HOT DRY ROCK RESOURCES OF THE CLEAR LAKE AREA, NORTHERN CALIFORNIA

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ABSTRACT

The Hot Dry Rock resources of the Clear Lake area of northern California are hot, large and areally uniform. The geological situation is special, probably overlying a slabless window caused by interaction between tectonic plates. Consequent magmatic processes have created a high-grade resource, in which the 300°C isotherm is continuous, subhorizontal, and available at the shallow depth of 2.4 to 4.7 km over an area of 800 km^2. The region is very favorable for HDR development.

1. INTRODUCTION

In northern California, recent research has built a case that links plate tectonic events in the northeast Pacific ocean to geothermal resources onshore at The Geysers and Clear Lake. This paper reviews some of the ideas that have been developed.

Units used in this paper include hfu and quad, where 1 hfu = 41.84 mW/m^2 and 1 quad = 3.345E+4 MWyt.

2. PLATE TECTONICS OF THE NORTHEAST PACIFIC

Steady-state Motions: A plate tectonic model of the north-east Pacific region was assembled independently by McKenzie & Parker (1967) and Morgan (1968). A transform plate boundary first formed at the coastal trench off southern California. About 23.3 Ma, at the start of the Neogene, the San Andreas fault jumped onshore, and the present era of "neotectonics" commenced.

The San Andreas transform fault terminates at its northern end, off Cape Mendocino, in the Mendocino Triple Junction, an FFT (fault-fault-trench) junction in the classification of McKenzie & Morgan (1969). The fault terminates at its southern end, off the Gulf of California, in the Rivera Triple junction, an RTF (ridge-trench-fault) junction (Figure 1).

As the Pacific plate moves towards the North American plate, the two triple points migrate away from each other, "unzipping" the San Andreas fault. The Mendocino fracture zone first made contact with the North American continent in central California somewhere near 30°N latitude. The Mendocino triple junction then migrated NNW to its present position off Cape Mendocino near 40°N latitude.

Transform jumps: Transform jumps were first postulated by Atwater (1970). These transfer slip from one fault to another. The second fault is parallel to the first, and further inland. The result is not one single transform fault, but a transform system. The offset on the San Andreas fault, 314 km, is far less

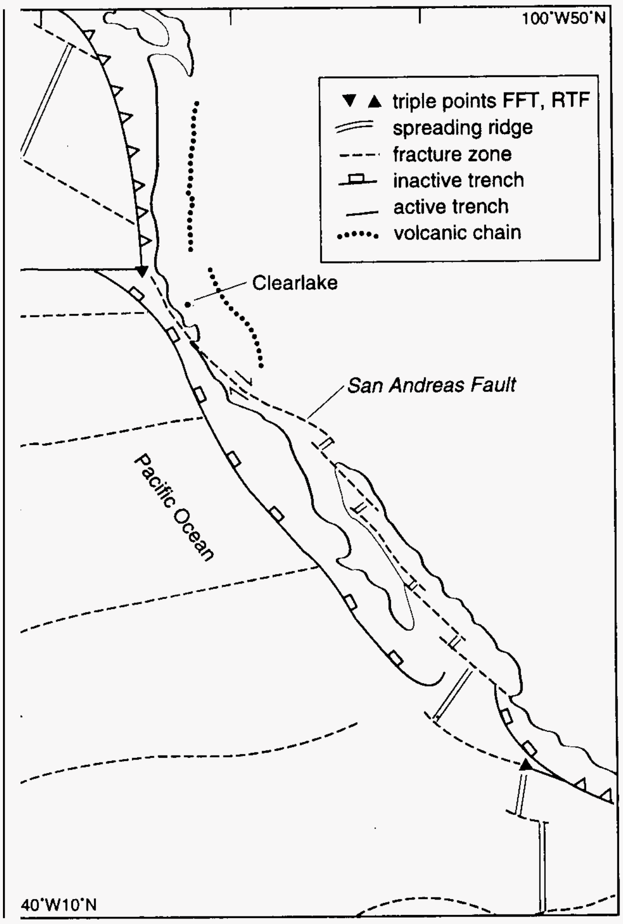

Figure 1: Tectonics of western North America. Mercator projection. The northern (FFT) is the Mendocino triple point, the southern (RTF) is the Rivera triple point.

than the total offset on the San Andreas system, 500 km (Atwater, 1970; Dickinson & Snyder, 1979a; Fox et al., 1985).

