Planetary Materials Research at APL

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Planetary materials research offers a unique approach to understanding our solar system, one that enables numerous studies and provides insights that are not possible from remote observations alone. APL scientists are actively involved in many aspects of planetary materials research, from the study of Martian meteorites, to field work on hot springs and craters on Earth, to examining compositional analogs for asteroids. Planetary materials research at APL also involves understanding the icy moons of the outer solar system using analog materials, conducting experiments to mimic the conditions of planetary evolution, and testing instruments for future space missions. The diversity of these research projects clearly illustrates the abundant and valuable scientific contributions that the study of planetary materials can make to space science.

INTRODUCTION

In most space science and astronomy fields, one is limited to remote observations, either from telescopes or spacecraft, to gather data about celestial objects and unravel their origins. However, for studying our solar system, we are less limited. We have samples of planetary materials from multiple bodies in our solar system. We can inspect these samples, examine them in detail in the laboratory, and try to unravel and interpret their history. By understanding these samples, we can understand the history of our solar system.

When people think of planetary materials, they commonly think of samples returned by space missions. Planetary materials available for study do include samples returned by space missions, such as samples of the Moon returned by the Apollo and Luna missions, comet dust collected by the Stardust mission, and implanted solar wind ions collected by the Genesis mission. However, samples from other bodies in our solar system are also regularly delivered to Earth in the form of meteorites and cosmic dust. Meteorites sample a diverse range of planetary materials from many more planetary bodies than just the few that have been visited by spacecraft—from remnants of the earliest solar system, to the deep interiors of evolved asteroids, to the only samples we have from the planet Mars. In addition, we have unparalleled access to abundant samples from one planet in our solar system: Earth. Though often overlooked when thinking about planetary materials, the study of Earth is fundamental not only for learning about our own planet but also for interpreting the materials from all the other solar system bodies. On Earth, field studies can be conducted to examine a wide range of geologic processes in person and in great detail. Numerous terrestrial samples can be used as analogs for understanding other solar system bodies. Well-characterized Earth materials can be used to test instruments for future space missions as well.

Scientists at APL are actively involved in the field of planetary materials research. Here we describe some of these research projects; their diversity illustrates the large range of information that can be learned through the study of planetary materials.

METEORITES

After traveling incredible distances through our solar system from their parent bodies, "meteorites" are the rocks that have safely made the passage through Earth's atmosphere and fallen to the surface. ("Meteor" refers to the material as it traverses the atmosphere; most meteors do not make it to Earth's surface to become meteorites.) The meteorites we have in our collections today, which come in all shapes and sizes, represent material from numerous solar system bodies. As sample return missions to planetary bodies are sparse, meteorites offer researchers a valuable opportunity to learn a great deal about the history of the solar system and the processes that have shaped it.[1]

Meteorites are found worldwide and are named for the location where they fall or are found. Currently, the most productive locations for finding meteorites are the world's deserts, namely, Antarctica and the Sahara, as they provide arid environments that promote the preservation of meteoritic materials by limiting their exposure to liquid water.

Meteorites are classified into different types based on their composition. The two primary types are stony and irons. The stony meteorites include chondrites and achondrites and are composed of silicate and oxide minerals, with an occasional metal grain. Chondrites, the most common type, are essentially rocks made up of early solar system materials, including a common component called chondrules, small blobs of primitive material that have undergone very little chemical change since their formation. Achondrites, on the other hand, lack these little blobs and are early solar system igneous rocks that have undergone partial melting and crystallization, often accompanied by chemical changes. Iron meteorites lie at the opposite extreme, being composed of iron-nickel metal with the occasional silicate or oxide grain. Stony-iron meteorites fall somewhere in between, containing approximately equal amounts of metal and silicate material. Often, stony meteorites represent the crust and mantle of a planetary body, iron meteorites represent the core of a differentiated planetary body, and stony-iron meteorites may represent material found at the boundary of these regions.

Most meteorites are samples from asteroids, but a few have been identified as originating from the Moon or Mars. The meteorites from the Moon have chemical similarities to lunar samples returned by the Apollo program and so are classified as having come from the Moon. Some of the meteorites from Mars contain trapped gas in parts of the rock; the composition of that gas is identical to the composition of the atmosphere of Mars as measured by the Viking landers, indicating that these meteorites are from the surface of Mars.

Martian meteorites currently represent our only "returned" samples of the surface of Mars, and as a NASA sample return mission to Mars is not slated to occur within the next 20 years, they will likely continue to be our only source of ground truth for the planet for some time. Studies of Martian meteorites have taught us a great deal about the processes that have affected the surface of Mars over the past 4.5 billion years. The ages of these meteorites range from ≈150 million years in the case of the group called the shergottites, which probably represent surface lava flows, to 4.5 billion years in the case of Allan Hills (ALH) 84001, which represents a rock formed farther below the surface of the planet, presumably from the ancient highlands. However, although we know these samples are from Mars, we don't know where on the planet they originated.

ALH 84001, as shown in Fig. 1a, is the famous Martian meteorite that reportedly contained fossilized evidence of Martian nanobacteria (i.e., life on Mars). Though this debate rages on, most researchers concur that the McKay et al.[2] study was inconclusive and that incontrovertible evidence for life on Mars remains to be discovered. Aside from the life on Mars debate, ALH 84001 offers a unique opportunity to study a rock from another planet that is nearly as old as the solar system and older than any rocks preserved on Earth's surface. ALH 84001 contains secondary minerals (Fig. 1b) that were not present when the rock first crystallized but formed during subsequent alteration processes such as during impact events or by exposure to water. APL scientists led a study that examined carbonate minerals in ALH 84001 and found that multiple generations of carbonate and other secondary minerals were produced in the rock.[3] It was concluded that

