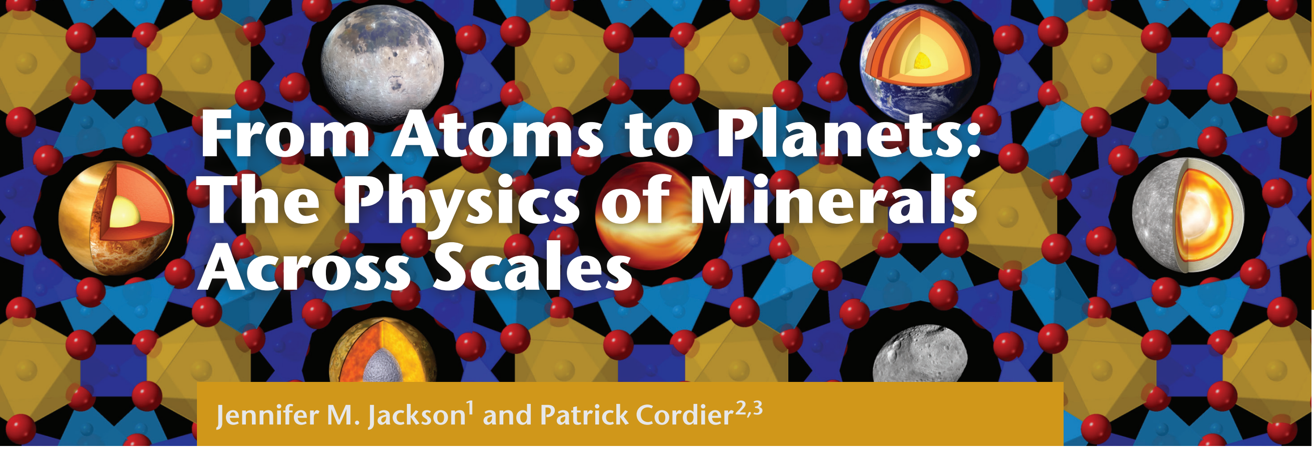

From Atoms to Planets: The Physics of Minerals Across Scales

IMAGE CREDIT: NASA.

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Mineral science emerged from humanity's earliest curiosity about the colors, hardness, and magnetic properties of stones and metals. Across centuries, observations by philosophers, naturalists, and early microscopists gradually revealed that these macroscopic traits arise from the hidden architecture of matter. The scientific revolutions of the 17th–20th centuries—from crystallography and optics to quantum mechanics and high-pressure experimentation—established the atomic foundations of minerals and transformed mineralogy into a modern physical science. Today, mineral physics links nuclei, electrons, defects, and crystal structures to the behavior of Earth and planetary interiors. This sets the stage for this *Elements* issue, showing how insights across disciplines continue to shape our understanding of minerals from atoms to planets.

KEYWORDS: history of mineral science; mineral physics; extreme conditions

THE ADVENT OF A SCIENCE: FROM EMPIRICAL INTUITION TO STRUCTURAL INSIGHT

It begins with a sense of curiosity, with mineralogy taking center stage. What underlying physical and chemical factors govern a mineral's color, transparency, hardness, and their capacity to be cut and polished? These are coveted qualities that have long determined the aesthetic and functional selection of minerals such as aquamarine, malachite, turquoise, and tourmaline for use in jewelry and art. Why do certain minerals exhibit magnetic properties, such as the ability to attract iron? Why were metals such as copper, zinc, and iron considered prized resources, how were they extracted and refined to produce tools, utensils, and weapons, and what materials and thermal conditions enabled the melting and formation of glass? Facilitated by remarkable discoveries, humankind has been asking these questions for millennia, as suggested by the emergence of glass in the Middle East during the Bronze Age, around 4,500 years ago. Originally opaque and colored with various metals, glass could be produced to be more transparent, testifying to a growing mastery of basic material properties. Contrary to the first philosophers of ancient Greece, who laid the foundations of scientific thought, we have little trace of how concepts in mineral sciences evolved. The first to articulate a materialist philosophy were the atomists—Leucippus of Miletus (active in the 5th century BCE) and his student Democritus of Abdera (c. 460–c. 370 BCE)—followed by Epicurus (341–270 BCE) and later Lucretius (c. 99–55 BCE). Central to their doctrine was the claim that the properties of bodies arise from the shape, arrangement, and position of imperceptible, indivisible corpuscles termed "atoms." Lucretius offers a striking example in his poem *De rerum natura*, noting how a "magnetic stone causes iron filings to leap."

