5013

Summary of Section II
Geology, Hydrology, and Geothermal Systems

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INTRODUCTION

This rapporteur report summarizes the ideas and data presented at the Second United Nations Symposium on the Development and Use of Geothermal Resources with respect to geology and hydrology of geothermal systems. The report makes no attempt to deal with mathematical models or reservoir engineering; both are treated by Manuel Nathenson in the rapporteur report for Section VII (Production Technology, Reservoir Engineering, and Field Management). The following discussion of geothermal geology and hydrology has three goals: (1) to outline generally accepted models, (2) to highlight areas of agreement, controversy, or uncertainty, and (3) to direct the reader to significant original references, both papers submitted to the Second UN Geothermal Symposium and recent papers published elsewhere.

GEOLOGIC ENVIRONMENTS

It is widely accepted in the scientific community that geothermal energy is the natural heat of the earth. This heat is stored in rock and water within the earth and can be extracted by drilling wells to tap anomalous concentrations of heat at depths shallow enough to be economically feasible (usually less than 3 km). Water or steam transfers heat from rock to a well and thence to the surface. Accordingly, a commercially attractive geothermal system must have sufficient permeability to allow large quantities of water or steam to be extracted for a prolonged time.

Regions of Normal Heat Flow

Most of the heat stored in the outer 10 km of the Earth is in regions of normal heat flow (1.5×10^{-6} cal/cm^2 sec = 1.5 heat flow units = 1.5 hfu) where geothermal gradients are 20 to 40°C/km (for example, Diment et al., 1975). Utilization of this energy is limited primarily by the great depths and consequent high drilling costs necessary to reach water with temperatures sufficiently high even for space heating, and secondarily by low porosity and permeability of most rocks at such depths. Although possible breakthroughs in drilling technology (for example, Altseimer et al., Abstract V-1; Altseimer, p. 1453) and hydrofracturing (for example, Smith et al., p. 1781) could permit widespread commercial extraction of heat from normal-gradient areas, utilization with present technology requires a large, porous, and permeable aquifer at a location where there is demand for fluids at less than 100°C for space-heating or agricultural purposes. These conditions currently are satisfied in the Paris Basin (Coulbois and Herault, p. 2099; BRGM, 1975; Maugis, 1971) and in some areas of the USSR (Mavritsky and Khelkvist, p. 179).

In addition, there are areas of normal heat flow where large, porous aquifers contain water at pressures well in excess of hydrostatic. These "geopressured" reservoirs are best known in the northern part of the Gulf of Mexico basin (Jones, 1970; Jones, p. 429) but are also found in deep, young sedimentary basins elsewhere in the United States, in the Niger delta of Nigeria (Nwachukwu, p. 205), in the Cambay graben of India (Krishnaswamy, p. 143) and in the USSR (Mavritsky and Khelkvist, p. 179). In the northern Gulf of Mexico basin, geopressured reservoirs are common at depths of 2.5 to at least 7 km at temperatures averaging 165°C (Papadopulos et al., 1975) and at pressures sometimes approaching lithostatic. These geopressured systems have the potential to supply immense quantities of both geothermal energy and energy from combustion of dissolved methane (Papadopulos et al., 1975). Although production of geopressured fluids appears technologically feasible, the economics of production have yet to be demonstrated (Wilson, Shepherd, and Kaufman, p. 1865).

Regions with No Associated Young Volcanic Rocks

Production of geothermal energy for space-heating and agricultural purposes has been shown to be feasible in a number of regions where heat flow is significantly greater than the worldwide normal value of 1.5 hfu. Prominent among these regions is the belt of high heat flow that extends along the Alpine orogenic zone in eastern Europe and western Asia (Čermák, Lubimova, and Stegena, p. 47). Within this belt, heat flow and thermal gradient maxima occur in the Pannonian Basin of Hungary and in the areas just north and south of the Caucasus Mountains in the USSR. Boldizsár and Korim (p. 297) state that the heat flow in the Pannonian Basin of Hungary is 2 to 3.4 hfu and that thermal gradients averaging 56°C/km persist to the base of the Cenozoic sedimentary section at nearly 6-km depth. It is generally believed that this high regional heat flow is transmitted into the sediments from beneath, but Shvetsov (p. 609) suggests that the heat liberated from compaction and diagenesis of sediments themselves, in areas of rapid sedimentation (for example 2.5 km per million years), can augment the heat flow substantially.

Regionally high heat flow also is found in the northern Basin and Range province of Nevada and Idaho, USA (Sass et al., Abstract III-80; Diment et al., 1975). Regional, permeable aquifers like the middle Pliocene Pannonian formation of Hungary do not exist in the Basin and Range province of the USA. Instead, many normal faults allow deep circulation of meteoric water and serve as loci for numerous thermal springs (Hose and Taylor, 1974).

