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STRATIGRAPHIC AND STRUCTURAL CONTROLS OF THE OCCURRENCE OF STEAM AT THE GEYSERS

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ABSTRACT

Over the past 20 years several stratigraphic/structural models have been proposed for The Geysers field. The one most compatible with drilling results is the one presented by McNitt (1968). This model consists of the simple superposition of a thick sequence of argillaceous graywacke over a more massive, deformed and indurated graywacke. Subsequent uplift formed a NE-dipping homocline broken by regularly spaced, steeply dipping faults. The geothermal reservoir is contained in randomly oriented fractures in the hard, indurated graywacke located on the structural highs formed by the tilted fault blocks. Because of its low density, steam migrates and becomes trapped in these structural highs in the same manner and for the same reason that oil and gas migrate into and become trapped in structural highs.

Introduction

The purposes of this paper are to review the stratigraphic and structural models which have been developed for The Geysers from surface mapping, propose a model which is the most compatible with drilling results and, based on the preferred model, show how stratigraphy and structure control the occurrence of steam.

Despite the fact that more than 600 wells have been drilled at The Geysers during the past 30 years, the geologic features that control the occurrence of steam still are not clearly understood. Two reasons for this lack of understanding are:

a. All drilling information is proprietary to the independent operators developing the field; consequently, most persons only have access to data from a limited leasehold, and not from the entire field.

b. With few exceptions, easily recognizable marker horizons are absent from the entire (>40,000 foot) thickness of the Franciscan assemblage. This makes stratigraphic correlations very difficult or impossible; without this correlation, structural concepts cannot be proven.

Although Franciscan stratigraphic units of several tens to several hundreds of feet in thickness normally cannot be correlated across horizontal distances of more than a few thousand feet, several attempts have been made to subdivide the Franciscan assemblage into thicker units and to correlate those units across the entire field and beyond.

Stratigraphy

The first detailed geologic mapping of The Geysers area was done by Bailey (1946) as part of a study of the mercury mineralization in the Mayacmas Mountains. Although serpentines and greenstones were differentiated from sediments, no attempt was made to sub-divide the sedimentary sequence or to assign relative ages to the units.

McNitt (1968) made the first attempt at stratigraphic sub-division of the Franciscan assemblage in the Geysers region. Sedimentary rocks were divided into Upper and Lower Units. The Upper Unit is characterized by recognizable bedding up to several feet in thickness, and relatively high ratios (about 1 to 1) of shale to graywacke. The Lower Unit, in contrast, consists almost entirely of massive, highly indurated graywacke. These units were defined entirely from surface mapping, and their relative stratigraphic positions were inferred from their relative intensity of deformation. The Lower Unit was assumed to be stratigraphically beneath the Upper Unit because of the relatively high degree of metamorphism of the Lower Unit as compared to the Upper. McNitt (1968) found no evidence that thrusting had altered the inferred depositional superposition of Upper over Lower Unit.

McLaughlin (1978; 1981) made the second attempt at sub-division of the Franciscan in The Geysers area, and recognized three structural, rather than stratigraphic, units:

Unit 1: A mixture of thin-bedded to massive graywacke and interbedded shale (least metamorphosed).

Unit 2: A melange of graywacke, shale, and associated greenstone, chert and metamorphic rocks.

Unit 3: A metagraywacke (most metamorphosed).

Based on a comparison of lithology and outcrop distribution, it is concluded that McLaughlin's Unit 1 is equivalent to the upper part of McNitt's Upper Unit; McLaughlin's Unit 2 is equivalent to the lower part of the Upper Unit, and the upper part of McNitt's Lower Unit, plus greenstones and serpentinites; and McLaughlin's Unit 3 is equivalent to the lower part of McNitt's Lower Unit.

McLaughlin	McNitt
Unit 1	Upper Unit
Unit 2	
Unit 3	Lower Unit plus greenstone and serpentinite

Because there is no direct fossil or radiometric evidence regarding the relative ages of the three structural units, McLaughlin made a structural interpretation of their relative position. He concluded that the most deformed Unit 3 was thrust over the less deformed Unit 2, which in turn was thrust over the least deformed Unit 1. This structural interpretation resulted in a unit superposition reversed from that of McNitt; that is, McLaughlin superimposes the most metamorphosed and indurated unit on top of the least deformed and indurated unit.

