Summary of Section IV Geophysical Techniques in Exploration

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INTRODUCTION

Geophysical exploration involves the study and measurement of physical waves, fields, and emissions of the solid earth and the interpretation of these observations in terms of realistic geological models. Geophysics therefore assumes the role of a science which relates physics to geology. Thus, when one realizes that each subfield of physics can be related to each subfield of geology, there is an appreciation for the potential size and rather complex nature of geophysics. The role of geophysics in the exploration for geothermal resources has been examined and discussed in several review papers (Bodvarsson, 1970; Banwell, 1970, 1973; Combs and Muffler, 1973; and in this symposium by Nakamura, p. 509; Duprat and Omnes, p. 963; McNitt, p. 1127; Meidav and Tonani, p. 1143; and Pálmason, p. 1175). Geophysics is a tool which can often provide important information about the nature of a geological feature (such as a geothermal system) as effectively and certainly at a lower cost than can a large number of boreholes. However, some boreholes for direct information about the subsurface physical properties are always necessary before a geophysical survey can be properly interpreted. Nongeophysicists as well as geophysicists must be aware of the fact that particular geophysical techniques and the interpretation of the resulting data can (or cannot) be expected to provide useful results in given circumstances.

Geophysics applied to the exploration for, and delineation of, geothermal resources spans a wide range of subject areas from the measurement of physical parameters of rocks (for example: Watts and Adams, p. 1247; Duba, Piwinskii, and Santor, Abstract III-19; Goss and Combs, p. 1019) to development of instrumentation and measurement systems (for example: Whiteford, p. 1255; Combs and Wilt, p. 917; Yuhara, Sekioka, and Ijichi, p. 1293) to data acquisition and digital data processing (for example: Hermance, Thayer, and Bjornsson, p. 1037; Isherwood, p. 1065; Iyer and Hitchcock, p. 1075) and to the modeling and geological interpretation of geophysical data (for example: Bodvarsson, p. 903; Risk, p. 1191; Williams, et al., p. 1273). A considerable volume of geophysical data pertaining to geothermal systems has been developed since the first United Nations Symposium on the Development and Utilization of Geothermal Resources held in Pisa, Italy, in 1970; the proceedings of which were published in the Special Issue 2 of *Geothermics*. In addition to refinements and increases in the effectiveness of existing geophysical exploration systems, some methods and techniques not previously used in geothermal exploration have been adopted from crustal geophysical studies as well as from the petroleum and mining industries (for example: teleseismic P-wave delays, Steeples and Iyer, p. 1199; tellurics, Combs and Wilt, p. 917; self-potential-SP, Corwin, p. 937; audiomagnetotellurics-AMT, Hoover and Long, p. 1059) and have been given thorough field tests. Several well-documented geothermal case histories have either been completed through the exploratory drilling phase or are presented as progress reports (for example: Noble and Ojiambo, p. 189; Cameli, et al., p. 315; Arnórsson, et al., p. 853; Blackwell and Morgan, p. 895; Jangi, et al., p. 1085; Nevin and Stauder, p. 1161; Swanberg, p. 1217; Williams, et al., p. 1273).

Considering the large number of contributions to this section and the diverse subject matter, I shall attempt here the onerous task of summarizing the ideas and data presented at the Second United Nations Symposium on the Development and Use of Geothermal Resources with respect to geophysical exploration for geothermal systems. The intent of my summary will be to clarify several concepts associated with geophysical exploration, to emphasize the need for realistic geological models that can be tested, to summarize the diversity of geophysical information presented, and to direct the reader to significant papers published elsewhere.

PHYSICAL PROPERTIES

A geophysical survey consists of a set of measurements made over the surface of the earth, in the air above and parallel to it, and in boreholes within the earth. The measurements are of the variations in space or time of one of several physical fields of force. These fields are determined, among other things, by the nature and structure of the subsurface, and because rocks vary widely in their physical properties, at least one of these properties usually shows marked discontinuities from place to place. These physical properties include thermal conductivity, electrical conductivity, propagation velocity of elastic waves, density, and magnetic susceptibility.

