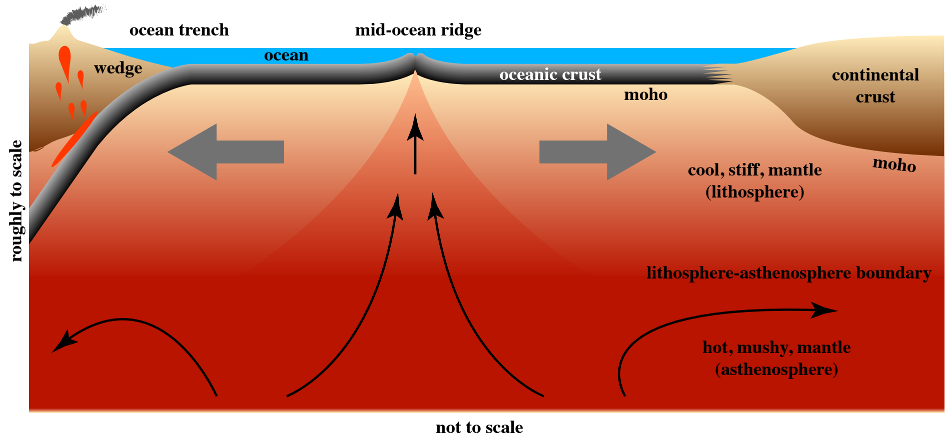
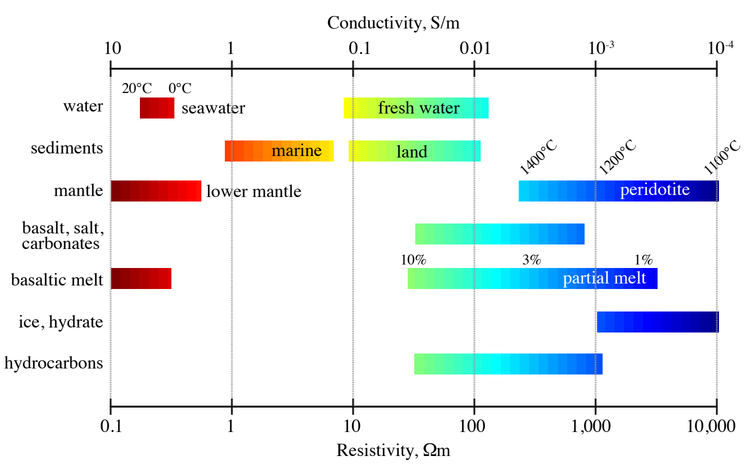
(Marine) Electromagnetic Methods Explained
Steven Constable, June 1, 2019

Geophysicists, people who study the physics of Earth and its geology, often try to understand what goes on inside Earth by making measurements from its surface. Seismologists study how fast (or slowly) sound waves travel through the ground, gravity can be measured to estimate how dense rocks are, and variations in the size of Earth's crustal magnetic field reflect changes in the concentration of magnetic minerals in rocks.