In the Middle Ages, Hildegard of Bingen (1098–1179) included a lapidary in the fourth part of her *Physica*, in which she described the physical properties of 26 stones. Albert the Great (ca. 1200–1280), in his treatises *De mineralibus* and *De rebus metallicis*, synthesized earlier writings—including contributions from the Arab world—together with practical knowledge drawn from miners, steelmakers, and alchemists. He studied what he called the "accidental" properties of stones: cleavage, which he explained by the action of water, compactness (effect of cold), colors (due to mixtures of **impurities***), hardness, and dispersion of colors by quartz (mixture of transparency combined with darkness). In Germany, Georgius Agricola (1494–1555), a

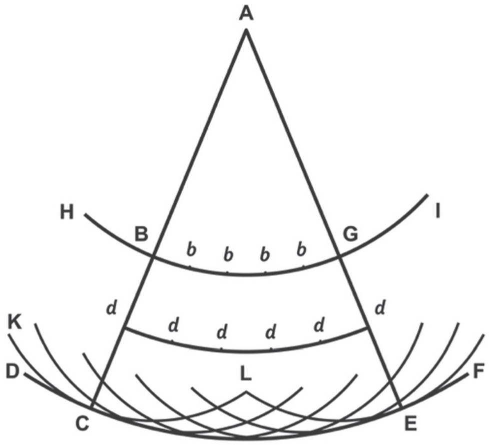

FIGURE 1 Christiaan Huygens' geometric illustration of the wavefront, demonstrating how a wave of light (or rather a pulse) emanating from a point propagates in smaller wavelets, the foundation of what became known as the Huygens-Fresnel Principle. From *Traité de la Lumière* (1690).

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

practitioner of mining and steelmaking, published his *De natura fossilium* in 1546, followed by his *De Re Metallica*, in which he devoted long passages to precise observations, particularly on the shapes of stones and minerals. It wasn't until the 17th century that the foundations of modern science were laid by physicists. Erasmus Bartholin (1625–1698) published a small treatise that was to become a milestone. In it, he described a physical property of a crystal that had been ignored by his predecessors:

> "Calcite crystals brought back from an expedition to Iceland: their great size, their perfect transparency, cannot leave unnoticed a truly strange property: they double the images of objects, texts and drawings on which they are placed."

These observations were taken up in detail by Christiaan Huygens (1629–1695). Best known as an astronomer who discovered Titan and unraveled the nature of Saturn's rings, Huygens also made foundational contributions to optics in his wave theory of light, described in *Traité de la Lumière*, principles that would later shape the mineral sciences (Fig. 1). Newton (1643–1727) laid the foundations for an experimental and predictive science, and the study of crystal properties played a decisive role in the progress of optics. Crystals are also solids that can be recognized by their characteristic shapes. Niels Stensen (Nicolas Steno in Latin: 1638–1686) was the first to recognize the constancy of their shapes, noticing that the angles of a hexagonal crystal did not vary, even though its sides could vary. Beautifully rendered by Robert Hooke (1635–1703), the external shapes were suggested to reflect an underlying coherency in their internal structure (Fig. 2). In the 1700s (Edo period), Japanese mineralogists and naturalists Gennai Hiraga (平賀源内) and Sekitei Kinouchi (木内石亭) were studying the science of minerals. Sekitei Kinouchi is particularly known as Japan's first systematic mineralogist, focusing on crystal shapes and cleavage.