Geothermal systems often give distinctive and fairly easily measured discontinuities in physical properties (such as high heat flow, low electrical resistivity, attenuation of high-frequency elastic waves). Clearly the ease with which discontinuities can be detected depends on the degree of contrast in the physical properties between the rocks comprising the geothermal system and the surrounding subsurface. An accurate and unambiguous interpretation of geophysical data is only possible where the subsurface structure is simple and known from drillhole data, and even then it is by no means always achieved.

Geothermal reservoirs usually have irregular shapes and occur in rocks of complex structure and varying type. The emphasis in geophysical exploration is therefore upon detection of geothermal systems and the determination of their relative physical properties, rather than on precise quantitative interpretation. Nevertheless some indication of the quality, size and depth of a geothermal system may often be obtained. In other words, geophysical surveys are conducted in order to provide data for the location of geothermal systems and the estimation of geothermal drillhole locations.

Considerable volumes of rock at high temperatures are known to exist below all major geothermal areas (Healy, p. 415; Muffler, p. 499; Eaton, et al., 1975). Almost any type of rock, igneous, metamorphic or sedimentary, may be involved. Although there can be little doubt that some types of recent igneous intrusions in the shallow crust and the associated cooling magmas constitute the ultimate heat sources for all high-temperature geothermal systems, little is known about the form of the intrusions. When the permeability due to fractures or pores is sufficient, meteoric water can circulate downward through the hot rock, extract and convect some of its heat content, and return to the surface through springs or boreholes as thermal water or natural steam (White, 1968; 1973).

The Geysers geothermal field in California represents a good example of the abovementioned phenomena. The steam field is undoubtedly associated with the Clear Lake volcanic field of late Pliocene (?) to Holocene age (Hearn, Donnelly, and Goff, p. 423; McLaughlin and Stanley, p. 475; Donnelly and Hearn, Abstract III-18) and with a major gravity low which Chapman (1966) suggested was produced by a magma chamber at depth. From a detailed analysis of the gravity and magnetic data of The Geysers, Isherwood (p. 1065) postulated that the gravity and magnetic anomalies are caused by a young intrusive body centered 10 km below the southwest edge of the Clear Lake volcanic field. Teleseismic P-delay data indicate that the postulated intrusive body may still be partly molten (Steeples and Iyer, p. 1199). A gravity high separating the main gravity low from a smaller gravity low is most likely due to a dense cap rock that directs hydrothermal fluids from beneath the volcanic field southwest to The Geysers (Isherwood, p. 1065) through a fault zone (McLaughlin and Stanley, p. 475) that remains permeable because of continued microearthquake activity (Hamilton and Muffler, 1972).

It is evident that geothermal reservoirs and their immediate surroundings have certain specific physical characteristics that are susceptible to detection and mapping by geophysical methods. The temperature within the reservoir, that is, the base temperature (Bodvarsson, 1964; 1970), is the most important physical characteristic of a geothermal system. Simply stated, the base temperature is the highest temperature observed in the thermally uniform part of a geothermal reservoir. The physical and chemical processes within the geothermal reservoir depend critically on this quantity, and the technique of heat extraction has to be selected with regard to these temperature conditions.

Additional important characteristics of geothermal reservoirs that can be determined to some extent by geophysical exploration are the probable dimensions of the reservoir, its depth, and the necessary physical conditions prevailing within it. From theoretical calculations, Banwell (1963) and Goguel (1970) indicate that a reservoir with a base temperature of 250°C would need to have a volume of 2 to 3 km^3 in order to justify exploitation for electric power production with present-day economics and technology. This then is the size of the target to be sought by geophysical exploration, although some of the larger geothermal systems already explored have volumes which may be from 5 to 10 times larger.

The geothermal reservoir rock must have an adequate and suitably distributed permeability. A good geothermal well should produce at least 20 t/hr of steam; many wells produce at much higher rates (Budd, 1973; Tolivia, p. 275; Grindley and Browne, p. 377; Mercado, p. 487; Petracco and Squarci, p. 521; Barelli, et al., p. 1537; Burgassi, et al., p. 1571; Fukuda, Aosaki, and Sekoguchi, p. 1643; Katagiri, Abstract VI-25). The maintenance of high flow rates implies a high degree of permeability in the reservoir, with porosity performing only a secondary part. Permeability is not a reservoir characteristic that is easy to measure using geophysical techniques (Risk, p. 1185).