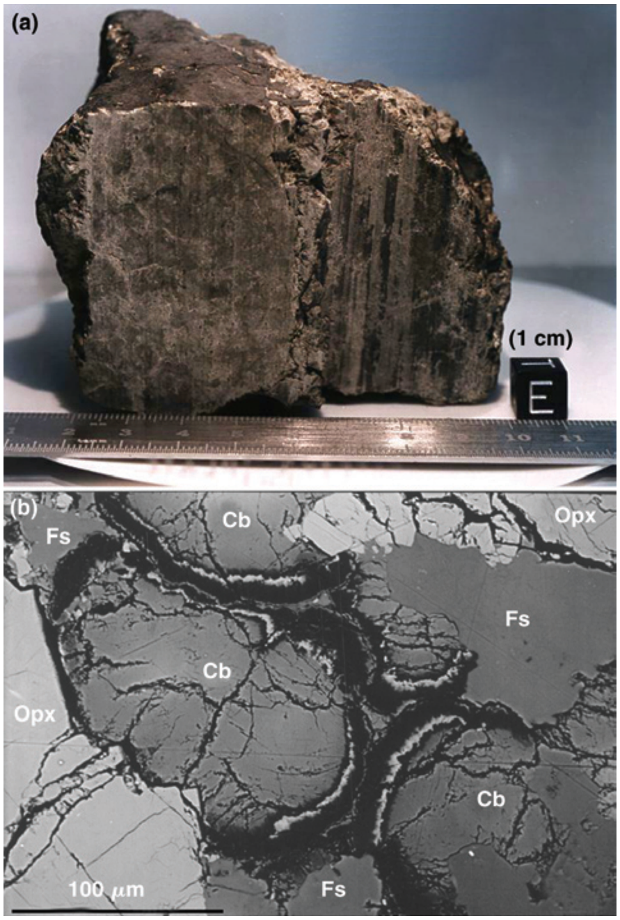

Figure 1. (a) The meteorite ALH 84001 is a sample from Mars. (Photo courtesy of NASA/JSC.) (b) By studying the detailed mineralogy of ALH 84001, insight can be gained into the past history of Mars. The carbonates identified here indicate that the sample has been altered by water (Cb = carbonates, Fs = feldspathic glass, Opx = orthopyroxene).

these minerals were formed by exposure to low-temperature water, likely released into the rock as a result of an impact event. This also led to the determination that water was released into the ALH 84001 host rock as the result of multiple events in the rock's history, but that these events occurred sporadically, therefore only exposing the rock to water for limited durations. ALH 84001 is just one example of how much information can be learned about solar system bodies from a single meteorite sample.

FIELD STUDIES

Field studies are an important aspect of solar system research because of our limited ability to study materials and processes on the other planets. Consequently, examining locations on Earth where relevant processes occur and studying these materials allows us to understand how geologic processes actually work, how the materials behave, and thus where to concentrate our research.

Terrestrial field studies have focused on a variety of geologic processes ranging from cratering, to volcanic and hydrothermal activity, to fluvial erosion, to desert processes and aeolian transportation of material. Field work at APL has focused on aspects of the cratering process[4–7] and the role of volcanic hydrothermal systems as niches for extremophile organisms and as an analog for possible Martian hydrothermal systems.[8]

Since reflectance spectroscopy, at UV to IR wavelengths, is commonly used to determine the mineralogy of surface materials, and as it has the potential to detect the presence of some forms of living organisms through the proxy of various pigment molecules (e.g., chlorophyll), both of which are important planetary objectives, the potential value of reflectance spectroscopy to detect hydrothermal systems has been tested by examining such environments in Yellowstone National Park and the Great Basin of Nevada. Hydrothermal systems are typically characterized by the flow of hot water saturated with silica and the production of siliceous sinter (amorphous silica [SiO_2]). Silica is dissolved in the heated water as it travels through the subsurface and is then redeposited when the water emerges onto the surface and cools (Fig. 2). These hydrothermal systems are also hosts to a variety of organisms that can survive in extreme environments ("extremophiles"), in this case at high temperatures (close to boiling) and high acidity (pH ≈2). As these extremophile organisms live and grow in the silica-rich waters they become entombed as sinter is deposited around them. Several questions have been examined: Do these extremophile communities have diagnostic reflectance spectra and, if so, do these spectral signatures persist after the organisms are entombed and die? Can this signature be detected on other planets (or even on planets around other stars)?

Reflectance spectra of these organisms, plotted in Fig. 2c, show that they have characteristic spectral signatures in visible to near-IR wavelengths, allowing them to be identified remotely, even in very low concentrations. The different photosynthetic pigments (e.g., chlorophylls, bacteriochlorphylls, and caretonoids) have well-defined absorptions at specific wavelengths. Each organism has different pigments in differing concentrations and bound in the cell in different ways, resulting in unique spectra. By examining the spectra of the springs, one can determine which type of organism is living there. Once the organism dies, the pigments decay and the diagnostic spectral signature disappears.

The search for life or evidence of past life in the solar system is a daunting task. If such life exists it is most likely primitive and the extremophile organisms studied here are relevant as they are among the most primitive terrestrial life forms. Since these types of organisms were among the first to develop on Earth, one might expect that they would be the first kinds to develop on

