

Plugged-in Planet: Accessing the Interior of the Earth and Other Terrestrial Bodies via Electrical Properties

Anne Pommier¹, Michael J. Tauber^{1,2}, Kate Selway³, and Daniel Heyner⁴

1811-5209/26/0022-0102\$2.50 DOI: 10.2138/gselements.22.2.102

Among the different methods used to probe the interior of planets and moons in the Solar System, the ones providing access to the electrical properties of rocks are particularly powerful. From field induction measurements to laboratory impedance spectroscopy experiments, several techniques explore the electrical response of geomaterials at different scales of observation, from planetary to atomic. Detailed snapshots of the Earth's crust and mantle are obtained from the combination of magnetotelluric surveys with laboratory measurements. In space, induction observations complemented by electrical laboratory experiments have been key to defining the layered structure and thermal state of several terrestrial bodies. Future electrical investigations will continue to reveal the present structure of planetary deep interiors, which is necessary to decipher their evolution.

KEYWORDS: planetary interiors; mineral physics; electromagnetism; induction measurements; impedance spectroscopy; space missions

INTRODUCTION

Elucidating the structure, composition, and thermal state of **terrestrial bodies***, i.e., celestial bodies characterized by a rocky crust and mantle and a metallic core, is fundamental to understanding their origin and evolution. Among the different tools available to study terrestrial bodies, electromagnetic techniques that provide access to the interior are particularly powerful. The electrical properties of minerals and rocks that comprise the crust and mantle of the terrestrial planets (Mercury, Venus, Earth, Mars) and moons (e.g., the Moon, Europa, Ganymede, Io) in the Solar System are probed both in the field and in the laboratory. The knowledge derived from widely differing scales of observation (primarily from nanometer to millimeter in the laboratory, and from meters to hundreds of kilometers in the field) can be integrated for an in-depth understanding of the structure and composition of planetary interiors (FIG. 1).

In the field, the inner structure of planets can be probed by analyzing naturally occurring geomagnetic variations. A time-varying magnetic field naturally induces

electric fields that encircle the region of magnetic variation. These fields can drive currents in electrically conducting materials, such as planetary interiors. In turn, the currents generate secondary magnetic fields that can be detected from a distance. By comparing the inducing field and the planetary response over a wide range of frequencies, one can derive the electrical conductivity of the materials as a function of depth. Electromagnetic **induction** studies originated in the 1880s, magnetotelluric methods originated in the late 1940s, and over many decades have benefitted from substantial technological and scientific

advances that have improved the quality of field data and the development of 2-D and 3-D modeling (Chave and Jones 2012 and references therein). Currently, these geophysical tools characterize the structure of the Earth's crust and upper mantle via high-resolution snapshots of the planet's electrical response, and can also provide information about the electrical structure of other bodies (e.g., the Moon, Europa). In the laboratory, electrical studies of rocks also have decades of history and development. **Impedance** spectroscopy is now a widely used and powerful approach, and various setups have been developed to perform these electrical measurements at extreme pressure and temperature conditions that represent planetary interiors.

The range in conductivity spanned by geomaterials ($>10^{10}$ S/m for metals to $<10^{-20}$ S/m for insulating materials) has long been recognized as the widest of any common physical properties (Parkhomenko 1967). Typical conductivity values of geomaterials are illustrated in FIGURE 2. Because of the high sensitivity of rock conductivity to chemical composition (particularly water), texture, temperature, and redox conditions, electrical experiments performed under carefully controlled conditions in the laboratory are crucial for gaining fundamental insights into conductivity across various length scales and for building a useful database. Electrical measurements on materials from the Earth and planetary bodies are used to develop electrical models of the crust and mantle that can be compared with electrical conductivity–depth profiles of a planet that are derived from field observations (FIG. 1).

1 Carnegie Institution for Science
Earth and Planets Laboratory
Washington, DC 20015, USA
E-mail: apommier@carnegiescience.edu

2 University of California San Diego
Department of Chemistry and Biochemistry
La Jolla, CA 92093, USA
E-mail: mtauber@ucsd.edu

3 University of Tasmania
School of Natural Sciences
Hobart TAS 7005, Australia
E-mail: kate.selway@utas.edu.au

4 Technische Universität Braunschweig
Institut für Geophysik und Extraterrestrische Physik
D-38106 Braunschweig, Germany
E-mail: d.heyner@tu-braunschweig.de

* Definitions of terms presented in **blue** are given in the glossary on page 81.