The principal geothermal heat carrier, water, must be available in adequate quantities. As hot geothermal fluids are withdrawn from wells or from surface manifestations, the hydrological balance of the system is restored, or partially restored, by the inflow of new or recharge water (White, Muffler, and Truesdell, 1971). Knowledge of water movements in geothermal systems can be obtained with geophysical techniques (Hunt, 1970; Bodvarsson, p. 33; Tolivia, p. 275; Gupta, Singh, and Rao, p. 1029; Macdonald, p. 1113; Risk, p. 1185).

Retention of heat is increased and the upward movement of fluids from a geothermal reservoir is restricted by a cap rock which is simply a layer of rock of low permeability overlying the reservoir. The cap rock may be formed by a stratigraphic unit (Tolivia, p. 275; Grindley and Browne, p. 377; Kurtman and Şâmilgil, p. 447; Petracco and Squarci, p. 521; Swanberg, p. 1217). A cap rock may also be produced by self sealing due to the deposition of minerals from solution, mainly silica, or by hydrothermal alteration of rocks to clays and/or zeolites (Bodvarsson, 1964, 1970; Facca and Tonani, 1967; Bird and Elders, p. 285; Grindley and Browne, p. 377; Kristmansdóttir, p. 441; White, et al., Abstract II-56). Cap rocks provide a recognizable geophysical exploration target because of the considerable contrast in physical properties.

The maximum depth at which a geothermal system might be found and exploited is limited on the one hand by the probability of decreasing porosity and permeability and on the other hand by drilling costs. A provisional upper limit under present economic and technological conditions is perhaps 2 km depth to the top of the geothermal reservoir.

Since the base temperature constitutes the most important physical characteristic of a geothermal system, thermal exploration methods, such as geothermal gradient measurements in boreholes and heat-flow determinations, are of primary importance. Thermal exploration techniques provide the most direct method for making a first estimate of the size and potential of a geothermal system with surface geophysical exploration. Although geophysical methods other than thermal methods only provide an indirect determination of the base temperature of a geothermal reservoir, they provide an estimate of depth, lateral extent, permeability, water supply, and cap rock distribution which cannot be obtained using thermal techniques.

The application of any geophysical method, other than thermal methods, in geothermal exploration is based on the fact that the physical property of the rock that is being measured is affected to some degree by an increase in temperature (Birch and Clark, 1940; Birch, 1943; Hochstein and Hunt, 1970; Keller, 1970; Murase and McBirney, 1973; Spencer and Nur, 1976; Watts and Adams, p. 1247). In the geophysical exploration for geothermal reservoirs, the most reliable indicator of abnormal subsurface temperatures is the direct determination of an anomalous heat flow. Any alternative geophysical indicator is less reliable since it provides an indirect determination of temperature.

For example, the application of electrical and electromagnetic methods in geothermal exploration is based on the fact that the electrical conductivity of wet porous rocks increases rapidly with increasing temperatures. Variations in electrical conductivity may be due to changes in salinity or porosity (Keller, 1970; Duba, Piwinskii, and Santor, Abstract III-19) rather than the temperature. There is no unique relationship between temperature and the electrical conductivity of the subsurface.

MODELS AND GEOPHYSICAL SURVEYS

From the foregoing discussion, it is evident that geothermal reservoirs and consequently geothermal fields owe their existence more to deep-seated tectonic processes and physical conditions than to any particular near-surface geological environment. However, it must be recognized that the total surface area thus far sampled by geothermal exploration is a very small fraction of the surface of the earth and the selection of exploration sites has been strongly biased towards areas with obvious surface thermal manifestations—near hot springs, geysers, fumaroles, and pools of boiling mud. Surface manifestations may or may not reflect conditions at depth depending on the extent to which the thermal system is masked by overlying nonthermal groundwater horizons.

Moreover, the presence of surface thermal manifestations implies that a geothermal reservoir has been breached by fault movement or erosion, and its contents are being dissipated by this natural leakage. The larger the outflow and the longer period of time that the discharge has been continuing, the less are the chances that a commercially useful geothermal reservoir still remains.

