STRUCTURAL ANALYSIS OF PRE-CENOZOIC ROCKS, COSO GEOTHERMAL AREA, CALIFORNIA

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ABSTRACT

Exploration and drilling at the Coso KGRA in eastern California has proven the existence of a fracture-controlled geothermal system capable of electric power generation. Structural analysis shows that zones of high joint density occur within the pre-Cenozoic metamorphic and granitic rocks which host the system. These zones, together with regional fault trends and fractures developed as a result of emplacement of Quaternary rhyolite domes, control permeability within the reservoir. Under certain conditions, interaction of these structural features will significantly enhance permeability and influence reservoir configuration. Evidence supporting this hypothesis is cited from recent drilling results.

INTRODUCTION

The Coso KGRA is located in Inyo County, California, along the western margin of the Basin and Range physiographic province and adjacent to the eastern Sierra Nevada fault system.

Active fumaroles, hydrothermal alteration and Quaternary volcanism focussed attention on the geothermal potential of the area and during recent years much literature has been published both by academic institutions and by federal agencies.

California Energy Company, Inc. contracted with the U.S. Navy to explore and develop 5424 acres of the Coso KGRA within the China Lake Naval Weapons Center. Subsequently, they acquired additional geothermal leases within the KGRA from the U.S. Bureau of Land Management. In December 1981, the Company commenced a six well drilling program which has proven the existence of a commercially viable, fracture controlled, hot water geothermal resource with relatively near surface temperatures in excess of 200°C.

Concurrent with this successful drilling program, a structural analysis was undertaken in the Devils Kitchen - Coso Hot Springs area, east of Sugarloaf Mt., covering the prospective production zone. (Fig. 1)

Much attention has been placed on exploration techniques that enable geothermal prospects to be identified, priority rated and evaluated prior to commitment of drilling funds. However, that period between initial resource identification and wellhead production sufficient to justify power plant construction often requires planning decisions that can only be made on scant and speculative geologic data. It was envisioned results from the structural analysis might identify permeability variations within surface rocks that could significantly aid estimation of probable resource size and configuration. In addition, a structural analysis of this type would provide necessary data for any future hydro-fracturing program which might be planned to artificially enhance permeability. Such a dual purpose survey has previously been described in detail for Roosevelt Hot Springs KGRA (Yusas and Bruhn, 1979).

GEOLOGY

Oldest rocks exposed in the Coso Range are a sequence of low to medium grade metamorphic rocks of intermediate to mafic composition and of uncertain but pre-late Cretaceous age. The metamorphic rocks have been intruded by dominantly mafic bodies, but which range in composition from hornblende gabbro to diorite and quartz diorite, and which are cut by dikes of felsite and quartz latite porphyry (Hulen, 1978).

The youngest pre-Cenozoic rocks in the Coso Range are a series of granitic stocks with associated aplite dikes and pegmatite veins. These stocks, composed of biotite leucogranite, quartz monzonite and granodiorite, have been intruded into the older metamorphic and mafic sequences and appear to be genetically related to the Sierra Nevada batholith of late Cretaceous age. A K-Ar date of 86 ±2.6 my has been cited by Duffield (1975).

The older basement metamorphic and mafic igneous rocks occur as discontinuous outcrops throughout the study area. They are seen as xenoliths and roof pendants within the younger granitic intrusives. A marked increase southward in the proportion of older basement rocks suggests that the top of the pluton dips generally to the south.