These two conflicting stratigraphic/structural interpretations were based primarily on surface mapping. After reviewing 200 well logs filed with the California Division of Oil and Gas, Thomas (1981) concluded that the host rock for most of the shallower portion of the geothermal reservoir is a thick graywacke present throughout The Geysers field and located below a "thrust assemblage" equivalent to McLaughlin's Unit 2. Thomas (1981) named this reservoir unit the "main" graywacke, and concluded that it consists of rocks from all three of McLaughlin's structural units.

Based on an independent review of several hundred lithologic logs throughout The Geysers field, of which many were drilled since the Thomas (1981) report, we have concluded that his "main" graywacke is not a mixture of all three units, but rather is equivalent to McLaughlin's Unit 3, which in turn is equivalent to part of McNitt's Lower Unit. This conclusion is based on the following considerations.

For the purpose of lithologic logging, a system for sub-dividing graywacke types on the basis of texture was developed (Cochran, 1979). This system is based on the textural sub-divisions originally developed in the north Coast Ranges by Blake *et al.* (1967). The units, used commercially by most well loggers working at The Geysers, consist of four types (1 through 4) with each higher number indicating an increasing degree of recrystallization, metamorphism and induration.

Well logs examined by the writers from leaseholds throughout The Geysers typically show metamorphic grade increasing with depth. The lithologic data, which is based on binocular examination of cuttings for rock texture, is supported by changes in the drilling penetration rate with depth. Drilling penetration rate decreases with well depth, reflecting the increase of hardness due to the increase of metamorphic grade of the graywacke with depth, as shown in figure 1. Although any one log may show some sections where relatively hard and soft zones are intermixed, the thickness of these zones is rarely more than a few hundred feet. However, on the scale of unit thicknesses which would be appropriate for a structural/stratigraphic model, none of the logs show sections of metagraywacke at a shallow depth

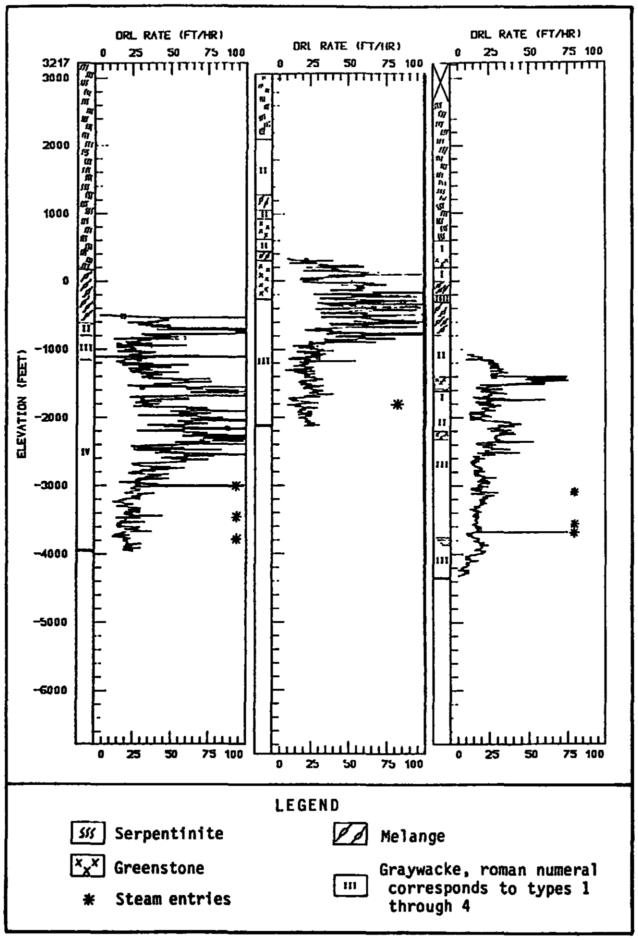

Figure 1. Typical lithologic/drilling rate logs from The Geysers. Drilling rates are shown only for the air-drilled interval.

overlying relatively unmetamorphosed units at greater depth, as would be expected if the dominant structural style of the area was the thrusting of metamorphosed over unmetamorphosed units. In short, the results of deep drilling at The Geysers support the relatively simple stratigraphic/structural model proposed by McNitt (1968): metamorphism increases with depth through a thick sequence of graywacke.

