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CHARACTERISTICS OF SELECTED GEOTHERMAL SYSTEMS IN IDAHO

James K. Applegate and Paul R. Donaldson

Department of Geology and Geophysics, Boise State University
Boise, Idaho 83725

Abstract. Many areas of Idaho exhibit geothermal potential. Large areas of the southern portion of the state have been explored by commercial firms, and numerous areas were identified by White and Williams (1975) as having high geothermal potential. Only limited drilling has been accomplished, and most evaluations have been based on geophysical, geological, and geochemical data. Regional geophysical data supplemented by local surveys suggest the lack of a localized heat source. Instead, geological and geophysical studies suggest that the occurrence of geothermal systems in this area results from heat concentration below an insulating layer. The insulation typically comprises an interbedded sequence of sediments and volcanics. The noncontinuous permeability in such a sequence restricts the development of large-scale convection systems. Otherwise the insulating properties of the sequence would be lost to convective heat transfer. Specific geothermal reservoirs result from structural controls such as fault and fracture related porosity. Initial studies in three areas of Idaho support these concepts.

Introduction

Geothermal exploration has, because of its infancy, been primarily based on geologically simple models with a discrete heat source and a discrete reservoir. This classical model invariably requires geological evidence, generally youthful rhyolitic volcanism, for the existence of the localized heat source. The lack of rhyolitic volcanism has the effect of eliminating many otherwise interesting areas from consideration for geothermal exploration. If acceptable alternative models exist that do not require such evidence, then the previously eliminated areas which may be more representative of the low to intermediate temperature systems prevalent throughout the western United States would again be prospective.

Initial studies in three geothermal areas of Idaho suggest a hypothetical model without a localized heat source. This alternative model is characterized by (1) heat entrapped beneath a thermally insulating cover of interbedded sediments and volcanics, (2) the absence of widespread convection in the insulating cover due to the lack of continuous permeability, and (3) resource localization controlled by structural features. In the following discussion, data from each of the areas will be used to establish the plausibility of the hypothetical model.

Boise Geothermal System

Portions of northeast Boise have been heated by geothermal water since the 1890's. The fluids are produced from two shallow (approximately 120 m) wells and are postulated to represent leakage from a deeper reservoir.

Exploration was initiated in early 1975 in an attempt to define the shallow resource and its relationship to the overall geothermal system. Studies undertaken include microseismic monitoring, electrical resistivity mapping, magnetometer profiling, geochemical thermometry, and general geological mapping utilizing vertical and oblique aerial photography. Additional data available included regional gravity, regional magnetics, and U-2 and satellite imagery.

Geology

The Boise area is on the northern edge of the western portion of the Snake River Plain (Fig 1) and lies in the transition zone between the plain and the Idaho Batholith. The Snake River Plain appears to be a tensional basin filled with over 4 km of sediments and volcanics.

The local geology consists of alluvium overlying Tertiary lacustrine sediments and volcanics which lap onto the Idaho Batholith. The batholith is primarily quartz monzonite of Cretaceous age. The local structure is dominated by the northwest-southeast trending Boise fault [Malde, 1959]. This normal fault, downthrown toward the plain, is located along the topographic break between the plain and the foothills.

The Boise fault and a series of north to northeast trending features extending from the batholith toward the plain are well defined on Landsat imagery (Fig 2). The intersections of these two sets of features present prime exploration targets.

Geophysics

Geophysical studies in the area were undertaken to define further the location and extent of the structures suggested by the linear features. If these features are representative of faults, they may be expected to exhibit microseismic activity and to be characterized by resistivity, magnetic, and gravity anomalies.

Continuous microseismic monitoring for over 18 months has failed to delineate any local (within 30 km) seismic activity. Significant activity has been detected from eastern Oregon and from within the Idaho Batholith, suggesting that the transition zone between the western Snake River Plain and the batholith is aseismic.

Resistivity data were acquired for the area by utilizing a rotating bipole source and roving dipole receivers [Furgerson and Keller, 1974; Donaldson and Applegate, 1975]. This technique is particularly sensitive to lateral resistivity changes, which may be indicative of geological structures.

Several electrical parameters can be calculated from this type of resistivity mapping data. Two commonly used parameters are apparent resistivity and total longitudinal conductance. The apparent resistivity map (Fig 3) and the total conductance map (Fig 4) are contoured from over 200 data points which approximate a 0.75-km grid of receiver stations in the survey area.