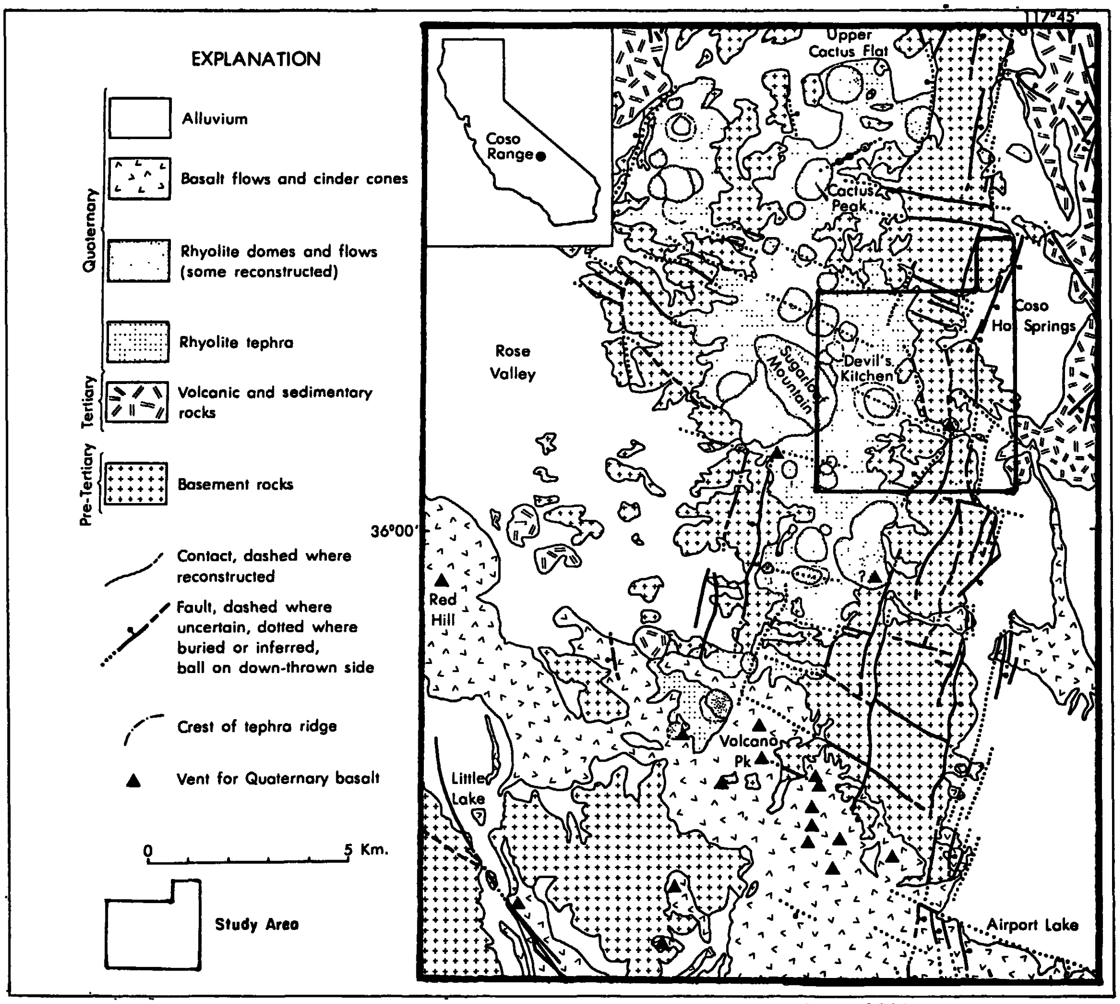


Figure 1. General Geologic Map (after Bacon, et al., 1980)

Extensive Plio-Pleistocene volcanic rocks cover much of the basement sequence throughout the Coso volcanic field. The central core of the field is dominantly rhyolite with minor basalt and contains at least 38 high silica rhyolite domes and flows ranging in age from 1.04 my to 0.06 my. Coeval basalt flows and cinder cones vented along the southern periphery of this central core. The rhyolite domes all have similar geomorphic characteristics and are covered by a carapace of perlitic, partly pumiceous, rhyolitic glass with obsidian protruding through some of the domes and flows (Duffield, et al., 1980). Older rhyodacite, dacite and andesite volcanics crop out on the outer flanks of the volcanic field.

The silicic magma reservoir that fed these rhyolitic domes is assumed to have provided the heat flux which has allowed development of the hydrothermal system. Geophysical evidence from teleseismic P wave delays (Reasenberg, et al., 1980), P wave attenuation (Young and Ward, 1980) and gravity (Plouff and Isherwood, 1980) suggest that the best available interpretation would be that of a partially molten body at least 8 km, but probably between 10 and 17.5 km in depth, centered beneath the heat flow anomaly. Maximum width is likely to be 5 km, and the body appears to be elongated at depth in a N-S direction.

In the center of the field, domes were probably fed by dikes developed radially from the top of the magma reservoir and controlled mainly by pre-Cenozoic fracture systems. Domes peripheral to the center of the field were fed by offshoots of the dike systems which developed parallel to the direction of maximum horizontal stress and produced the overall S-shaped configuration of the dome field (Bacon, et al., 1980).