Structure

Despite the scarcity of exposed bedding planes on which to measure strike and dip, McNitt (1968) and McLaughlin (1978) agree that the stratigraphic section N of Big Sulphur Creek, which includes The Geysers reservoir, dips to the NE. Although supported by bedding measurements, the major evidence observed for this uniform dip is the attitude of conformable greenstone, chert and serpentinite contacts which can be seen where these contacts cross steep terrain. Contact dips range from 25° to 70°, and probably average around 45°. Based on subsurface mapping, Thomas (1981) also shows a dominant NE dip on the top of the main graywacke.

Although there is general agreement on the dip of the graywacke units, and associated chert, greenstone and serpentinite, there is less agreement on the nature of the faults which displace the section. McNitt (1968) mapped relatively few, large-displacement, SW-dipping normal faults, because this structural style was the simplest way to explain repeating outcrops of the homoclinally dipping sequence. Reverse faults, dipping to the NE, could serve the same purpose, but this structural style requires compressional stress, whereas the presence of the homocline, and the absence of evidence for large-scale folding, imply that the causative stress was uplift with extensional relief rather than compression.

McLaughlin (1981), on the other hand, concluded that the reservoir graywacke occupies the NE limb of a faulted, SE-plunging antiform that forms the core of the Mayacmas Mountains. The existence of the SW limb of the antiform, however, could not be clearly demonstrated by him because of right-lateral shearing by Tertiary and Quaternary faults. The antiform concept of McLaughlin (1978, 1981) may have been

