production when cooling was first letected. The tracer return data and start of first cooling all suggest a reservoir volume of a similar order of nagnitude. Injection was relocated from Batz 1 to 85-18 February 1994. Pressure response as measured in Vulcan 2 was immediate, with the reservoir pressure increasing over 125 psi over the next two years.

CONCEPTUAL MODEL

Benoit and Stock (1993) have presented a conceptual model of the Beowawe hydrothermal system in which the Whirlwind Valley contained two fluid flow systems, a geothermal system and a much cooler ground water system. These two fluid flow systems showed only limited amount of shallow mixing near the sinter terrace. Thermal fluids rose from the southwest along the Malpais fault toward the sinter terrace and a larger amount of cold meteoric water flowed toward the east in the Whirlwind Valley. This model is modified by the results of this study.

A liquid-dominated hydrothermal system requires the presence of several key interrelated features; a fluid recharge region, permeable pathways, a heat source, a commercial or exploitable reservoir, and a discharge region.

Fluid Recharge

The Valmy formation is proposed as a deep reservoir with sufficient storage for the dilute sodium bicarbonate water. The intersection of the MFZ and a **N-S** deep seated structural features in the Horse Heaven area is offered as a likely region of recharge into the MFZ. The Boundary Fault which expresses itself in the potentiometric surface is offered as the likely N-S structural feature.

Flow and Permeability Structure

Sufficient permeability exists from a deep-seated source of fluid to the Malpais Fault system to provide a conduit for upwelling of thermal fluids by a combination of thermal buoyancy and pressure support. Temperature mapping shows a northeasterly upwelling of hot fluid along the Malpais Fault. The Malpais Fault and associated fractures and splays provide a conduit and a minor reservoir volume of hot fluid. Permeability of the deep Malpais Fault to the east of the sinter terrace is limited and acts to divert the thermal fluid in the Malpais Fault zone to upwell in the sinter terrace area. Shallow subsurface and surface fluid discharge occurs at the Geysers area. Olmstead and Rush (1987) have estimated the age of the sinter terrace at about 500 ky, suggesting a relatively young system. Zoback (1979) noted there is abundant evidence of past hydrothermal activity along the Malpais fault. Four specific examples were discussed and the inference could be made that the hydrothermal system has migrated to the west with time.

The Beowawe hydrothermal system has very high permeabilities, with kh of **230** to over 1,000 D-ft. The permeability structure inferred fi-om pressure transient testing exhibits two distinct systems. The deep system along the MFZ has a kh of 200 to 400 D-ft. The kh of the shallow system **is** from 500 to over 1,000 D-ft **or** about twice the permeability **of** the deeper hydrothermal system. This observation is consistent with the structural complexity of the shallow hydrothermal system and the simple structural aspects of the deep Malpais fault.

Details of the permeability structure can be inferred from the 1987 Batz testing program. The longer interference response times and much higher storativities for the two observation wells demonstrates the development of a vapor region in response to exploitation. This demonstrated the Batz communicates primarily through the sinter terrace with wells Vulcan 2 and 85-18, which by 1987 had evolved to a vapor zone.

The pressure communication with Vulcan 2 is especially diagnostic. This well has been used for continuous pressure observation of the deep production zone for over 11 years and is in excellent pressure communication. Thus, even though the Batz is in excellent pressure communication with Vulcan 2, it is in poor communication with the deep production zone. Permeable pathways for the Batz must be dominately through the shallow sinter terrace (which had by 1987 evolved into a vapor region). This is further supported by the pressure response in Vulcan 2 associated with the reallocation of injection from the Batz 1 to 85-18. Reservoir pressure response, as measured by Vulcan 2, abruptly stopped declining and began to increase, (Rose et al., 1995).

Heat Source

The Beowawe system is located within the Battle Mountain heat flow high. (Sass et al., 1971). The background heat flow in the Beowawe area was estimated by Smith (1983) at 110 mW/m^2 based on the Collins well, within the values for the Battle Mountain heat flow high. Deeply circulating water in a region of high crustal heat flow is the likely mechanism for the collection and concentration of heat.