In Europe, the taste for collecting developed and the need for a classification based on stable principles arose. Déodat Gratet de Dolomieu (1750–1801) defended the need to establish fixed bases in mineralogy in order to determine species. At the same time, Abbé René-Just Haüy (1743–1822) succeeded in determining the primary form of all minerals and showed, again using calcite, how secondary forms are derived from this form by simple laws of reduction. He was the first to give a rigorous definition of the mineral species: "The mineralogical species is a collection of bodies whose integral molecules are similar in their forms and composed of the same principles united in the same proportion."

As early as the early 19th century, prior to his appointment as a professor of mineralogy at the Freiberg Academy, Friedrich Mohs (1773–1839) was commissioned by J. F. von der Null, a Viennese banker, to prepare a systematic description of his significant mineral collection. Mohs was a distinguished student of Abraham Gottlob Werner (1749–1817; often considered as the "father of German geology") whose writings have been translated, enriched, and updated by Claudine Picardet (born Poulet, 1735–1820). In the course of this work, Mohs departed from the traditional approach, which was based essentially on chemical composition, to establish a classification of minerals based on their physical characteristics. This is how he came up with the relative hardness scale for minerals, based on a scratch test that has since been named after him.

The study of minerals played an essential role in the emergence of crystal science and to establishing the structural basis of matter. Advances in chemistry—particularly following Antoine Lavoisier's (1743–1794) foundational work—and in physics, which provided atomic theory and later quantum mechanics, furnished the conceptual and analytical framework of modern materials science. These tools, when applied to minerals, laid the foundation for mineral physics.

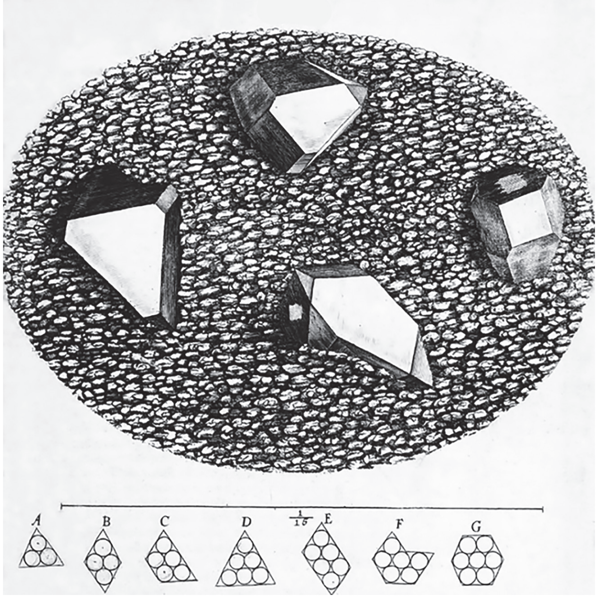

Figure 2 Robert Hooke was one of the earliest and most inventive microscopists. In his *Micrographia* (1665), he rendered with astonishing precision the regular external shapes of crystals, suggesting that their external forms reflect an underlying regularity in their internal architecture.

THE MODERN ERA: LAYING THE FOUNDATIONS OF A DISCIPLINE

The discovery of X-rays by Wilhelm Röntgen in 1895 launched a revolution in the physical sciences. In 1912, Max von Laue showed that copper sulfate diffracts X-rays, confirming its periodic atomic structure. William and Lawrence Bragg using diffraction from halite, diamond, and zinc sulfide, soon formulated Bragg's Law, a simple equation that made it possible to determine the atomic arrangement of crystals from diffraction patterns. This rapidly transformed mineralogy: for the first time, atomic positions in minerals could be directly resolved. Over subsequent decades, X-ray diffraction (XRD) became the primary technique for not only identifying mineral phases and tracking structural changes under varying external conditions, but for discovering new minerals. For example, Irish scientist Kathleen Lonsdale (1903–1971) used XRD to carefully study a variety of natural and synthetic diamonds (Lonsdale 1944), forming the basis for which lonsdaleite was named after.