Regions with Associated Young Volcanic Rocks

It has long been recognized that many geothermal systems have a close spatial and genetic relation to young volcanic centers (Healy, p. 415), in particular, to those of silicic composition. In addition, field studies of intrusive rocks of all ages have shown that most large magma chambers in the upper 10 km of the continental crust are silicic (Smith and Shaw, 1975). Hence, one approach in the search for geothermal resources is to identify silicic volcanic centers young enough and of sufficient size that molten or hot intrusive rocks still exist at depth and can drive overlying convection systems of meteoric water. This approach has been used by Smith and Shaw (1975) to rank geothermal exploration targets and to estimate the magnitude of geothermal resources related to silicic intrusions in the USA. In Figure 1, the ages and volumes of igneous intrusions, deduced to underlie young silicic volcanic centers, are plotted against a family of lines showing solidification times of hypothetical-source magma chambers as functions of various boundary conditions. The geothermal potential is greatest for large, young igneous systems (that is, down and to the right on Fig. 1). Basic data necessary for this approach include: (1) geologic mapping and petrology of volcanic rocks to allow calculation of volumes; (2) precise dating of volcanic rocks by K-Ar, ^{14}C, thermoluminescence, obsidian hydration, or fission-track methods; and (3) numerical models for cooling igneous bodies (for example, Smith and Shaw, 1975; Norton and Gerlach, Abstract II-35).

An example of this approach in the exploration for geothermal resources is given by MacLeod, Walker, and McKee, p. 465. K-Ar dating and geologic mapping define two belts of ryholite domes trending northwest across southeast Oregon, USA, and becoming progressively younger from 10 million years (m.y.) on the southeast to less than 1 m.y. near Newberry Volcano. The age-volume relations suggest that high-temperature hydrothermal convection systems are likely to exist only at the northwest end of the belt near Newberry Volcano.