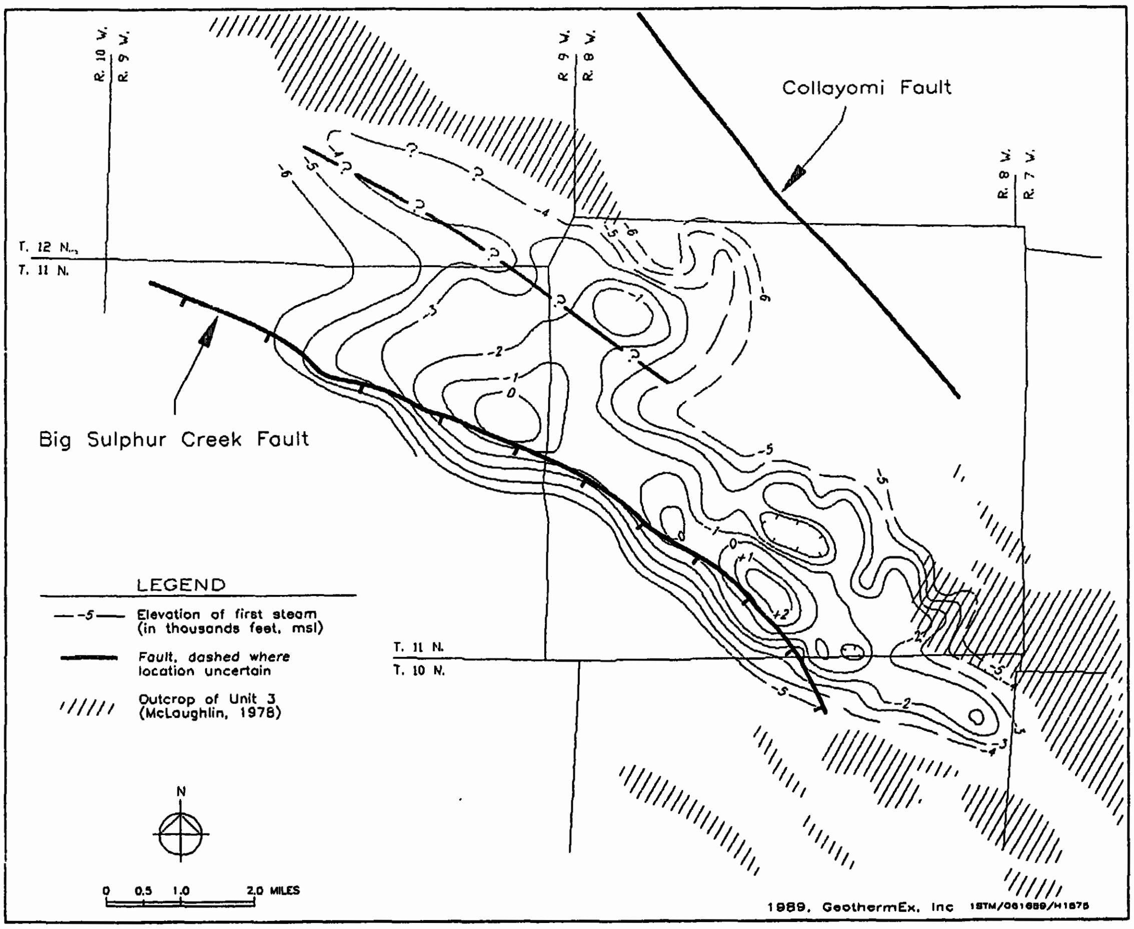

Figure 2. Contour map of elevation (feet msl) of first steam entries, The Geysers steam field, California

the basis for his reversed sequence of units discussed above. That is, because Unit 1 lies at the core of the antiform, Unit 1 should be the lowest of the three superimposed units.

The difficulties of resolving the geometry of faulting at The Geysers arise because exposures are too poor to allow actual measurement of fault attitudes at the surface, and because stratigraphic units are too thick and poorly correlated to allow recognition of repeated or missing sections in a drillhole. Consequently, the area has been mapped to conform to a preferred style of deformation rather than on the basis of observed offsets of units whose pre-faulted relationships have been clearly established.

Much of the ambiguity of structural interpretation, however, can be overcome by accepting the conclusion of Thomas (1981) that the main graywacke (within McNitt's Lower Unit) is a coherent, fieldwide stratigraphic unit coincident with The Geysers steam reservoir. A contour map drawn on the elevation of the highest steam entries in production wells, therefore, is equivalent to an elevation contour map of the top of the main graywacke. Figure 2 presents an updated and expanded version of such a contour map first produced by Thomas (1981). The following observations on geologic structure are based on the geometry of the steam reservoir as shown in figure 2.

1. In contrast to often-repeated descriptions of the complexity of The Geysers' structure, figure 2 shows that the reservoir has a simple geometry.

2. The boundary of the field is sharp and smooth on the SW and irregular on the NE.

3. The SW boundary corresponds to a normal fault mapped along Big Sulphur Creek by McNitt (1968). This same fault was mapped in the subsurface by Thomas (1981).

4. In transverse section, the top of the reservoir is asymmetric, being highest just NE of the Big Sulphur Creek fault, from where it declines in elevation to the NE. This decline to the NE conforms to the regional NE dip of the graywacke units.

5. In longitudinal section, the top of the reservoir deepens from +2000 feet (msl) in the SE to deeper than -6,000 feet (msl) in the NW. This conflicts with McLaughlin's interpretation of a SE-plunging structure, but is compatible with the outcrop of Unit 3 to the SE of the reservoir.

6. The NE boundary of the reservoir is formed by the NE-dipping, conformable contact between the reservoir (McLaughlin's Unit 3) and the cap rock (McLaughlin's Unit 2 and, in part, McNitt's Unit 1).

7. The greater width of the reservoir on the NW (4 miles) as compared to the SE (2 to 3 miles) probably is due to the uplift of Unit 3 on another fault parallel to, and NE of, the Big Sulphur Creek fault. None of the faults mapped by either McNitt or McLaughlin exactly correspond to the position of a fault (shown on figure 2) inferred from the location of this high.