Geothermal exploration, however, is moving beyond this stage of reservoir detection, and has turned towards the search for deeper-seated and well-sealed geothermal reservoirs which are unmarked by any surface evidence (for example: Cataldi and Rendina, 1973; Arnórsson, et al., p. 853; Baldi, et al., p. 871; Blackwell and Morgan, p. 895; Combs and Rotstein, p. 909; Swanberg, p. 1217; Williams, et al., p. 1273). New geothermal systems are being found by a process of geological analogy supported by geophysical measurements. However, the strategy of geothermal exploration is quite often hampered by the variability of the geological environment, by a lack of understanding of the geothermal systems, by the lack of reasonable geological models to be tested by geophysical surveys, and by a confusion about what results can be obtained from particular geophysical surveys.

The known geothermal fields of the world are all associated with various forms of volcanic activity (Healy, p. 415; Muffler, p. 499) and with faulting, with graben formation, and with tilting, uplift, and subsidence of crustal blocks, all of which are probably the result of processes in the upper mantle. The rock types present and the character of the volcanic rocks ejected are no more than a reflection of the composition of the crust in the immediate vicinity.

This close spatial and genetic relationship of many geothermal systems to young volcanic centers (Healy, p. 415) has formed the basis for a new rationale for the search for geothermal resources. This approach, developed by Smith and Shaw (1975), is to identify large, young, silicic volcanic centers which may be molten or have hot intrusive rocks at depth that can function as a heat source for the overlying convective systems of meteoric water. Although this approach has been restricted to silicic rocks, areas of intensive basalt extrusion may also have a significant geothermal potential (Smith and Shaw, 1975). For example, a major Quaternary basaltic feeder zone in southern Washington state is indicated by a pronounced negative gravity anomaly (Hammond, et al., p. 397) which would indicate that the basaltic feeder zone is partially molten if the gravity low is interpreted in the same manner as the major gravity low over The Geysers (Isherwood, p. 1065; Steeples and Iyer, p. 1199).

Since the intrusion of magma into the upper crust can produce the necessary heat source for a geothermal system, we are concerned with the identification and development of geophysical methods to determine the depth and areal extent of these large volumes of molten rock within the crust. Because of their considerable depth of penetration, electrical, electromagnetic, and seismic techniques are the types of geophysical surveys which are particularly suited for locating deep magma chambers.

In the central volcanic region of the North Island of New Zealand, where the Broadlands, Rotokaua, Tauhara, and Waiotapu thermal areas are situated, Keller (1970) conducted a large-scale regional electrical depth sounding using the time-domain/coil technique. With this electromagnetic survey, Keller (1970) located an apparent deep heat source which has been interpreted to be a slab of basalt with a partially molten interior (Banwell, 1970). From an extensive magnetotelluric survey of the neovolcanic zone in Iceland, Hermance, Thayer, and Björnsson (p. 1037) have found a systematically lower resistivity than was found in the older crust and have interpreted the lower resistivity to be partially caused by a small (several percent) melt fraction of basalt in the deep crust. Zablocki (p. 1299) has used the prominent self-potential anomalies found at Kilauea Volcano in Hawaii to determine the position of magma pockets on the flanks of the volcano.

Magma chambers and movement of magma within volcanoes have been recognized using seismological techniques, such as in the seismic prospecting carried out by Hayakawa (1970) at Showa-Shinzan in Japan and by Fedotov, et al. (p. 363) at the Avachinsky Volcano on Kamchatka; the use of seismic body waves from microearthquakes by Matumoto (1971) to identify the magma chamber underlying Mount Katmai Volcano in Alaska; and the use of teleseismic P-delay studies by Steeples and Iyer (p. 1199) to postulate magma chambers at Yellowstone National Park, The

Maasha, p. 1103; McNitt, p. 1127; Risk, p. 1185 and p. 1191; Stefánsson and Arnórsson, p. 1207; Tezcan, p. 1231).