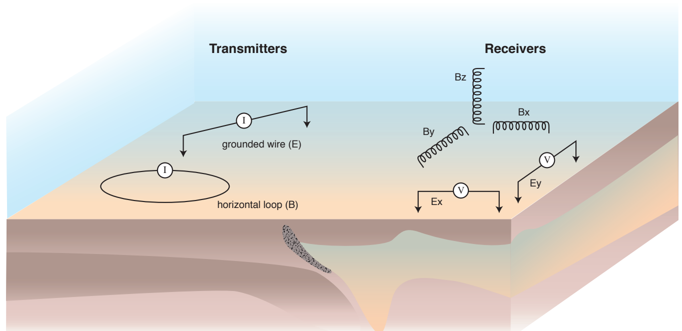


Another approach is to try and measure electrical conductivity variations in Earth's crust (typically the top 10–30 km) and mantle (below the crust all the way to the core). Conductivity varies a lot. Seawater is very conductive, between 3 and 5 S/m (siemens per meter, the metric unit of electrical conductivity). Molten rock (magma or lava) is about the same, and wet marine sediments are about 0.1 to 1 S/m. Volcanic rocks are around 0.01 to 0.1 S/m – now it gets easier to use units of resistivity, Ωm (ohm-meters), which is just the inverse of conductivity, so 10–100 Ωm. Igneous rocks like granite are 1,000 to 10,000 Ωm. For crustal rocks resistivity reflects the rock's porosity, because pore spaces are where conductive water sits and rock-forming minerals (e.g. quartz and felspar) are all insulators. Not all minerals are insulators: ore minerals can be very conductive, making electrical methods good for finding them. When water freezes to ice it becomes resistive. One variation on this is gas hydrate, which forms from seawater and methane at cold temperatures near the sea floor when the ocean is deep enough (about 400 m) to create high enough pressures. Finally, if oil and/or gas displaces water from the pores in sediments, the rock will become resistive. Measuring resistivity in boreholes is one of the primary tools for locating hydrocarbons.

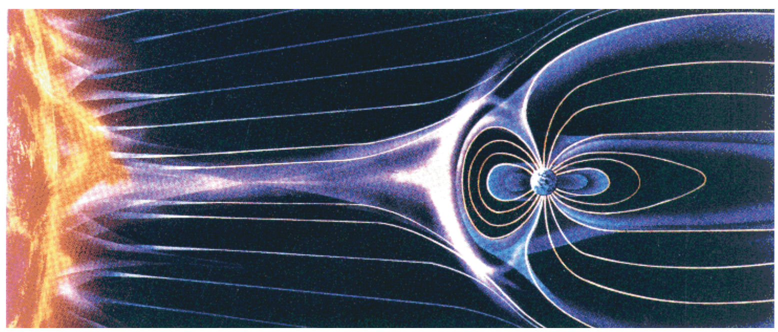


As you might expect, to measure electrical conductivity we need to pass an electric current through the rock. One way to do this is to pass a current between two metal electrodes driven into the ground. We can then measure the difference in voltage between two more electrodes – if we divide this voltage by the distance between these electrodes we get what we call the electric field. We can again use metal for measuring voltage, but most often we use an electrode which is more like the ones used in medicine to make contact with skin, using a conductive salt solution to connect to the ground.

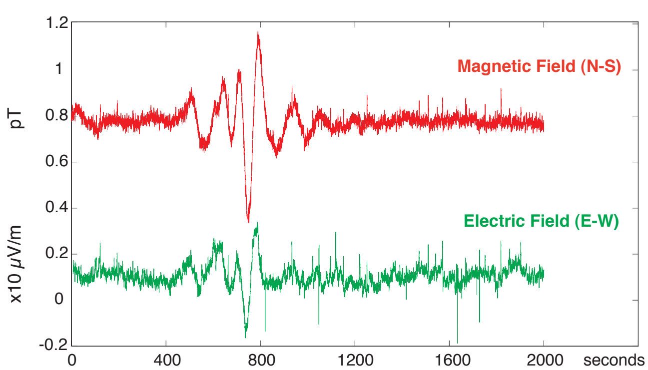
It might not always be convenient or even possible to use electrodes (for example, if you want to make measurements from a helicopter in the air). This can be done by using a big magnetic coil, or loop of wire, energized by an alternating current. The resulting alternating magnetic field induces electric currents in the conductive ground. This is really just like inductive chargers for electric toothbrushes, or the primary side of transformers inducing current in the secondary windings.