REGIONAL STRUCTURE

Both regional and local late-Cenozoic tectonism has been extensively discussed by Duffield, et al. (1980) and Roquemore (1980). The region is dominated by faults that have three dominant trends.

NW-WNW Faults: Throughout the Coso Range NW-WNW faults reflect major crustal structures, as evidenced by both gravity and aeromagnetic data (Plouff and Isherwood, 1980) and apparent resistivity data (Jackson and O'Donnell, 1980).

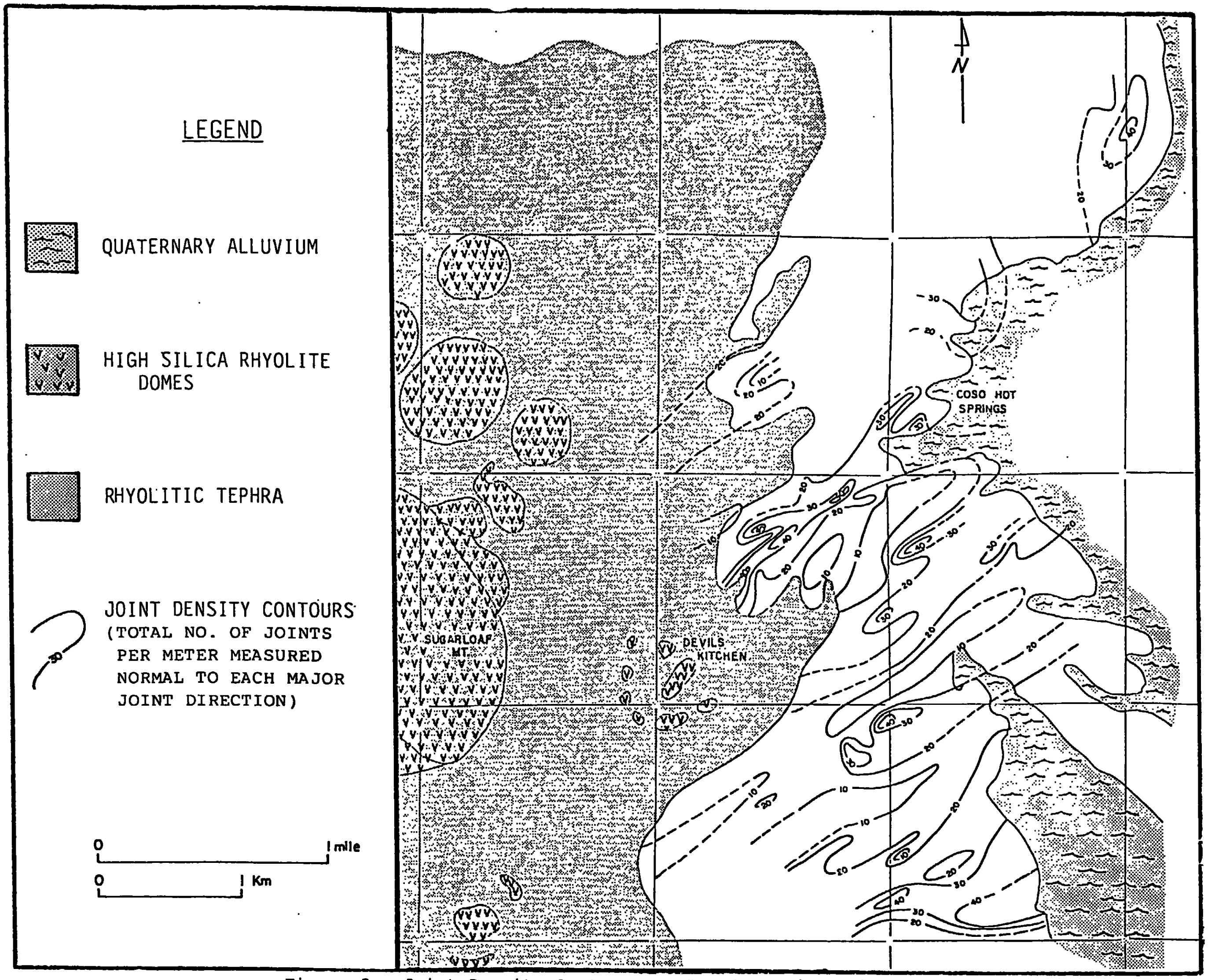


Figure 2. Joint Density Contours - Pre-Cenozoic Rocks

These faults have had a significant influence on emplacement of the rhyolite domes, although there is no evidence of displacement within the volcanics (Duffield, et al., 1980).