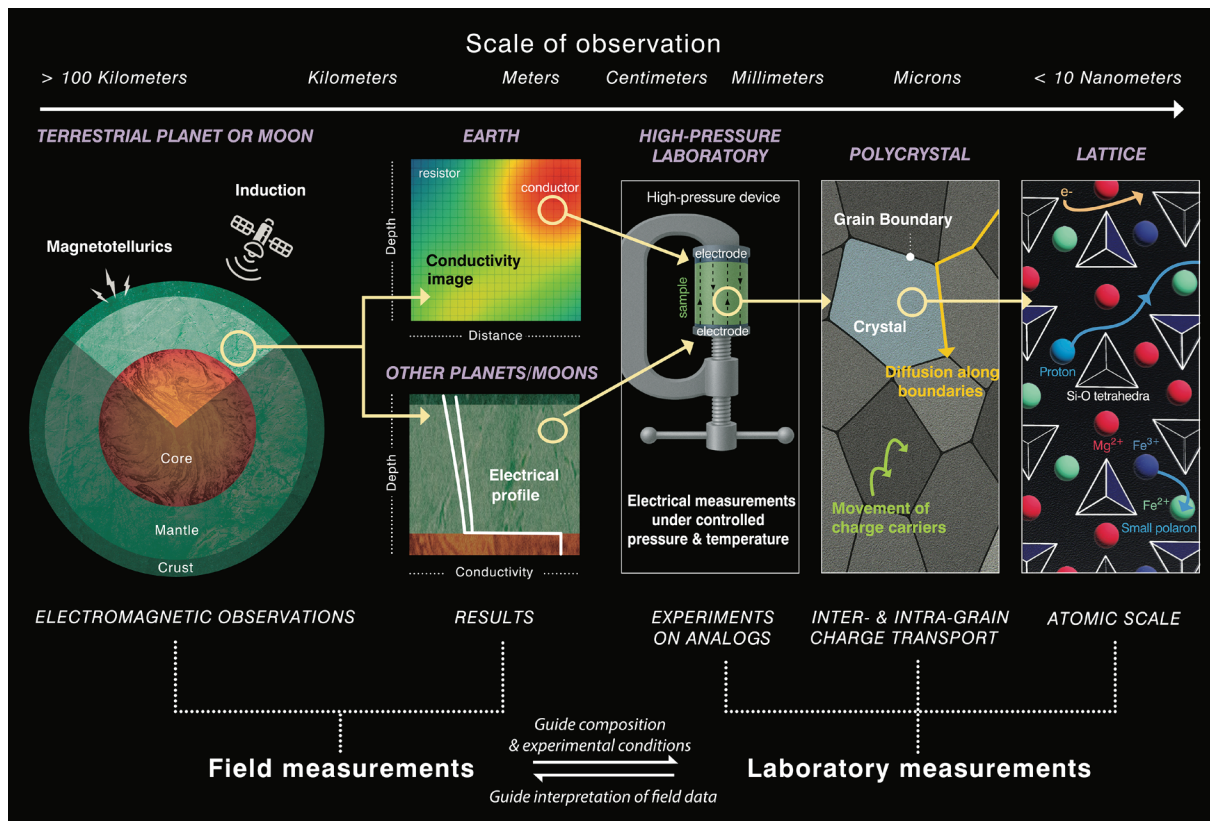


FIGURE 1 Different scales of electrical observation: from planets, to rocks, to laboratory samples, and to atoms (LEFT TO RIGHT), highlighting the synergy between field and laboratory measurements.

On Earth, the combination of field and laboratory electrical measurements is commonly used to interpret regions of anomalous subsurface conductivity in terms of composition, structure, and temperature. In particular, field and lab data can support the presence of fluids (magma, brine) or volatiles such as hydrogen and can guide exploration for minerals or hydrocarbons. Crustal studies have provided important constraints on tectonic structures and lithologies (e.g., faults, intrusive rocks, sedimentary basins) in different geological settings (e.g., Unsworth 2010) to understand past and present tectonic events. Surveys of the mantle have been conducted below the continental crust and the oceanic crust and define the electrical response both laterally and vertically. Subducting plates, deformation zones in the uppermost mantle, the structure of mid-ocean ridges, and cratons are among the large-scale tectonic features targeted with these surveys (e.g., Selway 2014).

In space, several missions have been equipped with instrumentation to measure induction and thereby probe the electrical properties of the interior. Among these missions are NASA's former *Apollo* program to the Moon, the ongoing ESA/JAXA's *BepiColombo* mission to Mercury, and NASA's *Galileo*, *Europa Clipper*, and ESA's *JUICE* missions to Jupiter's terrestrial moons. Magnetometers onboard the spacecraft detect the induced magnetic fields that originate from electrical currents within the terrestrial body. Measurements of this kind were fundamental to the discovery of subsurface oceans in icy worlds, such as in Jupiter's moon Europa (Kivelson et al. 2000) or the presence of magma inside Jupiter's moon Io (Khurana et al. 2011). Currently, defining the conductivity–depth profile of planet Mercury is an important scientific objective of *BepiColombo* (Genova et al. 2021) because the electrical

structure of the planet can provide valuable insights into its interior, such as the size of the core and the thermal state of the mantle.

ELECTRICAL PROPERTIES OF MINERALS

Basic Concepts

When an electric field (E) is applied to a rock, the displacement of charged particles is quantified by an electric current density (J) that depends on the electrical conductivity (σ , or its inverse, resistivity ρ) of the material. The magnitudes of these quantities are related by Ohm's law, which can be written simply for an isotropic material as

$$J = \sigma E \quad (1)$$

Geomaterials may be divided into three groups, based on their typical conductivity values (FIG. 2): conductors ($>10^5$ S/m), semiconductors (10^{-7} – 10^5 S/m), and dielectrics (or insulators; $<10^{-7}$ S/m) (e.g., Guéguen and Palciauskas 1994). Electrical conductivity in a rock depends directly on the concentration and mobility of charge carriers (typically electrons or small cations). The mobility of these charge carriers is sensitive to temperature and the frequency of the applied field.

In addition to conductivity (or resistivity), other electrical properties of geomaterials provide valuable information about rock structure and chemistry (e.g., Gerhardt 2005). Dielectric permittivity measurements reflect the polarization of a rock and, like conductivity, depend strongly on the mineralogy and the water content. Polarization measurements are sensitive to charges at various interfaces. For example, fluids or sulfides within a host rock are of particular interest in exploration geophysics, and the associated interfaces can be revealed with induced

