Imaging fluids using magnetotellurics:

Electrical conductivity as a proxy for viscosity?

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Introduction

Magnetotellurics is a natural-source electromagnetic method that can image lateral and vertical variations in electrical conductivity from the near-surface to the lithosphere-asthenosphere boundary (LAB) and beyond. The method involves recording orthogonal components of the time-varying electromagnetic field on the surface of the Earth, namely the three orthogonal components of the magnetic field (Hx, Hy, Hz) and the two horizontal components of the electric, or telluric, field (Ex, Ey), generated by distant lightning storms (for frequencies >1 Hz) and solar-magnetosphere interactions (for frequencies <1 Hz). The electric variations are related to the horizontal magnetic ones through an Earth response function that is a frequency-dependent 2x2 complex tensor termed the *MT impedance tensor*.

This tensor is estimated for a given frequency band at a site, and at a number of sites. The optimal frequency band and site spacing are dictated by the target depth and geometry. For problems within the top 2 kilometres (mineral exploration, geothermal exploration), the frequency band is typically 10 kHz – 10 Hz, and station spacing is typically 100 m to 1 km. Acquisition requires typically 15 minutes per site. At the other end of the spectrum, for lithospheric-scale problems, such as determining variations in the LAB, the frequency band is typically 0.1 – 0.0001 Hz with station spacing of 25 km to 50 km, and acquisition takes 2-5 weeks.

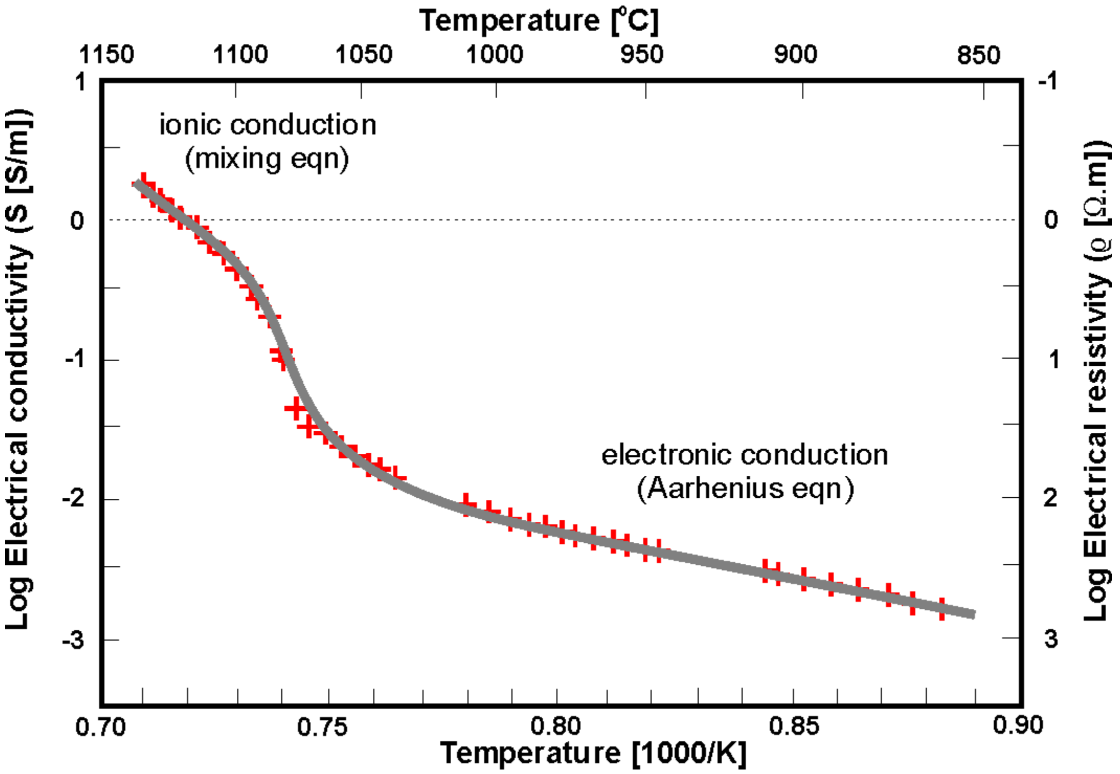
The impedance tensors are analysed for structural directionality and dimensionality, and are subsequently objectively modelled, using non-linear inverse methods, to obtain a two-dimensional (2-D) or three-dimensional (3-D) electrical conductivity model that best explains, in some sense, the observations. This model can then be compared with geology, geochemistry, petrology, and other geophysical data. Where MT can be powerful is in hypothesis testing, for example whether there exists an interconnected fluid phase at a certain depth or not.