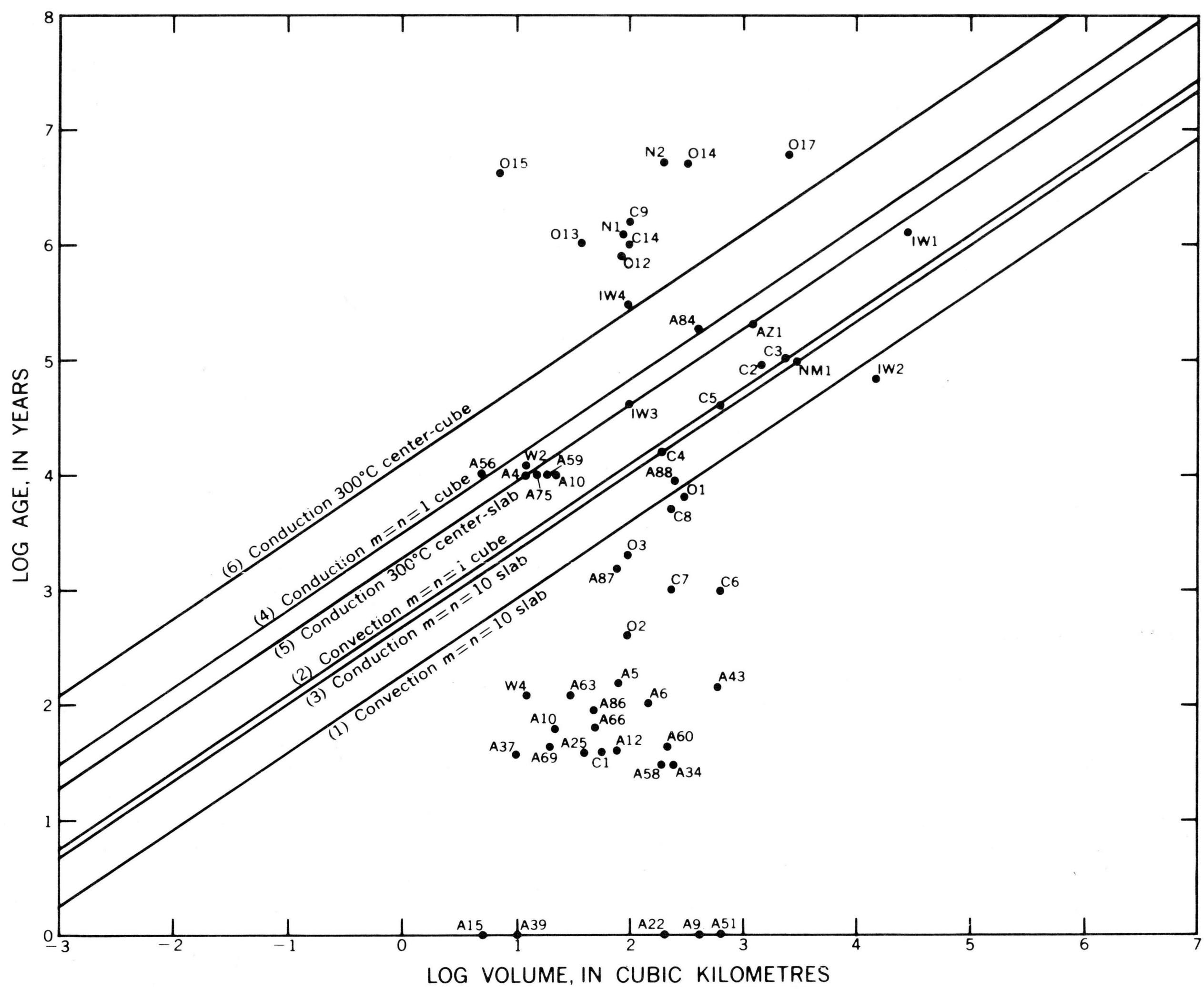

Figure 1. Graph of theoretical cooling times for various magma bodies (from Smith and Shaw, 1975, Figure 4). Points represent youngest ages and estimated volume for the best known young igneous systems of the United States (see Table 7 of Smith and Shaw, 1975).

Although the use of Figure 1 is restricted to silicic rocks, areas of intensive basalt extrusion may also have significant geothermal potential (Smith and Shaw, 1975, p. 78-83). One such area is in southern Washington State, USA, where a major Quaternary basaltic feeder zone is coincident with a pronounced negative gravity anomaly (Hammond et al., p. 397).

Intrusion of magma into the upper crust can generate one or all of three types of geothermal systems: (1) magma, (2) hot dry rock, (3) hydrothermal convection.

Magma bodies are known at a number of young volcanoes, most notably at Kilauea Volcano in Hawaii, where basaltic lava ponds in pit craters and remains partly molten for years after extrusion (for example, Peck, Wright, and Moore, 1966). The movement of magma within Kilauea Volcano is monitored using seismological and deformation techniques, and prominent self-potential anomalies on the flanks of the volcano are thought to indicate the position of subsurface magma pockets (Zablocki, p. 1299). Magma has been tentatively identified by teleseismic P-delay studies at Yellowstone, Wyoming, and The Geysers, and Long Valley, California (Steeples and Iyer, p. 1199) and is likely to exist under many other volcanoes.

The term "hot dry rock" is commonly applied to hot rock that is of too low porosity or is too impermeable to allow natural circulation of water at appreciable rates. An example of hot dry rock is in the Jemez Mountains, New Mexico, USA, where temperatures of 200°C have been found at 3-km depth in Precambrian gneiss and amphibolite of very low permeability (Smith et al., p. 1781; Albright, p. 847; Jiracek, Smith, and Dorn, p. 1095). Experiments are under way at this site to fracture the rock hydraulically and set up an artificial convection system. Similar research efforts are under way at the Avachinsky Volcano, Kamchatka, USSR (Fedotov et al., p. 363; Sviatlovsky, Abstract VII-24) and are planned for Japan and Italy. Another possible hot dry rock resource is under study in the Coso Mountains, California, USA, where Pleistocene rhyolite domes form a discontinuous veneer over Mesozoic granite near the center of a 40-by-20-km area of late Cenozoic ring faulting (Duffield, Abstract II-12; Duffield, 1975; Lanphere, Dalrymple, and Smith, 1975). Several drillholes to 1-km depth will be put down at Coso in 1976.

Igneous intrusions into permeable water-bearing rocks of the upper crust commonly set up overlying hydrothermal convection systems. Meteoric water circulates downward along faults or aquifers, is heated at depth by the intrusion, and rises buoyantly towards the surface in a column of relatively restricted cross section (White, 1968). For many years it was thought that this water had to be heated by conduction through country rock from the molten intrusion. However, recent studies of ^{18}O in Tertiary intrusive rocks have shown that meteoric water can circulate along fractures in a cooling intrusion (Taylor, 1971) and may even penetrate into the liquid magma (Friedman et al., 1974). Analytical studies by Lister (p. 459) suggest that heat output of a hydrothermal convection system is maintained by penetration of meteoric water into the solidified margins of an intrusion along fractures that propagate inward at 0.2 to 20 m/y. Fournier, White, and Truesdell (p. 731) speculate that heat is transferred from the magma under Yellowstone to the dilute hydrothermal convection systems via a hot, slowly convecting, highly saline brine.

Data on a number of hydrothermal convection systems related to silicic intrusive or volcanic activity were presented at the Second UN Geothermal Symposium. The Geysers, California, steam field is clearly associated with the Clear Lake Volcanics of late Pliocene (?) to Holocene age (Hearn, Donnelly, and Goff, p. 423; Donnelly and Hearn, Abstract III-18) and with a major gravity low. Isherwood (p. 1065) considers that the gravity and magnetic anomalies are caused by a young intrusive body centered 10 km below the southwest edge of the Clear Lake Volcanics, and teleseismic P-delay data suggest that this intrusive body may still be partly molten (Steeples and Iyer, p. 1199). A gravity ridge separating the main gravity low from a smaller low at The Geysers is most likely due to a northeast-dipping dense caprock that directs hydrothermal fluids from beneath the volcanic field southwest to The Geysers (Isherwood, p. 1065).

