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A SIMPLE BASIN AND RANGE FAULT MODEL FOR THE BEOWAWE GEOTHERMAL SYSTEM, NEVADA

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ABSTRACT

Data from wells as deep as 9,500 feet indicate that the Beowawe geothermal system can be described simply as an inclined thermal plume within the Malpais fault zone (MFZ). Though curved in plan view, this Basin and Range structure dips at a consistent 65-70° and does not flatten with depth. Productive MFZ intercepts in wellbores are typically interpreted at zones of abundant fluid loss or bit drops during drilling and stabilized temperature maxima. Deep 420°F waters within the MFZ rise obliquely from the southwest toward discharge in The Geysers area, where there is vigorous along-strike flow in the fault at shallow depths.

Permeability variations within the MFZ are shown by variations in permeability-thickness products measured in well tests. Regions of lower permeability in the MFZ seem to occur on the margins of the high-temperature plume, suggesting self-sealing and isolation of the plume from cooler portions of the fault. Permeable range-front faults, parallel with but apparently hydrologically unconnected to the MFZ, may be suitable injection sites. The producing area should ultimately expand downdip of the Ginn and 85-18 wells, and southwest of Ginn along the Malpais fault trend.

INTRODUCTION

The Beowawe geothermal field is located in north-central Nevada, about 50 miles southwest of the town of Elko. Active surface manifestations in "The Geysers" area (figure 1) cover one-half square mile, and include a large sinter terrace, geysers, fumaroles and hot springs. These occur at the base of the prominent ENE-trending scarp of the Malpais fault zone (MFZ). The geology of the region has been described by Zoback (1979) and in more detail by Struhsacker (1980) and Sibbett (1983). The ENE trend of the MFZ is atypical for Basin and Range normal faults in Nevada which typically strike NNE. This change in strike appears to be the result of "refraction" of younger Basin and Range structures across a pre-existing NNW-trending mid-Miocene rift (Zoback and Thompson, 1978). The Beowawe field is at the eastern margin of this structure, which is largely buried by Miocene volcanics generated during the rifting. Basement rocks are Paleozoic eugeosynclinal rocks which have been thrust eastward over a platform carbonate sequence of similar age. No wells have penetrated the carbonates, but the low salinity, sodium-bicarbonate nature of the Beowawe thermal waters (e.g., Sanders and Miles, 1974 and unpublished Chevron data) hints that these rocks are the ultimate deep reservoir.

Models proposed for hydrothermal flow in the Beowawe system are varied, but all involve the MFZ. Nolan and Anderson (1934) state that "...it seems probable that the thermal activity is in large part controlled by the recent (Malpais) fault..." Zoback (1979) reached a similar conclusion, regarding the "main range-front fault" at Beowawe, based on early well data and surface geology. Swift (1979) also implied that the MFZ is a hydrothermal conduit at Beowawe, and described permeability variations along the fault evidenced by geophysical and well data. Later geologic studies (Struhsacker, 1980; Struhsacker and Smith, 1980; and Sibbet, 1983) place greater emphasis on structures related to the mid-Miocene rift. All these studies propose a deep reservoir northeast of and feeding The Geysers, near the intersection of various NW-trending, rift-related faults with the MFZ. Smith (1983) mapped the elevation and temperature of a shallow thermal aquifer at Beowawe, and inferred thermal upwelling due west of The Geysers, along a hypothesized extension of the MFZ. Epperson (1983) does not present a detailed model for hydrothermal flow, but focusses on results of interference well tests conducted at Beowawe in 1981. These tests show that all Beowawe producing wells tap a common flow system of very high permeability.

This paper emphasizes drilling results to reiterate the importance of the MFZ, as defined below, as a primary hydrothermal conduit at Beowawe. Highlights of temperature, lithology, drilling history and flow test data are presented for all significant Beowawe wells. These well data, combined with fault locations from geologic mapping, are used to create a simple, predictive model to locate producing zones in the Beowawe field.