This paper will briefly describe the parameter being sensed, give some examples of experiments where it was concluded that MT has imaged fluids, and propose that in some instances MT can be a useful proxy for viscosity.

Electrical conductivity

Conduction currents are predominantly by electron flow in solids, and ion flow in fluids. The intrinsic electrical conductivity of silicate rocks at crustal conditions is very low. However, a very small percentage of an interconnected conducting phase can dramatically increase that conductivity by orders of magnitude. This is particularly true of fluids, either saline brines or partial melts.

Shankland and Ander (1983) compiled the then available laboratory data on electrical conductivity studies on dry and wet rocks, and emphasized the difference between the two. Wet rocks have conductivities that are many orders of magnitude greater than their dry counterparts.



Most studies of melt have either focussed on the melt phase or on the solid phase. There have been few measurements taking rocks from one phase to the other, due to the difficulties associated with undertaking such measurements in the laboratory. The two important exceptions to this are the work of Watanabe et al. (1993), who studied the melting of a simple two-phase system comprising H_20-KCl, and Partzsch et al. (2000), who studied the melting of a pyroxene granulite. Their results are shown above, where an increase of over two orders of magnitude in electrical conductivity occurred over less than 50 ^{O}C temperature change as the conduction mechanism changes from solid state electronic conduction (governed by the Aerhenius equation) to ionic conduction in interconnected partially molten rock. Conductivity rose significantly even for very low melt fractions (<0.1%), as determined from quenching experiments.

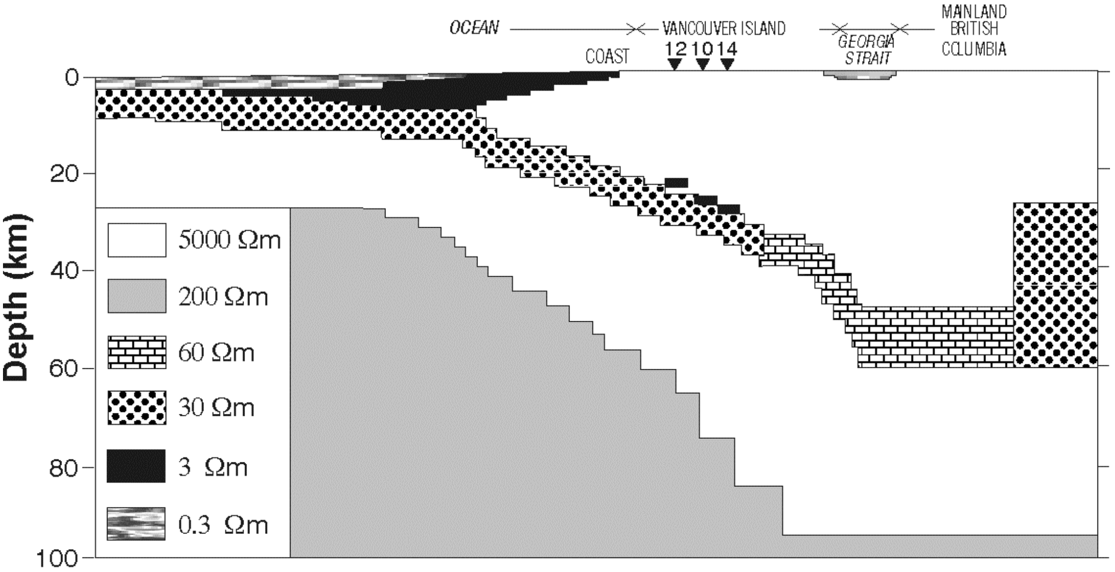
This dramatic increase in conductivity due to the introduction of a fluid phase gives MT high resolution of the existence of crustal fluids and of the onset of partial melt.

