Asteroids

New Challenges, New Targets
Formation and Physical Properties
Establishing Asteroid–Meteorite Links
Asteroid 2008 TC₃ and the Fall of Almahata Sitta
Unique, Antique Vesta
Asteroid Itokawa
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Right: Oxygen isotopic compositions of Itokawa minerals compared with those of San Carlos forsterite and Miyake-jima anorthite crystals.

From: Oxygen Isotopic Compositions of Asteroidal Materials Returned from Itokawa by the Hayabusa Mission.


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Vol. 10, No. 1 - February 2014

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The Mineralogical Society of Great Britain and Ireland is an international society for all those working in the fields of mineralogy and economic geology. The Society aims to advance the science of mineralogy and to promote and advance the knowledge of mineralogy and its application to other subjects, including crystallography, geochemistry, petrology, and environmental science and economic geology. The Society furthers its aims through scientific meetings and the publication of scientific journals, books, and monographs. The Society's journal, the Journal of Mineralogy, Petrology, and Economic Geology, is available online. Membership benefits include receiving the Society's journal, subscriptions to selected publications, and participation in annual meetings, workshops, and field trips.

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The Chemical Society of America (TMS) is a non-profit organization dedicated to the advancement of mineralogy, petrology, and geochemistry. Founded in 1908, the Society promotes education and research through scientific meetings and publications. Membership benefits include special rates for membership fees, discounts on publications, and participation in a society that fosters the knowledge of mineralogy and geochemistry.

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The Swiss Society of Mineralogy and Petrology (SSMP) was founded in 1924 by professionals from academia and industry and amateurs to promote knowledge in the fields of mineralogy, petrology, and geochemistry and to disseminate it to the scientific and public communities. The Society coorganizes the annual Swiss GeoScience Meeting and publishes the Swiss Journal of Geochemistry.

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The MeteoroItical Society is an international organization that was founded in 1953 for scientists, collectors, and educators to advance the study of meteoritics and other extraterrestrial materials and their parent asteroids, comets, and planets. Members receive our journal, Meteoritics & Planetary Science, reduced rates for scientific meetings, workshops, and field trips, and support young researchers. Through our medals and awards, we recognize excellence in meteoritics and allied fields.

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The Japanese Association of Mineralogical Sciences (JAMS) was established in 2007 by merging the Mineralogical Society of Japan, founded in 1955, and the Japanese Association of Mineralogists, Petrologists, and Economic Geologists, established in 1928. JAMS covers the wide field of mineral sciences, geochemistry, and petrology. Membership benefits include receiving the Journal of the Japanese Association of Mineralogical Sciences (JAMS), the Gansu-Koubatsukagaku (GKK), and Elements. Elements is available online.

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ASTEROID WHAT?

Asteroids have a PR problem. The name, ending in -oid, connotes being sort of like something else, but not quite. Aster means “star” in Latin; so what is an asteroid? There are no constellations of heroic warriors immortalizing asteroids because the Greeks couldn’t see them. Most were only found in the last decade. Today, the popular dream of space travel might mean going to the planets or beyond, but probably not to YP139. Most people, if they think about asteroids at all, consider them either far away and obscure or nearby and menacing, perhaps coming to end civilization.

This view has been fueled by the motion picture industry. In the summer of 1998, two disaster movies captivated millions with images of asteroids (or comets), death, and destruction. The plot lines were identical: heroic attempts with variable effect to save the Earth from NEAs (near-Earth asteroids) using manned spacecraft, rock drills, and nuclear devices. In Deep Impact, Robert Duvall lands on an 11 km diameter body and blows it into two pieces, one of which lands in the Atlantic causing a dramatic mega-tsunami. In Armageddon, Bruce Willis lands on an asteroid and blows it up, this time showering Earth with exploding rocks. Lamentably, Armageddon is overblown and portrays science and scientists poorly, yet it did better at the box office. I confess: I saw both films. I saw Armageddon in Mammouth Lakes, California, inside the Long Valley caldera. In an amazing coincidence, a magnitude-5 earthquake rattled the theatre just as a meteorite (in the movie) was vaporizing Paris. There were no injuries (in the theater), but what great special effects!