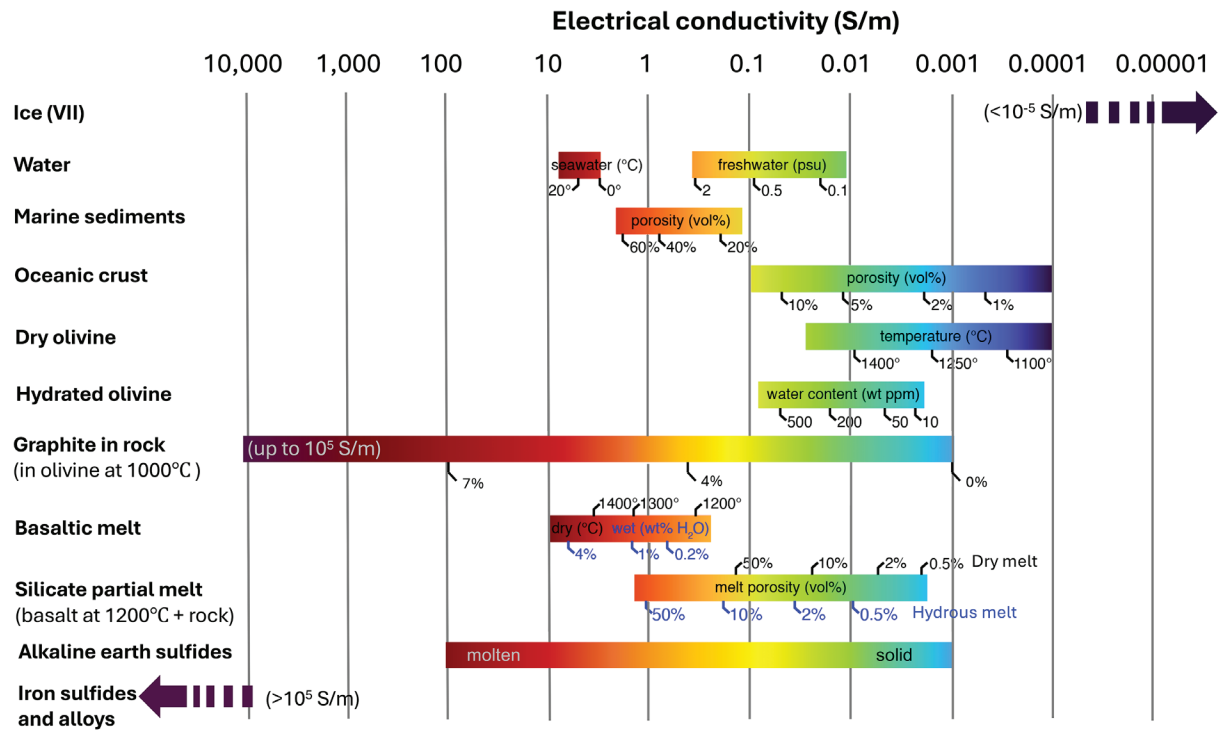


FIGURE 2 Electrical conductivity of representative geomaterials. MODIFIED AFTER NAIF ET AL. (2021).

polarization measurements. Electrical anisotropy, which can be measured both in the laboratory and in the field, describes how the electrical properties of rocks vary with direction. In this case, the σ term of EQUATION 1 is no longer assumed to be a single scalar value, but instead is a tensor. These measurements are fundamental to investigating rock deformation in the crust and mantle (e.g., mineral alignment in response to shearing or compression), layering, and fracturing. Finally, electrokinetic properties provide insight into the motion of fluids through a porous rock. These properties are an important component of self-potential geophysical surveys of the Earth's crust.

Electromagnetic Measurements on Earth and in Space

Different electromagnetic techniques exist to probe the Earth and other celestial bodies. On Earth, magnetotellurics (MT) measures the natural variations in the planet's magnetic and electric fields over depths ranging from tens of meters to hundreds of kilometers (e.g., Chave and Jones 2012). Several studies have demonstrated that this technique is a powerful approach for mapping fluids in fault zones, subduction zones, and mantle plumes (e.g., Evans et al. 2018 and references therein). Complementary techniques termed controlled-source electromagnetics (CSEM) involve artificial EM fields that are typically generated at the surface or in boreholes, but also from airborne platforms, and receivers are used to detect the induced fields. This technique provides high-resolution maps of the shallow subsurface (up to a few km depth) and is extensively used as part of mineral and hydrocarbon exploration and groundwater detection. While MT is generally used to probe depths from hundreds of meters to hundreds of kilometers, and CSEM from tens of meters to several kilometers, other techniques exist to probe shallower depths, such as ground penetrating radar (GPR), which uses radio waves to image the subsurface (tens of centimeters to tens of meters depth).

Electromagnetic induction sounding has been successfully used as part of several space missions to probe the interior of planets and moons. This technique focuses on how time-varying magnetic fields induce electric currents in a planetary body, providing insights into the electrical conductivity (and thus, composition) of the interior. Another approach to estimate the conductivity at depth is to use magnetic observations as a probe of field-aligned electric currents. These currents are important for the dynamics of the magnetosphere and are influenced by the electrical properties of the crust and mantle.

Like all techniques, electromagnetic measurements have some limitations and challenges. The most significant limitation is that a given dataset is unable to define a unique profile of electrical conductivity with depth in a key processing step that is known as "inversion." The number of plausible electrical profiles that are consistent with electromagnetic data can be narrowed down when additional information from petrology and laboratory measurements is incorporated (e.g., Pommier 2014). For magnetotelluric measurements of the deep Earth, another challenge is the requirement for long time-series measurements of many days or weeks duration, as well as environments with as little noise as possible. Noise from human activities, especially near large cities, will degrade the data quality.

ELECTRICAL MEASUREMENTS IN THE LABORATORY

Impedance spectroscopy is commonly used to investigate the electrical properties of geomaterials at pressure and temperature conditions relevant to planetary interiors. Using DC current and voltage is typically inadequate because of polarization at the rock/electrode interface, as well as depletion of charge carriers (e.g., ions) within the sample itself. During an impedance measurement, a sinusoidal voltage with fixed amplitude is applied to the sample over a range of frequencies (typically, from 1 MHz to

<1 Hz) and the amplitude and phase of the resulting current are recorded. The impedance of the sample (Z^*) characterizes the electrical properties at a defined frequency. In rocks, impedance usually consists of several resistive and capacitive components and is therefore a complex quantity with a real part (resistive component, Z') and an imaginary part (reactive component, Z'')

$$Z^* = Z' + iZ'' \quad (2)$$

The bulk DC resistance (R) of the sample is extrapolated from plots of frequency-dependent values of Z'' versus Z' (e.g., Gerhardt 2005). The shape of the impedance spectra provides information on the sample, such as the presence of melt or the contribution from grain boundaries. The low-frequency conductivity of the sample, σ , or its inverse, resistivity ρ , is obtained using the resistance value R and the geometric factor G (= area/length ratio of a sample with cylindrical geometry):

$$\sigma = 1/\rho = 1/(R \times G) \quad (3)$$

Uncertainties on electrical conductivity values are typically a few percent. However, performing these electrical measurements while the sample is subject to high pressures and temperatures is technically challenging, and different sample cells and methodologies have been developed to acquire impedance data that are most relevant for rocks at conditions of the mantle (e.g., Dai et al. 2020). Conductivity models of rocks can then be developed and compared with field electrical observations to interpret electrical anomalies in terms of temperature, composition, and texture.

Connecting Laboratory Measurements with Field/Space Observations

Interpreting geophysical data accurately using laboratory measurements requires understanding the connections and gaps between them. Both types of measurements rely on the same physical properties (e.g., conductivity, permittivity, polarization), and for instance, Ohm's law applies both in the laboratory and in the field. By measuring the electrical properties of geomaterials at controlled temperature and pressure conditions, laboratory studies provide crucial information to interpret field and space observations. As an example, the parameters used in Archie's law, which is an empirical relationship between rock conductivity and porosity, are usually derived from laboratory measurements and applied to the field.