THE MALPAIS FAULT ZONE

The importance of the MFZ to the Beowawe geothermal system is indicated by the leakage at the base of the Malpais Rim and the three-dimensional distribution of productive fractures in Beowawe wells. Offsets in volcanic units between wells have shown range-front faults exist northwest of and parallel to the MFZ, but these are not significant hydrothermal conduits. The surface trace of the MFZ is interpreted here to closely follow the topographic break at the base of the Malpais Rim, and change strike abruptly from NE to ENE on the west edge of section 17 (figure 1). Though buried by talus and alluvium along most of its strike length, the MFZ visibly displaces older siliceous sinter deposits at The Geysers just south of the 33-17 well (Nolan and Anderson, 1934).

MFZ intercepts (Table I) are interpreted in four deep Beowawe wells (Ginn, Rossi, 85-18 and Magma-Batz), and in five shallower wells drilled high on the sinter terrace, adjacent to and including 33-17 (only 33-17 shown in figure I). Neither the Collins (Getty-DOE) deep well, drilled in the footwall block of the MFZ, or the SP-4 (Sierra Pacific) which was too shallow, penetrated the MFZ. Fault intercepts are interpreted from temperature profiles, drilling history and cuttings descriptions.

Because the MFZ appears to have some thickness and because of slight depth discrepancies between different fault "indicators," elevations listed in Table I are probably accurate to within about 50-100 feet. Some thickness to the MFZ is indicated by the width of isothermal intervals of temperature maxima and by the possible extension of fluid loss zones below the depth of initial loss. In some wells additional permeable zones may occur above or below the MFZ pick, but these are at lower temperature.

Table I

INTERPRETED MFZ INTERCEPTS IN BEOWAWE WELLS

Wells	MFZ Elevation (ft)	Evidence
Ginn	-4,600	A, B, C
Rossi	-350	A, B
85-18	+3,000	A, C
33-17 and nearby wells	+4,300 to + 4,500	A, C
Batz	+2,200	A, D

KEY: A = temperature maximum, B = bit drop, C = lost circulation, D = breccia zone, from cuttings

Geometry and Displacement

Though the surface trace of the MFZ is curved (figure I), above 9500' the dip of the fault does not appear to change significantly with depth. A series of cross-sections orthogonal to the MFZ and through well control (figures 2-5) connect the surface trace to interpreted MFZ intercepts in wells. The farther away from the surface trace of the MFZ a well is drilled (in the hangingwall block), the deeper is the interpreted fault intercept in the well. In A-A' (figure 2), a remarkably simple planar fault surface dipping about 65° can be constructed through MFZ intercepts in the Ginn and Rossi wells up to the surface trace. Sections through the 85-18, 33-17 and Batz wells (figures 3-5) reveal a similar planar fault geometry, though the dip of the MFZ may be slightly higher (about 70°) northeast of the prominent bend in the fault in section 17. Muffler (1964) measured orientations of slickensided fault surfaces exposed along a 10-mile stretch of Crescent fault, the major range-front normal fault along the base of the Cortez Range, 13 miles southeast of the Beowawe field. The average dip from six measurements on the fault at the surface is 64°, very close to the value interpreted to extend largely unchanged from surface to below 9,500' at Beowawe. If this model is correct, then the overall geometry of the MFZ can be described as having constant northwest dip of 65-70° with variable strike.

Vertical displacements along the MFZ are indicated by offset of Tertiary volcanic units between wells in the footwall and hangingwall blocks (figures 2-5). Away from the MFZ, the upthrown footwall block dips homoclinally to the SE. Adjacent to the MFZ, displacement estimates are complicated by monoclinal folding of beds, evidenced by northward dips in the