Discussion

The above review indicates that The Geysers steam reservoir is contained in highly indurated and fractured graywacke, located on structural highs capped with less competent, and therefore unfractured, argillaceous graywacke. The structural highs are formed by two NE-tilted fault blocks, bounded on the SW by steeply dipping faults and on the NE by the contact between the graywacke-shale cap rock and the NE-dipping Unit 3 reservoir graywacke. It is most probable that the coincidence of the steam field with these structural highs is not accidental, but instead reflects the same physical processes that cause oil fields to be located on structural highs; that is, the upward migration of relatively low-density fluids into shallow structural traps.

The steep faults forming the SW sides of the two structural highs act as boundaries to the reservoir, rather than as conduits for steam entering the reservoir, because these faults juxtapose permeable Unit 3 graywacke against impermeable Upper Unit (McNitt) and Unit 2 (McLaughlin) graywacke. Furthermore, because production is found over the entire contoured area shown in figure 2, and beyond the contoured area at depths below -6,000 feet msl, fluid must enter the reservoir from depth through a network of fractures distributed throughout Unit 3.

In the writers' experience, attempts to find major feeder faults, which would provide specific drilling targets for systematic field development, have not been successful. Indeed, even a preferred direction of fracturing has yet to be convincingly demonstrated. Plotting the productivities of more than 50 wells drilled directionally on one lease toward all quadrants of the compass revealed no indication of a preferred direction of fracture orientation (figure 3). The directionally drilled wells tested an area of two square miles. The Geysers field is approximately 30 square miles in area. It is hoped that the stratigraphic/structural model presented here will be useful for stimulating the development of new concepts that will eventually explain other aspects of The Geysers field. For example, one of the more persistent questions about the occurrence of steam at The Geysers is the existence, nature and location of a recharge area. If the structural highs are the main feature controlling the location of the field, from where does the fluid migrate into these highs?

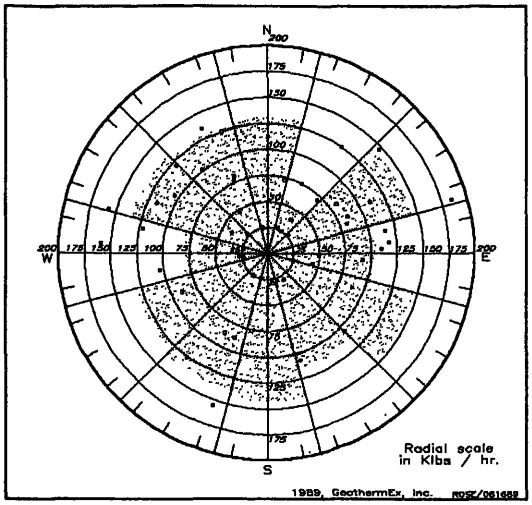

Figure 3. Rose diagram of initial well deliverability versus well direction. (Shaded area shows average deliverability of wells in each 30 degree segment.)

It has been suggested that fluids migrate updip from the NE, but this is not likely because the Collayomi fault (figure 2) juxtaposes the permeable Unit 3 graywacke against a thick sequence of impermeable shale underlying the Lower Lake basin to the NE. Recharge water would have to penetrate the shale sequence before entering a permeable, down-dip extension of the reservoir. The volcanic necks and pipes of the Clear Lake Volcanics located to the SW of the Collayomi fault have also been suggested as a possible recharge area, but the writers are not aware of supporting evidence for this possibility.

Perhaps a more likely location for recharge is the outcrop area of the reservoir itself. Figure 2 shows the outcrop pattern of McLaughlin's Unit 3, which for the reasons discussed above is believed to constitute the reservoir graywacke. The unit is exposed over a large area SE of the field and within the same major fault block as the reservoir; recharge could be occurring directly to Unit 3 through its outcrop area. Recharge of the reservoir from this direction could result in a natural flow within the reservoir from SE to NW. This flow, in turn, might explain the relatively low non-condensible gas content of the steam in the SE end of the field as compared to the NW end. Further examination of stable O and H isotopes and of changes in non-condensible gas concentrations across the field may help to resolve this question and other questions concerning the mechanisms controlling fluid migration to, and evolution within, the structural trap described in this paper.

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