Acta Geodaet., Geophys. et Montanist. Acad. Sci. Hung. Tomus 11 (3—4), pp. 377—397 (1976)

ELECTRIC CONDUCTIVITY STRUCTURE AND GEOTHERMAL RESERVOIRS

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As first, SCHMUCKER interpreted conducting anomalies of the Earth's crust and mantle by geothermal anomalies. Since then electromagnetic field methods and processing have developed significantly. It seems that electromagnetic methods yield important contribution to the investigation of geothermal reservoirs, mainly on a regional scale.

Introduction

The present rate of the world energy produced by geothermal sources is as little as 1%. According to sound estimations (2nd United Nations Geothermal Symposium: SFA Greider 1975), this rate of geothermal energy will grow till the end of this century to 16%. Maybe, this prediction will not be fulfilled, current and partly successful surveys however in the USA, USSR, Japan, Iceland, Turkey, New Zealand and in some other countries verify that geothermal energy will play a role of importance.

Diverse geophysical methods have been proposed for the prospecting of geothermal reservoirs: geomagnetic, gravity, seimic methods, the increase of microseismic activity, and so on. It seems, however, that geothermal and geoelectric methods are the most favourable for this purpose. Recent heat flow studies are often motivated by the importance of the Earth as a source of heat for the generation electrical power [23]. The aim of this review is to summarize the possibilities of electromagnetic measurements for geothermal reservoir studies, in connection with the respective geological conditions.

Geology of the geothermal reservoirs

Geothermal reservoirs are parts of the upper crust which are quite hotter than their environment. Geothermal generation of electrical energy becomes initially economical if the reservoir contains superheated steam ('vapour dominated' reservoir). Among these, Larderello (Italy) and The Geysers (California) are the best known, the temperatures and pressures in the steam reservoir at both localities are near those for the maximum enthalpy of steam (240 °C and 33 bars).

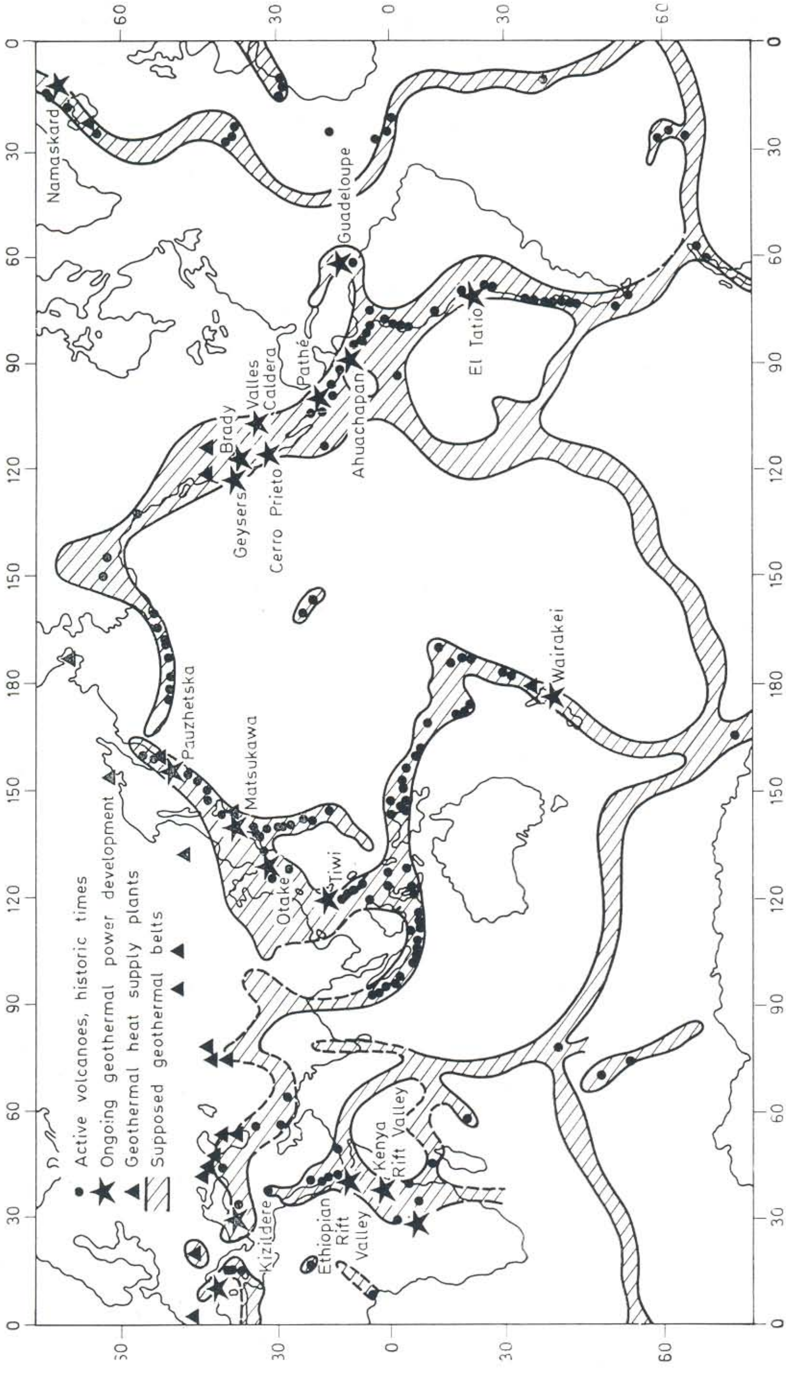

Fig. 1. Possible geothermal regions of the world. After *Geonomics* 1975, modified and redrawn