However, using laboratory data to interpret electrical anomalies in terms of thermochemical properties requires careful consideration. On one hand, the small size of laboratory samples (e.g., $\sim 1 \text{ mm}^3$ in a multianvil press) might not be a sufficient representation of the bulk rock. On the other hand, large volumes probed using field techniques may result in data that are based on excessive heterogeneity in rock chemistry and fabric, as well as possibly excessive averaging of temperature. Addressing the challenges related to scale effects and rock heterogeneity requires making assumptions about rock texture and chemistry. From a technical standpoint, laboratory measurements are often more sensitive to the different parameters (fluid content, temperature, pressure, etc.) than field measurements. Laboratory experiments allow direct measurement of electrical properties, whereas field/space methods are generally indirect and often limited by noise or instrument resolution. These challenges can be reduced when another physical property is added to the investigation: for example, joint measurements of electrical and seismic properties have shed light on the structure of subduction zones (e.g.,

McGary et al. 2014). In addition, integrating petrological information about the geological setting is key to interpret field data using laboratory measurements.

CONDUCTION MECHANISMS IN MINERALS AND ROCKS AND CONNECTION TO OTHER PHYSICAL PROPERTIES

Conduction Mechanisms

The electrical response of minerals and rocks is sensitive to chemistry, temperature, pressure (depth), redox conditions (i.e., chemical reaction between an oxidizing substance and a reducing substance), and texture (e.g., grain size) (Yoshino et al. 2024). In terrestrial bodies, most minerals are dielectrics in the crust, semiconductors in the mantle, while the metallic core is a conductor.

The electrical conductivity of crust and mantle minerals follows an Arrhenius equation

$$\sigma = (\sigma_0/T)\exp(-\Delta H/kT) \quad (4),$$

where σ_0 is the pre-exponential factor, ΔH is activation enthalpy, T is the absolute temperature, and k is the Boltzmann constant. The total (bulk) conductivity σ of a crystal is the sum of different contributions that are essentially controlled by the movement of charged particles within the crystal structure. These particles include ions (particularly protons (H^+) because of their relatively small size and much greater mobility than other cations or anions), relatively delocalized or unbound electrons (e.g., in graphitic regions of the crust or mantle, or within the metallic core), and polarons (electron-lattice distortions) (e.g., Yoshino 2010). In minerals containing a certain level of H^+ , the movement of these ions within a crystal or along grain boundaries can dominate conductivity, especially at low temperatures. The movement of other ions (e.g., Na^+) can be a significant or even dominant factor at high temperatures. In iron-bearing minerals, the transfer of charge between ferric and ferrous iron is called "small polaron" conduction, because the motion of electrons occurs simultaneously with distortion of the lattice (typically, oxygen atoms in the ligand environment of the iron metal centers). Pressure generally exerts a relatively minor influence on conductivity, at least in comparison with temperature; nevertheless, the impact can be quite revealing of the mechanism: increasing pressure usually lowers conductivity in the case of ionic transport (pore volume reduced, thereby impeding ion movement), whereas conductivity involving electron hopping between sites often increases with pressure (hopping distance reduced). In comparison, free electrons are the charge carriers in a metallic core, and the presence of **impurities** (elements such as H, S, C, Si) affects both the electrical and thermal properties of the iron alloy (e.g., Gomi and Yoshino 2018).

Rocks are multiphase systems made up of minerals with different electrical properties. Different models have been formulated to calculate bulk rock conductivity using the conductivity and amount of each grain (Guéguen and Palciauskas 1994; Glover 2015). The presence of fluids (aqueous fluids, partial melt) and impurities at grain boundaries (e.g., graphite, sulfides) can increase bulk conductivity significantly, depending on the amount and interconnectivity of these phases (Tauber et al. 2023 and references therein).

Rethinking Rock Digestion: Modern Dissolution Strategies in Geochemistry

Accurate elemental and isotopic analysis of geological materials depends fundamentally on complete and reproducible sample dissolution. While analytical instrumentation has evolved rapidly over recent decades, the digestion of silicate rocks remains one of the most critical steps in geochemical workflows.

Unlike many environmental, food, or biological matrices, rocks present extreme chemical and mineralogical diversity. Silicate frameworks, refractory accessory phases, high field strength elements (HFSE), and variable concentrations of Ca, Mg, and Al introduce both kinetic and thermodynamic constraints. The challenge is not simply dissolving a sample, but achieving complete decomposition without loss of target elements, formation of insoluble fluorides, or contamination from handling procedures.

Conventional Wet Chemistry Approaches

Whole rock digestion in academic laboratories has traditionally relied on two principal strategies: low-pressure hotblock digestion and high-pressure digestion in metal-jacketed polytetrafluoroethylene (PTFE) vessels.

Hotblock digestion using HF and HNO₃ in perfluoroalkoxy (PFA) beakers remains common for silicate rocks that lack resistant phases such as zircon or spinel. Operating at 130 to 170 °C for 48 to 72 hours, the method is long and requires prior knowledge of mineralogy, as incomplete dissolution may only become evident after residue inspection.

High-pressure digestion in metal-jacketed PTFE vessels improves recovery of refractory minerals and offers better control of reaction conditions. However, it involves multiple handling steps, HF conversion management, and extensive cleaning. Opening vessels after digestion introduces safety considerations, and the method remains reagent intensive.

These approaches have enabled decades of high-quality geochemical research. However, increasing demands for reproducibility, operational safety, and throughput have prompted renewed assessment of dissolution strategies.

The Role of Refractory Phases

Many digestion challenges stem from resistant mineral phases. Zircon, monazite, spinel, chromite, and rutile may host trace elements critical for petrogenetic interpretation. Partial digestion can lead to underestimation of HFSE and rare earth elements (REE), directly affecting geochemical modeling.

Fluoride complexation further complicates digestion chemistry. High Ca and Mg concentrations may promote formation of CaF₂ or MgF₂, while Al-rich systems can form AlF₃ complexes that sequester trace elements. Effective digestion therefore requires appropriate temperature, pressure, acid sequencing, and fluoride management.

Emerging Microwave Strategies

Microwave-assisted digestion has significantly improved sample preparation compared to conventional hotplate methods. Rotor-based microwave systems have enhanced reproducibility, operator safety, productivity, and analytical turnaround time, and they remain highly effective across many applications.