The development of quantum mechanics in the early 20th century provided the theoretical concepts to describe the forces binding atoms into crystals. With the formulation of the Schrödinger equation and wave mechanics, scientists could calculate electronic structures, bonding, and lattice dynamics from first principles (Dirac 1928). These quantum-mechanical approaches, particularly density functional theory (DFT), now underpin much of theoretical mineral physics (Stixrude 2026 this issue).

High-pressure research also advanced rapidly in the early 20th century. Percy Bridgman's pioneering apparatus, beginning with piston-cylinder systems and evolving into multi-anvil designs, enabled experiments at several gigapascals (Bridgman 1931, 1935). Awarded the 1946 Nobel Prize, Bridgman opened the path to simulating Earth's interior in the laboratory (Liebermann 2026 this issue). His measurements of material behavior under compression laid the groundwork for understanding mineral compressibility, phase stability, and rheology, including the compression of newly retrieved porous lunar regolith (Kanamori et al. 1970; Fig. 3). Bridgman's devices paved the way for later discoveries of high-pressure phases of olivine and garnet, which later became essential to understanding Earth's mantle transition zone and the role of mineral phase changes in mantle dynamics.

KEY MILESTONES IN THE EMERGENCE OF MINERAL PHYSICS...

Mineral physics soon established its identity by applying principles from condensed matter physics to fundamental geophysical and planetary questions. A cornerstone of mineral physics is the development of accurate equations of state (EoS) and determination of elastic properties—essential for interpreting seismic observations and modeling Earth's interior (Mazzucchelli et al. 2026 this issue). **Elastic moduli** govern how seismic waves propagate through Earth materials—hence, the determination of single-crystal elastic moduli, as well as bulk and shear moduli, is essential for interpreting seismic observations of Earth's mantle and core. Francis Birch's formulation of the Birch–Murnaghan EoS remains central to linking laboratory measurements with seismic velocity profiles. Advances in ultrasonic interferometry, Brillouin spectroscopy, inelastic X-ray scattering, and computational methods now allow precise determination of elastic moduli at high pressures and temperatures. First-principles calculations, particularly DFT, reveal how these **macroscopic** properties emerge from bonding and crystal structure, exemplifying mineral physics' ability to bridge scales from electrons to planetary structure. The ability to relate high-pressure laboratory measurements and quantum-mechanical calculations to whole-Earth geophysical observations is one of mineral physics' defining achievements.

High-pressure phase transitions have been especially transformative. The multistage transformation of olivine—first to wadsleyite, then ringwoodite, then decomposition into ferropericlase and bridgmanite—explains the seismic discontinuities at 410, 520, and 660 km depth and influences mantle flow and slab dynamics. Bridgmanite, a high-pressure magnesium silicate with a perovskite-type structure, is not found at the surface but is believed to be the most abundant mineral in the planet, comprising nearly half of Earth's total mass. The 2004 discovery of the bridgmanite to post-perovskite phase transition near the core–mantle boundary (~125 GPa and ~2500 K), enabled jointly by high-pressure experiments and first-principles quantum-mechanical calculations, provides a compelling explanation for some of the complex seismic features and opens new avenues for understanding chemical heterogeneity, especially in the context of processes controlled by **transport properties**, such as thermal conductivity and anisotropic flow.