Reservoirs of low enthalpy, containing hot water ('water dominated' reservoirs) are less economical, although many exist. Experiments are underway for fractionation of hot dry rocks by hydrofracturing, with the aim of using the heat content of hot rocks by circulating water in the fractures (man-made reservoir, SFA [77 31]). There are conceptions for the utilization of the energies of volcanoes (magma power station), the difficulties, however, seem to be tremendous.

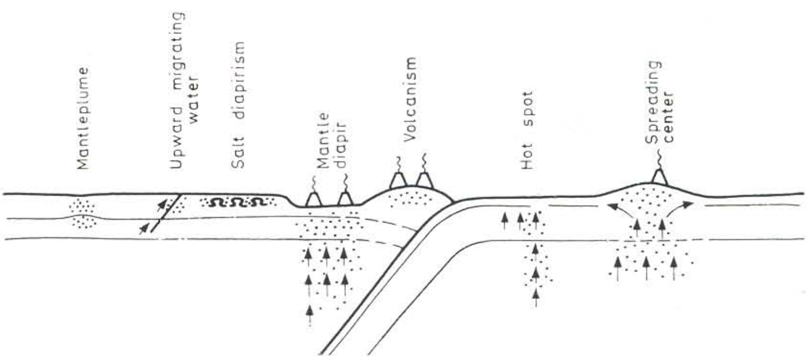

Fig. 2. Processes causing upward moving materials as possible sources of upward-directed thermal convection and geothermal reservoirs

Heat conducted from the inner Earth to the surface, generally 1.5 microcal/cm^{2}s, forms an extremely diluted source of energy, amounting to only about 1 : 100,000 part of the density of energy radiating from the Sun to the Earth's surface. The utilization of this latter also provides a difficult problem, for the density of the energy is still too low. In the course of the geothermal energy utilization never the heatflow, only heat accumulated during geological times has been used: this accumulated heat may be very significant; e.g., the heat content of the Neogene sediments of the Pannonian basin would satisfy the energy need of the world for several thousand years, in case of a total exploitation.

Such a total exploitation, however, is not possible, from both theoretical and practical reasons. Only particular, hot parts of the upper crust, the geothermal reservoirs, are suitable for energy production. Geothermal reservoirs occur firstly in the Circum-Pacific belt and secondly in the Alp-Himalayan Belt (Fig. 1). These areas are at the same time the areas of Alpine orogeny and volcanism. Geothermal energy utilization is at present mostly on volcanic areas. On these areas (Kamchatka, New Zealand, Iceland) the existence of reservoirs is quite evident and easy to search and exploit.

In terms of plate tectonics, geothermal reservoirs may occur near the consuming and transform (?) plate margins. Accreting plate margins (spreading centres) surely give good possibilities too; the loss of heat by creation of lithosphere for the total length of ridges is 30—40% of the total average heat loss of the Earth [45]. Accreting plate margins are mostly situated at oceanic areas, and thus hard to access. Exploration for geothermal energy has been performed on the areas of the African rift system (Afar, etc.).

Taking into consideration the low thermal conductivity of rocks, the statement of HERMANCE et al. [77 14] can generally be accepted, i.e. a geothermal reservoir can be formed only there, where upward-directed material transport occurs. The known types of upward moving material are: upward migrating fluids, volcanism, hot spot, mantle plume, mantle diapir. One can add, after JONES [37], the salt-diapirism (Gulf of Mexico) too (Fig. 2).

These are the general geological principles of the prospection of geothermal reservoirs: in regional sense, we have to search for those parts of the crust (and upper mantle) being hotter than their environment. In local sense, we have to prospect concrete hot reservoirs often containing water or steam and lying in the upper crust (in the depth of some km). Both tasks are favourable for electromagnetic methods, the latter specially if the reservoir contains water or steam.

Electromagnetic methods

Since CAGNIARD [21] developed his magnetotelluric method, electromagnetic methods have been used as convenient and valuable means for estimating the conductivity profile down to moderate depths. Shallow-depth resistivity methods are reviewed elsewhere. In crustal-scale resistivity surveys four specific techniques have been used, direct-current sounding, magnetotelluric sounding, induction sounding and geomagnetic deep sounding. WAIT [86], VOZOFF [84] and PRICE [65] describe in excellent comprehensive papers the theory and results of the magnetotelluric and geomagnetic fluctuation methods. Geoelectromagnetic studies have advanced tremendously in the past years as a result of improved instrumentation, computer analysis, and especially interpretation. These studies have steadily increased in importance as means of delineating the tectonic structure in the crust and upper mantle [12]. The strength of electromagnetic exploration resides in the ability of the method (1) to obtain information at great depths, (2) to help to define horizontal boundaries, and (3) to provide this informations in terms of parameters sensitive to temperature and composition. The lack of high resolution of electromagnetic methods is fortunately compensated, especially for searching geothermal areas, by the fundamental independence of electrical conductivity from physical properties other than temperature and water content, studied by other geophysical techniques.