The new geothermal discovery at Cesano, Italy (Calamai et al., p. 305), is clearly associated with the late Quaternary Sabatini volcanoes. The Cesano discovery well was drilled in Boccano caldera, the site of very young phreatic volcanism, and penetrated 700 m of hydrothermally altered diatreme breccia (Baldi et al., p. 871; Calamai et al., p. 305).

Other areas associated with silicic volcanism include the Seferihisar area, Turkey (Eşder and Şimşek, p. 349), and the Salton Sea geothermal field, California (Robinson, Elders, and Muffler, 1976). Areas associated with andesite volcanism include the Cerro Prieto geothermal field, Mexico (Reed, p. 539), El Tatio, Chile (Lahsen and Trujillo, p. 157; Cusicanqui, Mahon, and Ellis, p. 703; Hochstein, Abstract III-39), and the Kawah Kamojang area, Indonesia (Hochstein, p. 1049; Kartokusumo, Mahon, and Seal, p. 757).

LOCATION OF GEOTHERMAL SYSTEMS

The revolution in earth science that resulted from the theory of plate tectonics (Cox, 1973) was mentioned only in passing at the First UN Geothermal Symposium in 1970 in Pisa, Italy. By 1975, however, it was widely accepted that geothermal fields are localized in areas of young tectonism and volcanism, primarily along active plate boundaries (Muffler, p. 499; Healy, p.415).

Spreading Ridges

Spreading ridges are zones where new crust is created by intensive igneous intrusion and extrusion, and accordingly they are favorable sites for copious discharge of hydrothermal fluids. Williams (Abstract I-40) notes that 20% of the Earth's heat loss occurs along the 5.5×10^4 km of spreading ridges, which comprise only 1% of the Earth's surface area. Lister (p. 459) calculates that the probability of finding a major hydrothermal convection system at a spreading zone is a direct function of spreading rate (0.025 per km of rift length per cm/yr spreading rate). According to Lister's analysis, a major hydrothermal convection system might be expected every 20 km on the mid-Atlantic ridge, every 3 km on the fast-spreading East Pacific rise, and every 100 km on a slow-spreading continental rift zone (for example the East Africa rift or the Baikal rift).

By far the most thoroughly studied submarine geothermal area is the Atlantis II deep in the Red Sea. Saline brine trapped in this and other deeps along the axis of the Red

Sea has its origin in hydrothermal discharge from the sea floor. Schoell (p. 583) estimates that the hydrothermal brine responsible for the Atlantis II brine pool is discharging at 2.4×10^4 l/m and has a subsurface temperature of 210°C.

The spreading ridge that extends from the Indian Ocean through the Gulf of Aden to the Red Sea is emergent from the ocean in the Afar Depression (Tazieff et al., 1972). The southernmost emergent spreading element of this ridge is the Asal Rift, characterized by an axial zone 5 km across where new oceanic crust is forming and very young basalts have been extruded (Stieltjes, p. 613). Geothermal exploration wells were sited just to the southwest of the axial valley, which was interpreted by Stieltjes to be too "open" (permeable ?) to support a good hydrothermal convection system. One of the wells drilled in 1975 found a reservoir at 1050 m and 253°C containing a brine of 190 000 mg/l salinity (Gringarten and Stieltjes, 1975).

In a general sense, Iceland also represents a mid-oceanic spreading ridge that extends above sea level (Pálmason and Saemundsson, 1974). The neovolcanic zone extending northwest through Iceland is the locus of extensive Quaternary basaltic volcanism, scattered silicic volcanic centers, and at least 17 major high-temperature hydrothermal convection systems (Pálmason, Ragnars, and Zoëga, p. 213; Bodvarsson, p. 33; Hermance, Thayer, and Björnsson, p. 1037; Arnórsson et al., p. 853).

The best example of a spreading ridge that extends onto a continent is the East Pacific Rise as it passes north up the Gulf of California into the Salton Trough. Spreading segments separated by transform faults occur throughout the Gulf of California (Lawver, Abstract III-54; Williams, Abstract I-40), and similar segments are represented on land by the young volcanoes and geothermal fields at Cerro Prieto and the Salton Sea (Elders et al., 1972).

Intracontinental rifts are also the loci of young volcanism and geothermal fields, but their low rates of extension result in a lower probability of finding major geothermal areas than along fast-spreading oceanic ridges (Lister, p. 459). The best known example of an intracontinental rift is the East Africa rift, with associated geothermal areas in Ethiopia (Demissie and Kahsai, Abstract I-10), Kenya (Noble and Ojiambo, p. 189), and Uganda (Maasha, p. 1103).