More seriously, disastrous meteorite impacts are a continuing part of Earth history. The frequency is low and poorly understood, but the results can exceed even Hollywood’s lively imagination. Chelyabinsk (2013) and Tunguska (1908) were dramatic, but they were relatively small events. Some impacts recorded in the rock record were far larger, but are only known from geophysical evidence, thin spherule layers, or detrital shocked minerals. Others caused large craters or mass extinctions. Clearly, the study of past impacts and the prediction that those of the future are of more than academic interest, as is the study of asteroids themselves. Many organizations are searching for NEAs from Earth-based observatories and more recently from space. There are 1450 potentially hazardous near-Earth objects known. The NASA spacecraft NEOWISE (Near-Earth-Object Wide-Field Infrared Survey Explorer) reported discovery of the newest potentially hazardous NEA on December 29, 2013. Using its 20 cm telescope and infrared cameras, it determined the size (650 m), albedo, thermal properties, and trajectory of YP139, which is currently 43 million kilometers from Earth but is predicted to eventually pass within 490,000 km, about the distance from Earth to the Moon. In 2010–2011, the spacecraft discovered 34,000 new asteroids, bringing the total identified by all researchers to about 600,000.

If you are curious about asteroids, read on in this issue of Elements. Six articles review the discovery and different types of asteroids, as well as current and future space missions to study or recover them. Asteroids are highly organized, but they do not occur in one homogeneous “belt.” How do they form? What causes a well-behaved body to become a rogue NEA? Three special asteroids are singled out. The former asteroid 2008 TC3 became the Almahata Sitta meteorite after fragmenting above the Sudanese desert on October 7, 2008. The asteroid Iokawa was sampled by the JAXA mission Hayabusa, providing the only non-meteoritic samples of an asteroid. Vesta is the most-studied asteroid and the second most massive; it was visited by NASA’s Dawn mission and is interpreted to be the source of 100 known meteorites. Whether or not asteroids ever had a PR problem for you, I think you will find this a fascinating issue.

John Valley (valley@geology.wisc.edu)
Principal editor in charge of this issue

The 650 m diameter, potentially hazardous near-Earth asteroid YP139 (red dot in box) was discovered by NEOWISE on December 29, 2013. Image from JPL
WELCOMING GORDON BROWN

With 2014, Gordon E. Brown Jr. starts his term of office as principal editor for 2014–2016. Gordon is the Dorrell William Kirby Professor of Earth Sciences and chair of the Department of Geological & Environmental Sciences at Stanford University. He received his BS (1965) in chemistry and geology from Millsaps College (Mississippi) and his MS (1968) and PhD (1970) in mineralogy and crystallography from Virginia Tech. He has served as president of the Mineralogical Society of America (1995–1996) and is a fellow of the MSA (1975), the Geological Society of America (1997), the Geochemical Society / European Association of Geochemistry (1999), and the American Association for the Advancement of Science (2000). He has also received the Mineralogical Association of Canada’s Hawley Medal (2007), the Mineralogical Society of America’s Roebling Medal (2007), the Geochemical Society’s Patterson Medal (2007), and the American Geosciences Institute Medal in Memory of Ian Campbell (2012).

His research over the past several decades has focused on mineral–aqueous solution interface processes, the nanogeoosciences, and related societal issues. He was one of the first Earth scientists to use synchrotron light sources to address a variety of problems in high- and low-temperature geochemistry and environmental mineralogy and has helped popularize their use since the mid-1970s. His public service is reflected by the positions he has held and the more than 30 committees in which he has participated at various levels, including the key positions he has occupied advising and providing research management for NSF- and DOE-supported centers. He is also known for the many students he has advised and the extensive effort he has made to get students involved in mineralogy.

THANKING GEORGES CALAS

With this issue, Georges Calas retires as principal editor of Elements. During his tenure, he was the principal editor in charge of the following issues: Tourmaline (v7n5), Fukushima Daiichi (v8n3), Rare Earth Elements (v8n5), Serpentinites (v9n2), and Garnet (v9n5). He has also agreed to be in charge of the December 2014 issue entitled Graphitic Carbon. The editors and readers of Elements have enjoyed Georges’ dry French wit and his keen scientific knowledge. We appreciate his hard work and enthusiasm for maintaining Elements as the most readable and authoritative magazine in mineralogy, petrology, and geochemistry.