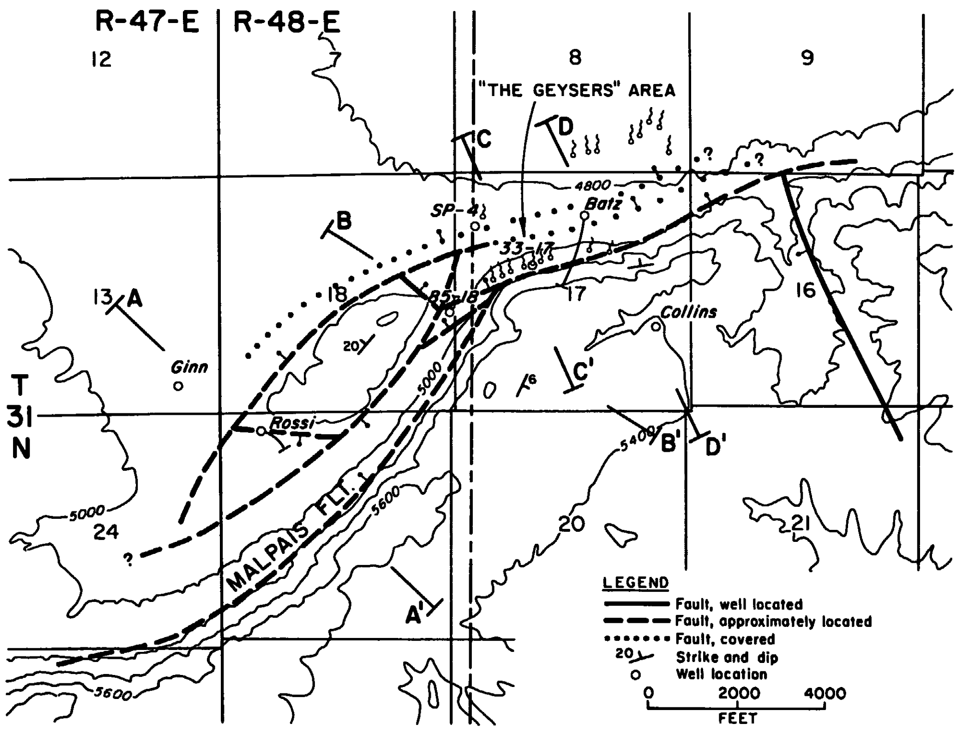
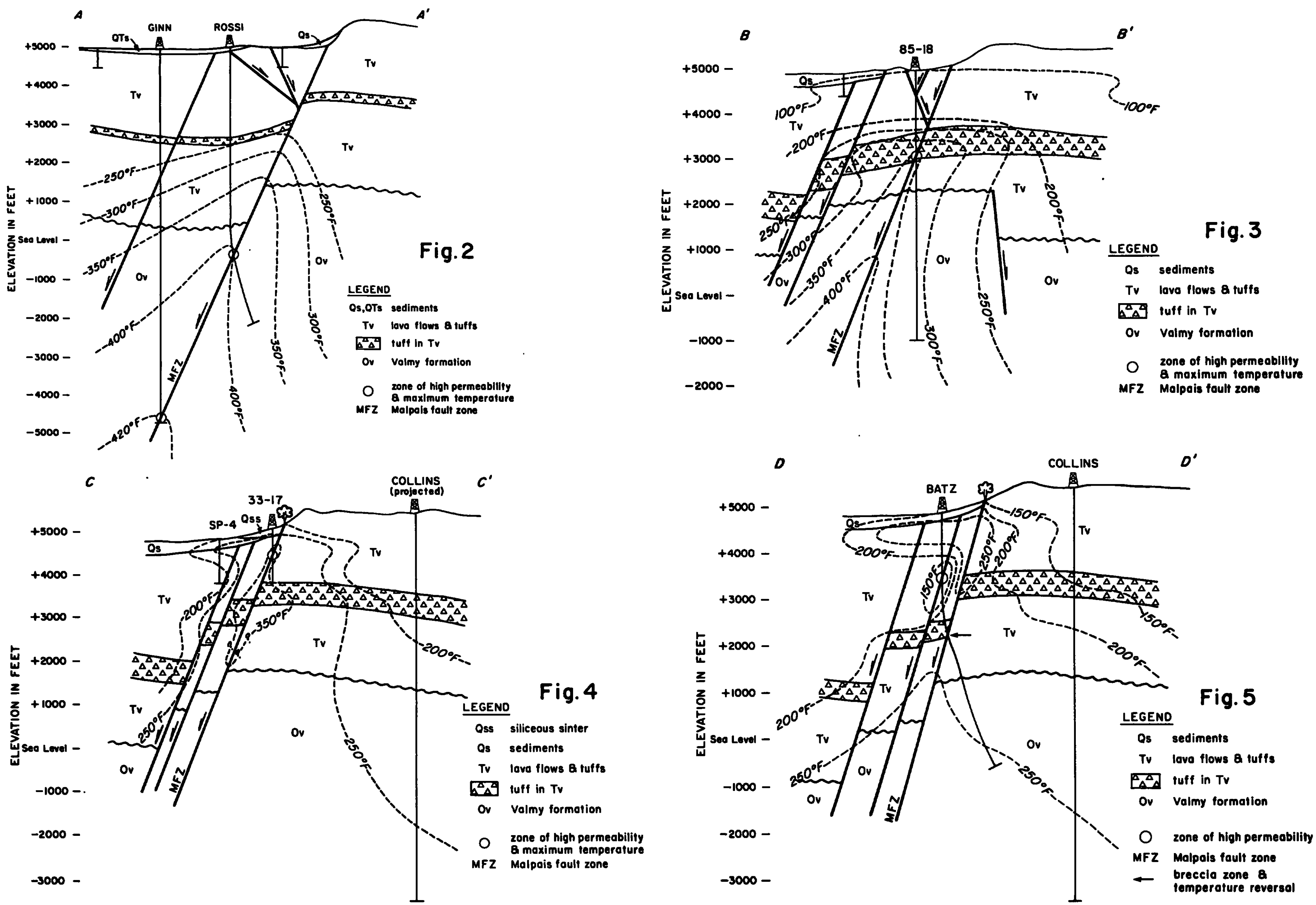


