

and below the softening point. These data were used to calculate the absorption coefficient $\alpha(\lambda, T)$ and the radiative thermal conductivity $K_r(T)$. K_r ranged from $3 \times 10^{-3} \text{ cal cm}^{-1} \text{ s}^{-1} \text{ K}^{-1}$ at 700°C to $12 \times 10^{-3} \text{ cal cm}^{-1} \text{ s}^{-1} \text{ K}^{-1}$ at 1145°C ; the 700°C value is comparable to lattice thermal conductivity K_l in obsidian of about $1 \times 10^{-3} \text{ cal cm}^{-1} \text{ s}^{-1} \text{ K}^{-1}$. Removing scattering effects from observed spectra increased K_r to $20 \times 10^{-3} \text{ cal cm}^{-1} \text{ s}^{-1} \text{ K}^{-1}$ at 1145°C . These measurements indicate that radiative heat transport in active plutons, where scattering is likely to be small, is greater than the lattice conductivity by more than a factor of 2 at 1000°C . Thus radiative heat transport is probably the dominant component of the total thermal conductivity $K = K_l + K_r$ in silica-rich magmas. The consequence of a larger K is that a larger temperature difference must exist across a magma body before convection can take place.

791A-09

Use of Temperature Inversion Data for Determining the Age of Fracturing in a Geothermal Area

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Temperature inversions at shallow to moderate depths have been observed commonly in boreholes drilled in geothermal areas. The inversions result from thermal disequilibria generated by steam and/or hot water invading shallow, horizontal, or sub-horizontal fractures or permeable zones, from a deep vertical, or sub-vertical feeder-fracture. Field data from a number of boreholes drilled in the Momotombo geothermal area in Nicaragua, Central America, were applied to a two-dimensional, time-dependent mathematical model of the temperature field along such a fracture system. The solution of the model is given by:

$$T(x, y, t) = T_0 - \frac{a}{\sqrt{4\pi k t}} \operatorname{erfc}\left(\frac{(x-y)/2}{\sqrt{k t}}\right) \quad (\text{Ziagos and Blackwell, 1981})$$

where: $a = K/v\sqrt{C}$

T_0 is the temperature of the hot fluid in the feeder-fracture;

v is the velocity of the fluid moving through the fracture;

M is the mass of the fluid in contact with a unit area of rock;

C is the heat capacity of the hot fluid;

K is the thermal conductivity of the rock;

k is the thermal diffusivity of the rock;

l is the depth of the horizontal fracture or permeable zone;

$T(x, s, t)$ is the temperature at a distance x from the feeder-fracture, at a depth s and for a time t since invasion of the fracture system by the hot fluids.

Preliminary results suggest that the tectonic event that generated opening of the fracture system at Momotombo occurred about 1.25×10^3 years ago.

791A-10

Gravity and Surface Elevation Changes at the Cerro Prieto Geothermal Field

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Four precise gravity and second order leveling surveys were carried out annually at the Cerro Prieto Geothermal field for the purpose of 1) providing information about temporal changes in the geothermal reservoir, and 2) obtaining the Bouguer gravity map of the field.

Seventy permanently monumented stations were occupied using the looping technique with a Leica C and a Leica G meter. Data were reduced by standard procedures to obtain observed and Bouguer gravity values. The precision of the observed gravity values was of the order of 7-11 microgals for entire surveys. Standard measurement errors for an individual year were about 8 microgals at the 95 percent confidence level. Precision of observed changes between two years was about 12 microgals. Changes in gravity exceeding 15-20 microgals are clearly significant.

Gravity and surface elevation changes over time displayed large changes associated with the 9 June 1980 Victoria earthquake ($M_w 6.1$). The field is located in a zone of intense aftershock activity which followed this earthquake. Gravity increases of up to 80 microgals and subsidence of the order of 25 cm were observed. Small seismic changes in gravity and surface elevation observed prior to the earthquake suggest the reservoir is being recharged by fresher and cooler water in response to continued production. The positive

Bouguer anomaly is due to hydrothermal densification of the subsurface sediments.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00096.