GOLDSCHMIDT UNION SESSION “ELEMENTS: 10 YEARS OLD”

A Union Session celebrating the 10th anniversary of Elements will be held during the Goldschmidt2014 conference in Sacramento on June 8–13, 2014 (www.goldschmidt.info/2014). This session will begin with two days of introductory invited and contributed talks on selected topics covered by Elements over its 10 years of activity. These presentations, each 30 minutes long, will reflect the philosophy of the magazine; that is, they will combine cutting-edge research and a style of presentation attractive to a nonspecialist audience in the fields of geochemistry, mineralogy, petrology, and societal/cultural aspects. The session will provide examples of the great diversity of the topics treated over the years and will also emphasize the major progress made in some of the topics since the original Elements issues. Invited speakers include Liane Benning, Bernardo Cesare, Don Dingwell, Barb Dutrow, Karen Hudson-Edwards, Rod Ewing, Laurence Galoisy, Jane Gilotti, Mike Hochella, Ruben Kretzschmar, Anhuai Lu, Eric Oelkers, Herbert Palme, Carolyne Ruppel, Nita Sahai, Eva Valsami Jones, David Vaughan, Friedhelm Von Blanckenburg, Frances Wall, and Naohiro Yoshida. The current principal editors will also contribute talks.

An oral and poster session will follow this introductory session to broaden the scope of the topics presented. It will allow more people to participate in this very special event. This oral and poster session will be an occasion to discuss with the Elements editorial team your expectations concerning the magazine. We want to gather all friends of Elements at this very special event!

Georges Calas, John Valley, Trish Dove, Gordon Brown, and Pierrette Tremblay

FROM THE EDITORS

THIS ISSUE

The year 2014 started with a bang in the asteroid world: on the night of January 1, Richard Kowalski—discoverer of asteroid 2008 TC₃, the first asteroid to have been observed before entering Earth’s atmosphere (see page 31)—saw a small streak of light moving quickly against the background stars. Over the next hour or so, he imaged that streak a total of 7 times and reported the positions of the asteroid to the Minor Planet Center. This new asteroid (1–3 m across) was designated 2014 AA, the first asteroid discovered in 2014. It was a near-Earth object, and only the second asteroid to be detected before hitting the Earth (http://minorplanetcenter.net/blog).

Coincidentally, our first issue of 2014 deals with asteroids and highlights this very exciting field of space exploration. Much of the information related in this issue is mind boggling and reads almost like science fiction, but it is real frontier science. Take, for example, the Hayabusa spacecraft: it traveled 300 million kilometers to a target less than one kilometer across. It brought back the very first sample of an asteroid—estimated at 100 to several hundred micrograms. Many of these tiny particles have been scrutinized and analyzed—and with the wide range of data acquired, special issues of journals have been published and many papers written speculating on what these tiny samples tell us. You can read more about this engineering feat on the JAXA website (http://www.jaxa.jp/projects/sat/muses_c/index_e.html).
FAST MAPPING WITH µ-XRF

In the February 2013 issue of the Elements Toolkit, I reported on field-portable XRF devices, which have become available over the past decade or so. This issue’s Toolkit is devoted to a related technology, which, though laboratory based, has likewise seen impressive leaps over recent years: mapping micron-scale X-ray fluorescence (µ-XRF). Both methods work on the same principle, whereby primary X-rays interact with the sample material, generating characteristic secondary X-rays that are used to quantify the elemental composition of the material under investigation. In the case of mapping µ-XRF instruments, a finely focused primary X-ray source is employed, resulting in spatially resolved chemical information at a length scale reaching down to a few tens of micrometers. Though not competing with the scanning electron microscope (SEM) in terms of spatial resolution, µ-XRF has a number of properties that may make it decisively attractive for certain applications.

