Cross-references

Barlow, Peter (1776–1862)
Geomagnetism, History of
Gilbert, William (1544–1603)
Halley, Edmond (1656–1742)
Voyages Making Geomagnetic Measurements

CONDUCTIVITY GEOTHERMOMETER

Introduction

The concept of the electrical conductivity geothermometer comes from the laboratory-demonstrated dependence of the electrical conductivity of rock material on temperature (Hinze, 1982). These laboratory results are consistent with theoretical considerations.

Beneath various complications that arise in the upper crust of Earth, rock material is generally considered to conduct electricity according to the physical mechanism of electronic semiconduction. The partial melting of rock material may also increase rock conductivity once connectivity is established for the melt fraction (Shankland *et al.*, 1981).

For electronic semiconduction, the relationship is the Arrhenius one between electrical conductivity σ and absolute temperature T, given by (Parkinson and Hutton, 1989)

$$\sigma = \sigma_e \exp(-E_e/kT) + \sigma_i \exp(-E_i/kT) \qquad \text{(Eq. 1)}$$

Here the first term in Eq. (1) describes extrinsic conduction, operating through thermally activated crystal defects and impurities, and the second term describes intrinsic conduction at higher temperatures. The terms σ_e and σ_i are the high-temperature asymptotes for each type of conduction, E_e and E_i are activation energies, and k is the Boltzmann's constant.

The strategy is to exploit the phenomenon of electromagnetic induction at Earth's surface by natural source fields (Campbell, 1997) to obtain a σ profile. Then, in terms of parameters σ_e, σ_i, E_e and E_i determined experimentally from laboratory studies or on the basis of other laboratory information, to obtain a T profile from the σ profile. The procedure is thus in two parts, which will now be discussed in turn.

Determining electrical conductivity as a function of depth

The observed data are time-series of magnetic and electric fields measured at various places over the surface of Earth. Generally these places are well-established magnetic observatories, sometimes supplemented by more temporary magnetotelluric stations. The primary signals have generally come to the solid Earth from outside it, and because they change with time they induce secondary fields within Earth, as the planet is an electrical conductor. At the surface, observations record both primary and secondary fields combined. A process of data inversion is needed, based on the known physics of induction in the Earth (Weaver, 1994), to give from these observations a profile of electrical conductivity with depth.

Activity in this topic is now such that specialist workshops on Electromagnetic Induction in the Earth have been held in different parts of the world every two years since the first one in Edinburgh, Scotland in 1972. Review and contributed papers are published, for example see Weaver (1999). Data on electrical conductivity structure from electromagnetic observations are used to obtain information on geological structure, composition, and history.

An important point is that the process of electromagnetic induction in the Earth is frequency dependent. An indication of the depth of penetration into a material by an induction process is given by the electromagnetic "skin depth," δ,

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} \qquad \text{(Eq. 2)}$$

where ω denotes angular frequency, σ denotes the electrical conductivity of the material, and μ denotes the permeability of the material (usually taken as that of free space).

Thus lower frequency signals penetrate deeper into the Earth and information on deep Earth conductivity depends on them. A natural limit to the lowest frequencies which can be observed is imposed by the spectrum of the source fields. Commonly the longest period studied is 1 year, exploiting a periodicity which has its origin in the seasonal cycle of Earth. A longer period of 11 years, which has its origin in a periodicity seen in solar activity, is also sometimes used. A limit may also be imposed by the length of observatory record needed to obtain data for these lowest frequencies.

If the Earth had ideal spherical symmetry, and its properties (including electrical conductivity) varied with depth only, the analysis of observations to give structure would be more straightforward. This situation, termed one-dimensional (1D), has mathematics which, while far from simple, are not as complicated as the next stages of complexity, which are termed two-dimensional (2D) and three-dimensional (3D) respectively (Weaver, 1994). For a 2D situation, the conductivity varies with two spatial parameters such as depth and one horizontal direction; while in a 3D situation the conductivity may vary in all directions.