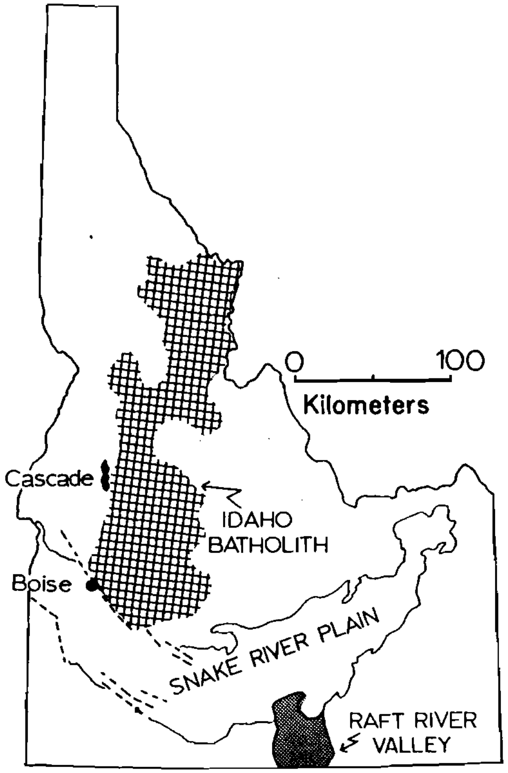

Fig. 1. Index map showing locations of the three (Boise, Cascade, and Raft River) geothermal areas to be discussed and their spatial relationships to the Idaho Batholith and the Snake River Plain.

The apparent resistivity (Fig 3) shows steep gradients probably related to the Boise fault and orthogonal structural features. There is a low apparent resistivity trend associated with hot water producing wells near the old State Penitentiary and a large low to the northeast of the source, which is in an area of former hot spring activity. The total conductance map (Fig 4) shows two linear trends. These two linears appear to correspond to the Boise fault and one of the major north-northeast oriented features. A Schlumberger equivalent equatorial dipole profile shows resistive basement at about 2.5-km.

Magnetic profiles (not shown) and the regional gravity map (Fig 5) provide corroborative evidence for two intersecting fault systems. Additionally, estimates of basement depth on the basin side of the Boise fault from gravity and resistivity data are in substantial agreement. Neither resistivity nor gravity suggests the presence of a localized heat source.

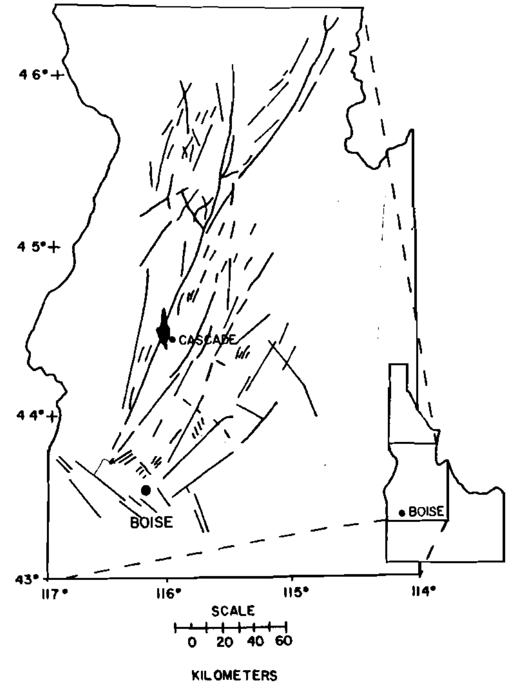

Fig. 2. Map showing major Landsat features in a portion of west central Idaho (modified from Day [1974]).

Discussion

The foregoing data suggest the following geologic model for the Boise geothermal system (1) a fault-controlled basin edge complicated by approximately orthogonally intersecting faults and (2) no indications of a localized heat source. Given the presence of an insulating cover, the existence of a basin boundary provides a mechanism for concentrating the trapped heat. The faults intersecting the basin edge provide the plumbing necessary for introducing the heat transfer medium, meteoric water.

A simplistic calculation [Diment et al., 1975] gives resulting temperatures of approximately 175° to 185°C at the base of a 2.5-km-thick thermal insulator with these properties (1) thermal conductivity of 7.0 mcal/cm s°C for the Idaho Batholith and 3.0 mcal/cm s°C for the sediments and (2) a heat flow of 3.0 μcal/cm^2 s [see Brott et al., 1976]. A silica geothermometry calculation using a mixing model for samples from existing Boise wells predicts an undiluted reservoir temperature of 165°C and 61% dilution (Fig 6). This excellent agreement strongly supports the validity of the model.