Right lateral, left lateral and normal displacement have all been suggested by various authors. Roquemore (1980) cites right lateral slip on the Little Lake Fault 15 km to the south where a 0.44 my basalt flow has been offset. Right lateral displacement is supported by first motion solutions for recent earthquakes on NW trending faults in the area (Walter and Weaver, 1980).

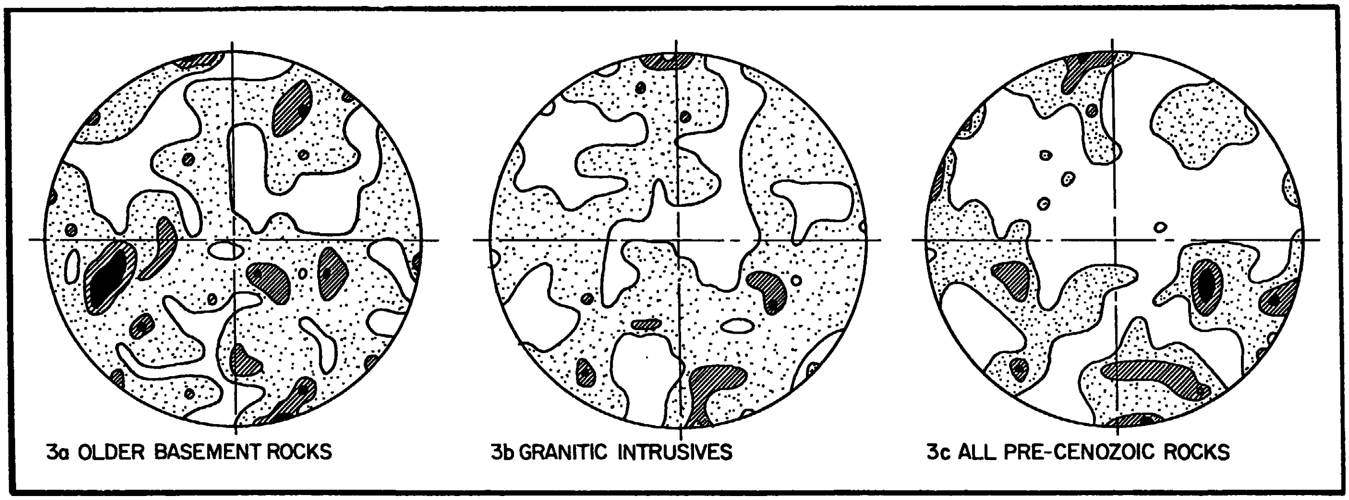
Pre-Cenozoic dikes mapped within the study area also show a consistent NW trend. Their age has been inferred as late Jurassic - early Cretaceous through similarity with the Independence dike swarm (Chen and Moore, 1979).

The apparent variability in displacement on these structures probably reflects variable stress fields with time, at least since the late Mesozoic.

N-NNE Faults: Expression of Basin and Range extensional tectonics is seen as a series of N-NNE normal faults mapped throughout the Coso area. These faults are responsible for the N-S horst structure on which the rhyolite dome field has been emplaced and many show a left stepping, en echelon arrangement.

At Coso Hot Springs, a normal fault with a 2 m scarp displacing late Quaternary alluvium is evidence of Holocene movement along the NNE trend. However, contrary to some interpretations, recent field mapping has suggested that the N trending faults may be older basement faults which have been reactivated in response to more recent stress fields.

Arcuate Faults: To the north within the Coso Range, arcuate faults showing a concentric relationship to the rhyolite field and dipping inward at 65-70° have been mapped. Intense jointing and shearing within the basement rocks, with some indication



Figures 3a,b,c: Lower Hemisphere, Equal Area Stereographic Projection of Poles to Joint Planes. Contours at 1% 2% 3% per 1% Area

of vertical displacement, suggest a volcanic related origin for the structures. Duffield, et al. (1980) discuss these faults in detail but conclude that the faults only partly circumscribe the volcanic center and are most easily recognized where they trend at high angles to the strike of planar faults. No direct evidence of arcuate faults was found within the study area.