The global market for µ-XRF mapping instrumentation is currently dominated by three competing products: the M4 Tornado by Bruker, the Orbis platform by EDAX, and the XGT-7200 instrument sold by HORIBA Scientific. Living in Potsdam, it was only a short train ride for me into Berlin’s Adlershof Technology Park, where I visited Bruker’s world headquarters for µ-XRF. During my visit I received an in-depth introduction to µ-XRF mapping and, in particular, was given a detailed demonstration of the capabilities of the Bruker Tornado instrument (FIG. 1). Having arrived with little understanding of this technology, I left four hours later with a good, albeit rather basic, understanding of what has become possible thanks to technical developments in recent years—one of these capabilities is truly impressive.

Mapping µ-XRF devices require a finely focused X-ray probe to impinge on the sample surface while maintaining acceptable beam brilliance. The Tornado achieves this using a polycapillary lens (inset, FIG. 1), basically a carefully designed bundle of micron-scale tubes that transports and focuses X-rays through grazing-angle reflections within each of the many channels. This arrangement is able to provide an ~20 µm diameter spot on the sample surface. The actual spot size depends on various design parameters of the polycapillary lens and on how close the lens can be positioned relative to the sample surface; therefore, the flatness of the sample does play a role here. In principle, it is possible to investigate materials with several millimeters relief, an example of which is the investigation of printed circuit boards in order to identify the location of selected elements (FIG. 2). XRF data acquisition employs a solid-state silicon drift detector (SDD), and the Tornado can be equipped with two such detectors to both increase the overall sensitivity of the instrument and suppress any topography-induced shadowing effects. Such SDDs work in an energy-dispersive mode, meaning that concentration data starting from Na and going up to all heavier elements will be acquired simultaneously. In double-detector mode, the system can readily cope with 200,000 counts per second; such a high-data acquisition rate is a key requirement for the fast mapping of samples.

One of the first things that I learned during my visit to Bruker is that the use of mapping µ-XRF is distributed among six different application fields in roughly equal proportions:

- Forensics
- Materials science and failure analysis
- Geoscience and environmental science
- Archeology
- Art and conservation analyses
- Microelectronics and thin film monitoring

Here I would like to present two geoscience examples that I found particularly interesting and that highlight well the capabilities of mapping µ-XRF technology.

The first case study involved a museum specimen of a 50 Ma old fossilized fish (FIG. 3) from the Eocene Green River Formation. Despite the somewhat rough topography of this shale sample, the Tornado recovered detailed information about the distributions of many elements across a large area. Also important, this image demonstrates that the Tornado’s scanning stage can work with large and heavy specimens, producing data rapidly and, with reliable positioning of the scanning sample stage, at the micron scale over long time periods. The second example is a scanned thin section of a gneiss, which was imaged in only 35 minutes with a step-size defined spatial resolution of 50 µm (FIG. 4). Although this particular specimen was only 30 µm thick, it was nonetheless possible to tune the instrument to give semiquantitative results. As the data are collected using an energy-dispersive spectrometer, it is possible to rapidly add, remove, or exchange elements displayed on the resulting map; there are an infinite number of color options to choose from so as to get the optimal presentation for interpreting the results. The software also allows regions of interest to be defined, for example, one of the bright red, iron-rich grains in FIGURE 4, in order to extract truly quantitative results for a long list of elements.
So how does mapping μ-XRF stack up against other competing technologies, and in particular, against chemical mapping using scanning electron methods? The Tornado system has a typical spatial resolution of around 20 μm, though this can be somewhat improved using over-sampling strategies and flat samples free from topographic relief. This scale is significantly coarser than the micron-scale imaging provided by an SEM. Even with the use of an evacuated measurement chamber, the Tornado is limited to analyzing only Na and heavier elements, whereas some electron-based systems will reach down to lighter elements. The use of X-rays means that XRF sampling is not limited to the topmost atomic layers of the specimen, which might or might not offer an advantage for any given application. On the plus side, sample-preparation requirements for μ-XRF are minimal: there is no need to either polish or coat the sample; an approximately flat surface will usually suffice. Another plus for μ-XRF technology is that it is totally nondestructive in nature, which might be a decisive consideration for rare or valuable objects such as museum specimens. A critical advantage of the method is also its speed: perhaps 10 minutes elapse between beginning the vacuum pump-down procedure and receiving the first data for the session. Compared to electron beam sampling, XRF has an order of magnitude or greater sensitivity for heavy elements, so if one’s research focus were, for example, copper distribution in silicates, then μ-XRF might well be the better-suited mapping technology. Finally, not to be overlooked are the economic aspects. A good mapping μ-XRF instrument sells at perhaps one-quarter the price of a middle-of-the-range SEM.