Rock resistivities and temperature

The electrical conductivity of rocks and minerals is treated on the basis of semiconductor theory [70]. It has been experimentally ascertained (e.g. [51]) that the temperature dependence of the electrical conductivity of rocks and minerals can be generally expressed as:

$$\sigma = \sum_i \sigma_i e^{-A_i/T} = \sigma_m e^{-E_m/2kT} + \sigma_n e^{-E_n/2kT} + \sigma_\sigma e^{-E_\sigma/2kT}$$

where the summation should be made for all conduction processes: impurity (m), intrinsic (n) and ionic (σ) semiconduction. E is the activation energy, k is Boltzmann's constant and T denotes the absolute temperature. In a relatively low, less than 600 °C temperature, impurity, between 600—1100 °C intrinsic, and above 1200 °C ionic, conduction predominates.

Based on some measurements of the activation energies of olivine and pyroxene, the temperature distribution within the mantle was calculated from the distribution of electrical conductivity [70, 82]. In view of the resolving power of the existing analyses of transient geomagnetic variations, the resulting temperatures are less convincing.

Presnall et al. [64] demonstrated that large increases in the conductivity of a basalt can occur on heating through its solidus, according to Waff's calculation [85], a small melt fraction can produce a marked increase in the bulk conductivity. This forms the basis for correlating zones of high mantle conductivity with partial melting [56].

At greater depths the exponential dependence of mineral conductivity on temperature has long been a prime motivation of research, the influence of composition is estimated as relatively unimportant. Laboratory measurements, however, do not form a consistent data set [25]. Duba and Nicholls [26] demonstrated that changes in the oxidation state of minerals in this temperature range can cause large changes in conductivity. Piwinskii and Duba [77 24] stated that the electrical conductivity of the albite, an important constituent of granitoid rocks, increases several orders of magnitude at temperatures below melting. They believe that large resistivity anomalies could represent lateral variations in plagioclase feldspar content rather than partial melt zones or rising thermal plumes. Some regional, studies, however, ([83] for Japan, [87] for the western USA, [79] for the Pannonian basin) show that most conductivity anomalies are closely correlated to upheavals of high-temperature isotherms (Fig. 3).

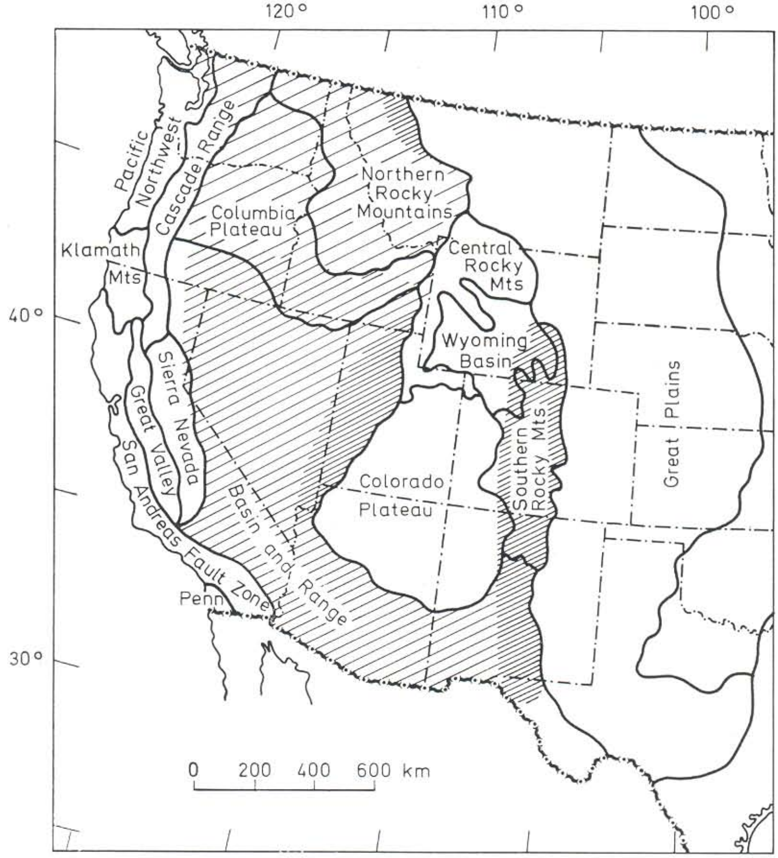

Fig. 3a. Conductive structure of the upper mantle in the western United States (after Gough [31] and Renner et al. [69]). Conductive upper mantle regions are stripped

Rock resistivities and water content

The other important parameter influencing the electrical conductivity in the crust and upper mantle (?) is the fluid content [20, 19, 18, 17, 16]. It is widely recognized that the conductivity of the upper crust is controlled by the free-water content of the rocks. Laboratory studies [54, 39] support this idea. The resistivity can be calculated approximately from the expression:

$$\varrho = \varrho_w S^{-n}$$

where ϱ_w is the electrical resistivity of the water filling the pores, S is the volume fraction of water present in the rock, and n is an experimentally determined parameter, about 1.6 for crystalline rocks.

