

The transition metals iron, nickel, and cobalt are responsible for most magnetism in natural materials. Minerals with the strongest ferromagnetic properties are typically iron oxides such as (titano)magnetite, hematite, goethite, and native iron. Iron sulfides, including the pyrrhotite group and pentlandite, also tend to exhibit magnetism strong enough to identify with a hand magnet. The magnetic behavior of these minerals has been well-characterized in recent decades, enabling advancements in paleomagnetism, magnetic data storage, aeromagnetic surveying, and materials science. Developments in the field of mineral magnetism have increasingly permitted a rigorous physical description of the atomic interactions which give rise to ferromagnetism. Fundamental mineralogical properties, such as electronic configurations, lattice structures, twinning, and symmetry play a significant role in predicting and modeling the magnetic behaviors of crystalline solids.

Due to the combination of their rarity and their very weak magnetic fields (which are several orders of magnitude weaker than for magnetite, and very difficult to detect outside of the laboratory), the magnetism of cobalt minerals is less understood than that of iron minerals. Modern high-sensitivity magnetometers provide an opportunity to investigate weakly ferromagnetic cobalt minerals and minerals which are ferromagnetic only below room temperature. These instruments allow for the measurement of magnetic hysteresis and remanence: characteristic ferromagnetic behaviors where materials store information about their past exposure to magnetic fields. Key experimental determinations include values for saturation magnetization (the maximum possible strength of the magnet), magnetic coercivity (the magnetic field required to overwrite a magnetization), magnetic susceptibility (the magnet's response to external magnetic fields), and magnetic remanence (the magnet's residual field in the absence of an applied external field) in addition to more complicated higher order effects. Furthermore, rather than characterize these properties as one-dimensional scalar values, modern techniques enable measurement of magnetic anisotropy (differences in values between lattice directions) with two- and three-dimensional tensors. Surprisingly, even isometric minerals like magnetite can exhibit magnetic anisotropy due to the sub-lattice scale of atomic and electron exchange interactions responsible for ferromagnetism. In-situ heating and cooling capabilities also permit the measurement of the variation of these parameters with temperature and the determination of a mineral's Curie temperature, above which it loses its ferromagnetic character.

We studied the magnetic properties of a suite of cobalt minerals using specimens from the Mineralogical and Geological Museum at Harvard University Mineral Collection, the Smithsonian Museum of Natural History National Gem & Mineral Collection, and the Dartmouth College ore collection, including specimens from various global localities and mines. We confirmed mineral structures and chemical compositions using powder X-ray diffraction and bulk-crystal energy dispersive spectroscopy respectively. We investigated magnetic hysteresis and remanence properties of both single crystals and fine powders using a high precision vibrating sample magnetometer. Our results include the identification of ferromagnetic behavior both at and below room temperature, development of models for magnetic anisotropy, and identification of magnetic and magnetostructural transition temperatures between 5 and 900 Kelvin. We also determined relationships between elemental composition and trends in certain magnetic properties. These and future measurements have the potential to assist in exploration, mining, separation, and refinement of critical cobalt resources for the renewable energy transition.



Weak Ferromagnetism of Cobalt Sulfide Minerals. Thom Chaffee, Sarah P. Slotznick,
Dartmouth College Department of Earth and Planetary Sciences, Hanover, NH 03755.

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Thom Chaffee, (941) 586-5260, thom.chaffee@dartmouth.edu

Dartmouth College Department of Earth and Planetary Sciences, Hanover, NH 03755