# Earth Materials

Rodney C. Ewing

In 1987, "Earth Materials"* made their formal debut at the Spring Meeting of the Materials Research Society as a symposium on silicate melts and glasses organized by Gordon Brown of Stanford University and Ray Jeanloz of the University of California, Berkeley. The symposium brought together a diverse group of mineralogists, geologists, and materials scientists to discuss a common problem—the structure of glasses and their relationship to silicate melts, precursors to igneous rocks. This was a much lauded symposium, and as a councillor to MRS as well as a geologist, I was pleased that the symposium enjoyed such a warm welcome from colleagues interested in such distant topics as silicon technology and electronic materials. This was not the first time geologic materials had been the subject of papers at an MRS meeting. The annual symposium on the Scientific Basis for Nuclear Waste Management has been a common forum for the presentation of research on radiation effects in minerals, corrosion mechanisms in natural glasses, adsorption of radionuclides onto clays, and the hydrologic transport of radionuclides. The symposium on Materials Issues in Art and Archaeology at the most recent MRS Spring Meeting in Reno included sessions on the hydration and alteration of natural, ancient, and modern glasses. Thus, there has been a growing trend to include earth materials as a subject in MRS symposia.

In fact, I have been pleased to see how easy and useful it is to sample all the MRS symposia in a search for new techniques and ideas that might be applied to earth materials. In this vein, I use this editorial to mention some of the significant areas of research in earth materials that go hand-in-hand with central aspects of research in materials science, and at the same time to point to some of the critical differences in research involving "earth materials" as compared to the more familiar "high tech" materials.

*"Earth Materials" is probably too restrictive a phrase, as geoscientists now are commonly involved in studies of lunar rocks, meteorites, cosmic dust, and other planets. Actually, simply said, geoscientists study naturally occurring materials, usually of great age and commonly of mixed phase assemblages with complicated compositions.

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A valuable summary of "Earth Materials Research" is found in a report (of the same title) by the National Research Council (National Academy Press, 1987) on a workshop on the physics and chemistry of these materials held in April 1986 in Airlie, Virginia. The purpose of the workshop was to bring geoscientists together to discuss how the national effort in earth materials research might be organized. The report makes interesting reading, and is here summarized, because it clearly shows the similarities in research between mineralogists/geologists and their colleagues involved in materials science, condensed-matter physics, and chemistry. But, the report also emphasizes important differences between research in the earth sciences and the materials sciences.

The most notable difference between the research problems which face earth scientists and those of materials scientists is the spatial and temporal scales involved in the study of earth materials which are far beyond human experience. For geologic processes, time scales may be ten orders of magnitude greater than those applicable to laboratory investigations, and spatial scales may be seven orders of magnitude greater. The behavior of earth materials over such extended scales differs from that measured in a laboratory experiment. Although rocks are solids which display brittle behavior in the laboratory, over geologic time scales they can flow plastically. For example, large portions of the earth's solid mantle behave as a convecting fluid.

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Laboratory measurements completed with precise attention to atomic-scale phenomena must be extrapolated to explain a diverse set of physical phenomena (such as the earth's magnetic field) which are intimately associated with compositional variations and the constitution of the earth's interior. Extrapolation from laboratory experiments or theoretical calculations requires an understanding of the relevant geologic processes and their long-term effects.

A lack of samples from even relatively shallow depths beneath the earth's surface is a further complication, as it obscures the applicability of laboratory experimental data. The physical and chemical heterogeneities of the mantle and their direct relation to tectonic processes and plate motions is a common focus of earth scientists. Yet, we have only a few samples which reveal these physical and chemical heterogeneities. The physical and chemical properties of the whole earth can only be inferred from large-scale geophysical measurements (e.g., the earth's bulk density or seismic velocities).

Another difference between earth materials and those typical of materials research is their complexity. Whereas materials in technological applications can typically be described as one or two component systems, geologic phases often consist of ten or more components. Even the simplest experiment with natural materials can involve a substantial effort in initial characterization and description. Despite the differences in composition, the structural and topologic overlap between the 3,000 naturally occurring minerals and the tens of thousands of synthetic materials is impressive. A noteworthy example is the perovskite structure type, so prominent in the discussion of superconductors, which is probably the most abundant structure type in the earth's lower mantle.

Analytical techniques used by earth scientists form a common bond to materials science, but the application of the data is distinctly different. The understanding of pressure, temperature, and volume relations is fundamental to evaluating models of the Earth's deep interior. Elastic and inelastic properties are required for the interpretation of seismic travel times. Crystal structure determinations contribute to an understanding of phase transformations (e.g., the cause of seismic discontinuities at 400 and 700 km). Thermal conductivity measurements are necessary to develop and interpret heat flow models, and rheological measurements are necessary to determine the mechanical state and structure of the earth's interior. Research into the properties of surfaces, interfaces, and aggregates is one of the most recently recognized areas of importance to earth materials science. The bulk physical properties of rocks depend in large part on phenomena that occur at mineral interfaces and surfaces. Chemical reactivity and sorptive properties of rocks depend on the nature of mineral surfaces. Techniques to modify and characterize thin films have important application in understanding the surface properties of minerals. Ion implantation techniques have been used to investigate the corrosion of important geologic phases, such as zircon, which is commonly used in uranium/lead age dating. Even this abbreviated list of research topics easily explains the lure and appeal of MRS symposia to geoscientists. Earth scientists need to apply the same sophisticated techniques and approaches to naturally occurring materials. It is only in the context of the large-scale and long-term interpretation of the data that these two subdisciplines diverge.

With these types of investigations, it is not surprising that the research needs of earth scientists are in concert with those of materials scientists. There is a growing need for the development of experimental and analytical facilities that will serve a wider group of users. Among those required are synchrotron radiation facilities and microscale, *in situ* analytical instrumentation. Of unique interest to geoscientists is the development of high-pressure, high-temperature, large-volume experimental techniques. In the next 5 to 10 years, earth scientists expect to develop the technology to make *in situ* measurements on sample volumes of 1 mm$^2$ at pressures of 1 Mbar and temperatures of 5000 K (conditions corresponding to the core-mantle boundary). In addition, the application of tandem accelerator mass spectrometry has opened a wide variety of cosmogenic radioisotopes to geologic applications—such as the determination of groundwater ages and rates of mechanical and chemical erosion.

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Thus, for earth scientists, the material in question is the whole earth with its complex and heterogeneous composition, and the duration of the experiment is all of earth history. The understanding of earth materials requires the application of the most sophisticated analytical techniques, but the "geologic" interpretation requires a keen sense of earth history and long-term phenomena. To this end, I am pleased to see that the science of geology has come full circle. Probably one of the earliest materials scientists was Nicolas Steno, who was one of the first to note the "law of constancy of angle" in the comments which accompany his drawings of quartz and hematite crystals (*De solido*, 1669). His observations lead to the first substantive speculations on the internal structure of solids. Steno (actually Nils Stensen, a Dane by birth) was a materials scientist much involved in geologic research. His work also included such diverse topics as the careful comparison between fossil shark teeth and modern shark teeth, and he is given credit for the first statement of the Law of Superposition of sedimentary strata. In the 17th century, materials science and the earth sciences were part of natural science with no disciplinary boundaries (if only universities could recall those days). Three hundred years later, we find the earth sciences and materials sciences are once again merging in a common effort to understand the planet Earth.

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