Subduction Zones

Subduction zones are belts along which two plates move toward each other, resulting in the consumption of lithosphere, commonly by the thrusting of one plate beneath the other. Melting of downthrust crust produces pods of magma that rise into the upper plate and act as heat sources for overlying hydrothermal convection systems. Geothermal fields clearly related to subduction zones include:

1. Kawah Kamojang, Java, Indonesia (Hochstein, p. 1049; Kartokusumo, Mahon, and Seal, p. 757), related to thrusting of the India plate under the China plate.
2. Puga, Chumathang, and Parbati Valley of the Himalayas of northwest India (Gupta, Narain, and Gaur, p. 387; Subramanian, p. 269; Krishnaswamy, p. 143; Shanker et al., p. 245; Jangi et al., p. 1085), related to the same subduction zone as Kawah Kamojang, but in a complex zone of convergence between continental crust of each plate.
3. El Tatio, Chile (Healy, p. 415; Lahsen and Trujillo, p. 157; Cusicanqui, Mahon, and Ellis, p. 703), related to subduction of oceanic crust beneath continental crust along the west coast of South America.

Intraplate Melting Anomalies

Intraplate melting anomalies are also the loci of recent volcanism and associated geothermal fields. Examples of these intraplate melting anomalies are Hawaii (Dalrymple, Silver, and Jackson, 1973) and Yellowstone (Christiansen and Blank, 1969; Eaton et al., 1975).

GEOMETRY OF HYDROTHERMAL RESERVOIRS

Regional Aquifer Systems

Many parts of the world are characterized by laterally extensive thick aquifers of permeable rock that can be tapped for geothermal resources over wide areas. Prominent among such aquifers is the upper part of the Pannonian formation (middle Pliocene) of Hungary, where discontinuous sandstones interbedded with siltstone and shale contain approximately 2800 km^3 of 80 to 99°C water, of which perhaps 10% is recoverable (Boldizsár and Korim, p. 297). The Pannonian formation also forms a major geothermal aquifer in the central depression of the Danubian basin of Czechoslovakia (Franko and Mucha, p. 979). Regional sandstone aquifers are found in Tertiary sediments of the Gulf Coast of the United States, where growth faults have broken sandstone formations into discrete, geopressured reservoirs (Jones, 1970; Jones, p. 429). Many of these reservoirs are found in the Oligocene Frio Formation of south Texas, USA (Bebout and Agagu, Abstract II-1; Dorfman and Sanders, Abstract II-11). In the Salton Trough of California and Mexico, geothermal resources occur in sandstone lenses in a thick sandstone-siltstone sequence that comprises the Colorado River delta (Swanberg, p. 1217; Reed, p. 539). Major regional aquifers are also found in the Paris Basin, where geothermal fluids at 70°C are produced from the Dogger Limestone of Jurassic age (BRGM, 1975; Maugis, 1971).

Large volcano-tectonic depressions are favorable sites for geothermal reservoirs (Yamasaki and Hayashi, p. 673; Healy, p. 415). Prominent among these depressions are the Taupo depression of New Zealand, a depression trending west-southwest from Beppu to Unzen in northern Kyushu, Japan, and the Guatemala-Quezaltenango depression of Central America. Large grabens not necessarily related to young volcanism contain geothermal resources in Turkey and India (Kurtman and Şâmilgil, p. 447; Krishnaswamy, p. 143).

Local Stratigraphic Reservoirs

Young calderas commonly are favorable sites for hydrothermal convection systems, both because of the underlying igneous heat source and because of the probability of permeable caldera fill. Major calderas described at the Second UN Geothermal Symposium include Yellowstone (Fournier, White, and Truesdell, p. 731; Truesdell et al., Abstract III-87; Morgan et al., p. 1155; see also Eaton et al., 1975), Onikobe, Japan (Yamada, p. 665), and the Valles Caldera, New Mexico, USA (Jiracek, Smith, and Dorn, p. 1095; see also Smith, Bailey, and Ross, 1970). Geothermal resources in the Long Valley caldera in California have also been described recently in a number of papers published in volume 80, no. 5 of the Journal of Geophysical Research (1976).

Basaltic central volcanoes in the Tertiary strata of Iceland have good reservoir characteristics (Fridleifsson, p. 371). The highly permeable basaltic hyaloclastites erupted under glaciers during the Pleistocene also form important aquifers along the neovolcanic zone of Iceland (Tómasson, Fridleifsson, and Stefánsson, p. 643; Fridleifsson, p. 371).

Fractured Reservoirs

Although many geothermal reservoirs seem to be associated with porous and permeable sedimentary or volcaniclastic rocks, perhaps a greater number are related to fractures in rocks that are otherwise impermeable. Bodvarsson (p. 903) states that ". . . fractures of various types are the most important conductors of circulating fluids in practically all major geothermal systems." Grindley and Browne (p. 377) emphasize that major production from many geothermal fields is derived not from the most porous stratigraphic units but from fractures in some of the least porous units. This phenomenon is clearly illustrated by the Kawerau area, New Zealand, where major production is from a dense, fractured andesite (Macdonald and Muffler, 1972).