3. PATTERNS OF VOLCANISM

Migrating volcanics: In central and northern California, the onset of rapid Miocene sedimentation in terrestrial basins and outbreaks of local volcanism migrates north with decreasing age (Dickinson & Snyder, 1979a; Fox et al., 1985). In addition, Hearn et al. (1981) demonstrated a steady northward migration within the Clear Lake Volcanics over the period 1.1-0.01 Ma.

Analysis of the rate of volcanic migration is complicated by the effect of offsets on the transcurrent faults of the San Andreas system. The distances shown in Figure 2 are with the offsets restored. In restoration, allowance was made for slip of 115 km on the San Gregorio-Hosgri fault, 314 km on the San Andreas fault, 43 km on the Hayward-Rodgers Creek fault, and 28 km on Carneros-Franklin-Sunol-Calaveras fault.

In the restored map of Figure 2, the displacements PA-CL are 248 km in 14.79 Ma in direction 340°EofN and the displacement QU-SU is 262 km in 9.55 Ma in direction **347.5°EofN,** virtually parallel. This suggests one explanation of the magmatism is a pair of migrating hot spots, as suggested for Cenozoic volcanism in Australia by Wellman & McDougall (1974). but the rates are incompatible with each other.

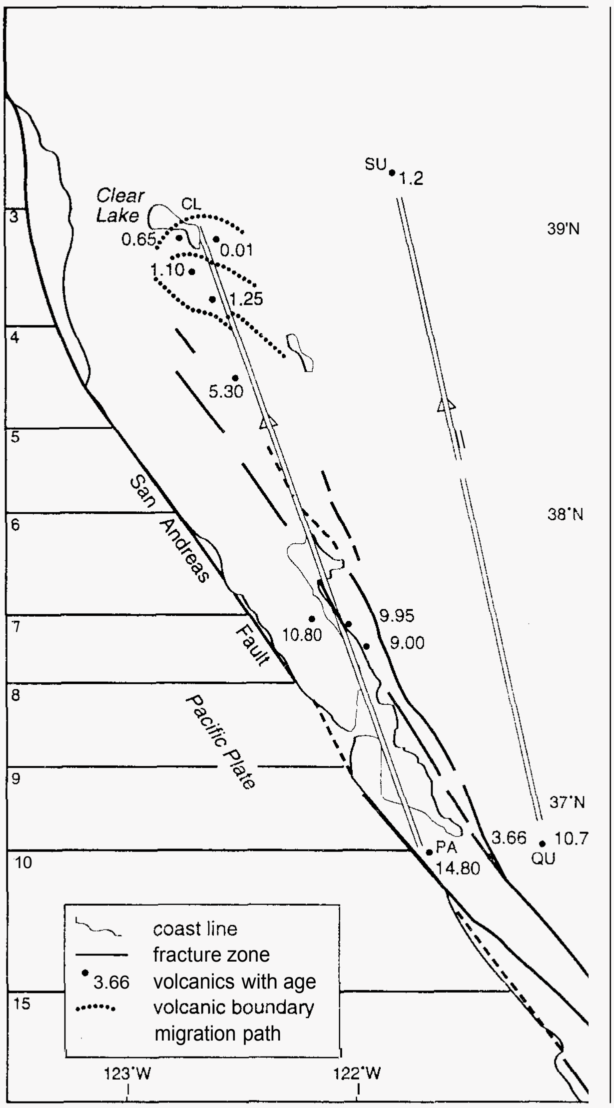

Figure 2: Restored map of northern California showing ages of volcanics. Four major occurrences are named: CL=Clear Lake, PA=Page Mill, SU=Sutter Buttes, QU=Quien Sabe. The centers of other volcanic fields are marked by filled dots with dates in Ma. Ages of volcanism from various sources. The offshore traces are locations of the Mendocino Fracture Zone at dates from 3 to 15 Ma. The Mendocino triple point is off the map at 40.35°N **124.75°W.The** migration paths QU-SU and PA-CL are conjectural.