Examples

Juan de Fuca plate

The Juan de Fuca plate subducts beneath northwestern North America, specifically beneath the states of Oregon and Washington and the province of British Columbia. This small plate is one of the remnants of the Farallon-Kula plate which was of Pacific-ocean in size. Two crustal-scale MT experiments have been performed over the plate during the 1980s in order to image it. The first was by Kurtz et al. (1986, 1990), and was located across Vancouver Island. An increase in conductivity at some 23-34 km beneath Vancouver Island (see model below), which correlated with a zone of high reflectivity, was originally interpreted as the top of the Juan de Fuca plate itself (*“A magnetotelluric sounding across Vancouver Island sees the subducting Juan de Fuca plate”*, Kurtz et al., 1986). The second experiment was the largest EM experiment conducted, namely EMSLAB (Booker and Chave, 1989). MT measurements were made both onshore and offshore, and a landward-dipping conductor was imaged beneath the Oregon Coast Range. The interpretation favoured by Wannamaker et al. (1989), based on correlation with a COCORP seismic line, also was that this conductor represents the top of the Juan de Fuca plate subduction decollement.

However, beneath Vancouver Island earthquake foci from the plate come from much deeper, and Hyndman (1988) suggested that the conductor/reflector was caused by fluids released from the plate rising buoyantly that become trapped beneath an impermeable barrier controlled by temperature (Jones, 1987). Subsequently, Kurtz et al. (1990) presented a revised interpretation, consistent with these earthquake foci and with seismic reflection studies from off-shore to on-shore Vancouver Island, in terms of a region of brine-filled cracks and pores. Analyses of shear wave arrivals on Vancouver Island demonstrated low S-wave velocities for this anomalous region, and essentially confirmed a fluid interpretation (Cassidy and Ellis, 1991, 1993).



Garibaldi Volcanic Zone

Both local and regional MT studies have taken place across the Garibaldi Volcanic Zone. The former as part of investigations of the geothermal energy potential of Mounts Cayley and Meager, and the latter as part of LITHOPROBE's Southern Cordilleran transect investigations. Interpretation of those data was in terms of a highly conducting zone at some 12 km depth, thought to be the magma chamber, within a conducting crust caused again by fluids released from the Juan de Fuca plate (Jones and Dumas, 1993).

Omineca Belt

The Omineca Belt is one of the five physiographic belts of the Canadian Cordillera, and has been studied using MT as part of LITHOPROBE's Southern Cordilleran transect investigations. Studies in the southern part of belt show a conducting lower crust beginning at about 10-12 km that becomes even more conducting below ~20 km depth (Jones et al., 1992). In contrast, the more northernly part of the belt is more resistive (Jones and Gough, 1995). Recent modelling of these data shows that whereas the neighbouring Intermontane belt to the west has a strike-independent lower crust, in stark contrast there is a strong along-strike variation in the lower crustal conductivity of the Omineca Belt (Ledo and Jones, 2001). The part of the belt that is highly conducting was extended during the Eocene, whereas the part that is not remains unextended. Ledo and Jones (2001) suggest that mantle fluids penetrated the crust as a consequence of extension and induced melting of the lowermost part of the crust.

Viscosity-conductivity relationship?

Electrical conductivity is dominantly controlled by the presence of an interconnected conducting minor phase of the rock. Where this phase is a fluid phase, then one can advance arguments that conductivity can be used as a proxy for viscosity. As argued some 20 years ago by Tozer (1979, 1981) to explain upper mantle conductive features, the presence of water reduces silicate creep resistance. Laboratory experiments have demonstrated that rheology is strongly affected by the presence of fluids (Kohlstedt et al., 1995). This relationship will be examined with the view that conductivity can provide a proxy for viscosity to control geodynamic models of active regions.

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