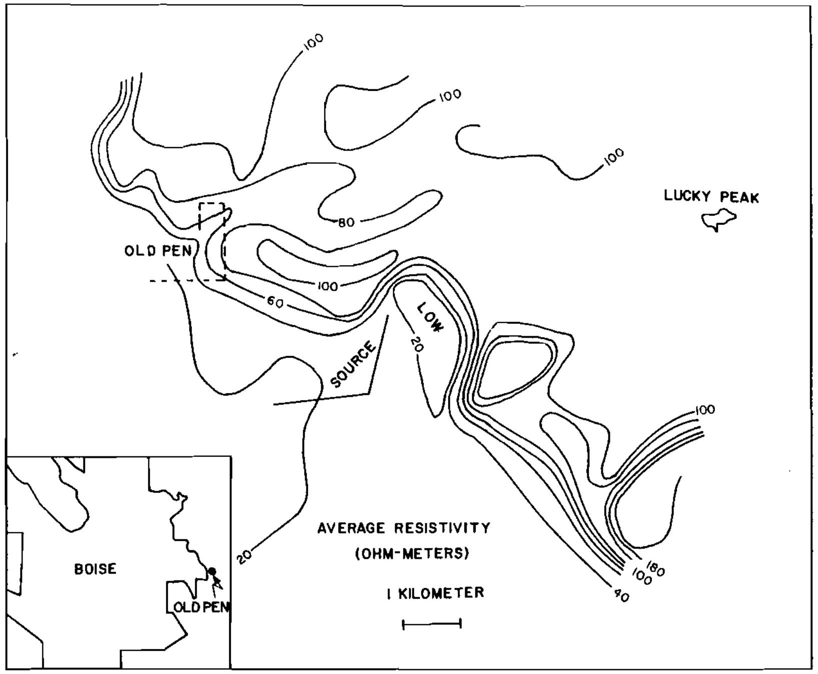

Fig. 3. Average resistivity map for a portion of the Boise area. The average resistivity is obtained by determining the apparent resistivity with the rotating bipole source and roving dipole receiver. A number of structural trends are clearly shown by the contours.

Cascade Geothermal System

The Cascade area lies in an area of extensive hot spring activity [see White and Williams, 1975]. Some local use has been made of the resource for recreation facilities, ice melting, and space heating.

Geological and geophysical studies were begun in 1975 to evaluate the feasibility of further exploration and development [Wilson et al., 1976]. Studies undertaken include microseismic monitoring, geochemical thermometry, aerial reconnaissance, and general geological mapping utilizing vertical and oblique aerial photography. Additional data available included regional and local gravity and satellite imagery.

Geology

The Cascade area is on the western margin of the Idaho Batholith. Three major rock zones in the area are quartz diorite gneiss, quartz

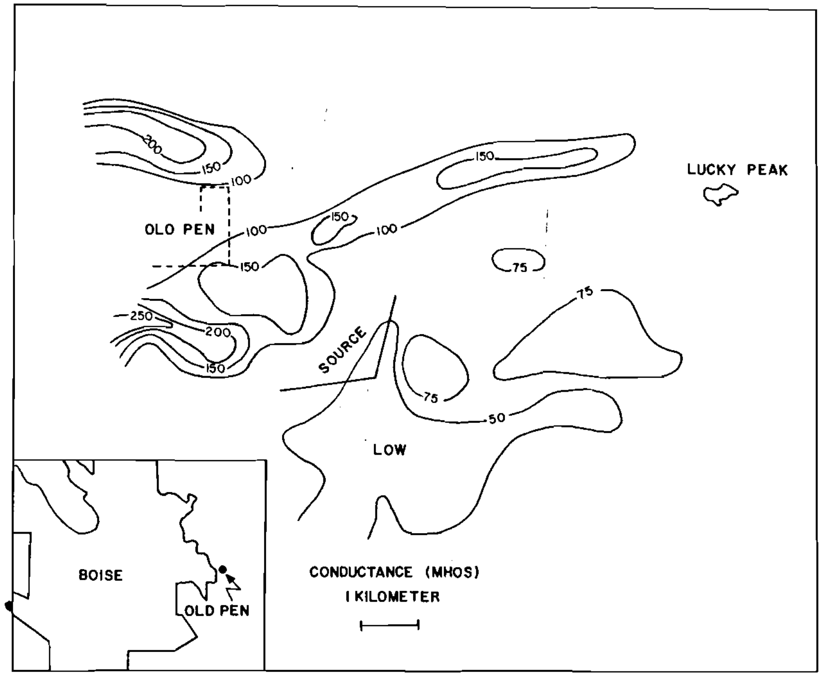

Fig. 4. Total longitudinal conductance map for a portion of the Boise area. The longitudinal conductance assumes cylindrical current spreading. Several major structural trends are prominent.

diorite, and granodiorite. In the western portion of the area, Columbia River basalts of Miocene age overlie the batholithic rocks [Wilson et al., 1976]. The Long Valley downwarp contains Quaternary and Pliocene(?) sediments [Schmidt and Mackin, 1970, p. 11]. A local gravity survey [Kinoshita, 1962] suggests basin fill thicknesses ranging from 600 to 2100 m.

Landsat imagery (Fig 2) shows a significant number of large-scale linear features with lengths of tens of kilometers. The major features have a north-northeast to north trend, while another set has a northeast trend. One of the major features trending north-northeast passes through the Cascade community [Wilson et al., 1976].