The Mendocino triple point has migrated north for the time periods 0-4.5, 4.5-10, 10-21.2, and 21.2-29 Ma, at the rate of 55, **40**, 13 and 40 km/Ma, respectively (Atwater & Molnar, 1973). The total displacement is therefore 532.5 km in 15 Ma, in the direction 325°EofN parallel to the San Andreas fault. The magmatism may be explained as triggered by the passage of the triple point, with **a** lag of about 4 Ma for the volcanics to appear at the surface. The inland component of volcanic migration is then attributed to transform jumps.

Volcanic Petrogenesis: According to Johnson & O'Neil (1984), Neogene magmatic activity north of San Francisco Bay began at about 12 Ma with the pyroxene-rich Tolay basalt-andesites. Partial melting of the crust began with the Sonoma Volcanics at about 9-11 Ma, with eruption of rhyolite and rhyodacite flows, and at 8 Ma, large volumes of andesite. At about 5 Ma. partial melting reached relatively shallow levels as evidenced by the oxygen geochemistry and the large volume of pyroclastic eruptions.

Between 2.7 and 2.1 Ma, the locus of magmatism shifted north to the Clear Lake area.

4. GEOPHYSICAL OBSERVATIONS

Heat flow: Lachenbruch & Sass (1980) found a band of high heat flow, 100-km from west to east, extending south from Cape Mendocino in northern California. North of the cape, the average heat flow is low, ahout 1 hfu. Southwards, the flow increases for about 200 km, to reach about 2 hfu near Clear Lake, which level is sustained for another 550 km further south.

They showed that the anomaly could be due to conductive heating of the North American plate after passage at the triple point. The increase southwards away from the Mendocino triple point indicates an increase in heat flow by a factor of 2 within 4 Ma after passage.

Velocity structure of lithosphere: The "average" thickness of the lithosphere in the western United States is 60-80 km. Zandt (1981) discovered a linear zone of lower-than-average velocity (0 to -4%) in the upper mantle at depths between 30 and 60 km under the Coast Ranges northwest of San Pablo Bay. The depth to the asthenosphere may be as little as 35 to 40 km beneath the eastern edge of the Coast Ranges. He explained the feature as a "narrow upwarp of asthenosphere" due to lithospheric extension.

Isostatic gravity anomaly: The isostatic gravity residual field of northern California shows two ranges of values. From 38°N to about 40°N latitude, residual values range from -10 to +10 mGal. North of about 40°N latitude, values range from -40 to -25 mGal. The boundary between the two regions is a gravity gradient trending 123°EofN for 120 km from near Cape Mendocino. The gradient also has expression in seismic and magnetic data.

The gradient was interpreted by Jachens & Griscom (1983) as the buried south edge of the Gorda plate, that is, the northern edge of the slabless window of Dickinson & Snyder (1979b). The data is fitted by an upper mantle density of 3.25 kg/m^3, a density for material in the slab window of 3.21 kg/m , and a thickness for the North American plate of *20* km

Topographic Uplift: Longitudinally, the highest elevations in the Coast Ranges occur near Cape Mendocino. There is a systematic southward decrease of 400-600 m to the San Francisco Bay area (Jachens & Griscom, 1983).

They suggested this was due to thickening and sinking of the North American plate with distance from the Gorda plate edge, analogous to sinking of oceanic plates away from midocean ridges.