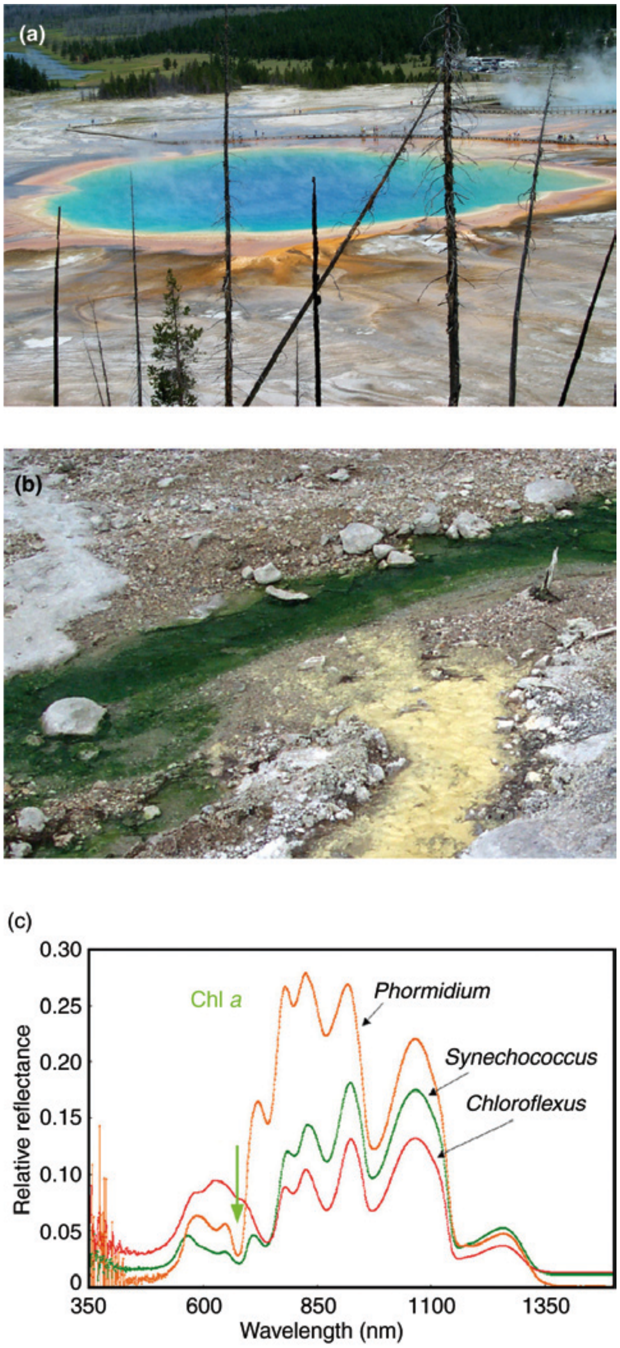

Figure 2. Yellowstone National Park. (a) Grand Prismatic Spring is a large vent where hot water reaches the surface. The colors of the surface surrounding the azure blue pool are produced by organisms growing in the hot alkaline water; the blue color of the pool is produced by colloidal silica. (b) Lemonade Spring is a high-temperature acidic spring. The green color is from the acidic-tolerant organism *Cyanidium sp.*; the yellow is sulfur deposited from the water as it cools. (c) Visible to near-IR reflectance spectra of three different microbial communities from Octopus Spring, an alkaline hot spring. The absorption from chlorophyll *a* is specifically noted. One organism, *Chloroflexus sp.*, lacks chlorophyll *a*; other absorptions at longer wavelengths are due to other biologic pigments.

other planets. Mars, for example, has widespread volcanic areas and evidence of water; it may well be possible that in the past, hydrothermal systems operated on or near the surface and provided a habitat for such life. By understanding the remote sensing signature of these environments from terrestrial studies, one is better able to look for them on Mars. Such data may also allow us to determine if life exists on extra-solar planets as well. While those planets are too far away to obtain spatially resolved images of their surface, one might be able to detect the presence of life by the diagnostic spectral signatures.

Impact craters are common geologic features on the solid planets and satellites in our solar system, but they are relatively rare on Earth because most of Earth's surface is young and because of erosion. Crater formation is important in the geologic history of all bodies because it fractures and deforms the crust, exposes materials from depth, and thereby allows sampling of deep levels of a planet. In the case of Earth, a giant impact of a Mars-sized body resulted in the formation of the Moon, and smaller impacts can seriously disrupt the biosphere (e.g., the Chicxulub impact in Yucatan at the end of the Cretaceous period that caused widespread extinctions). Craters on Earth are also associated with economic deposits (e.g., metals, oil, and gas). Because we have only remote sensing data for the other planets, and as the Apollo missions made only superficial examination of impact craters, the study and modeling of terrestrial impact and explosion craters are important to understand the fundamental processes that operate and how these processes influence the environment.

Much of what we know about the details of cratering mechanics is derived from the study of explosion craters, both chemical and nuclear. During the latter half of the 20th century, numerous tests were conducted at the Nevada Test Site (Fig. 3a) and on southwestern Pacific islands to examine the mechanics and dynamics of crater formation. By studying the resulting craters, critical criteria were established for recognizing impact craters on Earth. Explosions, when the explosive is buried beneath the surface, produce craters with the same morphologic features as impact craters.

Many of Earth's craters are highly eroded or buried, making normal geologic mapping impossible or incomplete. Geophysical measurements can provide the information necessary to understand the size and structure of an impact crater. Scientists at APL have been actively involved in research focusing on the Chesapeake Bay impact crater, the largest impact structure in the United States, with a diameter of about 85 km. The impact occurred around 35.5 million years ago when an asteroid some 4 km in diameter struck off what was then the eastern coast of North America in several hundred meters of ocean. The impact had an energy equivalent of 200–300 gigatons of TNT and formed the crater in a matter of only a few minutes.

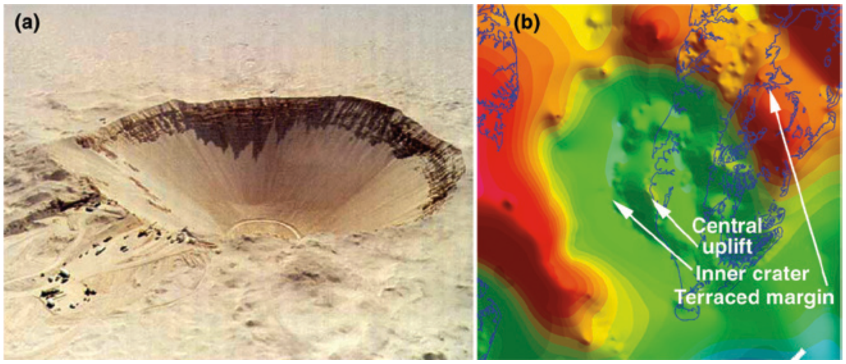

Figure 3. (a) Sedan crater at the Nevada Test Site was formed by a 10^4-kiloton nuclear explosion in July 1962. The crater has a diameter of 390 m and a depth of 98 m. The U.S. Capitol Building would easily fit within the crater. Such explosion craters on Earth exhibit all the characteristics of simple impact craters throughout the solar system: bowl shape, raised rim, surrounding ejecta, and shock features in minerals. (Image courtesy of the DoD/Nevada Test Site.) (b) Bouguer gravity map of the Chesapeake Bay impact structure: hotter colors denote gravity highs and dense rock at depth; cooler colors indicate lower gravity, and hence lower-density rocks.