Many case histories now demonstrate that departures from 1D are common in the electrical conductivity structure of the crust and upper mantle of Earth (Booker and Chave, 1989; Gough, 1989; Mareschal *et al.*, 1995). In addition to the possibility of "conductivity anomalies" caused by partial melt, other notable causes of increased conductivity are graphite and water (ELEKTB-Group, 1997).

However it is common to model the deeper regions of the Earth's mantle as 1D. This action is taken on the grounds that the material is expected to be more homogeneous than the more easily inspected crust.

An example of global conductivity profiles thus obtained by inverting surface observations are those of Olsen (1999) shown in Figure C15.

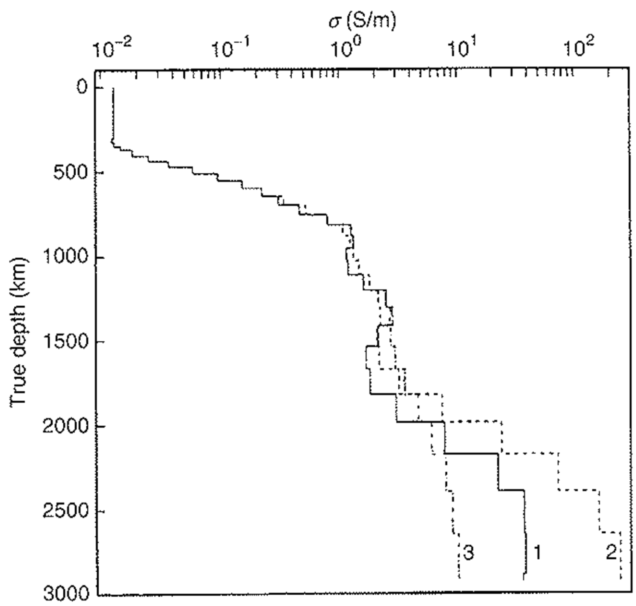

Figure C15 Profiles of electrical conductivity of the Earth as a function of depth, after Olsen (1999). The different profiles result from different data inversion procedures.

In this case, as in others, the mantle-core boundary is taken to be a step to effectively infinite conductivity, due to the molten metallic material of the Earth's core.

Determining temperature from electrical conductivity

When a conductivity profile with depth has been obtained, there is then the question regarding what mineral data should be used to convert the conductivity data to temperature. While there is general agreement about the main mineralogical composition of Earth, some fine points, upon which conductivity is highly dependent, remain uncertain. Prime amongst these is the oxygen state, in Earth's mantle, of the mineral olivine (Shankland and Duba, 1990; Constable and Roberts, 1997).

Figure C16 from Shankland (1981) combines data on rock and mineral conductivities. It shows firstly that electrical conductivity is an Earth quantity which varies by orders of magnitude in common rock materials. Then, within the range of conductivity values shown, the two lines (on the log-log graph) for synthetic "hot-pressed olivine" give an indication of the range of values in Eq. (1) possible when inverting conductivity data to give an "electrogeotherm" (and see Xu and Shankland (1999) for more recent experimental results). Such inversions are made on the basis (generally accepted by mineralogists) that the mantle of Earth is comprised mainly of olivine.

A number of research workers have thus published temperature profiles for the Earth based on analyses of electromagnetic induction at Earth's surface. The early result of Duba (1976), shown in Figure C17, is instructive regarding the general magnitudes of the quantities involved. Note that Constable (1993) explores the possibility that the temperature at 410 km is less than as shown in Figure C17, for consistency with experimental evidence that a phase transition at that depth should occur at 1400°C. The electrogeotherm models of Constable (1993), incorporating results from Constable *et al.* (1992), are shown in Figure C18.

It is important to note also that at the high temperatures near the base of the mantle, Eq. (1) becomes less temperature dependent, as its asymptotic form for high temperatures is approached. Thus electrical conductivity, even if known, becomes less useful in predicting temperature at such high temperatures.