Electrical resistivity studies have provided data for the detection and mapping of geothermal systems, for subsurface geological and structural interpretation, and for monitoring of groundwater flow patterns. Geophysical surveys, based only on electrical methods, have been used to determine the extent of the geothermal reservoir of the El Tatio geothermal field of Chile (Lahsen and Trujillo, p. 170; Hochstein, Abstract III-39). United Nations project experience (McNitt, p. 1127) indicates that the most suitable geothermal exploration technique is dipole-dipole resistivity profiling since this type of electrode array is easy to maneuver in rugged country and it provides the results that are simplest to interpret geologically. Risk (p. 1191) has presented an excellent analysis of fracturing at Broadlands, New Zealand using detailed bipole-dipole resistivity studies. In another study, Risk (p. 1185) has shown that the inflow of cold water to the Broadlands geothermal field can be determined by regular monitoring of the position of the reservoir boundary using electrical resistivity surveys.

During the last few years, there has been a serious effort made to test various electromagnetic methods which are designed to monitor the naturally occurring electric and magnetic fields that are observed at the surface of the earth (Beyer, Morrison, and Dey, p. 889; Combs and Wilt, p. 917; Cormy and Musé, p. 933; Hermance, Thayer, and Björnsson, p. 1037; Hoover and Long, p. 1059; Maas and Combs, Abstract III-56; Whiteford, p. 1255; Williams, et al., p. 1273). The development and testing of the telluric and magnetotelluric methods in geothermal exploration has been motivated partly in an attempt to find a rapid and low-cost method for reconnaissance surveys of relatively large areas and partly in an attempt to increase the depth of penetration under the conditions of high near-surface electrical conductivities which usually occur in geothermal areas.

Geothermal activity may generate significant self-potential anomalies by thermoelectric coupling or by generation of streaming potentials caused by the motion of subsurface fluids. Therefore, self-potential (SP) surveys can be used to determine the presence of zones of thermal activity and to identify possible shallow subsurface channels for the movement of geothermal fluids (Zohdy, Anderson, and Muffler, 1973; Combs and Wilt, p. 917; Corwin, p. 937; Jangi, et al., p. 1085; Williams, et al,. p. 1273; Zablocki, p. 1299).

It has been known for some time that high-temperature geothermal areas are characterized by a relatively high level of microearthquake activity (Ward, 1972; Combs and Rotstein, p. 909; Maasha, p. 1103). The study of these microearthquakes, and their precise hypocentral locations provide the data necessary to determine any active fault zones in a geothermal area, which may be functioning as subsurface conduits for the geothermal fluids. In addition, the results of a microearthquake survey can be used to speculate on the subsurface physical characteristics of the geothermal system (Combs and Rotstein, p. 909). Pálmason (p. 1175) has suggested that the main use of microearthquake surveys, at the present time, may be to try to predict the depth of water circulation in geothermal systems, something which cannot easily be accomplished with other geophysical methods.

Published case histories of geothermal fields are few and are generally incomplete. However, at least eight excellent geothermal case histories have been presented at this symposium, in addition to the four presented by McNitt (p. 1127). The eight include three from the United States, the Mesa Geothermal Anomaly in California (Swanberg, p. 1217), the Marysville Geothermal Area, Montana (Blackwell and Morgan, p. 895), and the Southern Raft River Valley Geothermal Area, Idaho (Williams, et al., p. 1273); two from Italy, the Cesano Geothermal Field (Calamai, et al., p. 305); one in Iceland, the Krisvik High-Temperature Area, Reykjanes Peninsula (Arnórsson, et al., p. 853), one in India, the Parbati Valley Geothermal Field, Kula District, Himachal Pradesh (Jangi, et al., p. 1085) and one in Kenya, the Olkaria Geothermal Field (Noble and Ojiambo, p. 189). I will not attempt to either highlight or summarize them here.

The papers covered in Section IV are extremely diverse: from the evaluation of geophysical exploration methods and techniques, to the collection of field data, to laboratory techniques and measurements, and to geothermal case studies using a myriad of geophysical surveys. Nevertheless, the unifying theme throughout is the attempt of each of the investigators to develop a better method of identifying the geothermal systems that are the target of the search and of defining potential drilling sites for exploratory geothermal boreholes. Geophysical surveys should not, however, be discontinued when the discovery well is completed but should be continued with a change in direction as pertains to the target being sought. That is, they should begin to examine water recharge and the nature of the heat source, to consider the prediction of permeable zones for future production-well drill sites, and to aid in the ongoing environmental monitoring.

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