The impact structure is now completely buried beneath the Delmarva Peninsula, the Chesapeake Bay, and adjacent Atlantic Ocean. Only through geophysics and limited drilling can the structure be understood. Drilling is expensive, and seismic reflection studies conducted by ships are limited by the shallow water of the Chesapeake Bay. Gravity studies, however, provide a rapid exploration tool to understand such buried impact craters. Gravity varies over the surface as a result of the density variations within Earth. Density variations in the upper crust produce the largest signals, and these are easily measured (1 part in 10^6). Figure 3b shows the gravity map of the Chesapeake Bay structure. This map reveals the major structural elements: the central uplift, inner crater, and terraced margin. Because the central uplift and the walls and floor of the inner crater are composed of high-density igneous and metamorphic rocks and the inner crater is filled with low-density marine sediments, a positive gravity anomaly occurs at the center, surrounded by a negative anomaly. The gravity signature allows direct determination of the lateral dimensions of the structure, and by measuring the densities of different rock types, modeling of the anomalies allows the depths to different structural elements to be estimated.

Impact structures are of interest not only to those who are studying the impact phenomena and their consequences, but in the case of the Chesapeake Bay structure, the crater itself provided a deep depositional basin for coastal sediments. The result is a sedimentary record reflecting changes in the climate and the environment from 35 million years ago to the present in exquisite detail. Because of the topographic low, the sedimentation rate was very high, and so the record is more detailed than elsewhere along the eastern coast of North America.

ASTEROID ANALOG MATERIALS

A common technique for trying to understand data from other bodies is to turn toward Earth to find similar material from similar environments. Studying analog samples from the wide variety of geologic environments on Earth and comparing them to data or materials from other planetary bodies can provide a great deal of insight into the geologic processes that have taken place on that body and in our solar system in general. For example, lava flows from Hawaii are an important terrestrial analog to planetary volcanic rocks as they provide some of the youngest and freshest materials we can obtain from Earth. Comparing Hawaiian basalts to the shergottite group of Martian meteorites, which are thought to be surface volcanic flows, has led researchers to better understand the volcanic processes taking place on Mars.

APL scientists are using analog materials in a newly funded study with the goal of better understanding the link between the reflectance spectra in the visible to near-IR range of terrestrial minerals and meteorites and the spectra of asteroids.[9] The hope is that this will improve the ability of researchers to use spectra from known minerals to interpret spectral data from asteroids. In particular, a focus of this study is to put better constraints on the origin of the asteroid 433 Eros (Fig. 4a), visited by APL's Near Earth Asteroid Rendezvous (NEAR) Shoemaker mission. The goal of this work is to better determine whether 433 Eros and other asteroids ever underwent certain geologic processes, such as melting, by better detecting the presence, abundance, and composition of the minerals exposed on their surfaces.

To begin this project, mineral powders were gathered from the collection of standard geologic materials developed and held by the Department of Mineral Sciences at the Smithsonian Institution's National Museum of Natural History. These minerals are extremely well characterized and are used as instrument standards in laboratories around the world. The minerals were ground into powders, sieved to a specific size-fraction, and mixed in varying proportions to create a wide range of mineral compositions that mimic those of ordinary chondrite meteorites. Though some minerals are known to be sensitive indicators of the melting process, we are limited to the minerals that have major absorption features in the visible and near-IR spectral regions. These powders were sent to Brown University's RELAB (Reflectance Experiment Laboratory) facility, where spectra were obtained of each of the 40 mixtures; some characteristic spectra are shown in Fig. 4b.

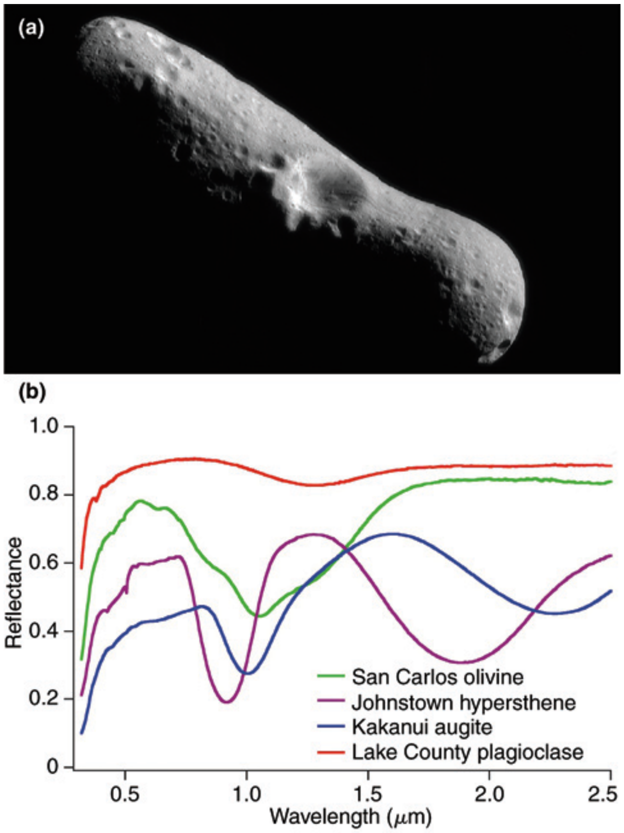

Figure 4. (a) The asteroid 433 Eros. (Image courtesy of NASA.) (b) The spectra of some common mineral standards are shown, with different minerals exhibiting distinctive spectral signatures. Gathering spectral data on many well-determined mixtures of analog materials will aid in interpreting the mineralogical composition of asteroids.

The major problem with current techniques is that one- or two-dimensional graphical solutions cannot cope with the number of minerals that make up an asteroid/meteorite or the variation in the composition of those minerals. As the next stage in this project, the spectra from the standard mixtures will be used to improve the techniques for interpretation of the spectra of asteroids. By creating reference spectra from these multi-component mixtures and understanding how the spectra change with the presence of more than two minerals, more sophisticated methods of extracting mineralogical and compositional data from asteroids can be developed. This will enable more accurate interpretations of the surface expressions of geologic processes visible on asteroids.

OUTER SOLAR SYSTEM ANALOG MATERIALS AND EXPERIMENTS

One of the greatest challenges facing planetary scientists studying the surfaces of solid surface bodies beyond the asteroid belt (e.g., the moons of the giant planets) is that mankind has yet to obtain samples (either directly or from meteorites) to "ground truth" our remote sensing observations. Unlike studies of the asteroid belt, Mars, and the Moon, conclusions are inferred solely from distant measurements of electromagnetic properties, and when spacecraft fly sufficiently near, some dust and particle measurements. Observations of these bodies are made with a plethora of instruments operating at wavelengths from the UV to radio wavelengths using Earth-based and Earth-orbiting telescopes as well as spacecraft. Yet without samples to constrain these observations, it is difficult to accurately stitch the various separate remote sensing measurements together to form a complete and accurate picture of these bodies.