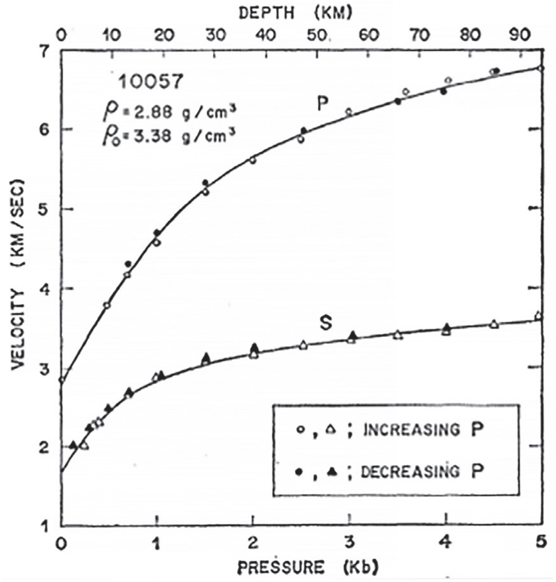

Figure 3 The P- and S-waves of *Apollo 11* lunar sample 10057 as a function of pressure, measured using ultrasonic interferometry. Below 2 kbar, the sample was highly attenuating, yielding a value for Q of 10 for both wave types. The upper scale is lunar depth converted from pressure. Reproduced from Kanamori et al. (1970) with permission of The American Association for the Advancement of Science.

...AND THE CHALLENGE OF BRIDGING SCALES

Transport properties form another crucial link between **microscopic** behavior and planetary-scale processes. Foundational 19th-century laws—Ohm's law for electrical conduction, Fourier's law for heat flow, and Fick's laws for diffusion—described bulk behavior. Subsequent kinetic theory connected these macroscopic laws to molecular motion. The quantum revolution introduced electron and phonon interactions as the basis of electrical and thermal transport at nanometer scales and ultrafast times. High-pressure and shock-wave experiments extended these insights to planetary-interior conditions, while nanoscale transport studies, ultrafast spectroscopies, and atomistic simulations now offer refined understanding over broad spatial and temporal ranges (Jackson et al. 2026 this issue).

The correlation between mineral texture and seismic anisotropy has also been pivotal. Lattice-preferred orientation in minerals such as olivine, bridgmanite, and post-perovskite provides evidence of mantle flow patterns in the upper mantle, subduction zones, and near the core–mantle boundary. However, unlike bulk elastic properties, the mechanical strength of minerals cannot be predicted solely from the stiffness of atomic bonds, which tend to yield values far higher than those observed in nature or even in laboratory experiments. This discrepancy arises from the critical role played by defects (whether microscopic, sub-microscopic, or even atomic in scale) that interrupt the ideal crystalline lattice. As a result, it is not only the intrinsic properties of a perfect crystal that matter, but the entire microstructure of a mineral, including dislocations, grain boundaries, and inclusions—features that often reflect the rock's thermomechanical history (Mazzucchelli et al. 2026 this issue). Because deformation in the mantle is governed by the slow, thermally activated motion of defects over geological timescales, bridging the gap between laboratory timescales and geologic time remains a major challenge. Addressing it requires integrating experiments, theoretical models, atomistic simulations, and microstructural analyses to extrapolate reliably from Ångströms to planetary radii and femtoseconds to the natural conditions that shape the evolution of planetary bodies over billions of years.

Magnetic properties present a similar multiscale hierarchy, from electron-spin interactions to mineral-domain structure to whole-rock fabrics. These nested levels of organization, including size, arrangement, and mobility, govern a mineral's response to external magnetic fields, including its ability to retain remanent magnetization. Advances in high-resolution paleomagnetic methods (Fu and Harrison 2026 this issue) promise new insights into this complex system.