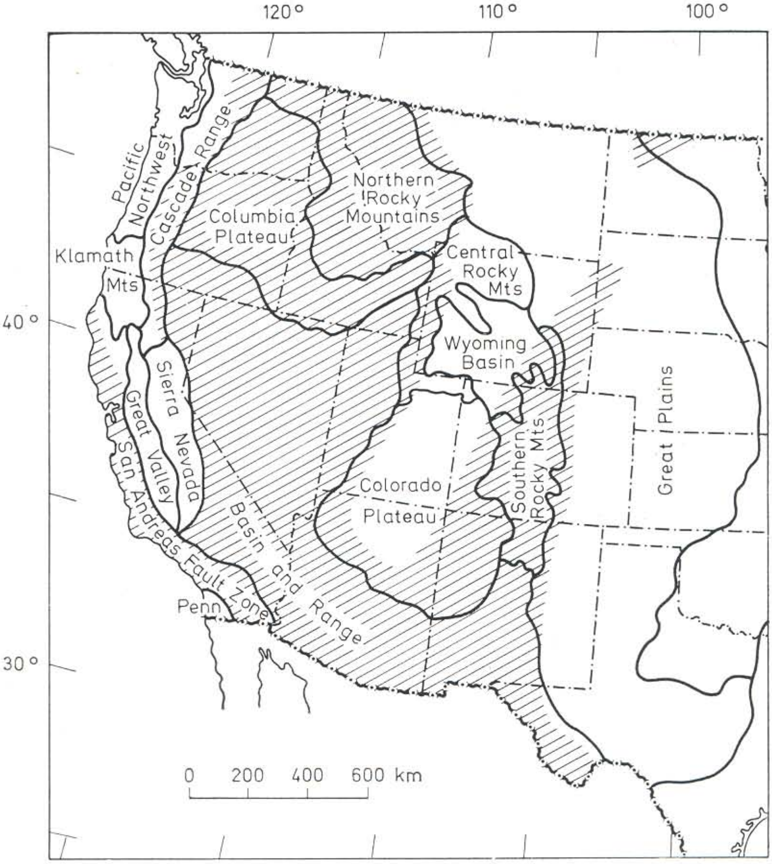

Fig. 3b. Thermal structure of the upper mantle in the western United States (after GOUGH [31] and RENNER et al. [69]). Hot crustal regions are striped

QUIST and MARSHALL [66] measured the conductivity of dilute aqueous solutions. Merely from inspection of Fig. 4 it is clear that the conductivity of a 0.01-molar NaCl solution would increase by a factor of about 6. Beyond 400°, however, there is a more complicated interaction of pressure and temperature effects.

The possibility that water is present in the crust, is a problematic one. It seems that an aqueous pore fluid could exist in equilibrium with any known crustal rock, provided that conditions of pressure and temperature are suitable [93]. By means of downgoing slabs, water can be convected at great depths.

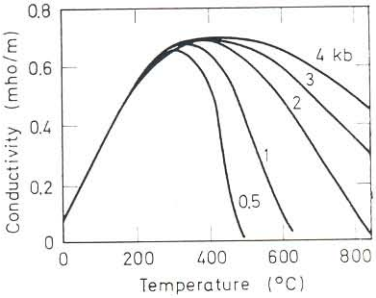

Fig. 4. Isobaric conductivity of a 0.01-m NaCl solution as a function of temperature, at pressures 0.5—4 kilobars (from QUIST and MARSHALL [66]

Regional studies

SCHMUCKER [72] first explained a variation anomaly in northern Germany in connection with depth temperatures. After RIKITAKE [70], KELLER [40] gave an excellent review on the electrical studies of the crust and upper mantle. As a conclusion, he found that in tectonically active areas, especially in areas overlying subduction zones, conductivity increases to moderately high values, in the range from 0.01 to 0.1 mho/m, at depth between 50 and 100 km. This increase might be attributed to higher than normal temperatures, water contents or to both factors. Active spreading zones appear to be underlain by similar conductive zones (Gulf of California [89]; Iceland [35]; Afar triple junction [15] by magnetotelluric and [59] by geomagnetic deep-sounding).

Reviewing the crustal resistivity anomalies from geomagnetic deep-sounding studies, PORATH and DZIEWONSKI [57] stated that a number of magnetic variation anomalies can be attributed to inhomogeneities of electrical resistivity in the upper crust. The electromagnetic induction in isolated conductors is usually too small to explain anomalies associated with crustal inhomogeneities, and anomalous variation fields mainly arise from concentration and channelling of currents induced elsewhere. The systems of currents are induced over a large region of the Earth and have dimensions comparable to those of the source field. Most of the crustal anomalies are associated with deep conducting sedimentary basins or with regions of a rapid change of sedimentary conductivity. Examples of anomalies of this origin are the North German basin (Fig. 5 [62], PORSTENDORFER supposed a certain temperature activation as the cause), the Anadarko basin, Oklahoma, north-central Texas [12] and the Pannonian basin [3].