In silicate rock digestion, however, material constraints must be considered. Rotor systems rely on polymeric digestion vessels that offer excellent chemical resistance but impose practical limits on sustained temperature and pressure. Routine operation above approximately 240 to 250 °C for extended hold times is generally not feasible due to thermomechanical limits of the vessel materials.

For many rock types this is sufficient. When highly resistant phases such as zircon or monazite are present, however, higher temperatures maintained for longer periods may improve dissolution efficiency. These operational boundaries have prompted development of alternative microwave architectures capable of sustained elevated temperature conditions.

Single Reaction Chamber Concepts

An alternative approach uses a single high-pressure reaction chamber in which multiple samples, each contained in individual vials, are

processed simultaneously. The entire chamber reaches uniform temperature and pressure conditions, while each sample can contain its own optimized acid mixture.

Uniform reaction conditions reduce variability, and independent acid chemistries allow felsic, mafic, sedimentary, and ore samples to be processed reliably. Automated pressure control and venting further improve workflow safety.

High-temperature capabilities above 250 °C enhance dissolution kinetics for refractory mineral phases. Combined with controlled fluoride management and dry down procedures, this approach supports reliable decomposition across a wide range of rock types.

Implementing High-Pressure Single Reaction Chamber Digestion in Academic Laboratories

The latest implementation of the single reaction chamber concept is the Milestone ultraWAVE 3 system, designed to address the challenges associated with complete digestion of complex inorganic matrices in geochemistry laboratories.

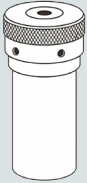

Unlike rotor-based systems, ultraWAVE 3 operates with a single stainless-steel chamber lined with PTFE, capable of reaching 300 °C and pressures approaching 200 bar. Individual quartz or PTFE vials allow each sample to be digested using its own optimized acid mixture while multiple samples are processed simultaneously. This configuration eliminates the need for uniform acid chemistry across a batch.

Independent acid composition is particularly valuable in geochemistry laboratories where lithological diversity is common. Felsic samples containing zircon or monazite may require HF, HNO₃, and HCl combinations with extended hold times, while other matrices demand modified fluoride management.

Elevated temperature improves dissolution kinetics of resistant phases. Combined with controlled dry down procedures, this supports accurate quantification of trace elements.

Blank control is equally important. Reduced acid volume per sample, use of high purity materials such as quartz and PTFE, and minimized surface contact contribute to lower procedural blanks. These characteristics are essential for laboratories operating at low detection limits or performing isotopic measurements.

TABLE 1 OVERVIEW OF THE CONVENTIONAL WET CHEMISTRIES APPROACHES.

	Metal-jacketed PTFE vessel	Screw-top PFA beaker
Type of digestion vessels		
Overall time	Up to 5 days	Up to 3–4 days
Heating source	Conventional oven	Hot plate
Throughput	Very limited	Good throughput
Cleaning	Laborious cleaning	Careful cleaning, including of beaker exteriors
Safety	Operator health and safety risks	Involves many manual steps with potential for spills

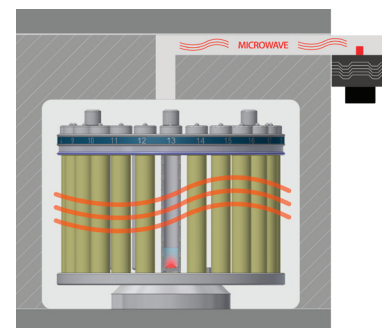


FIGURE 1 Rotor-based microwave digestion.

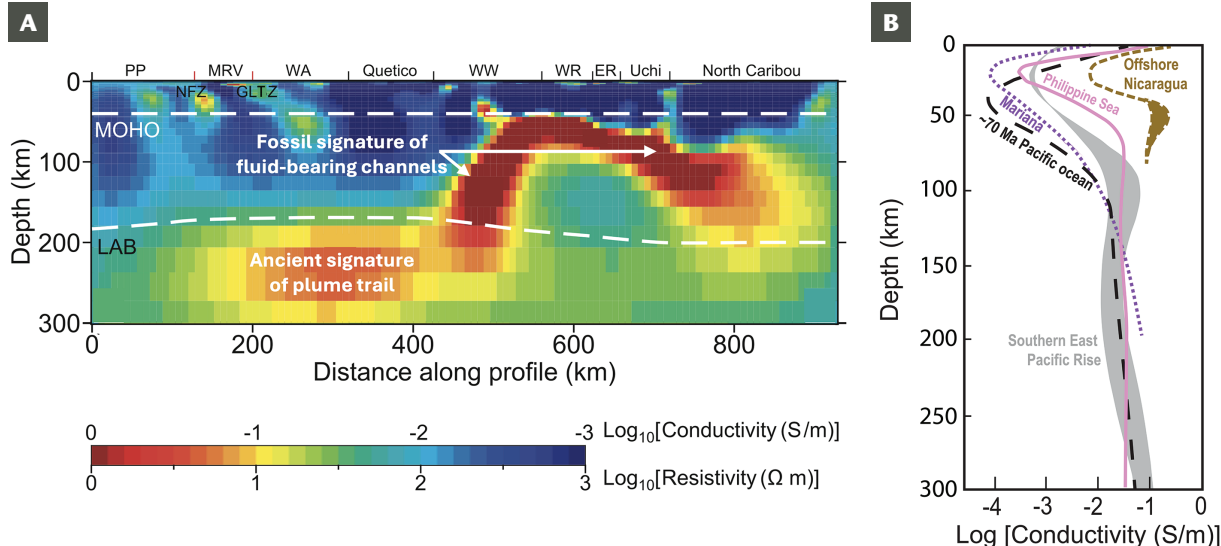


FIGURE 3 Examples of electrical imaging of the Earth's crust and upper mantle: **(A)** Conductivity model derived from MT 3-D inversion of the North American Midcontinent Rift system and possible interpretation of the main conductors (AFTER LIN ET AL. 2024). The dashed white lines indicate the seismic Moho discontinuity and the lithosphere-asthenosphere boundary (LAB). PP = Penokean Province; MRV = Minnesota River Valley; WA = Wawa-Abitibi; WW = Western Wabigoon; WR = Winnipeg River; ER = English River; NFZ = Niagara Fault Zone; GLTZ = Great Lakes Tectonic Zone. **(B)** 1-D conductivity–depth profiles from various oceanic settings (Evans et al. 2018 and references therein).