The transverse uplift is due to thermal expansion of the lithosphere, coupled with buoyant loading from below. Furlong (1984) modelled the flexural effect as a distributed load on an elastic plate. He found that the elevated topography of the Coast Ranges is dynamically supported by isostatically driven flexure.

Slabless Window: The geophysical observations indicate that the San Andreas transform is, at depth, a discontinuity in the structure of the lithosphere, with several processes proceeding simultaneously. These processes are observed through their coupled effects in the seismicity and lithospheric structure, topography and gravity field, heat flow and magnetic field.

Relative to the North American plate, the slabless window can be viewed as the instantaneous disappearance of the subducting slab, creating a sublithospheric void. The void propagates northwards in pace with the triple junction. The appearance of the void is a an impulsive change in the subsurface geometry and the resultant deformation as a transient response to that. The asthenosphere feels the passage of the triple junction as a sudden removal of load (effectively, instantaneous lithospheric thinning, Furlong, 1984), to which it responds by uplift and decompression.

As the Gorda plate moves northward relative to the North American plate, asthenosphere ascends in a narrow channel adjacent to the south edge of the Gorda plate, accreting to the North American plate as shown in Figure 3.

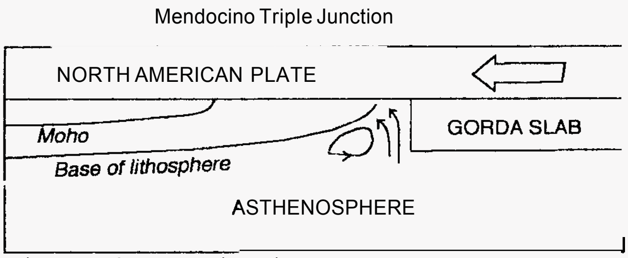

Figure 3: Longitudinal (north-south) cross-section of the Pacific-North American plate margin. Based on Lachenbruch & Sass (1980) and Zandt & Furlong (1982).

The slabless window supersedes earlier ideas of a potential gap in the subducting plate termed a "stable no-slab window" by Dickinson & Snyder (1979b), and an "unstable triple point" by Dickinson & Snyder (1979a) and Zandt (1981).

Tectonic Setting: Furlong, Hugo & Zandt (1989) modelled the thermo-mechanical evolution of the San Andreas transform fault zone in central and northern California and found the lithospheric configurations shown in Figure 4. The crust strengthens through underplating and cooling, then the transform jumps landward between (a) and (b), with a piece of lithosphere being transferred from the North American to the Pacific Plate, or "captured" by the Pacific Plate.

The Geysers steamfield and Collayomi fault are located on the tectonic profile of Figure 4(c). The steamfield is placed above the slabless window.