Regional Stress Field: Structural evidence from both seismicity (Walter and Weaver, 1980) and fault mapping (Bacon, et al., 1980) suggest, at least for the late Quaternary, that the axis of maximum horizontal compression was trending NNE, parallel to the direction of normal faulting, as suggested by the alignment of flank eruptive domes (Nakamura, 1977). The principal axis of maximum compressive stress (σ_1) must be vertical for normal faulting and NNE for strike slip faulting. Thus σ_1 and σ_2 (intermediate compressive stress) must be of near equal magnitude and capable of interchange as a response to minor variations in the stress field (Wright 1976).

Bacon (1983) suggests that high extension rates favor greater magma residence times in the crust, allowing magmatic differentiation and formation of high silica rhyolites. Under such conditions strain release would be facilitated by dike injection and surface faulting with the vertical stress (σ_v) approximately equal to the maximum principal stress (σ_1). Assuming relatively slow intrusion rates for highly viscous, high silica rhyolites and small eruptive/intrusion ratios, intense radial and vertical fracturing will probably occur adjacent to dikes and domes during emplacement.

STRUCTURAL ANALYSIS

Joint Analysis: A detailed study of joints and joint density distributions formed the basis of the structural analysis with additional data from dike orientations, foliation directions and zones of shearing.

Major joint directions were measured at each location, together with relevant information on rock type, planarity, surface coatings, etc. Joint spacing, in joints per meter, was recorded normal to each of the major directions and then summed for each location as an expression of joint density. (Fig. 2).

Intense jointing occurs in zones resembling shears, with minor displacement along some joint surfaces. In such zones, joint surfaces have variable, anastomosing orientations which were difficult to measure and showed greater alteration on surfaces.

The limited number of quartz latite and felsite dikes in the study area prohibited detailed structural interpretation but provided some indication of palaeostress fields.

Stereographic projections of poles to joint planes for the older metamorphic and mafic rocks (Fig. 3a) and for the younger granitic intrusives (Fig. 3b) are shown, together with a combined projection for all pre-Cenozoic rocks. (Fig. 3c).

As would be expected, the older basement rocks show a number of joint directions reflecting variation of stress fields with time. The younger granitic intrusives reflect the more dominant, near vertical ENE direction with additional NNE and NW trends.

Joint density contours clearly highlight NE-ENE trends within the pre-Cenozoic rocks. Seven individual zones were defined based on these joint density contours (Fig 4.). Zones III, V and VII have high joint densities (>20 joints/meter) and Zones IV and VI have relatively low joint