Commercial Reservoir

The rapid interference pressure transient response noted by Epperson (1983) is diagnostic of a high permeability, low storativity system. The reservoir fluid volume indicated from tracer testing is considered to be a much better estimate of the fluid volume in the fault. The combination of a very high permeability system, low storage, and limited reservoir volume are all very strong evidence confirming a fault-dominated conceptual model.

CONCLUSIONS

The Beowawe reservoir can be best described less as a typical reservoir and more as a narrow fault or breccia zone in the hanging wall of the MFZ. The MFZ provides a conduit for deep, upwelling thermal fluid at the intersection of the MFZ and an older rift feature in the Horse Heaven area. Thermal fluid flows at depth along the MFZ from west to east in a region with a ***kh*** of 200 to 400 D-ft. A deep permeability restriction is encountered in the MFZ beneath the eastern edge of the terrace causing thermal fluid to upwell and discharge at the Geysers area. The ***kh*** of the shallow system is from 500 to over 1,000 D-ft. The very high permeabilities in the shallow hydrothermal system are in excellent communication with shallow cold water. A dynamic equilibrium between buoyant thermal water and denser overlying cold water existing in the shallow thermal system and is present in the deeper MFZ. A schematic of the Beowawe flow and permeability structure is presented in Figure 4.

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Figure 1: Theoretical Open Regions