Figure I: Major structures in the Beowawe field



Figures 2-5 Beowawe Geologic and Temperature Cross-Sections

bedrock outcrop northwest of the Malpais Rim in section 18, and along the Malpais Rim in the NE ¼ of section 17 (figure 1). Displacements are very small (100') along the MFZ in section 18 (figure 2) because the isolated bedrock outcrop subsided less than the surrounding MFZ hangingwall block. The small graben separating the bedrock outcrop from the Malpais rim is of the "keystone-type" developed along the crest of the monocline. The graben dies out into a largely unfaulted fold below 2000' depth. MFZ displacements increase NE and SW of section 18 (figures 2, 4, 5) to the maximum estimated value of about 1,100' at the Batz well. There is no evidence that the productivity of the MFZ is correlated with the amount of displacement along the fault.

Temperature

Temperature contours superimposed on the geologic sections in figures 2-5 clearly show the importance of the MFZ in controlling hydrothermal flow at Beowawe. Of course, observed temperature maxima in wells were used in part to help pick the MFZ intercepts, but the coincidence of high temperature and permeability along this simple geologic structure is striking. The MFZ is relatively cool at the Batz well (240°F, figure 5), downdip of the 370°F measured at shallow depth in wells on the sinter terrace. This indicates lateral, eastward flow of thermal waters within the MFZ at shallow depths in The Geysers area. Lateral outflow of thermal waters away from the MFZ is also indicated by the temperature sections (figures 3-5). A shallow thermal aquifer occurs at about 4,500' elevation (described by Smith, 1983) and is fed from The Geysers area. Deeper outflow near The Geysers is interpreted in the tuffaceous unit of "Tv," based on a break in the temperature profile of the Collins well. However, neither of these outflows appears to to have sufficient permeability or a large enough high-temperature area to be commercially significant.

Mapping of temperatures in the MFZ shows how thermal fluids move along the fault (figure 6). Approximate elevation contours on the MFZ indicate the interpreted subsurface shape of the fault. Deep 420° waters near the Ginn well rise obliquely up the MFZ towards the northeast where, in NE ¼ section 18, there is a fairly abrupt, up-dip diversion of flow. Whether this diversion is related to the prominent bend in the MFZ is unclear. This upwelling feeds the surface discharge at The Geysers and the vigorous, shallow, along-strike flow within the MFZ, updip from where the fault is intersected by Batz.