Traditionally, fractures in geothermal areas have been interpreted to result from tectonic stress and the resulting formation of faults, joints, fractures, and breccias. At the Second UN Geothermal Symposium, however, several papers proposed other mechanisms for the development of fractures.

Bodvarsson (p. 903) presents calculations showing the effect of temperature changes on the width of fractures and suggests that fractures along dikes can form by thermal contraction during soldification of the dikes or by inflow of cold water along the dikes, gradually extending downward the open space against the country rock. Increasing temperature due to ascending hot fluids will close cracks at intermediate depths (a fracture of initial width of 1 mm will be closed in 0.5 yr by a 10°C increase in fluid temperature) but will *cause* fracturing at higher levels due to overall expansion of the region.

An elegant analysis of fracturing at Broadlands, New Zealand, is given by Risk (p. 1191), who used detailed bipole-dipole resistivity studies to define the fracturing pattern around a buried rhyolite dome. Measuring stations over the center of the dome show no preferential direction of conduction of electricity, but stations over the periphery of the dome show strong preferential conduction of electricity in directions radial to the center of the dome, suggesting the presence of radial fractures. Borehole data and electrical soundings indicate that these fractures are beneath the dome and hence were probably formed during its extrusion.

Grindley and Browne (p. 377) propose that many breccia zones in geothermal fields are produced by natural hydraulic fracturing in situations where (by self-sealing, for example) fluid pressures exceed the least principle stress by an amount equal to the tensile strength of the rock. According to Grindley and Browne (p. 377), rapid extension of a fissure by hydraulic fracturing may sharply reduce fluid pressure in the fissure and cause adjacent impermeable rocks to fail explosively. This theory of fracture formation in geothermal areas is based in great part on papers by Phillips (1972; 1973). Natural hydrofracturing is also referred to by Norton and Gerlach (Abstract II-35).

Another method of fracturing is proposed by Vartanyan (p. 649), who hypothesizes a substantial decrease in specific volume of rock at depth by degassing during regional metamorphism, thus producing fractures in overlying rock.

Several examples of geothermal reservoirs in fractured rock were presented at the Second UN Geothermal Symposium. Blackwell and Morgan (p. 895) show clearly that flow of hydrothermal fluids at Marysville, Montana, is controlled by fractures in a Tertiary intrusion in Precambrian country rock. In the Larderello and Travale regions of Italy, production of steam is from fissures in the Upper Triassic to Jurassic limestones that in general have low matrix permeability (Petracco and Squarci, p. 521; Burgassi et al., p. 1571; Celati et al., 1975). The steam reservoir at The Geysers is in fractured, indurated Mesozoic graywacke in a complex, southeast-plunging antiform broken by young, northwest-trending faults (McLaughlin and Stanley, p. 475). In Japan, fracture control of geothermal fluid production is emphasized by Sato and Ide (p. 575), Yamada (p. 665), and Todoki (p. 635). At Ahuachapán, El Salvador, permeability of the geothermal reservoir (the Ahuachapán andesite) is predominantly due to fractures (Romagnoli et al., p. 563).

Artificial fracturing to increase permeability and thus allow exploitation of hot dry rock has received much recent attention. In the Jemez Mountains of New Mexico, USA, a program is underway to hydrofract Precambrian gneiss and amphibolite found at 3-km depth and 200°C just west of the Valles Caldera (Smith et al., p. 1781). Similar efforts have begun in the USSR (Diadkin and Pariisky, p. 1609; Fedotov, et al., p. 363; Sviatlovsky, Abstract VII-24) and are being considered in Japan (Hayashida, p. 1997).

HYDROLOGY OF GEOTHERMAL SYSTEMS

Movement of Geothermal Fluids

Vertical upwelling of hot geothermal fluids is suggested by the geometry of the Broadlands area, New Zealand, where resistivity studies have shown the field to be nearly circular with vertical boundaries at least to a depth of 3 km (Risk, Macdonald, and Dawson, 1970). Detailed bipole-dipole resistivity and I.P. studies by Risk (p. 1185) show that the south boundary zone of the Broadlands field is 100 to 150 m thick and is probably an impermeable barrier created by deposition of hydrothermal minerals, particularly quartz. The broader boundary on the east side of the field may indicate intrusion of cold water through a leaky boundary (Risk, p. 1185), as required by Macdonald's (p. 1113) model of the field. A tongue of low-resistivity material extending northwest along the Waikato River suggests subsurface outflow of thermal water (Macdonald, p. 1113).