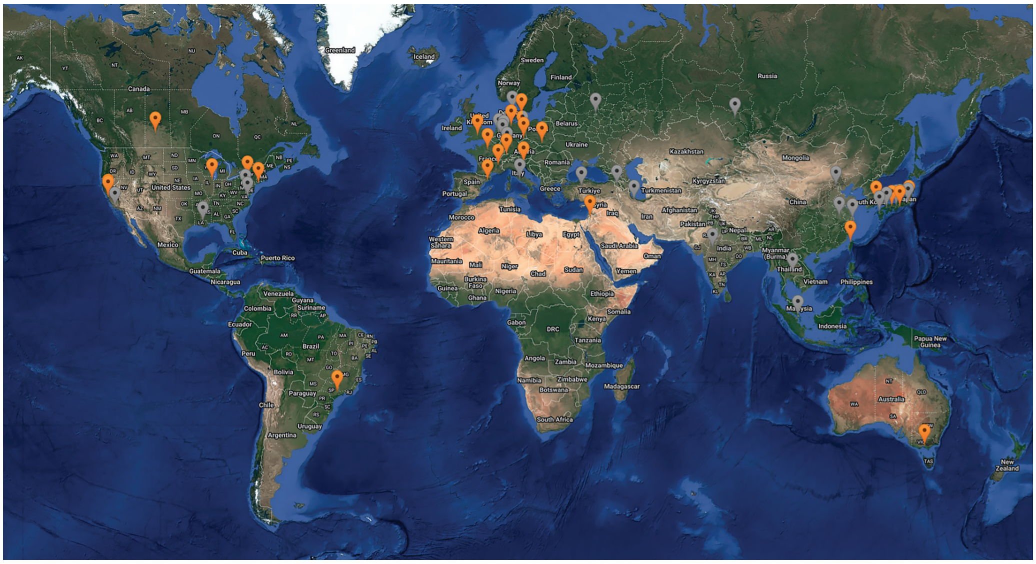

Figure 4 There are approximately 50 ultra bright light sources in the world, including free electron laser facilities (operational or under construction). Members of the lightsources.org collaboration are marked with orange pins. For more details, we refer the reader to lightsources.org.

MERGING FORCES: EXPERIMENTAL INNOVATION AND A GLOBAL COMMUNITY

The rapid evolution of mineral physics over recent decades has been driven by a convergence of technical and methodological breakthroughs. Initially distinct, these fields developed along separate trajectories: development of diamond anvil cells and multi-anvil presses to simulate the conditions of Earth's interior, while synchrotron radiation facilities emerged as tools for probing matter with unprecedented spatial, temporal, and spectral resolution, enabling in situ measurements of structure, elasticity, and electronic properties at extreme conditions (Liebermann 2026 this issue; Öztürk et al 2026 this issue; Campbell 2026 this issue; Fig. 4). This integration expanded experimental ranges, standardized methods, and fostered international collaborations. Purpose-built beamlines helped define modern experimental geoscience. These cross-disciplinary innovations now influence planetary science, materials engineering, solid-state physics, chemistry, and biology under extreme environments, demonstrating how technical advances can open entirely new scientific directions.

LOOKING AHEAD

In this article, we have seen how insights from one field can illuminate another, a principle that lies at the heart of modern mineral physics, and that curiosity continues to drive discovery. Huygens' career exemplifies the deeply interdisciplinary nature of scientific discovery: he moved fluidly among astronomy, physics, and early chemistry, driven by a curiosity about natural phenomena, from planetary systems to the properties of crystals and light. His work on optics, wave theory, and the behavior of light laid the groundwork for techniques such as optical mineralogy and spectroscopy, which rely on understanding how minerals interact with electromagnetic waves. By establishing how crystal structure, bonding, pressure, temperature, and defects influence vibrational and electronic transitions, concepts cultivated within the field of mineral physics provide the foundation for interpreting optical and infrared absorption features from spacecraft and telescope observations in terms of the hydration and oxidation state of the surface mineralogy (Solomatova et al. 2026 this issue). By establishing the electrical and dielectric properties of minerals and rocks that make up the crust and mantle of terrestrial planets and moons, Pommier et al. (2026 this issue) show how mineral physics provides the laboratory-scale foundation needed to interpret field-scale and remote electromagnetic sounding techniques of planetary interiors.