Detailed geologic mapping (Fig 7) shows faults with trends similar to the Landsat linears, suggesting that these linears are major fault features. The mapping also indicates a series of east trending faults that are essentially perpendicular to the direction of primary faulting. There are some indications of left lateral movements along these faults [Wilson et al., 1976]. The lack of erosion on these features suggests that there has been recent movement. Work by Cluff and Idriss [1972] indicates evidence for very recent movement along the Cascade-Sweet

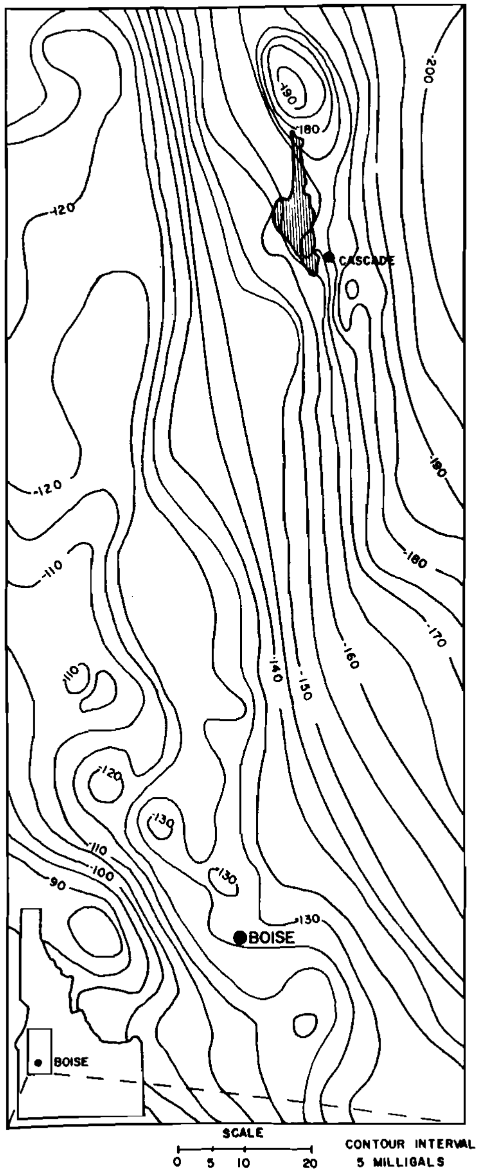

Fig. 5 Regional gravity map of a portion of west central Idaho showing the apparent lack of shallow intrusives [Mabey et al. 1974].

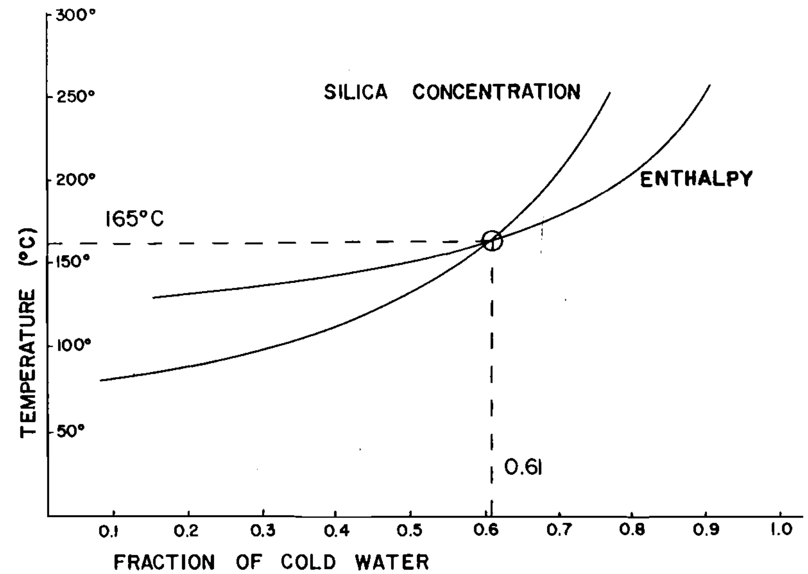

Fig. 6 Graph illustrating a mixing model calculation of a silica predicted temperature for the undiluted reservoir at Boise. The predicted temperature is 165°C with 61% dilution for the water produced.

fault system. This system appears to be related to the major linear through the Cascade area.

Geophysics

Studies of geophysical data from the area were undertaken to define further the location, extent, and activity of the faults indicated by the geological mapping. The earthquake data file from the National Earthquake Information Service indicates 13 locatable events in Valley County, Idaho, and 4 additional events for which 'felt' reports are available. The largest event was a magnitude 6.0 in 1945 located approximately 55-km northeast of Cascade. In 1970 there was a six-event swarm with earthquakes of magnitudes 3.5, 3.7, 3.8, 3.9, 4.3, and 4.3. This swarm occurred about 40-km east of Cascade. The events nearest Cascade were a 1966 quake of magnitude 3.5 20-km north of Cascade and a smaller event (1962 no magnitude given) located 10-km north of Cascade.