791A-11

Heat Flow, Gravity and Magnetism in the Cascade Range of the Pacific Northwest

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Over the past six years an extensive heat flow program resulting in 300 heat flow measurements has been carried out in the Cascade Range of the Pacific Northwest. These data combined with recent data published for the California and British Columbia portions of the Cascade Range allow an almost complete picture of heat flow lengthwise along the Cascade Range. Very high thermal gradient and heat flow values are found in the Oregon part of the Cascade Range. There measurements over an E-W width of 20-30 km and N-S length of 200 km indicate regional gradients $60\text{--}65^\circ\text{C/km}$ and heat flow values of 100 mW m^{-2} . From Mt. Hood north to the vicinity of Mt. Ranier, average gradients are approximately $45\text{--}50^\circ\text{C/km}$ and heat flow values are approximately $70\text{--}90 \text{ mW m}^{-2}$. North of Mt. Ranier, heat flow values range between 50 and 70 mW m^{-2} with geothermal gradients of approximately 25°C/km . This pattern appears to be typical of the Cascade Range into British Columbia. Extensive drilling in the vicinity of three of the stratovolcanoes, Mt. Lassen, Mt. Hood and Meager Mountain demonstrate that the thermal character of the volcanoes depends on the individual volcanic and hydrologic setting and history. In general heat flow is consistent with the 5 to 10 decrease in the amount of Quaternary volcanism. The discontinuous heat flow changes correspond to areas where rates of volcanism also change. Heat flow data have been interpreted to indicate a large subvolcanic magma chamber in the Oregon Cascade Range. This magma chamber is either not present in the northern end of the Cascade Range or is very subdued, consisting only of isolated local pockets which are hot enough to be partially molten. Analysis of gravity data from Central Oregon outline a gravity anomaly which may be associated with a magma chamber and show no such gravity anomaly in the Washington part of the Cascade Range.

791A-12

Geothermal and Structural Implications of Magnetic Anomalies observed over North-Central California

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To aid in assessing the geothermal potential of the Cascade Range and Modoc Plateau of north-central California, the Geophysics Group at Oregon State University made total field aeromagnetic measurements between $40^\circ 15'$ and $42^\circ 00'$ N latitude and $120^\circ 45'$ and $122^\circ 45'$ W longitude.

A broad low-amplitude negative anomaly, trending N 35° W, suggests the Big Valley fault zone may extend as far north as Timber Mountain beneath the quaternary volcanics of the Modoc Plateau.

Spectral analysis of the aeromagnetic anomalies provided source-depth and depth-to-bottom calculations. Shallow magnetic source-bottom depths in four of five regions were interpreted as Curie-point isotherm depths. Those regions with elevated Curie-point isotherm depths were (1) Secret Spring Mountain and National Lava Beds Monument areas, (2) Mount Shasta area, (3) the Big Valley mountains area, and (4) an area northeast of Lassen Peak. Assuming a Curie-point temperature of 580°C , the elevated Curie-point depths within these areas, as shallow as 4 to 6 km BSL (below sea level) in the Big Valley Mountains area and 4 to 7 km BSL in the Secret Spring Mountain, National Lava Beds Monument, Mount Shasta, and northeast of Lassen Peak areas, imply vertical temperature gradients in excess of 70°C/km and heat-flow values greater than 120 mW m^{-2} . A fifth shallow region, in the Eddy Mountains area, had a 4 to 5 km BSL bottom-depth and was attributed to a lithologic boundary.