The coming decades promise transformative advances in understanding the physics of minerals at all scales, pushing the limits of achievable pressure and temperature through microfabrication of sample assemblies, dynamic compression and shock-wave experiments, coupled with ultrafast X-ray diagnostics capable of capturing transient states. Expanding theoretical and experimental approaches to more chemically complex systems will tighten links with geochemistry and illuminate phenomena from core formation to volatile cycling. Multiscale modeling—integrating quantum mechanical, atomistic, and continuum methods—promises new ways to connect microscopic mechanisms with macroscopic observables. The field of mineral physics is therefore poised to redefine our understanding of planetary diversity, interior dynamics, and conditions that sustain habitability.

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Solomatova NV, Scheller EL, Trumbo SK (2026) Illuminated worlds: how spectroscopy lights the way in Earth and planetary sciences. Elements 22: 82-88

Stixrude L (2026) Mark Bukowinski and his legacy in theoretical mineral physics. Elements 22: 118-120 ■

KEY CONCEPTS IN MINERAL PHYSICS FOR EARTH AND PLANETARY SCIENCES

Charge transfer transition An electronic excitation where an electron moves between atoms or between ligands and a central cation, usually producing strong UV–visible absorption bands.

Conduction Transfer of energy or charge through a material without bulk movement of the material itself, mainly via vibrations/oscillations of particles (and electrons in metals). Example: Heat conduction: A metal rod getting hot on one end when the other is in a fire.

Continuum models Provide a framework to describe the mechanical and thermal evolution of rocks by treating them as continuous media, without explicitly resolving atomic-scale processes. These models combine conservation laws with constitutive equations to relate stresses, strains, and heat transport. The material and effective properties used as inputs (e.g., elastic moduli, equations of state, flow laws, etc.) are typically obtained from laboratory experiments or inferred from atomistic simulations.

Convection Movement of fluid or ductile material caused by temperature and density differences for gravity to act upon. Hotter, less dense material rises; cooler, denser material sinks. Example: Boiling water or mantle convection beneath Earth's crust.

Creep Time-dependent, permanent deformation that occurs when a material is subjected to sustained, constant stress, typically at elevated temperature.

Crystal field transition An electronic transition between split δ-orbitals of a transition-metal cation in a crystal. When the cation is surrounded by ligands or neighboring ions, their electric fields break the degeneracy of the otherwise equivalent δ orbitals, splitting them into distinct energy levels. Transitions of electrons between these levels produce diagnostic absorption features in the visible and near-infrared.

Dipole moment A measure of the separation of positive and negative charge in a molecule or bond. Vibrations that change the dipole moment are detectable with infrared spectroscopy.

Elastic moduli Describe how a material deforms elastically under applied stress, relating strain to stress. In isotropic materials, only two moduli are needed to define the elastic response, whereas anisotropic crystals require up to 21 independent moduli.

Electromagnetic spectrum The full range of electromagnetic radiation, from gamma rays through X-rays, ultraviolet, visible, infrared, and radio waves, distinguished by wavelength or frequency.

Electromagnetism The study of interactions between moving electric charges and changing magnetic fields, forming the electromagnetic force.

Flow laws: Equations that describe the relationship between stress, strain rate, and temperature in deforming rocks, by capturing the dominant creep mechanisms. They are key inputs for geodynamic models and are derived from laboratory experiments or inferred from microphysical simulations. Their validity depends on pressure, temperature, strain rate, grain size, and the active deformation mechanism.

Fourier-transform infrared (FTIR) spectroscopy An infrared technique that measures how a sample absorbs IR light as a function of wavenumber, yielding bands linked to specific vibrational modes and functional groups. The measured interferogram is converted into a standard infrared spectrum through a mathematical Fourier transform.

Impedance The total opposition to the flow of alternating current (AC) in an electrical circuit.

Impurities Secondary substances present within a primary mineral that significantly influence the physical, chemical, and optical properties, such as its color, melting point, conductivity, and even how the mineral interacts with light or deforms under pressure. Types: substitutional (e.g., Fe^{2+} substituting for Mg^{2+} in olivine), interstitial atoms or molecules (occupy spaces between atoms), vacancies, and inclusions.