Microseismic monitoring was carried out for 8 days during the summer of 1975. The survey detected 24 events with S-P times of less than 4 s. Sixteen of these events occurred in the last 24 hours of monitoring. Locations for seven of these events (Fig 7) suggest activity along the east trending faults through Cascade. The depths for these 7 events fall in the range of 5 to 10 km. The two largest events in this swarm had magnitudes of approximately 0.75. The 17 other events were too

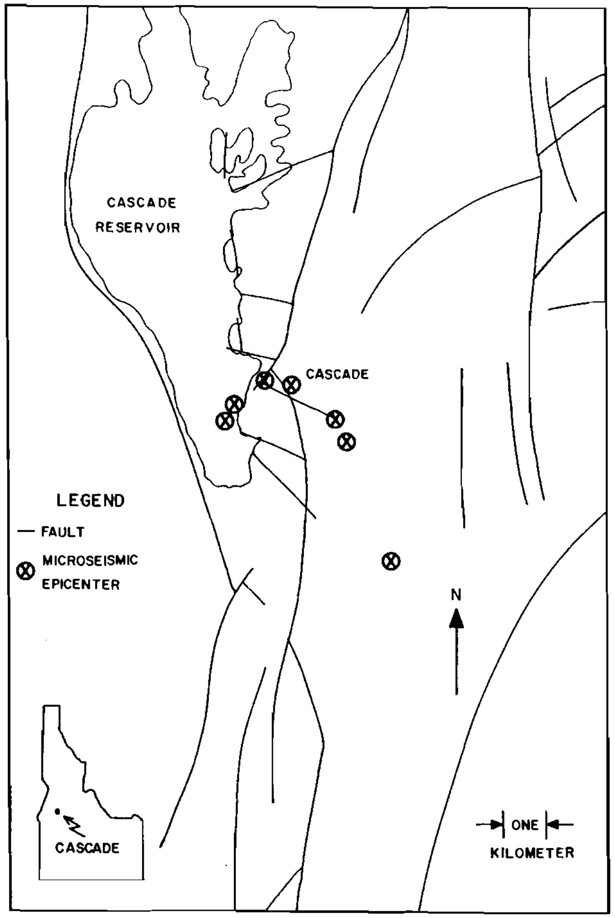

Fig. 7 Map of the Cascade area showing relationship between mapped faults and microseismic events recorded in one 8-day period.

small to be located but were similar in character to the located events [Wilson et al., 1976].

Gravity data [Kinoshita, 1962] (Fig 5) indicate several intermontane basins. The data suggest that these basins are fault bounded.

Discussion

Numerous active hot springs occur in the area and all appear to be fault controlled. The Cascade Reservoir has inundated what are reported to have been the largest and hottest springs. The reported location of

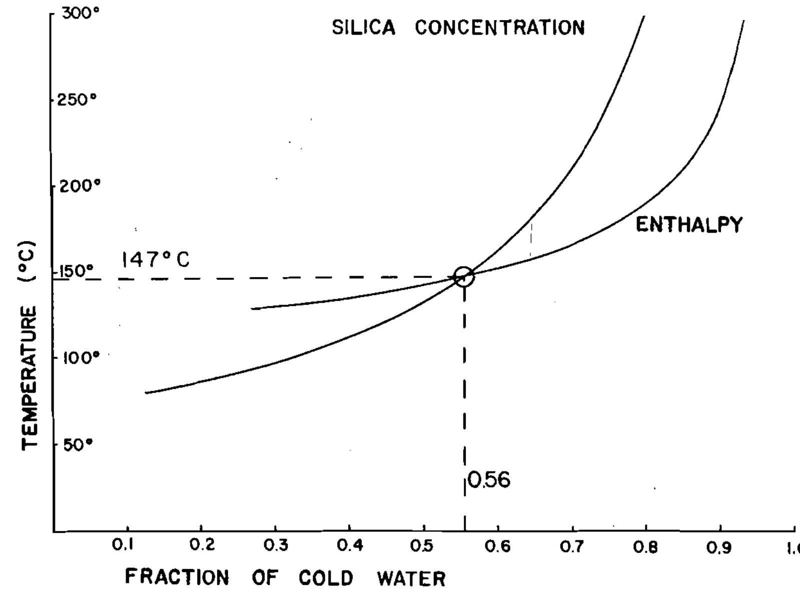

Fig. 8 Graph illustrating a mixing model calculation of a silica predicted temperature for the undiluted reservoir at Cabarton Hot Springs at the south end of Cascade Reservoir. The predicted reservoir temperature is 147°C with 56% cold-water dilution for the spring.

these springs is near the apparent intersection of one of the east trending faults and the major north-northeast trending linear feature. The hottest accessible spring in the area has a surface temperature of 71°C. A silica geothermometry calculation using a mixing model predicts an undiluted source temperature of 147°C and 56% cold-water dilution for this spring (Fig 8). The highest temperature predicted by geothermometry for any of the springs is 179°C [Wilson et al., 1976].

Interestingly, gravity data suggest a greater basin depth beneath springs with higher predicted undiluted temperatures and lesser depths beneath springs with lower predicted temperatures. These observations support the previously postulated model of heat concentration beneath a thermal insulating blanket of sedimentary fill. A thicker insulation would result in greater heat retention and thus higher temperature at the base of the blanket. Furthermore, there is no indication in the gravity data to suggest that near-surface intrusives provide a local heat source.