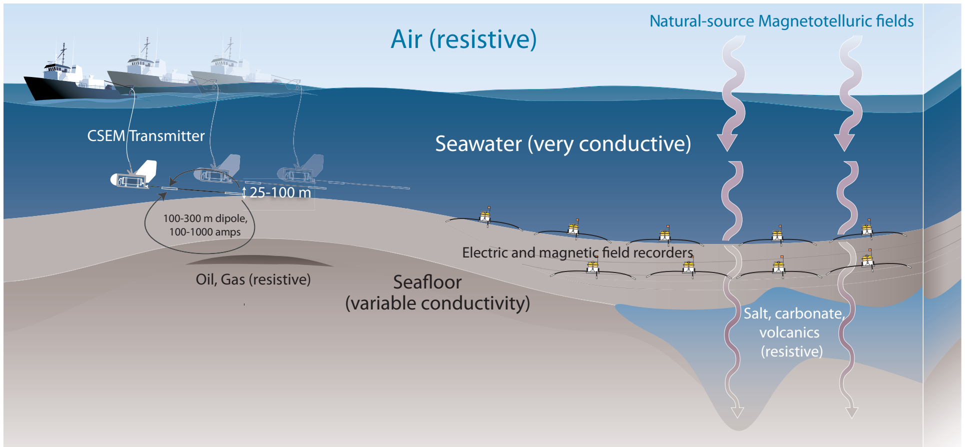
We sometimes measure the ground currents using electrodes, but usually it is more convenient to use magnetometers, maybe towed behind a helicopter, to measure the magnetic fields that the ground currents produce. Electric currents always produce magnetic fields, so you can also measure the currents injected into the ground through electrodes using magnetometers. There are lots of variations and combinations that are used, but they all fall in the category of **controlled-source electromagnetic (CSEM) methods**, because the transmitter that generates the electromagnetic fields, either coil or electrodes, is under our control. The magnetometers and electrodes used to measure the resulting fields can be called receivers. The amplitude and phase of the received fields, as a function of transmission frequency and transmitter/receiver position, provides information on Earth conductivity.



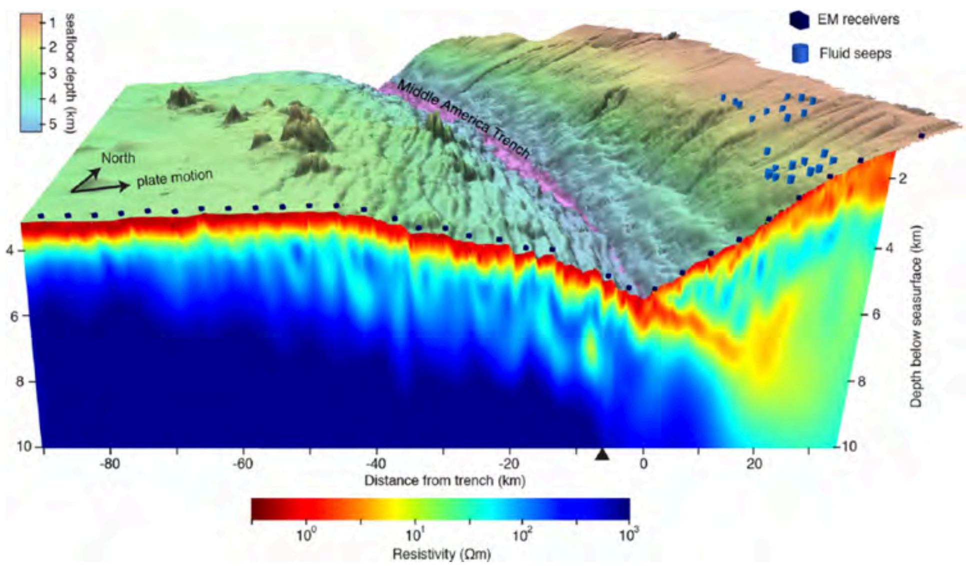
Man-made transmitters can only get so big, limiting the depth we can "see" into the crust to a few kilometers (a few tens of kilometers in extreme cases), but time variations in Earth's external magnetic field acts as a big transmitter in the sky. What we normally think of as Earth's magnetic field, the one that makes compasses point north, is made in the liquid iron core in the deep center of Earth. Earth's magnetic field acts as a shield that protects us from the stream of charged particles – radiation – emitted by the sun. The charged particles of the solar wind get deflected around Earth, but push on Earth's day side magnetic field as they do so. Some of these particles sneak inside Earth's magnetic field though the auroral zones and the night side, to get trapped and orbit Earth in the radiation belts, creating an electric current of up to ten million amps and an associated magnetic field. Time variations in the solar wind and radiation belt currents create time variations in the magnetic field that, although much smaller than the main field formed in the core, are still big enough to induce measurable electric currents in the crust and mantle, just the same way man-made transmitters do. These magnetic and electric fields form the basis for the **magnetotelluric (MT) method** (telluric being short for telluric current, another name for Earth currents).