Induction The process of generating an electromotive force (emf) across an electrical conductor in a changing magnetic field. In space, induction fields are important in shaping magnetic fields.

Macroscopic perspective An approach that examines systems at the large-scale level (e.g., measuring bulk properties such as temperature, pressure, volume, mass, and density; using concepts like energy, entropy, and heat without reference to individual particles; applying thermodynamic laws and continuum mechanics).

Microscopic perspective The behavior and properties of systems are described at the smallest scales, typically the level of atoms, molecules, and subatomic particles (e.g., vibrations, rotations, translations; van der Waals forces, chemical bonds; statistical distributions like Maxwell-Boltzmann distribution of particle speeds; thermal and quantum fluctuations).

Plasticity Irreversible deformation of a solid under stress. Plastic deformation occurs once the applied stress exceeds a threshold known as the yield stress. In crystalline solids, plasticity is mainly accommodated by the motion of defects such as dislocations, by diffusion processes, or by phase transformations, and provides the microscopic mechanisms underlying creep.

Polarizability The tendency of the electron cloud around an atom, ion, or molecule to be distorted by an electric field, including the oscillating field of incident light or changes in the local bonding environment. Vibrational modes that change polarizability produce Raman scattering and are therefore detectable with Raman spectroscopy.

Polarized light microscopy Optical microscopy using polarizers to study anisotropic minerals in thin section, revealing properties such as birefringence, interference colors, and extinction angles.

Radiation Emission of electromagnetic waves (mostly infrared) from a surface. Unlike conduction and convection, radiation does not require a medium and can occur in a vacuum. Example: Heat from a campfire felt on your skin, Earth radiating heat into space, and heat from the Sun reaching planetary surfaces.

Raman spectroscopy A technique that measures inelastically scattered light from a laser to detect vibrational modes that change molecular polarizability, used for phase identification and structural information.

Remote sensing Measurement of reflected or emitted radiation from a distance, using airborne or spaceborne instruments, to infer surface composition and properties.

Strain A dimensionless measure of material deformation, defined by how distances or angles change relative to their original state. For uniaxial deformations, it is the relative change in length ($\Delta L/L_0$). In general, it is described by a tensor that captures both volume change and shear. Strain is fundamental for understanding how minerals deform under stress.

Strain rate The rate of deformation of a material, defined as the time derivative of strain. Strain rate is key for processes such as creep, viscous flow, and plasticity in minerals. The unit is s^{-1}.

Terrestrial body Planets, moons, and asteroids that are composed of a rocky outer portion and a metallic core. There are four terrestrial planets in our Solar System: the Earth, Mars, Mercury, and Venus. The Moon, several moons of the gas giants, and asteroid Vesta are also terrestrial-like bodies.

Transport properties The physical characteristics of geomaterials that govern the movement of mass, energy, or momentum within a system. These properties characterize how particles flow, diffuse, conduct heat and electricity in planetary interiors.

Umklapp processes Phonon–phonon interaction that plays a key role in limiting thermal conductivity in solids. The process occurs when two phonons (quanta of lattice vibrations) collide and produce a third phonon, dissipating heat by transferring phonon momentum to the crystal lattice, effectively acting as a resistance to heat flow.

Viscosity Property of a fluid that quantifies its resistance to flow, relating stress to strain rate. In a Newtonian fluid, this relationship is linear, with viscosity defined as the proportionality constant between stress and strain rate. In geological contexts, viscosity is used to describe the time-dependent, macroscopic deformation of rocks, which can behave as highly viscous fluids over long timescales. Effective viscosity emerges from underlying plastic mechanisms (e.g., dislocation motion, diffusion, grain-boundary processes) and depends strongly on temperature, pressure, grain size, and fluid content.