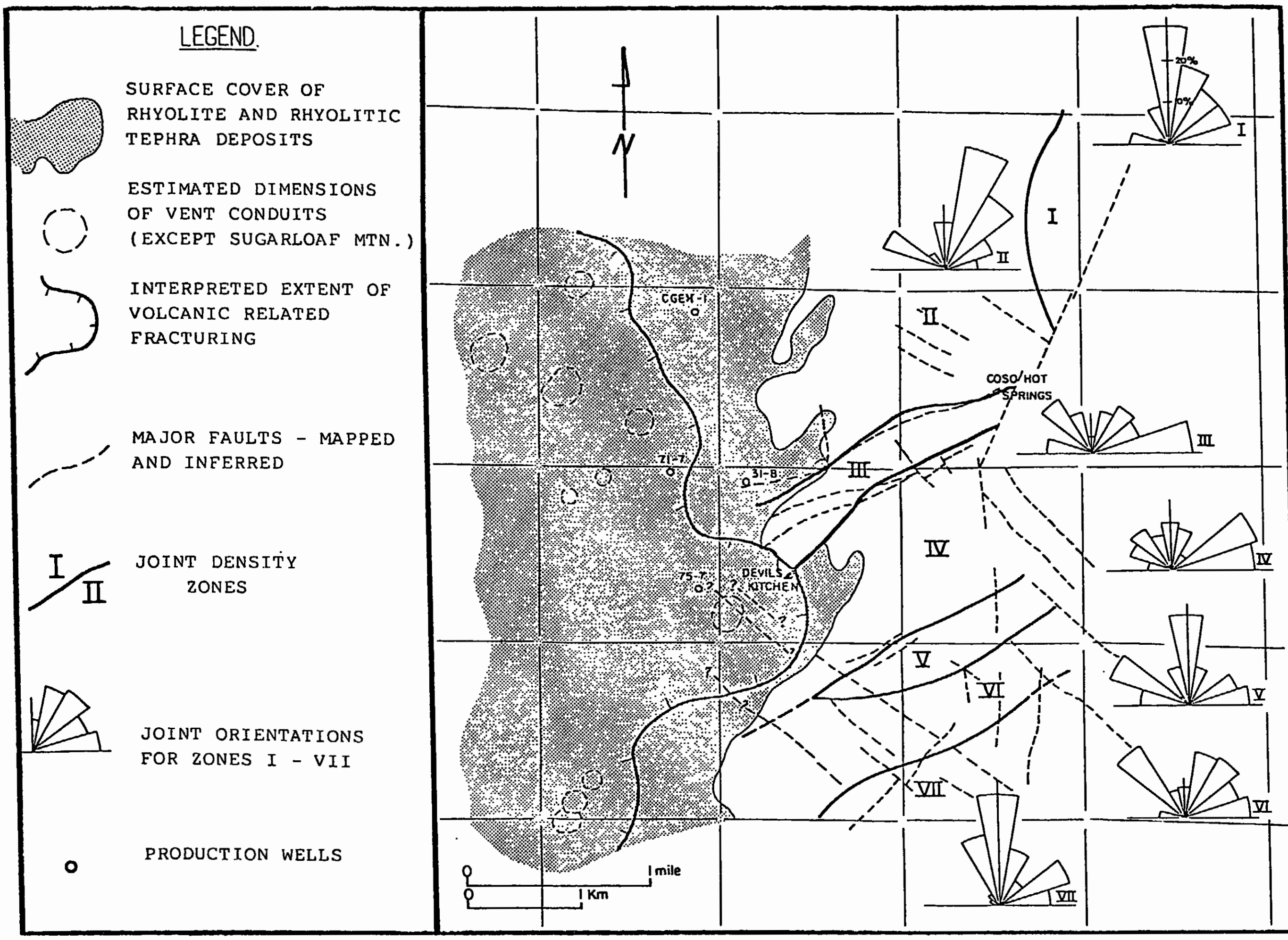


Figure 4. Joint Density Zones and Estimated Extent of Volcanic Related Fractures

densities (<20 joints/meter). Zones I and II had a limited number of sample sites which restricted interpretation. However, there is an indication that Zone I joint directions have a trend similar to the NNE Coso Hot Springs fault.

The major high density zone occurs between Devils Kitchen and Coso Hot Springs and can be broadly associated with a shallow electrical resistivity anomaly outlined by Fox (1978), although displaced marginally to the south. This zone includes outcrops showing evidence of shearing along joint surfaces, suggesting that the ENE joints are shear joints rather than extension joints and therefore not related to cooling and contraction of the pluton. If this is correct, the axis of maximum horizontal compression would be approximately N40E or S80E.

Other high joint density zones also trend ENE to NE. The southernmost zone shows evidence of horizontal displacement along a NW strike slip fault with apparent right lateral movement. (Fig. 2)

Rose diagrams for joint directions within each zone are given in Fig. 4. Most notable is the prominent ENE joint (shearing) orientation for Zone III. The frequency of joints in that direction is responsible for the high joint density in that zone. Zone V and VII do not appear to show a similar prominence in that direction.

For such an analysis to be of value, the assumption must be made that surface variations in fracture permeability can be projected to reservoir depths. Segall and Pollard (1983) suggest that jointing in the granitic Sierra Nevada batholith in the Florence Lake area were formed at depths of at least several hundred metres and possibly as deep as 15 km. The author has seen evidence from within the mining industry that significant fluid flow through joint sets can occur at least to depths of 1 km. Laboratory studies of electrical conductivity of rocks, (Brace and Orange, 1968), indicate that pressures of 3-4 Kbars are required to close most of the crack porosity, and under normal conditions, these pressures would occur at depths of 10-12 km. Thus it seems probable that the extent of the upper part of the Coso reservoir could be largely controlled by zones of high joint density with the result that production zones with widths of hundreds of meters could be envisioned rather than limited to discrete fault planes. Seemingly, secondary sealing would be less effective in such a system than in the more restricted fault zones.

Volcanic Related Stress: Emplacement of a large number of rhyolite domes in such a relatively small area has undoubtedly caused local distortion of the regional stress field. The effect of such localized stress regimes could significantly alter the distribution of permeability and control the dimension of the shallow parts of the reservoir.