However, several tools are available to help in interpreting the multiple measurements. For instance, by using the knowledge base of the physical, chemical, and geologic processes on Earth and other bodies one can infer much about the nature of these outer solar system objects, including styles of geologic deformation, chemical pathways, and processes that can modify their surfaces. Of course, the "terrestrial" perspective is not perfect and can handicap and skew interpretations at times, raising doubts about unexpected discoveries and fomenting arguments over the proper interpretations. As an example, the source of Io's volcanism was thought to be caused either by fricitional heating due to the dissipation of internal tides or by electromagnetic heating. This debate went on for years until it was finally accepted as tidal heating. There are even stories that the discovery of the thermal anomalies on Io may have "first" been discovered via telescopic observations but ascribed to instrumentation artifacts and not published. Similar fundamental arguments exist today. The dominant chemical process on the surface of Europa, Jupiter's icy moon, with a suspected ocean underneath its crust, may be the exposure of subsurface materials by surface cracking and other geologic processes or the alteration of preexisting material by the bombardment of ions and other particles in the Jovian magnetosphere.[10,11] The answer would have very significant implications for the potential existence of life in the subsurface Europa ocean due to the likely transport of materials between the surface and subsurface. Solving this puzzle would undoubtedly be a major objective of any future mission to this icy world. Other questions are related to icy satellites of the outer solar system that are limited by remote sensing observations alone: What composes the surface of Titan other than water ice? What processes are responsible for the plumes on Enceladus? What chemicals make up the dark, organic-rich materials discovered on the various Galilean and Saturnian icy satellites?

To help answer these questions, analogs are used to test hypotheses and formulate new ones. At the Remote Sensing Laboratory, APL scientists are investigating the optical properties of analog materials under terrestrial conditions and will soon do the same under conditions found on these outer solar system bodies. The precision of the equipment is similar or superior to the instruments used on spacecraft, and the experiments are tuned to cover the near-UV through long-wavelength IR (>40 μm) to obtain data directly relevant to spacecraft and telescopic measurements. The work is part of a consortium of researchers investigating the origin and composition of the dark, rocky, non-ice material on Europa (Fig. 5a). This group has been exploring the possibility of an internal origin and a composition dominated by heavily hydrated salts, in contrast to a group of Jet Propulsion Laboratory scientists who are pursuing a theory of a radiolytic origin and a composition dominated by hydrated sulfuric acid. The answer will have significant ramifications for the composition of the subsurface ocean and consequently for the likelihood of life. This research has expanded to several groups at different institutions, and the consensus is growing that both processes operate, although which process is dominant is still quite contentious.

The research at APL has recently expanded into understanding the intriguing relationship between the rocky material on the satellites of Jupiter and Saturn. There appear to be many compositional similarities, with volatile gases trapped onto the surfaces of these moons that would otherwise rapidly escape into space (Fig. 5b). What is the significance of these volatiles, most notably carbon dioxide (CO_2)? Are they gases degassing from the interior, or could radiolysis again be contributing some effects? The physical mechanisms by which these gases could be stably held onto the "warm" surfaces are being investigated; these processes may also operate elsewhere in the solar system, potentially even in the permanently shadowed regions of the Moon. Using Earth analogs such as clays, with plans to eventually include extraterrestrial analogs such as primitive carbonaceous meteorite samples, it has already been discovered that physisorption at cryogenic temperatures can be sufficiently strong to overcome the kinetic energy of the gases, preventing their escape from these surfaces.[13] These analog studies have sent APL scientists across the country to collaborate with Department of Energy research scientists at the Environmental Molecular Science Laboratory at the Pacific Northwest National Laboratory in eastern Washington state. Physisorption experiments have been pursued there, and a linear accelerator is being used to bombard analogs with MeV ions of oxygen, sulfur, and hydrogen in an attempt to simulate possible radiolystic processes analogous to similar processes in the Jovian magnetsophere to which the satellite surfaces are exposed.[14]