EQUATION 7 only provides a lower bound of thermal conductivity because phonons also contribute to κ (e.g., Williams 2018).

Electrical properties of geomaterials can be used in parallel with the aforementioned transport properties to gain a richer view of a planet's interior structure and dynamics.

Electrical Conductivity and Other Physical Properties of Geomaterials

The electrical properties of geomaterials are related to other **transport properties**, such as diffusion, viscosity, and thermal conductivity. For instance, ionic conductivity is directly related to the diffusion of ionic species, as expressed in the Nernst-Einstein equation:

$$\sigma = fDnq^2/(RT) \quad (5)$$

where f is a constant, D is the diffusion coefficient of the charged species, n is the concentration of ionic species, q is the electric charge of the species, R is the gas constant, and T is the temperature. The **viscosity** η of a silicate melt can be inferred from its electrical conductivity using the modified Stokes-Einstein equation

$$\sigma T = a (T/\eta)^b \quad (6)$$

where a and b are constants. Relating conductivity and viscosity provides an opportunity to interpret electrical field observations in terms of melt dynamics at depth (Pommier et al. 2013). The fundamental connection of melt viscosity to seismic velocity, as well as to electrical transport (Eq. 6), makes joint magnetotelluric and seismic measurements a powerful approach to estimate mantle viscosity (Ramirez et al. 2022). Electrical conductivity data of core analogs can be used to estimate their thermal conductivity. This physical property is key to model the power available to the dynamo as a planetary core cools (Williams 2018). The Wiedemann-Franz law expresses a simple correlation between both properties

$$\kappa = L T \sigma \quad (7)$$

where κ is the thermal conductivity generated by thermal transport by electrons, and L is called the Lorenz number (approximately $2.44 \times 10^{-8} \text{ W } \Omega \text{ K}^{-2}$). For iron alloys,

ELECTRICAL IMAGING OF THE EARTH'S CRUST AND MANTLE

Electromagnetic studies of subduction zones, mid-ocean ridges, or cratons provide a snapshot of the present-day structure and thermal state of the Earth. The variations in conductivity revealed in these studies have been key to understanding geological, geothermal, and tectonic processes. As an example, our understanding of the structure and rheology of the Tibetan Plateau has strongly benefited from MT studies that have revealed a highly conductive lower crust (e.g., Le Pape et al. 2012), with localized electrically conductive anomalies with values ranging from 0.1 to 1 S/m. Based on electrical laboratory measurements, these values are best reproduced with the presence of aqueous fluids and/or partial melting, and partial melting is consistent with the significant heat flow in this region. Another example is the recent investigation of the North American Midcontinent Rift using EarthScope USArray and Lithoprobe magnetotelluric data (Lin et al. 2024; FIG. 3A). The 3-D inversion of the data revealed multiple conductors in the crust and uppermost mantle, including a highly conductive linear anomaly extending for over 300 km within the Superior Craton lithospheric mantle. Highlighting the ambiguities in interpreting conductive bodies at depth, this feature was interpreted by Lin et al. (2024) as the signature of a former plume tail but has been re-interpreted by Roots et al. (2025) as an artifact caused by large-scale anisotropy.

More generally, electromagnetic studies of the Earth's crust and mantle have revealed the layered structure of the planet (FIG. 3B): the crust (~0–10 km depth for the oceanic crust, ~25–70 km for the continental crust) has a variable conductivity caused principally by different rock types and the distribution of fluids and temperature, which are ultimately controlled by tectonic setting and geologic history. On the basis of temperature alone, the lower crust should be more conductive than the upper crust, but crustal conductivity is also determined by the presence of fluids, partial melt, and conductive minerals such as graphite or sulfides. In the upper mantle (up to 410 km depth), the

lateral and vertical distribution of temperature, partial melt, and volatiles (H, C) in mantle silicates result in a large variation in conductivity values (from $\sim 10^{-3}$ to $\sim 10^{-1}$ S/m). The transition zone starting at 410 km depth is electrically conductive, possibly because of partial melt and/or hydrogen. The lower mantle (>660 km) is poorly resolved by MT measurements but appears usually more resistive than the transition zone, reflecting changes in mineralogy.

ELECTRICAL STRUCTURE OF OTHER PLANETS AND MOONS

Electrical conductivity profiles of the interior of the Moon, Mercury, and Io are shown in FIGURE 4. Electromagnetic measurements as part of the *Apollo* missions to the Moon have inferred bounds on the electrical conductivity of the crust and mantle (Hood et al. 1982). Using electrical laboratory experiments of lunar crust and mantle analogs, as well as petrological constraints, conductivity–depth profiles of the Moon have been developed and compared with field-based models. Results indicate that the deep interior is consistent with the presence of silicate melt.

Upcoming measurements of Mercury’s magnetic field will shed light on the interior structure, as well as the dynamo generated in the metallic core (Heyner et al. 2021). Electrical measurements in the laboratory on analogs of the mantle and core can be used to develop conductivity–depth profiles of the planet for a defined thermal state (Pommier et al. 2025). These profiles can be tested with induction data from future observations from *BepiColombo*. Mercury represents a special case among terrestrial planets because

it lacks a substantial ionosphere (caused by a low gravitational constant, in combination with a hot surface). As a result, field-aligned currents originating in the magnetosphere are not diverted through an ionospheric layer—as at Earth—but may instead penetrate the planetary interior and close the loop at depth. This system of currents generates secondary magnetic fields that are observable outside the planet (Heyner et al. 2021). The interior conductivity profile of the planet significantly affects the geometry and amplitude of the field-aligned currents. This unique electromagnetic coupling between the magnetosphere and the solid planet provides a valuable means of probing the compositional and thermal properties of Mercury’s crust and mantle.