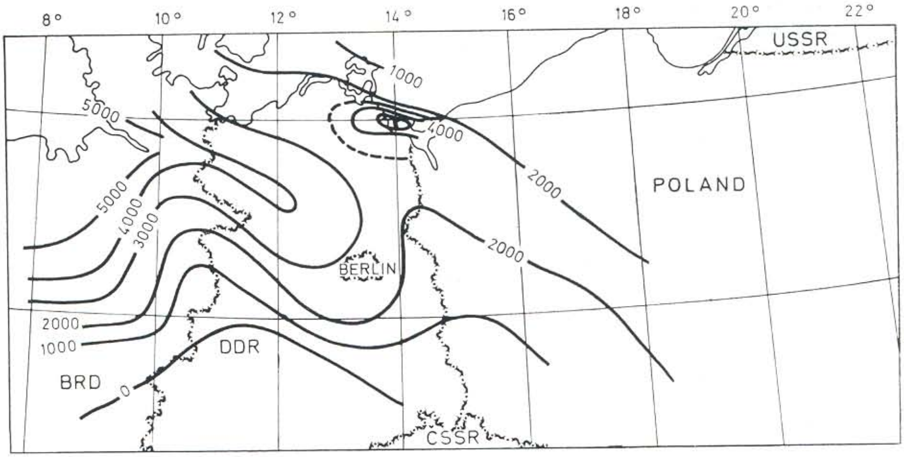

Fig. 5. The North German–Polish conductivity anomaly, determined by magnetotelluric and geomagnetic deep soundings (PORSTENDORFER [63]). Isolines: total length conductivity in mho

Pertinent data for crustal or subcrustal layers of high conductivity have been published for Yakutia [14], for the Pannonian basin [3] (Fig. 6), and for Iceland [35].

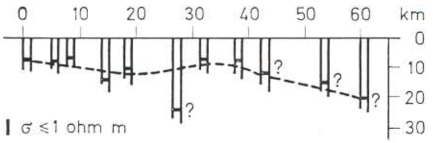

Fig. 6. Depth of the high conducting layer (1 mho/m) along a 70 km long profile in Western Hungary, based on 11 magnetotelluric soundings (ÁDÁM [3])

Other conductive zones at shallow to intermediate crustal depths have been observed by both magnetotelluric and geomagnetic variation studies under the Dakota Black Hills [32, 67] and in South Australia [81, 33], by geomagnetic variation studies in Scotland [27] and in the St. Lawrence region, Canada [8], and by magnetotellurics in Texas [92, 49]. It seems to be difficult to model such zones, since they are considered to be due to the flow of current induced over a large irregular shaped region. However, it is possible to estimate their maximum depth, and some of these structures are undoubtedly linked to temperature anomalies. PORATH [55] questioned the presence of any conductive layer in the Earth's crystalline crust, because in all instances studied an alternative solution can be presented or the geological setting in which measurements were made does not allow a unique interpretation. In the light of the above recent results, conductivity highs existing in the crust seem to be reasonable.

Many studies have indicated mantle zones of high conductivity which can often be plausibly interpreted as zones of high temperature and/or partial melt (Rhine graben [91]; East African rift, Kenya [10]; Rio Grande rift [73]). Gough [31] suggests that the low-frequency anomaly observed in South Africa is evidence of a mantle plume.

A geomagnetic substorm field simultaneously recorded with an array of 46 variometers, in the NW USA and SW Canada [22], and in SW USA [58], linked the variometer profiles of Schmucker [73]. It was shown that the observed magnetic variation anomalies could be related to lateral changes in the electrical conductivity of the upper mantle (Fig. 7), probably caused by regional variations in temperature.

A magnetic variation anomaly with very large amplitude in the northern Great Plains, USA has been tentatively attributed to a zone of conducting graphite schishts.