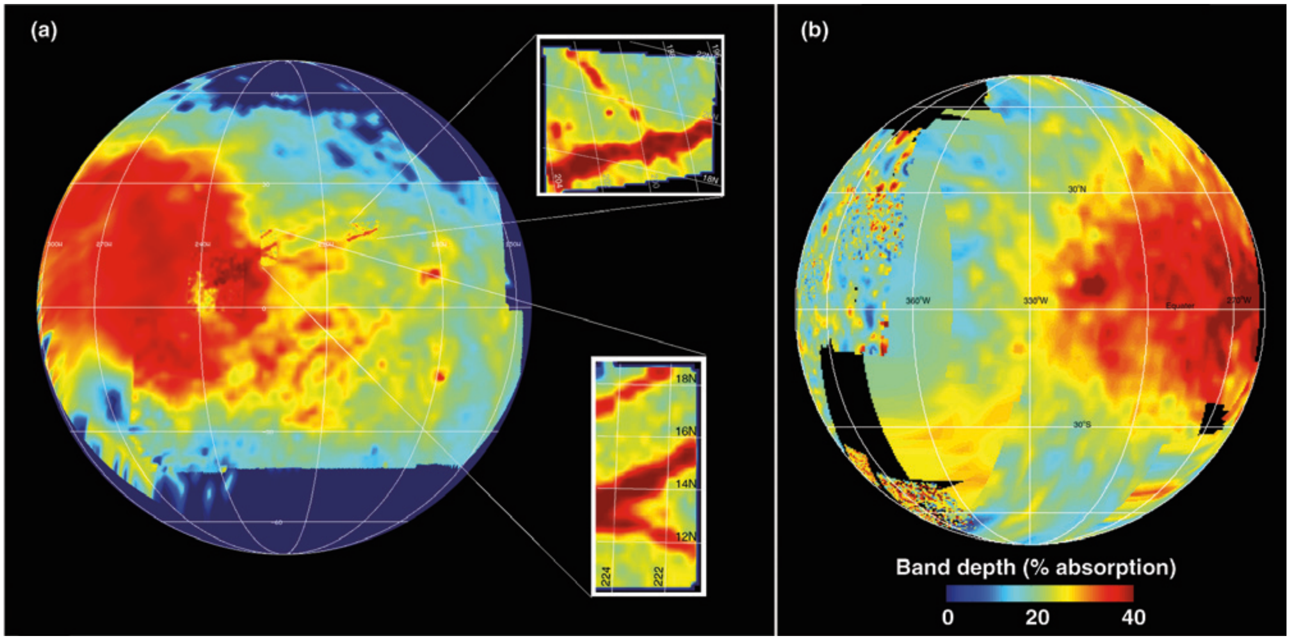

Figure 5. (a) The distribution of the non-ice material on Europa (from the Galileo NIMS [Near-Infrared Mapping Spectrometer] observations), with warmer colors indicating a higher concentration. The non-ice material is associated with young geologic features and the center of the trailing hemisphere. (Reproduced, with permission, from Ref. 10.) (b) The distribution of CO_2 on Callisto on this 4.25-μm-band map is shown, with warmer colors corresponding to higher relative abundances. The highest relative abundance is centered on the trailing hemisphere but is also commonly associated with young impact craters. In both cases, laboratory studies using analogs are proving essential to understanding the origin, composition, and physical state of these outer solar system bodies. (Reproduced, with permission, from Ref. 12.)

The APL laboratory facility also has the potential to help ongoing APL-led missions such as the MESSENGER (Mercury Surface, Space Environment, Geochemistry and Ranging) mission to Mercury. Thermal gradients in Mercury's sunlit surface, where the surface temperature can exceed that of molten lead, could affect its apparent emissivity. Measuring the effects of thermal gradients on the spectral properties of particulate materials in the laboratory may help us to better understand the geologic implications of the MESSENGER spacecraft's IR measurements.

PLANETARY EVOLUTION EXPERIMENTS

One can take a planetary material sample into the laboratory and measure its elemental composition, determining its mineral phases and other components. However, determining how that composition formed or what it is telling us about the history of the solar system body from which it came can often be more difficult. By conducting experiments under well-controlled conditions and comparing the results to the compositions observed in planetary materials, the similarities and differences can provide insight into the conditions and processes experienced on the parent planetary bodies. Such experimental work by APL scientists has focused on understanding the formation and evolution of rocky planetary bodies in our solar system, in particular Earth, the Moon, and asteroids.

From Mercury to the moons of the outer solar system, central metallic cores are common. How these cores formed is thus a fundamental planetary process, experienced over and over again in the evolution of our solar system. Was planetary differentiation, the process by which denser metal migrates to the center of a body and leaves a rocky silicate mantle behind, the same for all the planetary bodies? Or can planets evolve through multiple paths but all still have a similar central metallic core? To answer questions such as these, it is necessary to understand the process of planetary differentiation. Fortunately, as metal separates from silicate, a chemical signature of the process is left in the rocky mantle; trace elements are forced to choose whether to partition into the separating metal or stay within the silicate mantle. This chemical signature is a fingerprint of the core formation process. By examining it, insight can be gained into how planetary cores formed.

To interpret the chemical signature of core formation, it is necessary to understand the metal-silicate partitioning behavior of the relevant trace elements (e.g., Ni, Co, W, Mo, Au, Pt, Re), and this is where an experimental approach proves useful. The partitioning behavior of trace elements can be affected by a number of variables, including pressure, temperature, amount of available oxygen, and bulk composition. For example, planets of different sizes will have different internal pressures, and thus the process of core formation will leave different chemical signatures for these bodies. Experiments are conducted that isolate the effect of each of these variables; by holding all other conditions constant while varying only one factor, the influence of that variable can be determined. This new understanding of the metal-silicate partitioning behavior is then applied to interpreting the chemical signature imparted by core formation, providing insight into the pressure, temperature, and other conditions present during core formation on that planet.[15,16]

Figure 6a shows the core formation process envisioned to have occurred on early Earth. Here, metal is thought to have separated from silicate in a deep magma ocean, where Earth was largely molten and metallic liquid rained down through silicate liquid. By interpreting Earth's chemical signature of core formation, some idea of the depth of an early magma ocean can be obtained. Thus, experiments are conducted that contain molten metal and molten silicate, just as occurred in a magma ocean environment. The experiment shown in Fig. 6b is part of a series of experiments currently being conducted in the APL Space Department's Planetary Materials Laboratory that are varying the composition of the metallic liquid to determine how different compositions might have affected elemental partitioning behavior during core formation.

When planetary cores formed, the metal is believed to have been completely molten. As time passed, the planetary bodies began to cool. This decrease in temperature caused the molten cores to begin to solidify. Earth's core is currently in the middle of this process. Earth has a solid inner core surrounded by a liquid outer core; the inner core is actively growing as Earth continues to cool. For smaller bodies in our solar system, such as asteroids, the solidification of central metallic cores occurred over 4 billion years ago. There is evidence that the cores of both Mars and Mercury are at least partially molten. The MESSENGER mission will provide more information about the state of the core of Mercury.

Though central metallic cores are common throughout our solar system, iron meteorites are the only samples of such planetary cores, probably from asteroid-sized parent bodies.[17] As such, understanding these iron meteorites provides the unique opportunity to gain insight into the process by which planetary cores evolve and solidify. Many iron meteorites are thought to sample the same parent body core and, as such, are classified into iron meteorite groups. Within an iron meteorite group, trace elements form well-defined trends attributed to the fractional crystallization of the core. By interpreting these trends, one can understand the conditions under which these cores crystallized and solidified. By doing this for multiple iron meteorite groups, comparisons among the similarities and differences experienced on different parent asteroids during the cooling of these bodies can be made.[18]

To interpret the fractional crystallization trends in iron meteorite groups, it is necessary to understand how the trace elements behave during the solidification of the core. During the solidification process, both solid metal and liquid metal will coexist, and trace elements will partition between these two different metallic phases. For asteroidal cores, different concentrations of sulfur have been found to be quite influential on the process. Experiments that contain both solid and liquid metal, just like a crystallizing core, are conducted with varying amounts of sulfur to aid in the interpretation of iron meteorite trends.[19] Figure 7 shows an iron meteorite sample and an experiment conducted by APL scientists to mimic the potential compositional conditions under