Conclusion

Increasing research into the various elements needed to construct an electrical conductivity geothermometer has produced the result (common in research) that the matter is more complicated than might have at first been expected. While increased computer power enables continued progress in the numerical modeling of complicated conductivity structures and of the inversion of observed data in terms of them

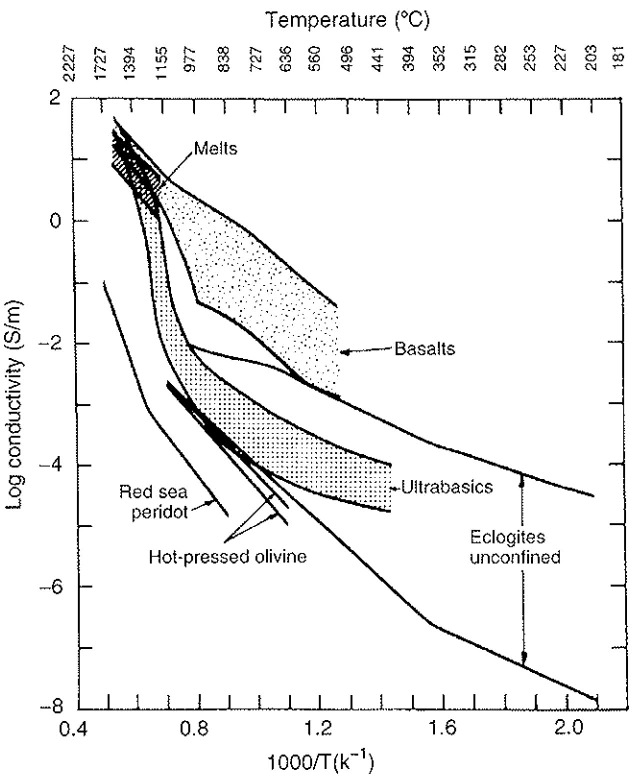

Figure C16 Conductivities of possible upper mantle constituents (after Shankland (1981) and Rai and Manghani (1978)).

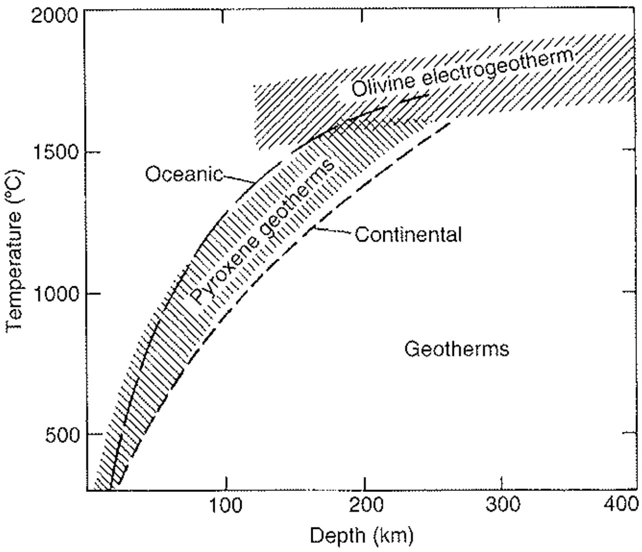

Figure C17 Olivine electrogeotherm for Earth's upper mantle compared with geotherms determined petrologically (after Duba, 1976).

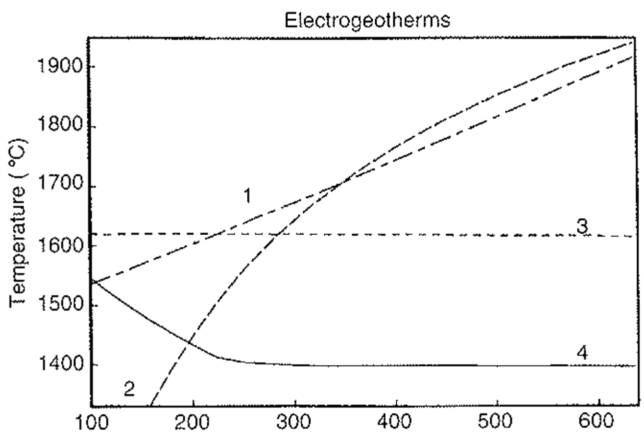

Figure C18 Upper mantle electrogeotherms, after Constable (1993). The different curves result from different data inversion techniques, especially regarding a possible step increase in electrical conductivity at depth 600 km.