Defining the electrical structure of Jupiter’s moon Io is important to understand the distribution and amount of magma at depth, the present-day thermal state, and inform about cooling processes. Io is a highly active volcanic world, with several peculiarities concerning its interior, surface, atmosphere, and relationship to other bodies within the Jupiter system (Pommier and McEwen 2022). Assuming a partially molten silicate mantle hosting a sheared, melt-bearing shallow layer, and a metallic core, a preliminary conductivity profile of the interior can be calculated. New observations as part of future missions are needed to compare this profile with field electromagnetic measurements. On Ganymede, in situ measurements from the past *Galileo* mission and ongoing measurements from the *Juno* mission point to the presence of a global liquid water ocean underneath a thick icy crust (Kivelson

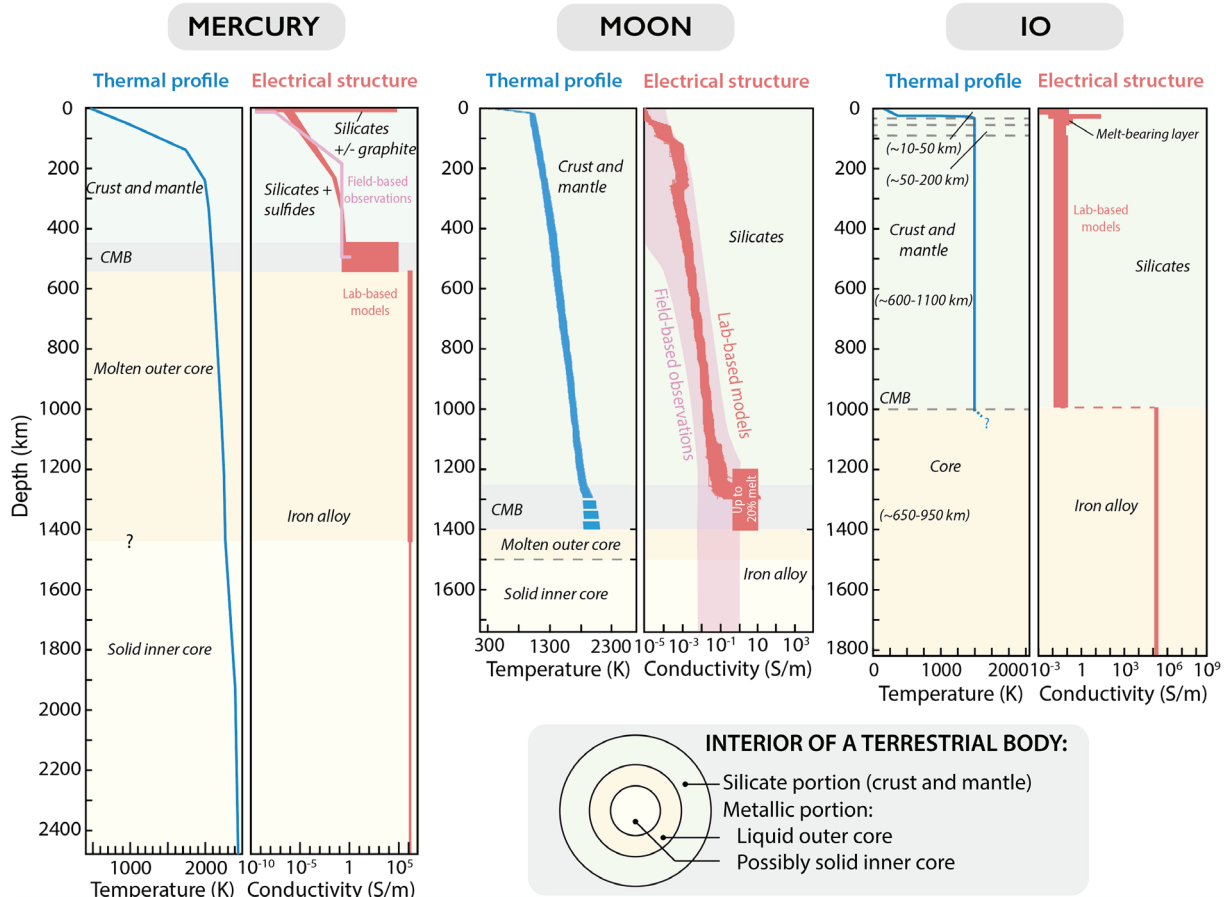


FIGURE 4 Electrical conductivity–depth profiles (RED) of Mercury, the Moon, and Io for the corresponding thermal profiles (BLUE). Electrical conductivity models are based on laboratory experiments. For the Moon and Mercury, field-based

models are also shown (PINK). The internal structure of Io is still uncertain; therefore, the thicknesses of the different layers are given as ranges. References are listed in the online supplement.

et al. 2002). Jupiter's tilted magnetic dipole and the moon orbit provide the time-varying inducing field. Exploiting different induction frequencies can help place constraints on the estimated thickness and salinity of the global water ocean. In addition, at the Galilean moons, the *Clipper* and *JUICE* missions aim to estimate density and conductivity in tandem. In turn, results from gravity measurements impact those from conductivity measurements, and vice versa.

PERSPECTIVES

Electrical measurements are an extraordinary tool to visualize the interior of terrestrial bodies and understand the chemical and physical processes in geomaterials that comprise their interior. Major technological advances, both in the field and in the lab, allow the electrical properties of planets and moons to be probed from the scale of atoms to that of crusts, mantles, and cores. The combination of laboratory results with field observations has yielded important insights into the structure and dynamics of the Earth's crust and mantle, and is an excellent approach to investigating other planets and moons in the Solar System. Electrical measurements complement other geophysical methods, such as seismology and gravimetry, providing unique insight into the thermophysical properties of our

planet and other bodies in the Solar System. This synergy can be strengthened both with new field surveys and laboratory studies, especially on samples with complicated textures and chemistry, as observed in nature. Induction measurements are a key component of space missions and should definitely be part of future missions to terrestrial bodies.

ACKNOWLEDGMENTS

We thank Guest Editors Jennifer M. Jackson and Patrick Cordier for their invitation to contribute to this *Elements* issue, and Navid Marvi from the Carnegie Institution for Science for his help with FIGURE 1. AP acknowledges support from the Carnegie Endowment. MJT acknowledges a Visiting Scientist affiliation with the Carnegie Institution for Science/EPL. DH was supported by the German Ministerium für Wirtschaft und Klimaschutz and the German Zentrum für Luft- und Raumfahrt under contract 50QW2202. We thank Heather Watson and Lidong Dai for their helpful comments, and Principal Editor Sumit Chakraborty for his rigorous handling of the manuscript.

For supplemental material, visit elementsmagazine.org/supplements/.