Horizontal movement of geothermal fluids has been emphasized by Healy and Hochstein (1973) and Healy (p. 415), mainly on the basis of extensive hydrologic data available from El Tatio, Chile (Cusicanqui, Mahon, and Ellis, p. 703; Lahsen and Trujillo, p. 157; Healy, p. 415). Meteoric water originating 15 to 20 km east of El Tatio flows westward and becomes heated as it passes under the volcanic crest of the Andean Mountains. This horizontal flow, primarily through the fractured Puripucar ignimbrite, is impeded to the west by relatively impermeable rocks of the Tucle horst. Upward movement of the thermal water in the Tatio basin occurs on northwest- and northeast-trending fractures. Cusicanqui, Mahon, and Ellis (p. 703) interpret preliminary tritium data to suggest a time of 15 years for passage of water from the recharge area to the El Tatio basin. A similar model seems to apply to the Ahuachapán area in El Salvador (Romagnoli et al., p. 563).

Horizontal movement of thermal water over long distances has also been deomonstrated in Iceland (Bodvarsson, p. 33). Deuterium isotope data and volcanic structure indicate that the thermal water of the Reykjavik and Reykir areas originates as precipitation in the interior highlands of Iceland and flows over 100 km southwest through buried Quaternary hyaloclastite ridges (Tómasson, Fridleifsson, and Stefánsson, p. 643).

Predominantly vertical flow of geothermal fluids along faults is common in many areas, for example, the northern Basin and Range province in Nevada and Idaho, USA, an area of regional extension where meteoric water circulates to many kilometers depth along young normal faults (Hose and Taylor, 1974; Olmsted et al., 1975). This type of geothermal circulation is well illustrated by the Raft River area in Idaho (Williams et al., p. 1273). Geothermal wells were sited at the west edge of the Raft River basin at the intersection of the north-trending Bridge fault and the northeast-trending Narrows structure, which is probably an old shear zone in the Precambrian basement. Large flows of 147°C water were found at the predicted depth and at the reservoir temperature predicted by SiO_2 and Na-K-Ca geothermometers (Young and Mitchell, 1973). Igneous rocks in the area are too old (8 m.y.) to be the source of heat for the geothermal system. Heat flow in the area is 2.5 hfu (T. C. Urban and W. H. Diment, oral commun., 1976), approximately the same as the regional heat flow of the northern part of the Basin and Range province.

Fault control of geothermal fluid movement has also been demonstrated at the East Mesa area of the Salton Trough, California, USA (Swanberg, p. 1217), in the Parbati Valley of northwestern India (Jangi et al., p. 1085), and at the Sempaya area in Uganda, where the thermal fluids are clearly related to the Bwamba fault that bounds the western rift valley on the east (Maasha, p. 1103).

Movement of geothermal fluids along dikes in basaltic terrane has been emphasized by Bodvarsson (p. 33 and p. 903). Thermal water systems in northwestern Iceland are commonly controlled by flow along dike margins, for example, at Reykholar (Björnsson and Grönvold, Abstract II-3). Flow of thermal fluids along basalt dikes also has been demonstrated in the Konkan region of India (Gupta, Narain, and Gaur, p. 387).

Cap Rocks and Self-Sealing

Upward movement of geothermal fluids is commonly restricted by relatively impermeable rock (a "cap rock"), allowing accumulation of fluids in a geothermal reservoir directly beneath the cap rock. In some areas the cap rock has been interpreted as an impermeable stratigraphic unit. At Larderello, the cap rock is the allochthonous "argille scagliose" of Cretaceous to Eocene age that overlies the Triassic reservoir rocks (Petracco and Squarci, p. 521). At Wairakei the cap rock is the Huka Falls formation, whereas at Broadlands a cap rock is provided by the Huka Falls formation and various buried rhyolite domes (Grindley and Browne, p. 377). In the geothermal fields of the Salton Trough, a cap rock is formed by relatively impermeable clays and shales that extend to a depth of 600 to 700 m (Swanberg, p. 1217; Tolivia M., p. 275; Mercado G., p. 487; Paredes A., p. 515). At Kızıldere, Turkey, reservoirs appear to be in both Miocene limestone and Paleozoic marbles, each overlain by relatively impermeable cap rocks (Kurtman and Şâmilgil, p. 447; Tezcan p. 1805).

In perhaps the majority of hydrothermal convection systems, however, the cap rock is produced by self-sealing (Bodvarsson, 1964; Facca and Tonani, 1967), most commonly owing to the deposition of silica, but also owing to hydrothermal formation of clays, zeolites, and other minerals (for example, Kristmansdóttir, p. 441; Grindley and Browne, p. 377; Sheridan and Maisano, p. 597) or by deposition of calcite as CO_2 is lost from a fluid. Examples of a cap rock being created by self-sealing include the Dunes geothermal system in the Salton Trough, California, USA (Bird and Elders, p. 285) and the hot-water geothermal systems of Yellowstone National Park, Wyoming, USA, where self-sealing has produced vertical hydraulic gradients exceeding hydrostatic by 11 to 47% (White et al., Abstract II-56; White et al., 1975).