Permeability

Variations in permeability within the MFZ can be inferred from the location of surface leakage, from geophysical data, and from permeability-thickness (kh) values from well tests. Surface leakage at The Geysers shows the MFZ is open at shallow depths and connected to the deep system in the west half of section 17. Seismic emission and self-potential surveys corroborate this, and suggest that the MFZ is not open up-dip of the Rossi well in section 19 (Swift, 1979). Flow test kh values from wells completed in the MFZ (in part from Epperson, 1983) can be mapped along with approximate contours on the MFZ (figure 7). The region of the MFZ penetrated by the Ginn, 85-18 and 33-17 (and adjacent shallow wells in The Geysers area) wells, is open and very permeable. All these wells are in strong pressure communication with each other, and with the Rossi well. However, the MFZ at the Rossi well is much less permeable (only 9,000 md-ft), but the permeability is much higher only a short distance from the wellbore, based on pressure build-up and inter-well interference data (Epperson, 1983). At Batz, the MFZ does not seem to be in pressure communication with any of the other wells. Though the kh at Batz (95,000 md-ft) is intermediate between the Rossi and the other Beowawe wells, a much broader interval is open to the formation, and there is probably some flow contribution from some of the volcanic units. In addition, no fluid was lost while drilling into the MFZ at Batz. Thus the MFZ is probably tight at Batz, and it appears to be futher removed from the high permeability region than Rossi.

Based on the above data, the permeability distribution in the MFZ can be approximately divided into "high" and "low" regions along a permeability boundary (figure 7). The rough coincidence of this boundary with the cooler margins of the high-temperature plume (figure 6) suggests this boundary limits flow of thermal fluids within the MFZ. The low-permeability region of the fault is probably sealed by silica, deposited as waters spread up along the fault, cool, and become supersaturated. Siliceous vein-filling material is present in cuttings from the Batz and Rossi wells (as well as from other more productive wells) near the MFZ intercepts. Prominent silica veins parallel to the MFZ which crop out in the NW ¼ section 16 (Sibbett, 1983) probably mark a former northeastward extension of the Beowawe thermal plume, prior to self-sealing.

Injection Sites

Despite the very low salinity of Beowawe waters, development of the field may require re-injection of spent brines. The danger of breakthrough of cooler injected waters into producing zones in high-permeability, fractured systems is well-documented (e.g., Horne, 1982). A shallow, cool zone of very high permeability in Batz (figure 5) above the MFZ intercept appears to be an appropriate target for injection wells. This zone is interpreted as a range-front fault parallel with and hydrologically unconnected to the MFZ (figure 1). The fault offsets Tertiary volcanic units between 33-17 and Batz. Long-term flow tests have yielded no evidence of pressure communication between this fault and the producing MFZ (unpublished Chevron data). This range-front fault, if the interpretation is correct, remains parallel to the MFZ throughout its length and is not connected to the hydrothermal system.

CONCLUSIONS

The Malpais fault zone (MFZ) appears to be the primary structural control on hydrothermal flow in the Beowawe field. This normal fault is planar in cross-section, dipping 65-70°, but curved in plan view. Natural flow of hot waters within the MFZ is not a simple vertical upwelling but has a locally strong, along-strike component. Flow directions are influenced largely by permeability boundaries within the fault, interpreted as self-sealed zones formed by silica deposition in the cooler margins of the thermal plume. These self-sealed zones isolate cooler portions of the MFZ from the hot, producing region. There is good potential for expansion of the producing area downdip of the MFZ from the 85-18 and Ginn wells, and along strike southwest of Ginn. A permeable range front fault north of The Geysers, parallel with but hydrologically unconnected to the MFZ, is an attractive target for injection wells.