Raft River Geothermal System

Hot water produced from springs and shallow wells in the Raft River Valley has been used for agricultural purposes for many years. Studies have been undertaken recently to evaluate the commercial potential

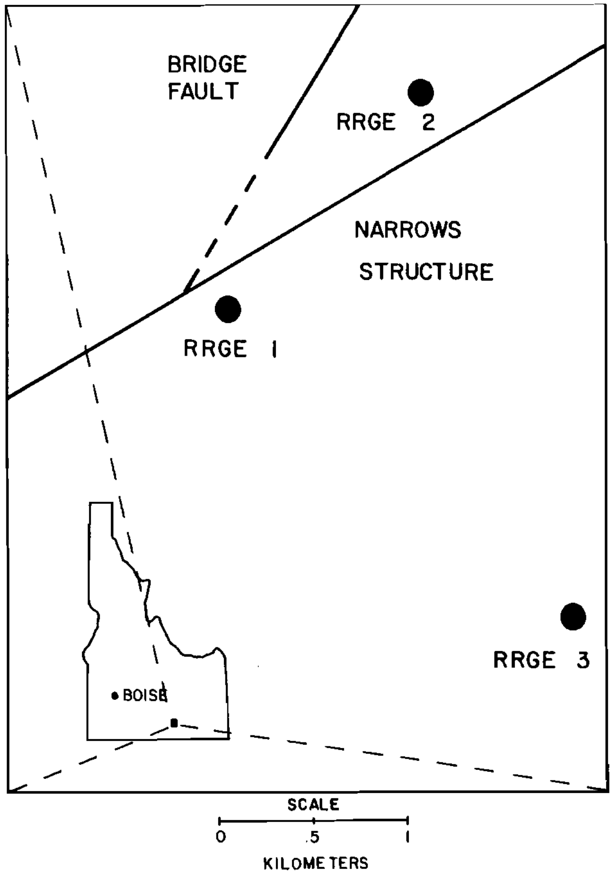

Fig. 9. Schematic map of the Bridge fault, the Narrows structure, and RRGE 1, 2, and 3. The Bridge fault is along the eastern flank of the Jim Sage Mountains, and the Narrows structure separates the Jim Sage Mountains from the Raft River Mountains (Fig. 10).

of the Raft River Valley further [Mabey et al., 1975; Williams et al., 1975; Zohdy et al., 1975; Ackerman, 1975; Nichols and Applegate, 1974]. These studies include a broad spectrum of geophysical and geological investigations. On the basis of these studies, three wells were drilled to depths of approximately 1500 to 1900 m in 1974 and 1975.

Geology

The Raft River Valley, a part of the Basin and Range geomorphic province, is located in south-central Idaho, south of the Snake River

Plain and north of the Utah-Idaho state line (Fig 1). The valley is a late Cenozoic structural downwarp bounded by faults on the west, south, and east [Williams et al., 1975]. The downwarp is filled with Tertiary and Paleozoic sediments and volcanics which overlie Precambrian rocks. The Tertiary deposits are composed of (1) 5 to 70 m of Pleistocene and Holocene fan gravels and alluvium, (2) 0 to 200 m of silt and sand, which comprise the Pleistocene Raft Formation, and (3) up to 1800 m of the Pliocene Salt Lake Formation, which consists of tufaceous sediments, volcanics (felsic lava flows and ash flows), and basin fill tufaceous sediments and conglomerates [Williams et al., 1975]. These are underlain by complex Paleozoics which overlie Precambrian rocks.

Two major features appear to be important in the regional structure. The geothermal area appears to be controlled by the intersection of the ENE trending feature through the Narrows (the Narrows structure) and a north trending basin edge feature (the Bridge fault) (Fig 9). The Narrows structure and the Bridge fault are major features on Landsat imagery.

Geophysics

Extensive surface geophysical surveys were conducted by the U.S. Geological Survey. The study includes gravity, magnetic, refraction seismic, resistivity, audio magnetotelluric, self-potential, and telluric current surveys. The geophysical surveys indicate a maximum thickness of about 2-km of Cenozoic sedimentary and volcanic rock, in agreement with the general geologic interpretation [Mabey et al., 1975]. The presence of structural features interpreted from the Landsat imagery is also clearly evident in these geophysical studies (for example, gravity map (Fig 10).

Discussion

Drilling in the Raft River Valley was intended to intersect areas of increased porosity postulated to exist at the intersection of the Narrows structure and the Bridge fault [Nichols and Applegate, 1974; Williams et al., 1975; Mabey et al., 1975]. The first well (RRGE 1) produced water of 145°C from a zone between 1150- and 1370-m deep. Subsequently, two other wells were drilled (RRGE 2 and RRGE 3) to evaluate the reservoir further. These produced equivalent temperature water from zones located between 1170 and 1340 m for RRGE 2 and 1310 and 1580 m for RRGE 3. Figure 9 is a sketch of the locations of RRGE 1, 2, and 3 and of the Narrows structure and the Bridge fault zone.