Fluid Recharge

Recharge to geothermal systems consists both of heat and water, and the balance between the two is important in determining whether a geothermal system is hot-water or vapor-dominated (White, Muffler, and Truesdell, 1971).

Fluid recharge is of critical importance to convective hydrothermal systems but is poorly understood, owing primarily to lack of deep drillhole data in the recharge parts of geothermal systems (Healy, p. 415). However, several intensively developed geothermal systems do provide some quantitative data. At Wairakei, Hunt (1970), from an analysis of subsidence data and gravity changes from 1961 to 1967, showed that only 20% of the fluid discharged during that time had been replaced by recharge. Bolton (1970), however, presented an analysis of the 1968 shutdown of the Wairakei field which indicated an inflow of water equivalent to two-thirds of the field discharge and at a temperature equal to or higher than the maximum measured in the field. At Larderello, Panichi et al. (1974) have identified steam derived from recharge from the south by its low and variable ^{18}O compared to steam from the center of Larderello region. According to Petracco and Squarci (p. 521), approximately 30 to 40% of the steam produced at Larderello comes from these aquifers in the south.

Fluid recharge in some systems, however, appears to be of little importance. According to Boldizsár and Korim (p. 297), the thermal water of the Pannonian aquifer of Hungary "does not participate in the hydrologic cycle." The geopressured fluids in the northerm Gulf of Mexico basin have been clearly demonstrated by Jones (1970) to be derived from diagenesis of sediments rather than from circulation of meteoric water. Jones (p. 429) describes in detail a model for the formation of the geopressured reservoirs, emphasizing that they result from the compartmenting of sandstone beds by growth faults and the resultant retardation of fluid expulsion through the bounding, low-permeability clays. Fluid pressures will decrease with time as the confined water gradually escapes. Temperatures also decrease with time, as shown by comparison of paleotemperatures (determined by the electron spin resonance of kerogen) with modern temperatures in Cretaceous rocks at depths of 3 km in south-central Texas (Pusey, 1973). Inasmuch as the depositional axis of the Gulf Coast deposits migrates gulfward with time, one would expect the locus of the geopressured deposits also to migrate gulfward with time (Jones, p. 429).

GEOTHERMAL RESOURCE ESTIMATION

Several methods of geothermal resource estimation are currently in use, with little agreement on which method is best. Heat stored in water in the geothermal reservoir is used by Alonso (p. 17) and Tolivia (p. 275) to estimate the geothermal resources of Cerro Prieto, and by Swanberg (p. 1217) to estimate the geothermal resources of East Mesa, California, USA. On the other hand, many authors have calculated the heat stored in both water and rock and have calculated (or assumed) an extraction efficiency. Recent examples of this approach include Bodvarsson (p. 33) in Iceland; Macdonald and Muffler (1972) at Kawerau, New Zealand; Macdonald (p. 1113) at Broadlands in New Zealand; Muffler and Williams (1976) in Long Valley, California, USA; and Renner, White, and Williams (1975) and Nathenson and Muffler (1975) for geothermal systems of the United States. Healy (p. 415 and 1976), however, considers that estimates of resources and reservoir life based on stored heat calculations are unreliable, since no reservoir may in fact exist. That is, the permeability distribution of rock in the "reservoir" is such that most of the heat is inaccessible to circulating fluids and thus cannot be transmitted to the wells. This possibility is also explicitly recognized by Muffler and Williams (1976).

A second method of estimating the power potential of a new hydrothermal convection system is to compare the area of surface alteration in the new field with the altered area in a developed field, under the assumption that the area of surface alteration is proportional to the power potential. A refinement of this method used in Japan involves careful determination of the areal extent, type, and age of surface alteration and correlation with the age of associated volcanism (Sumi and Takashima, p. 625).

The total natural heat flow can also be used to estimate the geothermal potential of a hydrothermal convection system. Healy (p. 415) notes that estimates based on natural discharge are minima because experience at several geothermal fields (particularly Wairakei) has shown that natural discharge can be increased several times for many years. Accordingly, one can estimate field production by comparing natural discharge with that of another field whose capacity is known. Using this approach, Healy and James (1976) have estimated that heat discharge from Kawerau might be increased to four times natural discharge (that is, to 420 megawatts thermal = 420 MWt); this compares to 350 to 600 MWt for 50 years calculated from the 0.55 to 0.95 $\times 10^{18}$ J of extractable heat estimated by Macdonald and Muffler (1972) for Kawerau.

Dawson and Dickinson (1970) have estimated the natural heat discharge from Broadlands to be 84 MWt. Using the same fourfold factor, derived from the Wairakei example for increase of production over natural heat discharge (Healy and James, 1976), the productive capacity of Broadlands is calculated to be 336 MWt. This compares to 2350 MWt for 50 years estimated from the stored heat in the Broadlands system (Macdonald, p. 1113). Clearly, development of the Broadlands geothermal area will provide an important case history for evaluating the accuracy of the two contrasting methods of geothermal resources estimation.

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