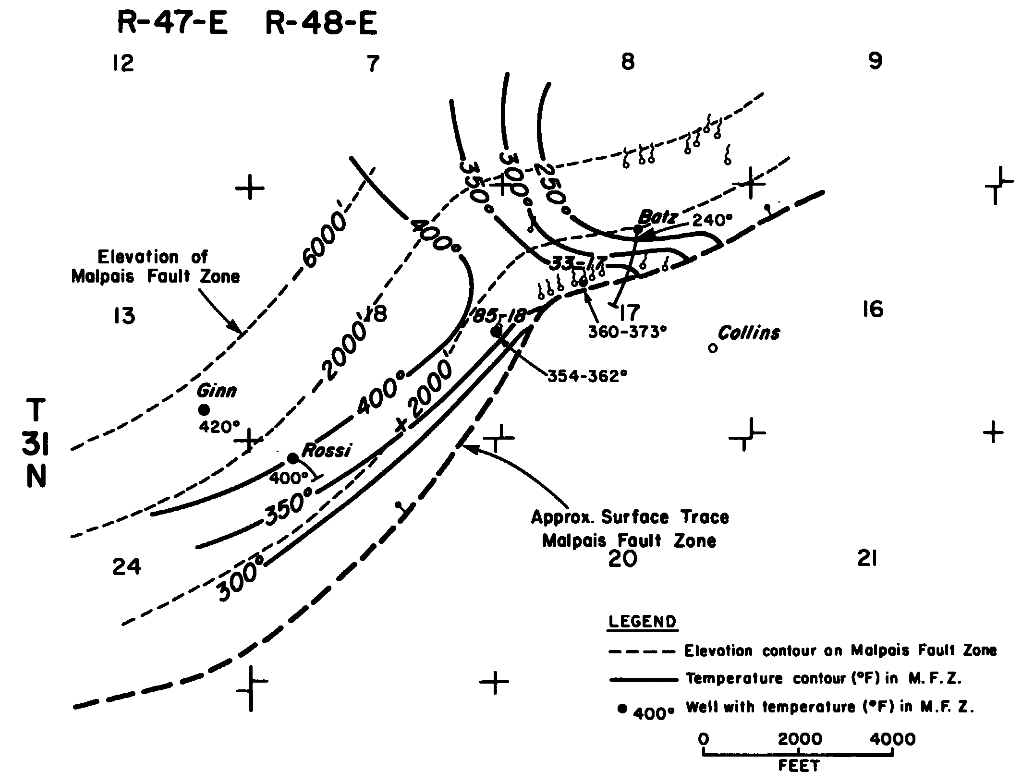


Figure 6: Temperature and elevation of the Malpais fault zone

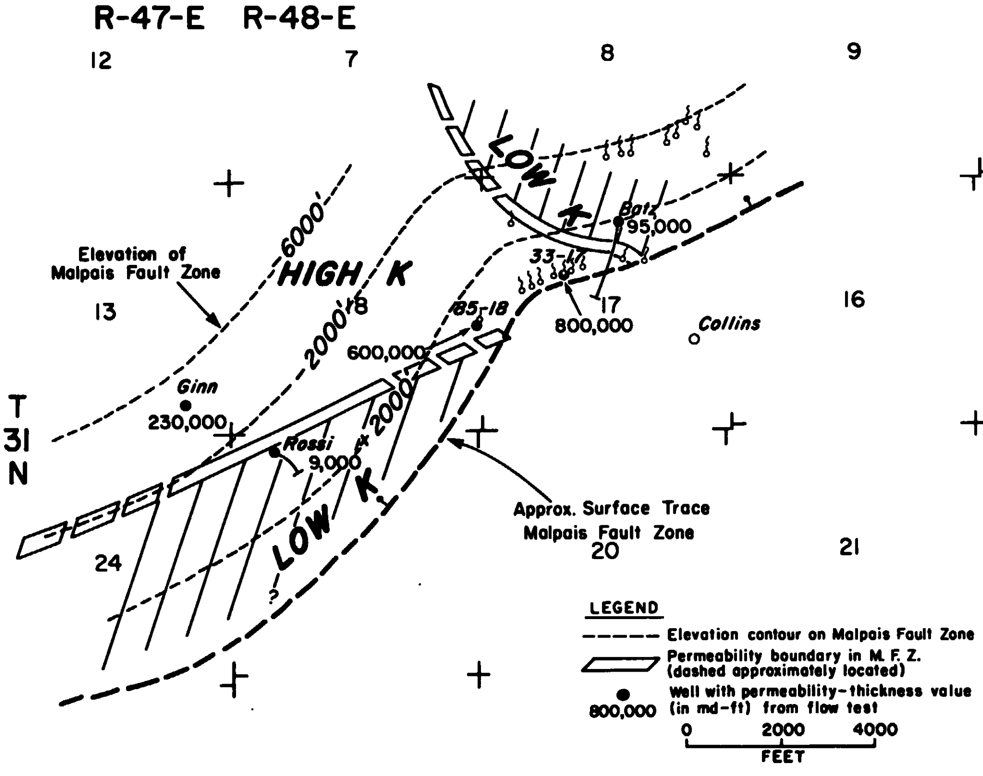


Figure 7: Permeability and elevation of the Malpais fault zone

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