What I have described here is largely based on the half day I spent at Bruker’s demonstration facility in Berlin. I cannot really say how the Tornado stacks up against the instruments offered by EDAX and HORIBA Scientific, but in view of the intense competition in the global market, I imagine that the capabilities of the various instruments must be roughly similar. At the turn of the millennium, mapping μ-XRF hardly existed. Now, with worldwide installations for such devices standing at around 700 units, access to this tool will increase at an ever quickening pace over the coming years. As software improves and hardware advances, this relatively new technology will soon open many new research options.

Before ending the Toolkit, I would like to thank Dr. Andreas Wittkopp and Dr. Roald Tagle for having taken the time to provide such a detailed demonstration of the Tornado’s capabilities and for having so much patience for the many questions I posed, which they answered in great detail.

Best regards from Potsdam,

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XRF? ...Our XGT ROCKs!

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Maria Cristina De Sanctis is a scientist working in the field of planetary surfaces and small bodies in the Solar System. She holds a degree in physics and a PhD in astronomy. She is an expert in instrumentation for planetary missions, spectral data processing, and thermal-evolution models of planetary bodies. She uses observational and theoretical approaches in her study of the thermal evolution of icy bodies and of the composition of the surfaces of the airless bodies, comets and asteroids. She has been involved in a large number of space missions. She is the scientific director of the Small Bodies Node of Europlanet. The asteroid (17899) Mariacristina is named in her honor.

Michael J. Gaffey is the Chester Fritz Distinguished Professor of Space Studies in the John D. Odégar School of Aerospace Sciences at the University of North Dakota. He received a BA and an MS in geology from the University of Iowa and a PhD in Earth and planetary sciences from MIT. He has specialized in the calibration of visible and near-infrared spectra for meteorites and in the interpretation of VNIR spectra of asteroids for determining compositions and geologic histories. He was a participating scientist on the NEAR spacecraft mission to asteroid 433 Eros and is currently a participating scientist on the DAWN spacecraft mission to asteroid 4 Vesta.

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Asteroids: New Challenges, New Targets

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Asteroids: New Challenges, New Targets

At present, we know of \textasciitilde 600,000 asteroids in the asteroid belt, and there are very likely millions more. Orbiting the Sun between Mars and Jupiter, they are thought to be the shattered remnants of small bodies formed within the young Sun’s solar nebula that never accreted enough material to become planets. These “minor bodies” are therefore keys to understanding how the Solar System formed and evolved. As leftover planetary building blocks, they are of great importance in understanding planetary compositions. They may also provide clues to the origin of life, as similar bodies may have delivered organics and water to the early Earth. For these reasons, several international space agencies have funded sample-return missions to asteroids.

Keywords: meteorites, meteors, asteroids, minor planets, sample-return missions

The Celestial Police and the Minor Planets

Over several nights in January 1801, Giuseppe Piazzi (Fig. 1), a professor of mathematics and astronomy at the University of Palermo in Sicily, tracked a faint stellar object that was moving against the background of stars. This object had an orbit that matched the orbit predicted by the Titius–Bode law of a missing planet between Mars and Jupiter. Such an object had long been chased by the “Celestial Police,” a 19th-century international association of astronomers formed to find this missing planet; several astronomers were assigned to different sections of the ecliptic (plane of the Earth’s orbit around the Sun). However, the object observed by Piazzi was not a planet—nor was it a comet, as he initially believed. Instead, the object was a minor planet—an asteroid—and was the first of its kind to be discovered. Piazzi named the asteroid Ceres Ferdinandea, after the Roman goddess of agriculture and fertility, and King Ferdinand IV of Naples and Sicily.\textsuperscript{1} Ceres, as it is now dubbed by the Minor Planet Center (www.minorplanetcenter.net; MPC, a branch of the International Astronomical Union), is a body about 950 km in diameter, making it the largest asteroid. It is thought to be differentiated (Thomas et al. 2005), consisting of a rocky core and an icy mantle.