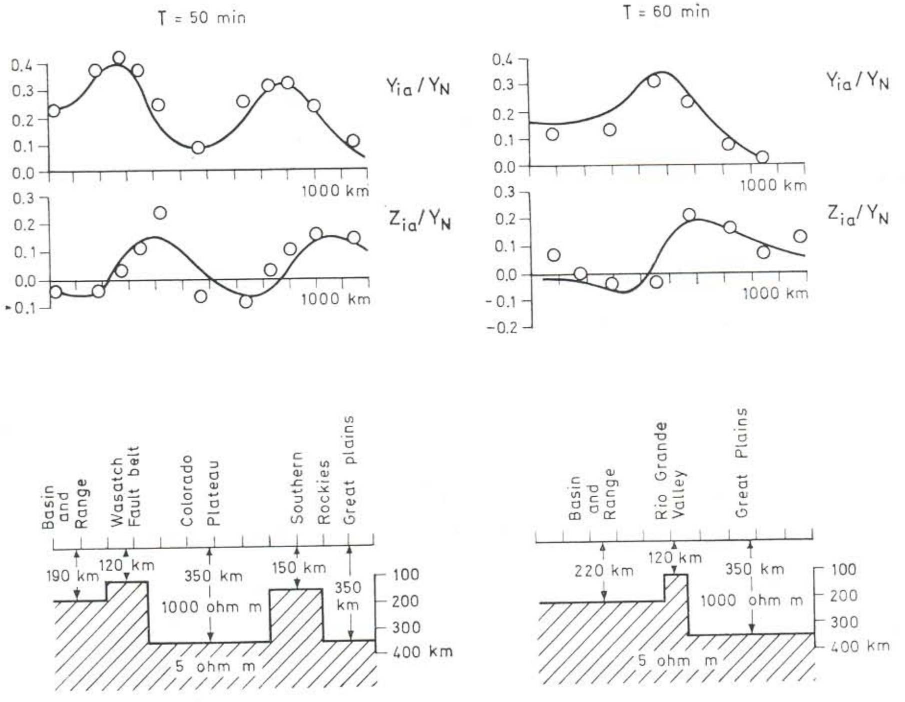

Fig. 7. Mantle conductive structure models for 2 United States traverses, based on magnetic variation measurements (Porath and Gough [58], for the right profile observed data after Schmucker]74]

High conductivity at depth beneath the extensive recent volcanics of SW Victoria, Australia, has been suggested by Bennett and Lilley [13]. The Mud Volcano system in Yellowstone Park was first recognized as a vapour-dominated system. Resistivity data [94] suggest that the vapour-dominated part extends to a depth of 1—1.5 km and is underlain by a better electrical conductor [69]. The rate of magma supply from deep sources was identifed as the dominant source of this system [78]. The magnetotelluric traverse across the Yellowstone geothermal region [44] stated an upheavel (up to 5 km depth) of the high conducting zone, showing that magnetotellurics offers a tool for thermal measurements, due to the strong dependence of electrical conductivity on temperature.

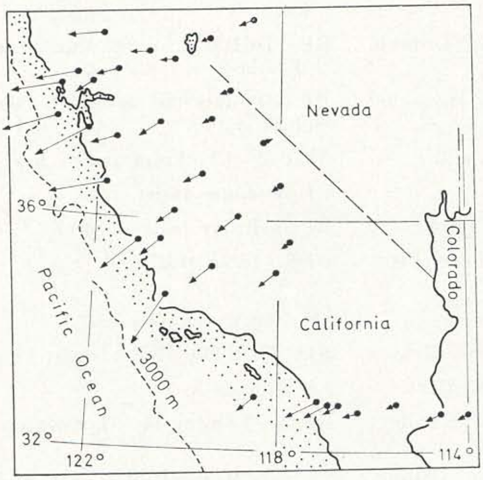

Fig. 8. Parkinson vectors for 1h-period geomagnetic variations, showing the Californian coast anomaly (Schmucker [73])

Other anomalies are related to currents concentrated in channels of conducting sea water (Bonifacio straits, the Alert anomaly). In an excellent review of regional induction studies Schmucker [75] emphasizes the transition areas from the continent to the ocean offshore. As he states, there is increasingly reliable evidence for high conductivities (0.02 —2.1 mho/m) at subcrustal or even at crustal depth beneath certain parts of the continents (Fig. 8). Electric structure beneath the oceans remains a problem of great interest. Only a few offshore studies have been made up-to-date [83, 74]. A reinterpretation of Schmucker's data [43] suggests a much less conductive crust and upper mantle beneath the Pacific off the California coast. Dosso's work [24] reviews electromagnetic analogue model studies of the coastal effect.

Local studies

During the last years electromagnetic measurements have been carried out on many geothermal fields. The following table summarizes some of these, in the light of the San Francisco Geothermal Conference. Figs 5, 9 and 10 show examples.

Geothermal area	Method and result	SFA reference
Kawah Kamojang, W. Java, Indonesia	RP, DCRS 3—10 ohmm resist. low	I. 29, III. 40
Puga and Chummatang, Ladakh, India	RP, DCRS 1.5—21 ohmm resist. low	I. 34, III. 33, 35
Parbati Valley, Kuru, Himachal Pradesh, India	RP, SP detected zones of thermal activity	III. 46
Broadlands, New Zealand	AMT 2—12 ohmm resist. low	III. 92
Sempaya, W. Uganda	RP 3 ohmm resist. low	III. 57
Lake Kitagata, W. Uganda	RP inclusive (salt waters)	III. 57
Buffalo Valley and Leach Hot Springs, Nevada	DDS, TS 'useful'	III. 6
North Central Nevada	SP 70 mV anomaly	III. 14
Jemez Mountains, New Mexico	RD, DDS 30 ohmm resist. low	III. 47
Roosevelt Hot Springs, Utah	EMS no data	III. 90
Southern Raft Rives Valley, Idaho	RP 2—5 ohmm low (hot waters)	III. 93
Dunes, Imperial Valley, California	TS, SP Mesa, Dunes geotherm. areas	III. 56, 84
Kilauea, Hawai	SP 1600 mV anomaly	III. 97
Meager Creek, British Columbia	DDS 10—200 ohmm resist. low (hot springs)	III. 69
Cerro Prieto, Baja California, Mexico	RS, DDS resist. low	III. 30, 31
El Tatio, N. Chile	RP, RD, DCRS 3 ohmm resist. low	III. 39
Southern Lowland, Iceland	RS 3 hydrothermal systems separated	III. 84
Iceland	TS, MTS broad and sharp hot zones	III. 38
Sarayköy-Kizildere, Turkey	RS resist. low (hot waters)	III. 86
Cesena, Latium, Italy	VES belts of resist. low	III. 10