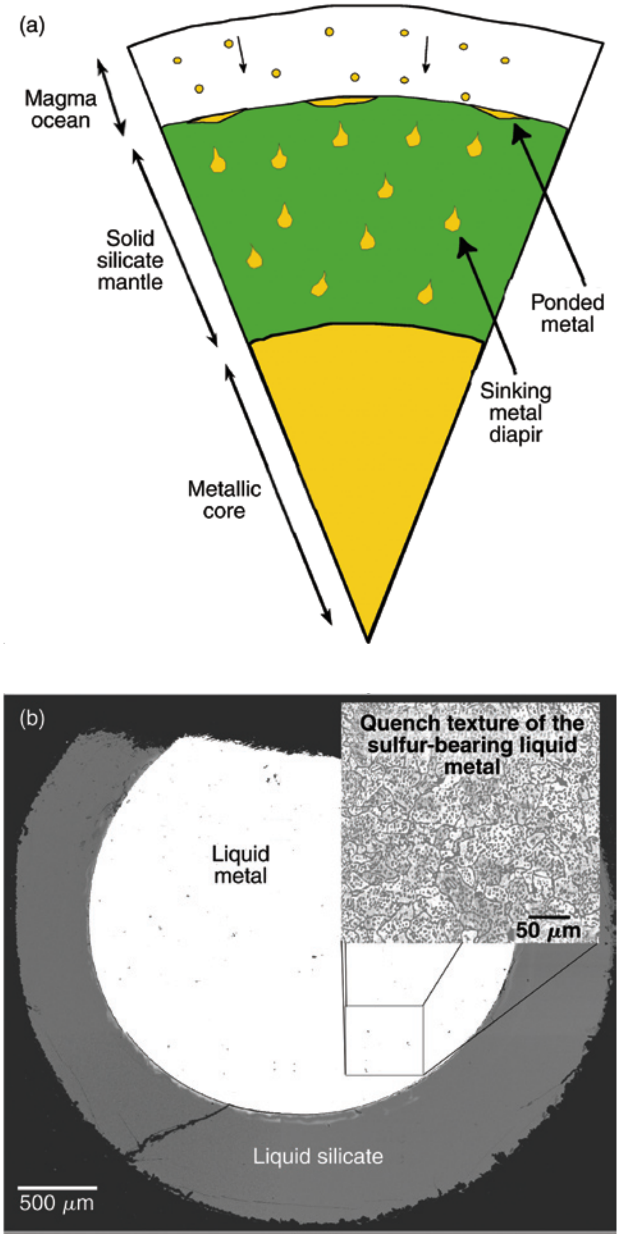

Figure 6. (a) Early Earth is envisioned to have had a magma ocean, an environment where molten rocky silicate material coexisted with molten metal. As a result of the much higher density of the metal, it settled through the magma ocean, grew large enough to pond at the base of the ocean, and migrated through the solid mantle, collecting at the center of Earth and creating the core. (b) By conducting experiments that contain coexisting molten silicate and molten metal, the chemistry that occurred during Earth's core formation can be examined. Here a backscattered electron image of an experimental run investigating the chemistry of an early magma ocean on Earth is shown.

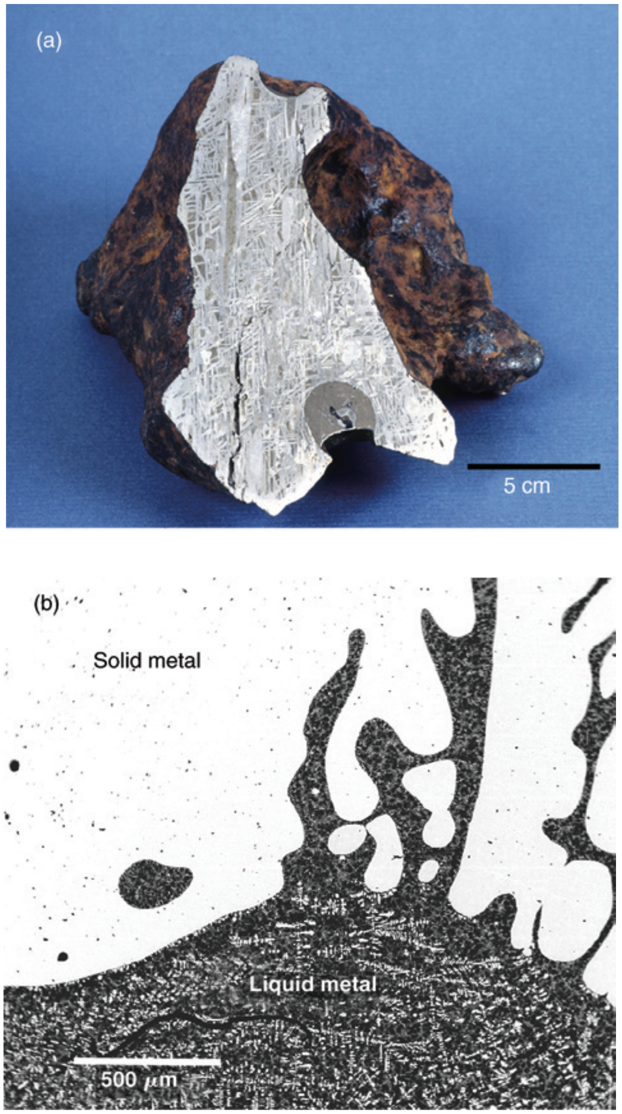

Figure 7. (a) Iron meteorites, many of which are thought to be pieces of the central metallic cores of asteroids, are the only samples of any planetary core and are thus unique for study. (Reproduced from Ref. 20.) (b) By conducting experiments with coexisting liquid and solid metal, insight into how asteroidal cores crystallized and evolved is gained. A backscattered electron image shows an experiment that was designed to mimic the crystallization of an asteroidal core.

which it solidified in an asteroidal core. Sulfur may also be an important element in Earth's core, and if so, these experiments have implications for understanding the currently ongoing solidification of Earth's core.