The very extensive geological and geophysical studies completed in the Raft River Valley quite clearly define the geologic setting of the geothermal system. This setting is in many ways analogous to the Boise and Cascade geothermal systems. As was true in the previously discussed systems, the resource exists in a structurally controlled sediment-filled basin. The approximately 2-km-thick sedimentary cover [Mabey et al., 1975] constitutes sufficient thermal insulation to account for temperatures in the range 145° to 155°C, given the following additional parameters (1) thermal conductivity of 7.0 mcal/cm s°C for basement rocks and 3.0 mcal/cm s°C for the sediments and (2) heat flow of 3.0 $\mu cal/cm^2$ s.

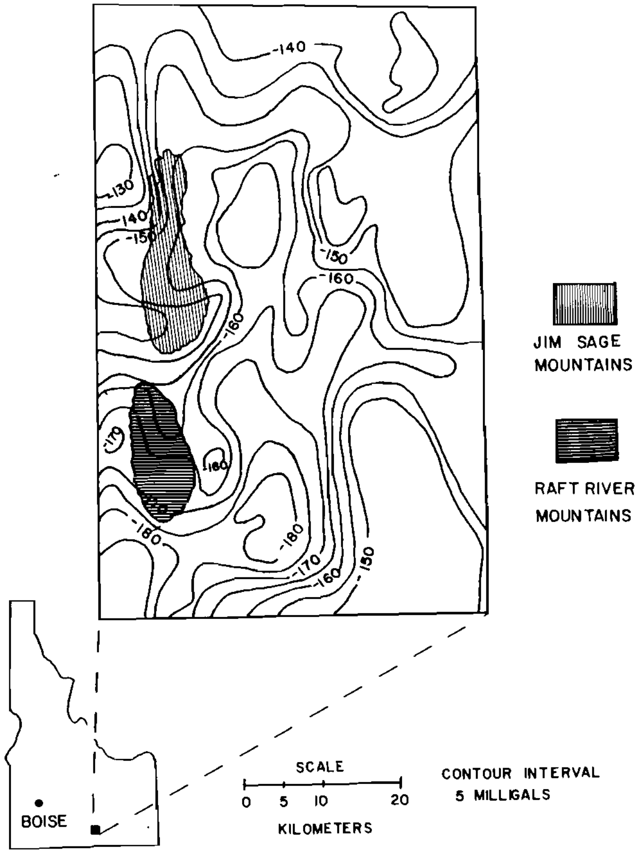

Fig. 10. Gravity map of the Raft River Valley. The Narrows structure separates the Jim Sage Mountains from the Raft River Mountains. The Bridge fault is along the eastern flank of the Jim Sage Mountains. Gravity data is from Mabey et al. [1974].

Once again, the heat which would be trapped at the base of the described column of sediments and volcanics is sufficient to account for temperatures predicted and in this case substantiated by deep drilling. Again, the regional geophysical data do not suggest the presence of a youthful shallow heat source, and indeed none is needed to produce the temperatures observed.

The hypothetical model for this and the previously discussed systems has assumed negligible convective heat transfer due to an absence of continuous connected porosity in the basin fill. This condition has been postulated to exist in the Boise and Cascade geothermal systems

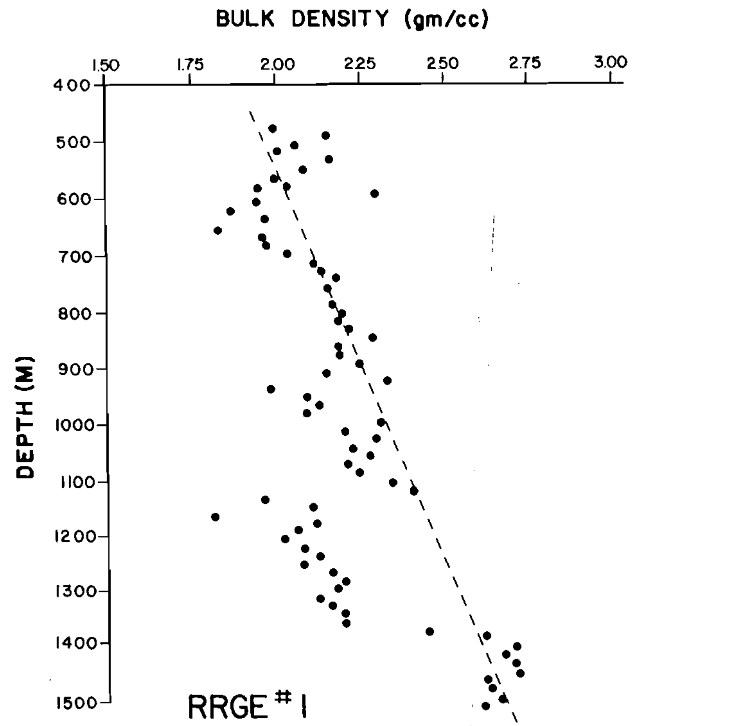

Fig. 11. Plot of bulk density from density log versus depth for RRGE 1. The general trend is that density increases with depth in a sedimentary sequence because of increasing compaction and decrease of porosity. The graph then shows a decrease in porosity with depth until the productive zone (1150 to 1370 m) is encountered [Applegate et al., 1976].

on the basis of the presence of nonpermeable basalt flows interbedded with a variety of permeable and nonpermeable sediments. Geophysical well logs in the Raft River wells provide a picture of widely varying porosity throughout the sedimentary section (Fig 11), which implies the noncontinuous permeability previously postulated.