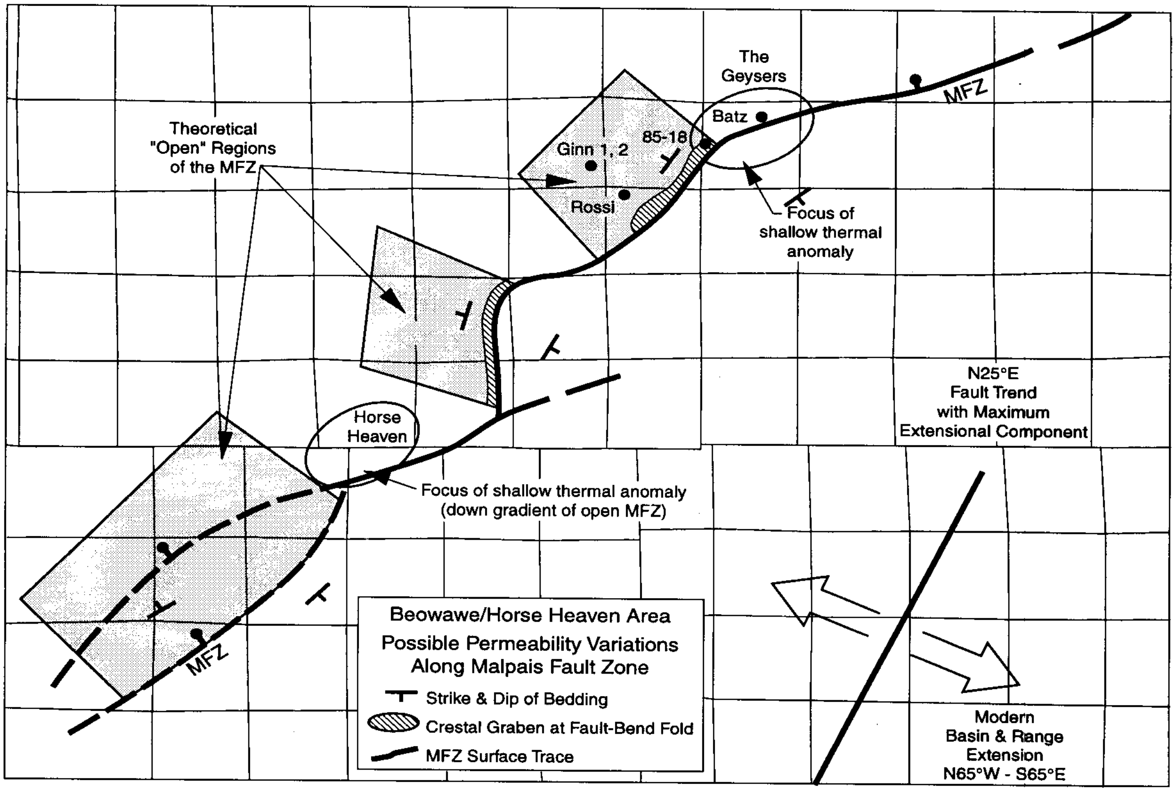

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Figure 2: Potentiometric Surface, modified from SMI & BCI, 1995

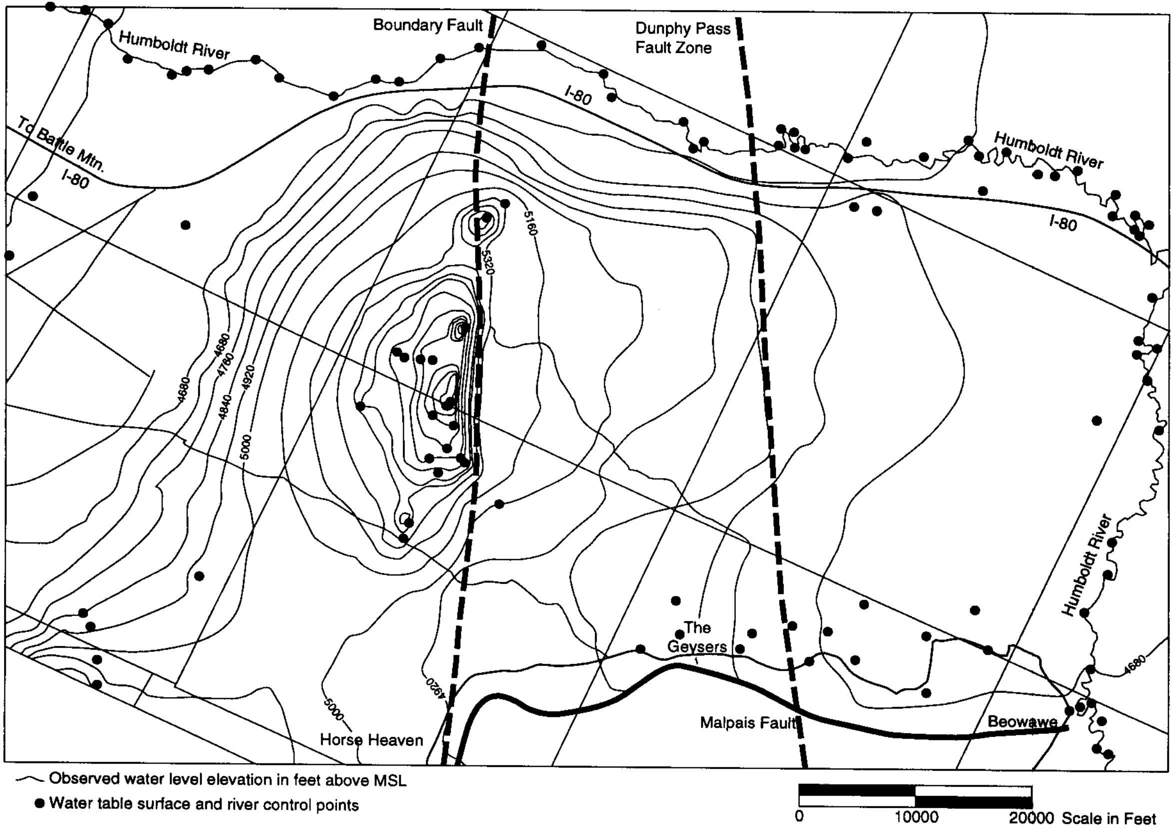

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Figure 3: Pre-Exploitation Temperature Surveys