Abbreviations: SFA — Abstracts of the San Francisco Symposium. RP — resistivity profiling, DCRS — direct current resistivity sounding, SP — self potential method, AMT — audio magnetotelluric method, DDS — dipole

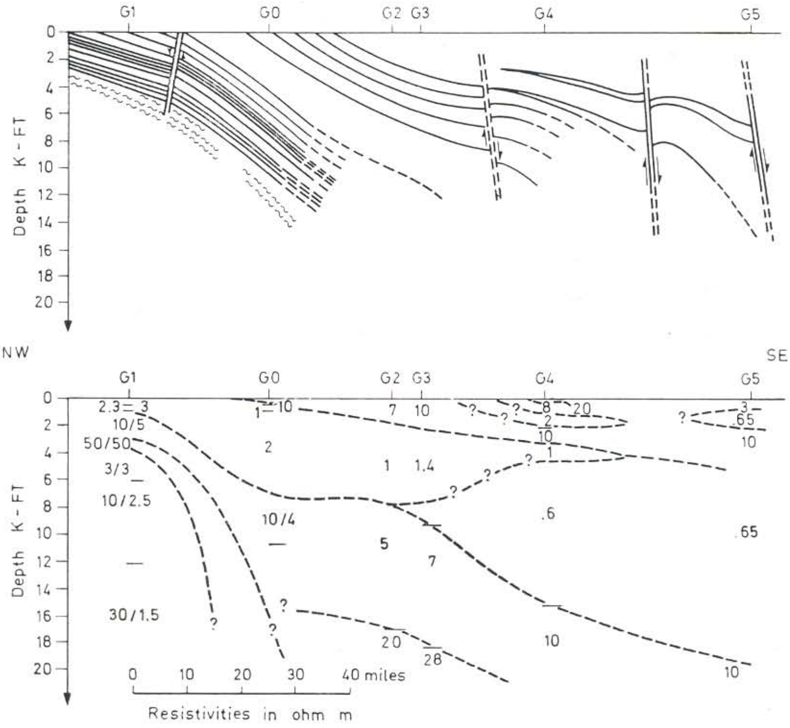

Fig. 9. South Texas traverse geological cross section, and interpreted resistivity cross section based on 6 magnetotelluric soundings (VOZOFF [84])

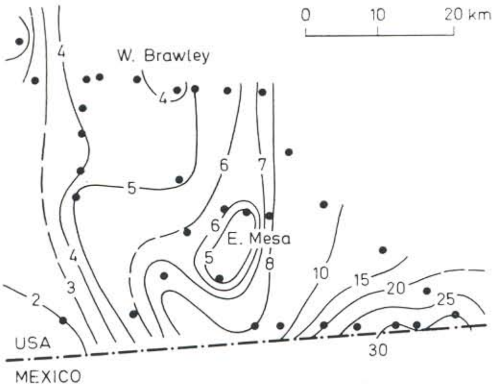

Fig. 10. Apparent resistivity isolines (in ohm) for 200' depth. Imperial Valley, California (MEIDAV and FURGESON 1972). Note the regional resistivity gradient upon which geothermal fields (W. BRAWLEY, E. MESA) are superimposed

dipole sounding, TS — telluric sounding, RD — roving dipole resistivity method, EMS — electromagnetic sounding, RS — resistivity survey, MTS — magnetotelluric sounding, VES — vertical electrical sounding.

Limitations

Since Wait (1954) and Price (1962) certain limitations of the telluric and magnetotelluric methods have become known. As mentioned, magnetotelluric observations near current concentrations are rarely adequate as representations of resistivity curves. The uncertainty introduced into the interpretation of magnetotelluric soundings by the effect of lateral changes in the electrical properties of near-surface materials is a major shortcoming of the technique. Lateral variations of the conductive caprock generally mask the influence of temperature on resistivities [77 8]. Both magnetotelluric and geomagnetic variation studies preferentially outline zones of high rather than low conductivity. A thick surface cover of conductive sediments can give rise to marked anomalous induction effects [56]. These effects extend to surprisingly low frequencies [57].

The resolving power of induction methods for measuring crustal resistivities constitutes the central problem of its application for reservoir studies [46]. In spite of these difficulties, the geomagnetic, telluric and magnetotelluric deep-sounding technique can yield important informations for reservoir studies, especially in the reconnaissance stage. Deep sounding, using some form of direct-current electrode method appears to be best suited for detailed investigations of the electrical structure of the Earth's crust, since the source field has a known configuration and is limited compared to the global dimensions of the field used in natural electromagnetic techniques.

Instruments and methods

After Serson's review [76] newer techniques have been proposed for resistivity measurements, influenced at first from reservoir surveys. MT-5EX is a five-component magnetotelluric apparatus with exponential solutions [77 6]. Ádám and Major [5] describe a magnetic variometer based on photoelectrical detection. Several magnetometer principles have been proved satisfactory for observations on the deep ocean floor (chopper stabilization techniques [28]; superconducting quantum magnetometers [12]).