TESTING FUTURE SPACE INSTRUMENTS

The Laser Mass Spectrometry Laboratory in the APL Space Department uses terrestrial analogs to guide the development and testing of instrumentation intended for *in situ* planetary exploration. Lasers are used to sample solid materials for detection with a mass spectrometer, usually based on the time-of-flight (TOF) technique (Fig. 8). Various TOF configurations and laser energies are selected to characterize the elemental, isotopic, and molecular compositions of samples under variable environmental conditions.[21] These samples range from well-characterized geologic standards to rock and meteorite samples. Standards containing well-defined abundances of key elements are used to determine the accuracy and precision of each instrument under development. Once the correct geochemical information from standards is consistently obtained, actual field samples are analyzed. The use of realistic analogs of geologic samples is critical because the presence of multiple minerals or other compositional phases within one sample complicates the analysis of any one chemical species. An example of such a complication is a "matrix effect" in which an element is suppressed in a spectrum as a result of the quenching of its ionization by a large amount of neutral atoms from its host mineral, which might not be present in a standard sample for that element. This combination of analyzing both "known" and "unknown" samples allows one to be confident that the instrument response is an accurate reflection of the samples being studied, either in the lab, in the field, or on future planetary missions.

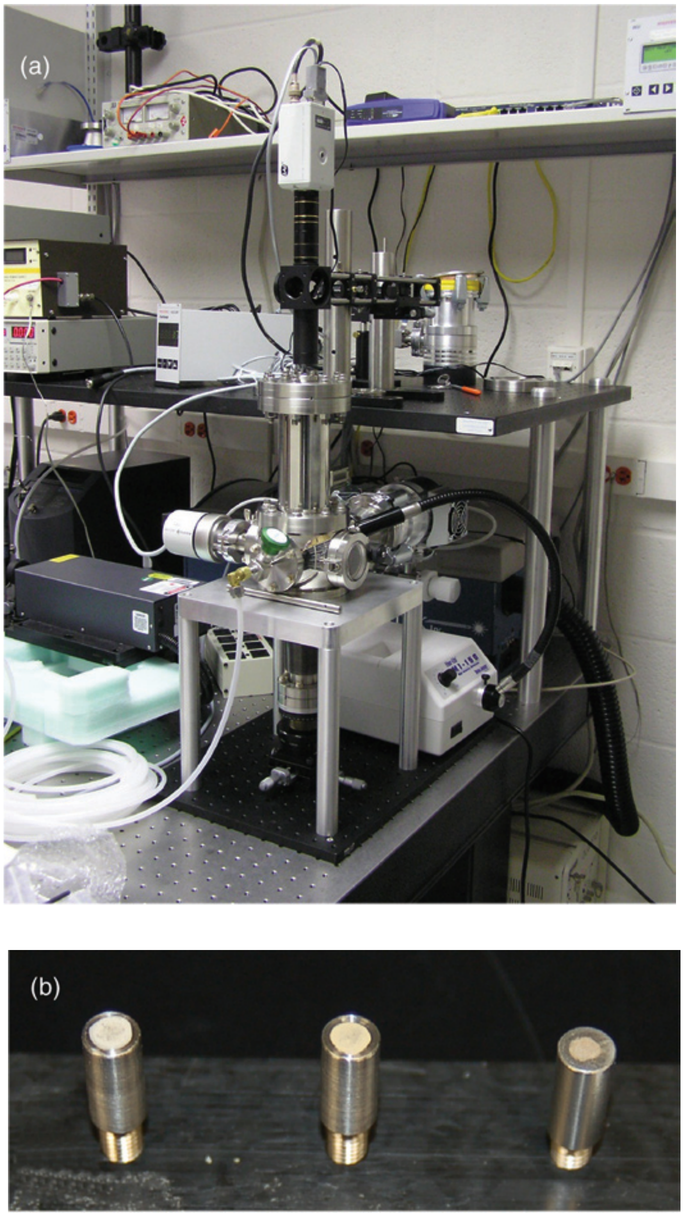

Figure 8. (a) The miniature Laser Desorption Mass Spectrometer (LDMS) under development for analysis of geologic materials on future planetary missions is shown. (b) Terrestrial analog samples are placed on sample holders appropriate for analysis in the LDMS. Analog materials are carefully analyzed in instruments such as these in preparation for future missions.

Many of the analogs used contain organic materials. These are analyzed with both prototype and well-established laboratory facility instruments. While most organic compounds found in natural samples on Earth are biogenic, it is crucial to understand the response of these instruments to various levels of complex organics associated with host mineral phases to aid in the ultimate search for signs of life in the solar system, particularly on Mars. In this regard, samples from extreme environments on Earth are invaluable in trying to understand how life may have developed in the hostile conditions likely present in early solar system environments. At the same time, such samples serve as a reasonable proxy to the conditions in which such organics might be found *in situ*.

In addition to using analog samples to guide the testing and development of laser mass spectrometers in the laboratory, a number of collaborations exist with scientists and engineers involved in the development of missions. For example, APL scientists are working with the Sample Analysis at Mars (SAM) team based at NASA Goddard Space Flight Center to help develop the instruments that will travel to Mars on the Mars Science Laboratory (MSL) mission in 2009. A suite of preselected analog samples is being shared "round-robin" style among a number of laboratories worldwide. By analyzing this common set of samples for both inorganic and organic composition with standard laboratory and prototype space instruments, the interpretation of MSL/SAM data from "unknown" Martian samples should be relatively robust. Laser mass spectrometry is contributing to this round-robin analysis through its high sensitivity to nonvolatile complex organics. This method is complementary to the methods used on MSL.

CONCLUSIONS

Planetary materials research provides a unique approach to investigating our solar system and yields insights that would not be possible from remote observations alone. The study of planetary materials becomes increasingly important as technology advances and future space missions expand beyond just orbital observations. Because sample returns are difficult, expensive, and risky, *in situ* landers and rovers will become more common, and the study of planetary materials forms the basis for interpreting the surface data that are returned. Past and future sample return missions promise to increase the world's collection of planetary materials. Already, two Discovery-class space missions have accomplished a sample return: Stardust returned thousands of particles in aerogel from a close pass to the comet Wild 2, and Genesis, though experiencing an unplanned crash landing, collected solar wind ions that are being prepared for analysis. The recent Japanese mission, Hayabusa, was the first mission to attempt to return a sample from an asteroid, though the success of that sample return remains to be seen.

The future of solar system exploration involves not just observing surfaces remotely but actively landing on them, measuring them, and even returning samples from them. The National Research Council's Decadal Survey for exploration of the solar system recommends multiple sample return missions as high scientific priorities for future NASA missions. The more recent NASA roadmap further echoes these important priorities. The study of planetary materials is and will continue to be critical to accomplishing these space science goals.

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