In order to assess the influence of shallow magma emplacement on the regional stress field, it was necessary to make a number of assumptions concerning the configuration of the domes and their vents. Each dome was assumed to be fed through a cylindrical conduit even though it is reasonable to postulate dike feeders at greater depths. The diameter of each vent conduit was arbitrarily estimated at 0.8 times the diameter of the summit depression. Emplacement of magma through these vent conduits would produce both local vertical and radial stress fields, the extent of which would be controlled by magma volume, confining pressure, timing of emplacement and rock type. An estimate of five times the conduit radius was taken as an area in which significant fracturing would occur as a result of dome emplacement. (Fig. 4).

Estimates of the percentage of the basement rock displaced or assimilated during dome emplacement were calculated using the vent conduit diameter. Percentages calculated were 5% for the immediate area around Sugarloaf Mtn., 3% for the complete rhyolite dome field and 2% for the overall N-S horst block. It should be noted that no consideration has been taken of possible fracturing as a result of inflation or deflation of the magma reservoir at depth.

IMPLICATIONS FOR DRILLING STRATEGY

A working hypothesis established as a result of this structural analysis suggests that highest permeability should occur where either major faults or zones of high joint density overlap areas fractured by dome emplacement, as indicated in Fig. 4.

This somewhat obvious conclusion is apparently compatible with results obtained from a program of six production wells completed in April 1982. The wells were completed from three separate pads in the Devils Kitchen area (Fig. 4).

Highest production rates and greatest lost circulation problems were experienced from the three wells (75-7, 75A-7 & 75B-7) drilled close to where Zone III is projected to intersect the rhyolite dome at Devils Kitchen.

The initial discovery well (75-7), drilled to a depth of 405.1m (1329 ft.), produced dry steam at 387.7m (1272 ft.) after experiencing lost circulation zones below 300.2m (985 ft.). Wells 75A-7 and 75B-7 were both drilled to greater depths from the same pad and produced significant hot water entries. Static fluid levels were at 426.7m (1400') and 402.6m (1380') respectively, which, together with the temperature data, suggests that steam from 75-7 is flashing from hot water at a depth not much below the production zone (Moore and Austin 1983).

Wells 71-7 and 71A-7, 1000m (3281 ft.) to the NNW, were drilled outside the zone of high joint density but still within the influence of volcanic fracturing. Although lost circulation was encountered, the geologic logs and production rates suggested that these wells penetrated sequences which were significantly less permeable.

The deepest well completed in the program (31-8) was spudded NNE of Devils Kitchen outside the high joint density Zone (Fig. 4). Permeability appeared to be negligible in the upper 548.6m (1800 ft.) of the well, which would be anticipated by its location to the north of Zone III (Fig. 4). Structural data indicates the ENE joints which dominate Zone III dip to the NW (Fig. 3). This significant increase in permeability below 548.6m (1800 ft.) in well 31-8 suggests it may have intersected the intense jointing at depth. A temperature reversal in 31-8 was seen between 548.6m-908.3m (1800-2980 ft.), below which the gradient became isothermal to TD at 1219.2m (4000 ft.). The overall temperature profile displayed a distinct similarity to CGEH-1 drilled in 1977 by U.S. DOE and located 914.4m (3000') to the north of 75-7 (Fig. 4) (Galbraith 1978).

CONCLUSIONS

Preliminary exploration for fracture controlled geothermal reservoirs relies strongly on the study of regional structures and major fault trends. However, when a resource has been identified, it becomes necessary to gain more detailed information on the local permeability variations which may influence the configuration of the reservoir. In some geologic environments this can be accomplished by analysis of the structural relationships within the surface rocks. The structural analysis within this part of the Coso geothermal area produced the following general conclusions:

1. Structures controlling permeability are major fault zones and high joint density zones related to regional tectonics, and fracturing as a result of localized volcanic emplacement.

2. Where any of these three structural features overlap, permeability is likely to be significantly enhanced.

3. Within the Coso geothermal area, joint densities show a dominant ENE trend. A distinct high density zone occurs between Devils Kitchen and Coso Hot Springs and additional high density zones are recognized to the south.

4. Results from preliminary production drilling suggest that wells sited at the

intersection of high joint density zones and the envelope of volcanic induced fracturing produced highest permeability. Wells close to the volcanic centers but outside of the high joint density zones showed significantly lower permeabilities.

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