New electric and electromagnetic methods have been proposed for geothermal reservoir researches: roving dipole method (Fig. 11 [77 18]), audio-magnetotelluric method [77 17, 77 29], rotating dipole survey [77 9]. A higher speed reconnaissance capability as practiced in the USSR, leads to more favourable consideration of the method when rapid coverage at low cost is more important than great accuracy [84].

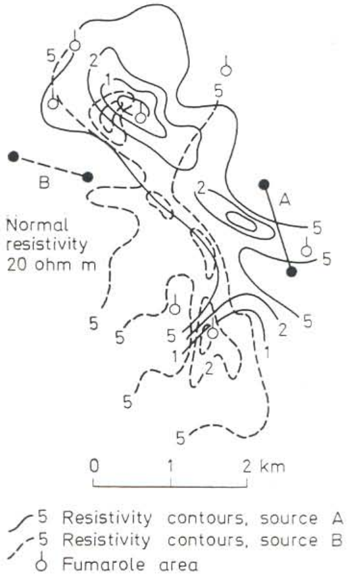

Fig. 11. Roving dipole survey using two (A and B) transmitter locations, on an area with fumaroles. Indonesia, *Geonomics* (1975)

A set of magnetotelluric sounding curves show the importance of anisotropy [42, 80]. This may be of importance for searching linear conducting structures. If the rock of a geothermal hot-water reservoir has a set of parallel fractures, its resistivity is likely to be anisotropic [77 25].

Interpretation

Interpretation is the area of both the greatest progress and the greatest need for improvement [84]. The advent of large modern computers has made the solution of many problems possible. Several mathematical and computer techniques have been developed. Bailey [7], Jones [37] and Weaver [88] reviewed the methods of interpretation: the modelling methods, exact inversion methods, the heuristic [6] method, induction in laterally non-uniform conductors, induction by elementary harmonic sources and so on. Model calculations of Jones and Price [38] showed the important differences in the apparent resistivities calculated for H and E polarization. Hermance [34] showed that estimates of the apparent resistivities are more stable when calculated from the tensor elements rather than from simple orthogonal field ratios (Cagniard estimate).

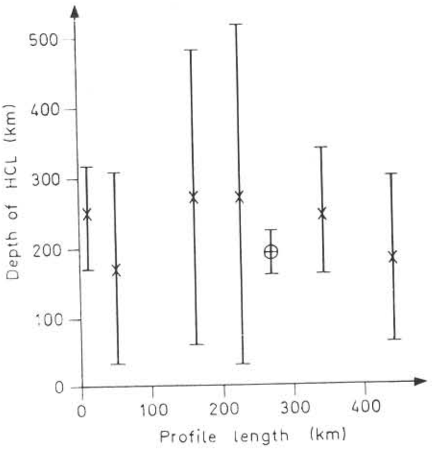

Fig. 12. Depth of the HCL (high conducting layer in the mantle), along a 450 km long MTS-profile. NE from Moscow. Depths are calculated by maximum estimate function for 6 MTS points separately and together (cross). The large errors of separately calculated points diminished remarkably in case of a common interpretation (after Porokhova [60])

The rate of change of the surface impedance with respect to the various parameters of the structure is one of the most important piece of information needed for determining the conductivity-depth function. Abramovici et al. [1] show two methods for calculating the partial derivatives of various components of the impedance tensor with respect to the conductivities at different depths and to the thickness of different sublayers. These partial derivatives are used for finding the model that fits the data "best" in a certain way.

On a similar way, Soviet researchers [95, 60] introduced into the interpretation of electromagnetic soundings the theory of errors of the solution of inverse problem, and information theory. These works are based on the fundamental ideas of Goltsman [29], a synthesis of information processing, based on statistical analysis. This kind of interpretation strategy, the numerical solution of the direct problem and of the inverse transformation of electromagnetic soundings based on algorithms built up on the basis of the theory of linear systems, consists of the following steps [7]. On the basis of (1) statistical information theory and (2) discrete convolution-algorithms borrowed from the theory of linear systems, one can build up an interpretation furnishing a nearly optimal result. Using this strategy one obtains (1) the information-theoretically optimal number of parameters (sublayers), (2) an estimate of the errors of the parameters, (3) an estimate of the values of the parameters, and (4) the efficiency of interpretation based on statistical considerations.

An example of this kind of interpretation is showed in Fig. 12 [60]: a separate interpretation of individual magnetotelluric soundings gave the depth of the high conductive mantle within an error of 16—90%. In a joint interpretation of all soundings, an accuracy of 10% resulted.

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СТРУКТУРА ЭЛЕКТРИЧЕСКОЙ ПРОВОДИМОСТИ И ГЕОТЕРМИЧЕСКИЕ РЕЗЕРВУАРЫ

Л. ШТЕГЕНА

РЕЗЮМЕ

Хорошо проводящая аномалия земной коры и мантии геотермической аномалией впервые был интерпретирован Шмукерым. С тех пор значительно были развиты электромагнитные методы измерений на местности и обработки. Кажется, что электромагнитные измерения дают значительный вклад в исследовании геотермических резервуаров, в первую очередь, в региональном смысле.