Summary

Geophysical and geological studies of the Boise, Cascade, and Raft River geothermal systems suggest that the classical model requiring a shallow molten or recently molten mass as a heat source is not valid. These arguments can be extended to account for many geothermal systems in the western United States.

Therefore it is necessary to consider geothermal models which do not

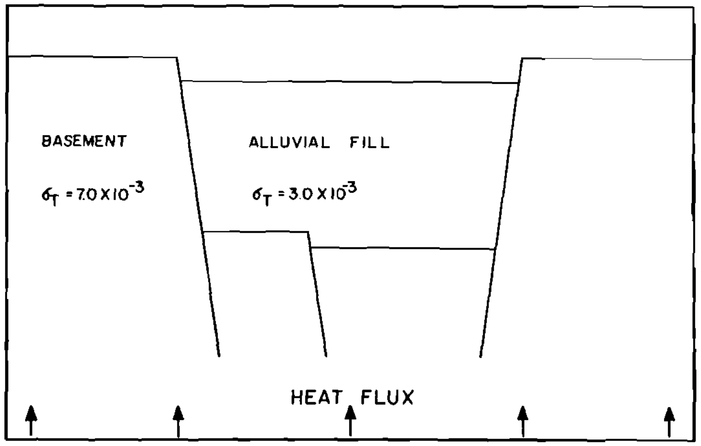

Fig. 12. Schematic diagram of the proposed geological model for the Boise, Cascade, and Raft River geothermal systems. Thermal conductivities (σ) of 3.0 x 10^{-3} and 7.0 x 10^{-3} cal/cm s ^{o}C were used for the sediments and basement rock, respectively, to calculate the temperatures at the base of the sedimentary section.

require a localized heat source. In this case the ultimate source of heat must be the lower crust or upper mantle. There are several possible explanations for the deep heat source. Whatever the nature of the deep-seated heat source, the result is increased heat flow into the upper crust. If there is increased heat flow into the upper crust, then specific geologic conditions must exist which result in heat entrapment and hence a shallow geothermal system.

The foregoing discussions present a set of conditions sufficient for establishing such a geothermal system. Other authors [Keller, 1975; Diment et al., 1975; Crewdson, 1976] have also suggested similar models to account for geothermal systems without shallow localized heat sources.

The model presented (Fig 12) is compatible with geological and geophysical observations from all three areas considered in Idaho. While other models can be postulated to account for these systems, the parameters specified in previous arguments for this model best fit the observed conditions.

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FLUID CIRCULATION IN THE EARTH'S CRUST

Denis Norton

Department of Geosciences, University of Arizona
Tucson, Arizona 85721

Abstract. Numerical simulation of thermally driven fluid flow caused by igneous intrusives in the upper crust indicates that fluid circulation is an inevitable consequence of lateral density gradients in pore fluids characteristic of these environments. Thermal perturbations associated with igneous plutons are predicted to be sufficiently large to generate hydrothermal systems in which the magnitude of convective heat transport exceeds that of conductive heat transport for rock permeabilities greater than 10^{-18} m^2 [Norton and Knight, 1977]. Furthermore, the style of the heat transfer is significantly different from systems in which conduction is the dominant heat transfer mechanism, particularly when the transport and thermodynamic properties of the fluid phase are taken into account. As a consequence of the critical end point which exists in the H_2O and related systems, the region above plutons is predicted to contain extensive vertical zones of nearly constant temperature. These first-order approximations of fluid circulation reveal two points relevant to predicting the thermal regime of the crust: (1) thermal gradients above convection-dominated systems are very nonlinear and cannot uniquely predict subsurface temperatures within our present scope of knowledge and data and (2) since fluid circulation may extend through a considerable portion of the upper crust in tectonically active regions, the thermal regime of these crustal regions is poorly understood.

Introduction

Temperature conditions in the earth's crust are normally predicted on the basis of extrapolated temperature-gradient data, petrologic arguments, and numerical approximations of conductive heat transfer processes in which various thermal energy sources, as well as rock properties, are considered. Analyses of thermal convection have usually indicated fluid circulation to be an important heat transport process, at least in geothermal areas [Elder, 1965; Ribando et al., 1976; Lister, 1974; Lowell, 1975]. However, the consequences of fluid circulation on the thermal conditions in the crust have only recently been analyzed for situations in which (1) the transport and thermodynamic properties of the fluid phase are allowed to vary with temperature and pressure changes and (2) an igneous intrusive body is present in the upper crust.

The unique characteristics of fluid systems for which H_2O is a principal component suggest that the properties of these types of fluids should contribute significantly to the heat transport process in con-