791A-13

Heat Flow in The Colorado Plateau

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The silica heat flow method has been used to estimate heat flow in the interior of the Colorado Plateau (4094 points) and areas immediately adjacent to the

Plateau (5344 points) with the following results: 1) The interior of the plateau has a mean heat flow of $55 \pm 11 \text{ mW m}^{-2}$ (1.35 J/KU). Thermal perturbation in the mantle which caused isostatic uplift has not yet been conducted to the earth's surface over most of the plateau. 2) The margins of the plateau generally have high ($\sim 82 \text{ mW m}^{-2}$) heat flow where the thermal lithosphere is being "eaten away", possibly by lateral transfer of heat into the plateau lithosphere from neighboring Basin and Range and Rio Grande provinces. In the north, however, the plateau is thermally indistinguishable from adjacent areas. 3) The parts of the plateau which have the lowest heat flow ($< 44 \text{ mW m}^{-2}$ or 1 S.D. below the mean) are general in the west and most are located in Utah. The parts which have the highest heat flow ($> 66 \text{ mW m}^{-2}$ or 1 S.D. above the mean) are more common in the east and most are in Colorado, New Mexico, and eastern Arizona. These high heat flow areas contain most of the earlier traditional heat flow measurements and this has led to overestimates in the mean plateau heat flow. 4) Hot spots in the plateau are related to magmatic convection of heat into the plateau lithosphere, manifest by surface volcanism. 5) Of the 19 localities where both traditional and silica heat flow can be defined by a large and consistent data set, the agreement is better than $\pm 10\%$ for 17 of the areas and better than 20% for all areas.

791A-14

A Heat Flow Anomaly in the Great Plains

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Five heat flow and 27 temperature gradient measurements indicate anomalous heat flow as high as 140 mW m^{-2} and temperature gradients ranging from 60 K km^{-1} to 110 K km^{-1} extending over an area of about 4000 km^2 in South Dakota and Nebraska. In previous reports of the anomaly, we attributed the high heat flow to upflow flow in the Dakota Aquifer which underlies the area at depths ranging from 700 m in the west to 300 m in the east. However data from a new heat flow hole near Burton, Nebraska indicate that the heat source lies below the Dakota and is probably on or in the Precambrian basement. Preliminary heat flow numbers calculated from estimated thermal conductivities are about 107 mW m^{-2} for all lithologic units in the Burton well. We propose two possibilities for the heat source: (1) regional groundwater flow in an unrecognized aquifer near the top of the Precambrian surface, or (2) high radioactive heat generation in the crystalline basement. Geological data do not favor the existence of a continuous aquifer in the Paleozoic rocks in the area, however the data are not numerous and the possible existence of a deep aquifer is not discounted. Data on the Precambrian rocks are also few and are conflicting, i.e., some sources report granites and others report schists. The possible existence of high radioactivity basement rocks has interesting implications for the nature of the basement and for economic geology considerations such as the maturation of hydrocarbons and the occurrence of geothermal resources.

ISOTACTY, THE LITHOSPHERE, AND MID-PLATE TECTONICS

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792A-01

The Origin of Positive Bouguer Gravity Anomalies Adjacent to Mountain Systems

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The gravity anomaly associated with mountain ranges is a sensitive indicator of both the mechanical properties of, and the distribution of loads acting on or within, the continental lithosphere. The Bouguer gravity anomaly over the Alpine and Appalachian mountains is characterized by a generally asymmetric gravity "low" which spans the mountains and associated foreland basins. In contrast, the hinterland basins (Po Basin of the Alps and coastal plain of the Appalachians) are characterized by a generally symmetric gravity "high". We have interpreted this gravity anomaly couple as evidence for flexure of the continental lithosphere by surface (topographic) and subsurface (buried) loads. The magnitude of this "high" represents the integrated gravity effect of these loads which includes obducted crustal blocks mobilized during continental collision. However, since these blocks are not significantly represented in the mountain topography, an additional buried load is required to explain the Bouguer anomaly. The existence of this load explains why: (1) Crustal blocks have had low relief throughout their history, (2) Molasse basins are not destroyed when their respective mountains have been eroded, and (3), Proterozoic suture zones show the same characteristic positive-negative gravity

Blackwell (Heat)