REFERENCES

- Chave AD, Jones AG (2012) *The Magnetotelluric Method: Theory and Practice*. Cambridge University Press, 552 pp
- Dai L and 7 coauthors (2020) An overview of the experimental studies on the electrical conductivity of major minerals in the upper mantle and transition zone. *Materials* 13: 408, doi: 10.3390/ma13020408
- Evans RL, Sarafian E, Sarafian AR (2018) The evolution of the oceanic lithosphere. In: Yuan H, Romanowicz B (eds) *Lithospheric Discontinuities*. American Geophysical Union, Washington DC, pp 35-53, doi: 10.1002/9781119249740.ch2
- Genova A and 17 coauthors (2021) Geodesy, geophysics and fundamental physics investigations of the BepiColombo mission. *Space Science Reviews* 217: 31, doi: 10.1007/s11214-021-00808-9
- Gerhardt RA (2005) Impedance spectroscopy and mobility spectra. In: Bassani F, Liedel GL, Wyder P (eds) *Encyclopedia of Condensed Matter Physics*. Elsevier Press, Oxford, pp 350-363, doi: 10.1016/B012-369401-9/00685-9
- Glover PWJ (2015) Geophysical properties of the near surface Earth: electrical properties. In: Schubert G (ed) *Treatise on Geophysics* (Second Edition). Elsevier, Oxford, pp 89-137, doi: 10.1016/B978-0-444-53802-4.00189-5
- Gomi H, Yoshino T (2018) Impurity resistivity of fcc and hcp Fe-based alloys: thermal stratification at the top of the core of super-Earths. *Frontiers in Earth Science* 6: 217, doi: 10.3389/feart.2018.00217
- Guéguen Y, Palciauskas V (1994) *Introduction to the Physics of Rocks*. Princeton University Press, 294 pp
- Heyner D and 31 coauthors (2021) The BepiColombo planetary magnetometer MPO-MAG: what can we learn from the Hermean magnetic field? *Space Science Reviews* 217: 52, doi: 10.1007/s11214-021-00822-x
- Hood LL, Herbert F, Sonett CP (1982) The deep lunar electrical conductivity profile: structural and thermal inferences. *Journal of Geophysical Research: Solid Earth* 87: 5311-5326, doi: 10.1029/JB087iB07p05311
- Khurana KK and 5 coauthors (2011) Evidence of a global magma ocean in Io's interior. *Science* 332: 1186-1189, doi: 10.1126/science.1201425
- Kivelson MG and 5 coauthors (2000) Galileo magnetometer measurements: a stronger case for a subsurface ocean at Europa. *Science* 289: 1340-1343, doi: 10.1126/science.289.5483.1340
- Kivelson MG, Khurana KK, Volwerk M (2002) The permanent and inductive magnetic moments of Ganymede. *Icarus* 157: 507-522, doi: 10.1006/icar.2002.6834
- Le Pape F, Jones AG, Vozar J, Wenbo W (2012) Penetration of crustal melt beyond the Kunlun Fault into northern Tibet. *Nature Geoscience* 5: 330-335, doi: 10.1038/NGeo1449
- Lin W, Schultz A, Yang B, Harris LB, Hu X (2024) Mantle plume trail beneath the ca. 1.1 Ga North American Midcontinent Rift revealed by magnetotelluric data. *National Science Review* 11: nwae239, doi: 10.1093/nsr/nwae239
- McGary RS, Evans RL, Wannamaker PE, Elsenbeck J, Rondenay S (2014) Pathway from subducting slab to surface for melt and fluids beneath Mount Rainier. *Nature* 511: 338-340, doi: 10.1038/nature13493
- Naif S, Selway K, Murphy BS, Egbert G, Pommier A (2021) Electrical conductivity of the lithosphere-asthenosphere system. *Physics of the Earth and Planetary Interiors* 313: 106661, doi: 10.1016/j.pepi.2021.106661
- Parkhomenko EI (1967) *Electrical Properties of Rocks*. Plenum Press, 314 pp
- Pommier A and 5 coauthors (2013) Prediction of silicate melt viscosity from electrical conductivity: a model and its geophysical implications. *Geochemistry, Geophysics, Geosystems* 14: 1685-1692, doi: 10.1002/ggge.20103
- Pommier A (2014) Interpretation of magnetotelluric results using laboratory measurements. *Surveys in Geophysics* 35: 41-84, doi: 10.1007/s10712-013-9226-2
- Pommier A, McEwen A (2022) Io: a unique world in our Solar System. *Elements* 18: 368-373, doi: 10.2138/gselements.18.6.368
- Pommier A, Tauber MJ, Renggli C, Davies C, Wilson A (2025) Electrical properties of alkaline Earth sulfides and implications for the interior of Mercury. *Journal of Geophysical Research: Planets* 130: e2024JE008651, doi: 10.1029/2024JE008651
- Ramirez FDC, Selway K, Conrad CP, Lithgow-Bertelloni C (2022) Constraining upper mantle viscosity using temperature and water content inferred from seismic and magnetotelluric data. *Journal of Geophysical Research: Solid Earth* 127: e2021JB023824, doi: 10.1029/2021JB023824
- Roots EA and 6 coauthors (2025) Channelized metasomatism in Archean cratonic roots as a mechanism of lithospheric refertilization. *Nature Communications* 16: 7701, doi: 10.1038/s41467-025-62912-6
- Selway K (2014) On the causes of electrical conductivity anomalies in tectonically stable lithosphere. *Surveys in Geophysics* 35: 219-257, doi: 10.1007/s10712-013-9235-1
- Tauber MJ, Saxena S, Bullock ES, Ginestet H, Pommier A (2023) Electrical properties of iron sulfide-bearing dunite under pressure: effect of temperature, composition, and annealing time. *American Mineralogist* 108: 2193-2208, doi: 10.2138/am-2023-9054
- Unsworth MJ (2010) Magnetotelluric studies of active continent-continent collisions. *Surveys in Geophysics* 31: 137-161, doi: 10.1007/s10712-009-9086-y
- Williams Q (2018) The thermal conductivity of Earth's core: a key geophysical parameter's constraints and uncertainties. *Annual Review of Earth and Planetary Sciences* 46: 47-66, doi: 10.1146/annurev-earth-082517-010154
- Yoshino T (2010) Laboratory electrical conductivity measurement of mantle minerals. *Surveys in Geophysics* 31: 163-206, doi: 10.1007/s10712-009-9084-0
- Yoshino T, Manthilake G, Pommier A (2024) Probing deep hydrogen using electrical conductivity. *Elements* 20: 247-252, doi: 10.2138/gselements.20.4.247 ■