(Fujii and Schultz, 2002), uncertainty about the details of the main constituent of the mantle (olivine, and in particular its oxygen fugacity) remain and limit the application of the strategy.

In fact at mantle depths the relationship between electrical conductivity and temperature is increasingly being examined from another view point. Rather than assume that the material in the mantle is known, it is increasingly the case that the temperature is estimated from other considerations. Then, such temperature estimates are used with laboratory measurements of different minerals to determine, from electrical conductivity profiles, the mineralogy of the mantle (Shankland *et al.*, 1993; Constable, 1993).

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Cross-references

Conductivity, Ocean Floor Measurements
Geomagnetic Deep Sounding
Magnetotellurics
Mantle, Electrical Conductivity, Mineralogy

CONDUCTIVITY, OCEAN FLOOR MEASUREMENTS

The ocean floor presents a particularly harsh environment in which to carry out electrical measurements, with pressures of up to 600 atm (60 MPa), temperatures of around 3°C, and no possibility of radio contact with instrumentation. Furthermore, seawater is a corrosive, conductive fluid. Thus, progress in the field of electrical conductivity studies has largely followed the availability of reliable underwater technology and has not become truly routine until recently.

Most electromagnetic methods can be adapted for seafloor use, but the high conductivity of seawater dominates both how data are collected and how they are interpreted. Seawater conductivity depends on salinity and temperature; in practice salinity variations are too small to be significant and so to a good approximation seawater conductivity is given by $(3 + T/10)$ S/m where T is temperature in degree celsius. The bulk of the ocean thus has a resistivity of about 0.3 Ωm, with warmer surface waters 0.2 Ωm.

DC resistivity is only practical for shallow investigations where the seafloor conductivity is similar to or greater than the seawater. The most common EM method applied to seafloor studies is the *magnetotelluric* (MT) method (*q.v.*). First experiments date from the 1960s, and Charles Cox, Jean Filloux, and Jimmy Larson (1971) report an MT response from measurements made in the Pacific in 1965, using 1 km long cables on the seafloor and a new seafloor magnetometer developed by Filloux. Filloux later also developed a system for making electric field measurements using short (about 3 m) pipes acting as salt bridges and a device to reverse the connection of electrodes to the pipes, allowing any electrode self potential to be removed from long period electric field variations (Filloux, 1987). Although this technique is still important for studies of ocean currents using seafloor E-field recorders, it has since proved unnecessary for MT studies, and it is now common practice to simply mount electrodes at the ends of four approximately 5 m plastic arms to give 10 m E-field dipoles. The torsion fiber magnetometers originally used by Filloux to keep power consumption low have been replaced in more recent instrumentation by fluxgate sensors and induction coils.

There are advantages and disadvantages to the seafloor MT method. On the advantage side, it is easy to make a low impedance, low noise electrical contact with the environment. The sensor of choice for this is silver-silver chloride nonpolarizable electrodes although a new carbon fiber electrode has been developed for short period studies. The seafloor is also free of the cultural noise that can plague land MT surveys. Access is good and permitting, if required, is usually valid for the entire survey area. Arrays of seafloor MT recorders lend themselves well to the new array processing techniques available.

On the other hand, the skin depth (exponential decay length for EM fields) at 1 Hz in seawater is only 270 m and so the overlying ocean removes the short period source fields, a problem exacerbated by the red nature of the geomagnetic spectrum (see *Geomagnetic temporal*