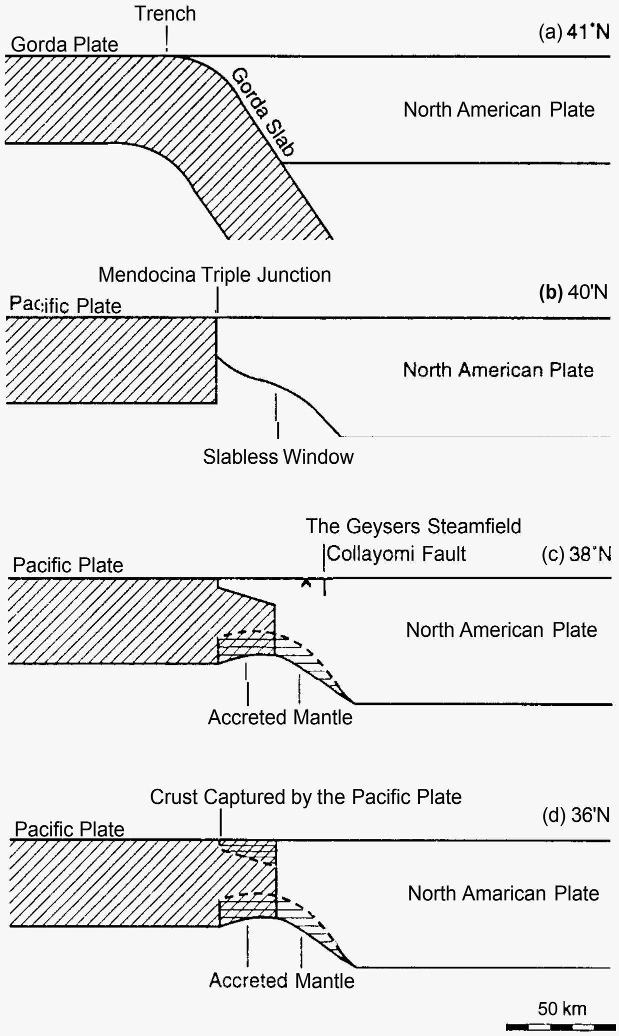

Figure 4: Lithospheric configuration and fault zone evolution after passage of the Mendocino triple point. (a) is in northern California at. 40°N, (b) is near San Francisco Bay, (c) is in central California near 36°N. Based on Furlong, Hugo & Zandt (1989).

Configuration of Heat Source: Liu & Furlong (1992) modelled the pressure-release partial melting in the upwelling asthenosphere. They found that a huge basalt pool might be formed at a depth of about 30 km, nearly 10 km thick and 50 km wide, with a temperature of about 1350°C. Melt drawn from this pool, and injected as large sills at shallow depth, is likely to be the most important source term in the shallow heat flow.

It is deduced that basalt sills underly most of the region, so the heat source is shaped more like a buried plate than a buried cylinder. The wide area of horizontal temperature gradient is caused by the plate Subtending a large and fairly constant solid angle at all points in the field.

5. HOT DRY ROCK RESOURCES

The Geysers-Clear Lake geothermal anomaly: The Geysers-Clearlake geothermal anomaly is shown in Figure 5. The heat flow in the steamfield has a flat central high at about 12 hfu, elongated in the NW direction. The steamfield high declines steeply to 8 hfu, where the rate of descent lessens. The steep decline enables us to separate the geothermal anomaly into two parts, The Geysers steamfield with heat flow of 8 hfu and larger, and a surrounding Geysers-Clear Lake anomaly.