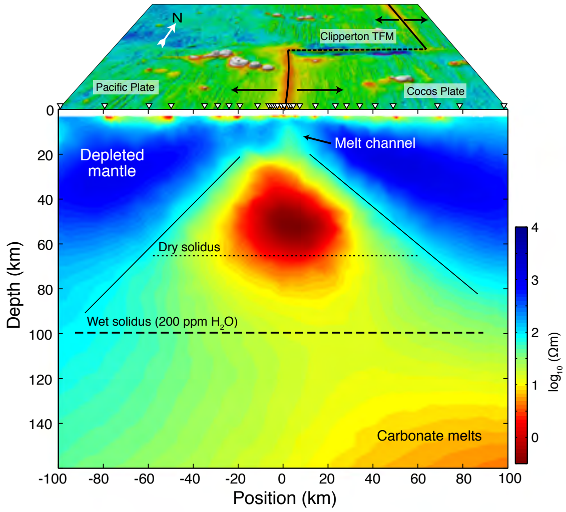
Unlike CSEM transmitters, where we know what magnetic field we are making, the MT source field is basically random, and we need to measure it using a magnetometer. The induced Earth currents are then measured with electrodes. Even the direction of the MT fields is random, so we usually make measurements both in a north-south direction and east-west direction. The ratio of the magnetic (source) to electric (induced) fields is a measure of conductivity, and again we make the measurements as a function of frequency and position. Because Earth's magnetic field varies on all time scales, we can go down to very low frequencies, as low as a cycle per hour, which allows signals to penetrate hundreds of kilometers into Earth's mantle.



Both the MT and CSEM methods can be used in the marine environment, by deploying battery powered, self recording MT/CSEM receivers on the seafloor and towing a CSEM transmitter close to the seabed. Electric transmitters work better than magnetic transmitters in the ocean, since it is easy to pass hundreds of amps through simple copper electrodes, and we can operate continuously as the transmitter moves through the seawater. The transmitter needs to be close to the seabed because the signal going up into the conductive seawater is absorbed while the signal reaching the seafloor gets propagated to the receivers. It is a bit counter-intuitive, but inductive signals propagate best though resistors. MT signals can reach the seafloor from the magnetosphere, but with some signal loss in the seawater.



Here is a conductivity image from a CSEM experiment on the subduction zone off Nicaragua (from Naif et al., 2016). Red is conductive, and shows where the sediments are. We can see them going down with the subducting slab and slowly losing water and porosity. Deep blue is very resistive, here representing the gabbros of the lower crust. The light blue vertical stripes in the crust of the incoming plate probably represent water in normal faults, and we see them opening up as the plate bends, (stripes are getting wider, greener, and deeper). We are not sure what the conductive blob in the wedge above the subducting plate is. It could be sediments scraped off the slab, faulting, or fracturing. It is intriguing that it sits below some seafloor fluid seeps.



This picture shows results from an MT experiment at about 9°N on the East Pacific Rise (from Key et al., 2013). Now the red part of the image represents melting resulting from decompression as the mantle rises beneath the mid-ocean ridge (in the center of the plot). We used to think that melting started 60–70 km beneath the ridge, where dry mantle rocks would melt, but we see deeper melting, consistent with a small amount of water dissolved in mantle minerals, and in agreement with modern thinking. The tent-like sides of the melted area suggests that melting is associated with passive upwelling of mantle as the plates spread apart, rather than upwelling driven by convection. This upwelling focusses the melt towards the spreading center. We can see that the high resistivities of the lower crust seen in the subduction zone actually extend several tens of kilometers into the mantle as the plate cools and moves away from the ridge.

Key, K., S. Constable, L. Liu, and A. Pommier, 2013. Electrical image of passive mantle upwelling beneath the northern East Pacific Rise. *Nature*, **495**, 499–502.

Naif, S., K. Key, S. Constable, and R.L. Evans, 2016. Porosity and fluid budget of a water-rich megathrust revealed with electromagnetic data at the Middle America Trench. *Geochemistry, Geophysics, Geosystems*, **17**, 4495–4516.