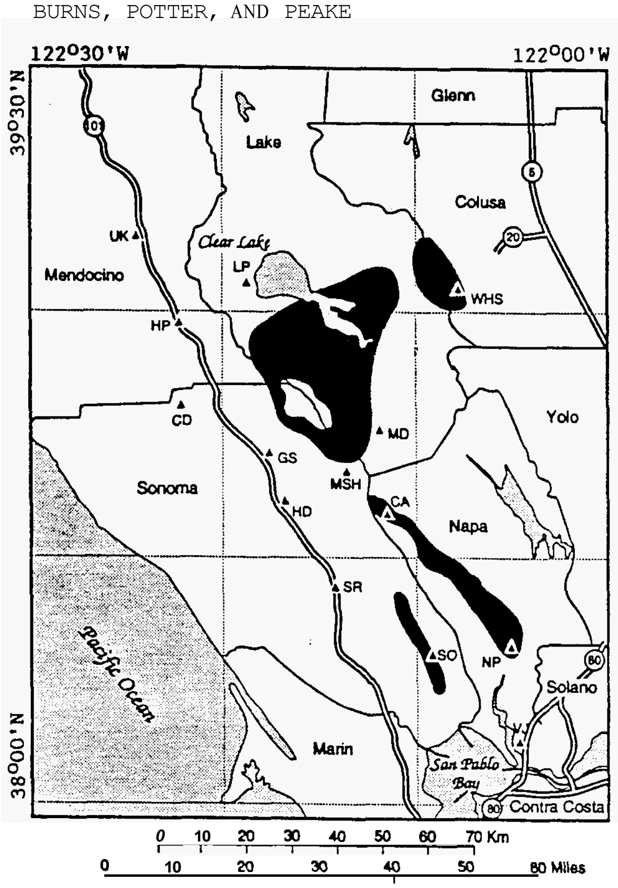

Figure 5: The Geysers-Clear Lake area. The shaded areas are geothermal anomalies, with heat flow higher than 4 hfu, after Higgins (1980). The largest region is The Geysers-Clear Lake area, with The Geysers steamfield shown blank. The smaller regions are Wilbur Hot Springs (WHS); the Napa Valley (CA-NP); and the Sonoma Valley (SO).

The Geysers-Clear Lake anomaly has a "heat flow axis" trending NNE from the steamfield. Along this axis, the heat flow drops off at the rate of 6.3 km/hfu. The rate of decrease of heatflow across the axis is steeper, at 3.9 km/hfu. The outer boundary of the anomaly is arbitrarily placed at the 4 hfu contour by Higgins (1980).

Heat flow data has been collected by three workers, with results as shown in Table 1. The averages show the decline of 2 hfu down from the steamfield, followed by slow decline from the area of the central axis to the area of the outer margin.

Region	No.	Min.	Mean	S.D.	Max.
Steamfield	124	1.4	7.7	5.1	46.3
NW central axis	86	1.5	5.7	2.9	16.4
Outer margin	67	3.1	4.3	0.7	6.1

Table 1: Heat Flows. Data in row 1 is from Thomas (1986). row 2 is from Burns (1989), row 3 from Walters & Combs (1989). Units are hfu.

Conductive geothermal gradient: The region outside the steamfield is a conductive heat flow regime, as illustrated in Figure 6. The prime HDR target area is the Geysers-Clear Lake geothermal anomaly minus The Geysers steamfield. The area is about 810 km^2. Estimated gradients range from 86.21 to 92.13 °C/km. Gradients higher than 100°C/km occur, and are due to localised advective disturbances.

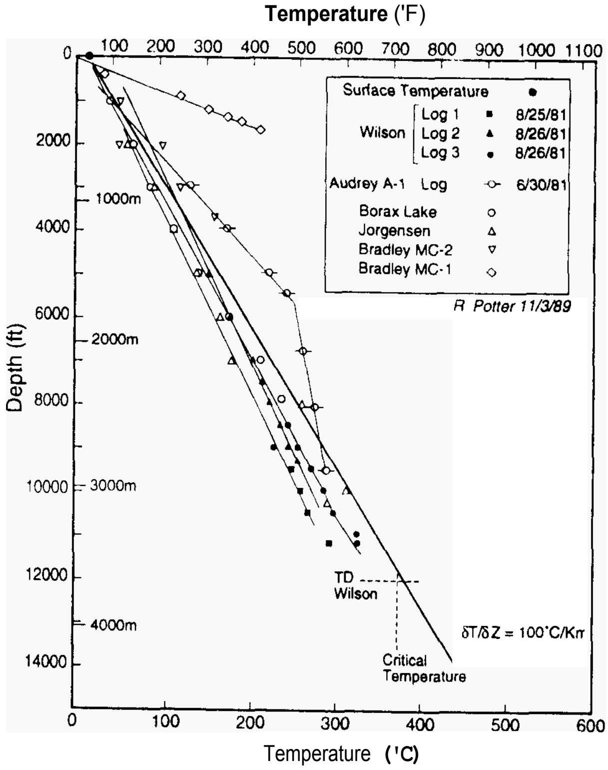

Figure 6: Geothermal gradients for some deep wells located on the "heatflow axis". After Burns & Potter (1990).

Heat resource: The geothermal anomaly was initially regarded as a collection of several centers, comprising The Geysers steamfield, a Clear Lake volcanic field centered on Mt. Konocti, and a large hot water spring at Sulphur Bank, and heat resources were calculated for each of these separately. Smith & Shaw (1979) ascribed the temperature field of the Clear Lake volcanics to lateral conduction from high level silicic magma chambers and estimated the heat content at 3422 quads (using conversion factors from Armstead & Tester, 1987). The existence of a large HDR resource in the Franciscan basement was recognized in Goff & Decker (1983) who calculated the same heat content.

Restricted resource base: The calculation of heat content requires knowledge of the geothermal gradient in depth, which usually has to be inferred from geological models of the heat sources. Armstead & Tester (1987, p.38) define the restricted resource base within reach as the heat contained in crustal rocks above a minimum useful temperature and at an attainable depth of penetration. The impermeable part of The Geysers-Clear Lake geothermal anomaly has an area of 810 km^2, and a geothermal gradient in depth of approximately 100°C/km as shown in Figure 6. We adopt 5 km as the attainable depth, and 15°C as the minimum useful temperature. The resource at Clear Lake is then 2268 quads This amount is 2.8 quads per km^2 down to 5 km, which might be compared to the average of 1 quad for the same depth in U.S. thermal areas (Armstead & Tester, 1987, p.49). Clear Lake is thus a very high-quality resource compared to the US thermal average.

Production Potential: The previous figure of 2.8 quads/km2 is an estimate of the heat content above ambient surface temperature. The figure is useful for comparing geological processes. However all this heat is not extractable and a different estimate is required which takes into account accessibility and efficiency of extraction.

For initial development, we define the HDR resource as a layer 1 km thick with an average temperature of 300°C. The depth to the 300°C isotherm is estimated as 4.7, 3.2 and 2.4 km for heat flows of 4, 6, and 8 hfu respectively. So we define a "production layer" which undulates beneath Clear Lake at depths from 2.4 to 4.7 km. The Fenton Hill reservoir is at 4.35 km which shows that these depths are readily accessible.

Within this layer, reservoirs would be created by stimulation, as at Fenton Hill. However water at 25°C introduced into fractured rock at 300°C would produce severe contraction, with cracking and spallation, so we suggest that it may be possible to construct at Clear Lake large, low-impedance reservoirs similar to block caved openings in the minerals industry or "rubbilized retorts" in oil-shale. The heat could then be produced by methods analogous to the bottom-up water-flood of the oil industry (Armstead & Tester, 1987, p.252). The cold water is injected at the bottom and rises very slowly, at a rate compatible with effective heat transfer from the faces of solid blocks to the water. This rate can be lowered for given production rate by enlarging the reservoir. Produced water is taken out the top. The water column is convectively stable so that the hot water is carried upwards ahead of a dense, cold layer. The process stops at cold water break-through. The reservoir then becomes a cooled pocket of rock and is abandoned.

The thermal energy contained in a cubic kilometer of rock cooled from a mean 300°C to 15°C is 0.6 quads or 20 000 MWyt. This is the heat contained in the "production layer" at one potential extraction site.

The heat that could be usefully recovered at each site depends upon reservoir, plant and market conditions. Burns & Potter (1990) described one scenario with a production temperature of 300°C, condensation temperature of **37.5°C**, and estimated the financial break-even point could be achieved at a production rate of 2.4 MWe or 12 MWt.

7. CONCLUSIONS

The geothermal areas of northern California have heat flows exceeding 4 hfu over a combined area exceeding 1 280 km^2. The high heat flows have been attributed to an asthenospheric upwarp generated at a slabless window trailing the northward-moving Mendocino triple junction. Decompression melting of the mantle has led to basaltic underplating, and crustal anatexis. The Geysers-Clear Lake geothermal anomaly has a broad, NE-trending heat flow "axis" with crest averaging 5.7 hfu above which The Geysers steamfield rises to more than 12 hfu. The conductive region surrounding the steamfield is the Hot Dry Rock resource. It has an area of 810 km^2 in which the heat flow exceeds 4 hfu, the geothermal gradients approach 100°C/km, and the 300°C isotherm is at depths from 3.2 to 4.7 km.

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