In March 1802, just over a year after Piazzi’s discovery, Heinrich Wilhelm Olbers, a physician in Göttingen, Germany, discovered a second object, \textasciitilde 545 km in diameter, which he named Pallas. In 1807, he also discovered Vesta, a 525 km diameter differentiated body (see McSween et al. 2014 this issue). Pallas and Vesta are the only asteroids that are visible to the naked eye (Ceres is too dark, with an albedo of less than 10\%). Pallas is now hypothesized to be closely analogous to primitive carbonaceous meteorites, although it is not clear if Earth has received any material from this body or if it is even possible for Earth to intercept meteorites from Pallas. Vesta is the source of the HED meteorites (for howardites, eucrites, and diogenites), of which we have many in our collections.

It took less than a decade for Ceres, Pallas, and Vesta, “the big-3 asteroids,” to be discovered. Many new asteroid findings followed, and by the middle of the 19th century, approximately 100 asteroids had been located. Credit for this is mainly due to the use of astrophotographic techniques developed in 1891 by Maximilian Wolf (University of Heidelberg, Germany) to automate the discovery of asteroids. A total of 1000 asteroids had been found by 1921, 10,000 by 1981, and 100,000 by 2000 (source: MPC). Modern asteroid survey systems (LINEAR, CATALINA, LONEOS, SPACEWATCH, NEAT, PAN-STARRS, WISE) use automated means, so that new asteroids are being located in ever-increasing numbers. Currently, over 200 asteroids are known to be larger than 100 km in diameter (of which 26 are more than 200 km in diameter). A survey in the...
infrared wavelengths (Tedesco and Desert 2002) suggests that the cumulative number of main belt asteroids with diameters greater than 1 km is $1.2 \times 0.5 \times 10^6$. The number of asteroids increases markedly with further decrease in size, and the existence of about 25,000,000 objects with a diameter of ~100 m has been inferred from mathematical models.

Asteroids revolve around the Sun in elliptical orbits that are characterized by the three Keplerian orbital elements: the semimajor axis (one-half of the longer dimension of the ellipse), the eccentricity (degree of elongation of the ellipse), and the inclination with respect to the ecliptic plane. Most asteroids have orbits that are more eccentric and more inclined (in general, up to 30°) than those of the planets. Telescope photometric observations provide information on the rotation of asteroids. While most have a regular rotation around a fixed axis, very small asteroids with an irregular shape have complex tumbling rotations. Asteroids smaller than 150 meters in diameter usually have rotational periods shorter than 2 hours (down to a few seconds for those with a diameter around tens of meters). Asteroids above 150 meters in size generally have rotational periods ranging from 2.3 to 20 hours. Superslow rotators with periods longer than 30 days also exist. Some bodies are known to have a small companion moon or two moons. There are also cases in which two equally sized asteroids orbit each other.

Asteroids are categorized with respect to their distance from the Sun (Fig. 2). Those that have orbits that closely approach Earth are called near-Earth asteroids (NEAs; see below). Asteroids whose orbits lie between those of Mars and Jupiter, with semimajor axes between 2.1 and 3.3 astronomical units (AU; the average Earth–Sun distance) form the main belt, also called the asteroid belt. The Trojan minor bodies are farther away from the Sun, with an average semimajor axis of about 5.2 AU. They are seated on the two Lagrangian points (L4 and L5) of Jupiter’s orbit (that is, the stable points on Jupiter’s orbit where the centrifugal and gravitational forces from Jupiter and the Sun balance): the L4 Trojans (about 60° ahead of Jupiter) are called “Greeks”, and L5 Trojans (about 60° behind the planet) are more specifically termed “Trojans” (Fig. 2). The Jupiter Trojans, being more similar to trans-Neptunian objects (those beyond 30 AU) than to asteroids, are not discussed in this issue.

As illustrated in Figure 2, the main belt houses the greatest number, and largest mass, of asteroids. The total mass of the main belt is estimated to be between $2.8 \times 10^{21}$ and $3.2 \times 10^{21}$ kilograms, which is approximately 4 percent of the mass of the Earth’s Moon or less than $1/1000$th of the mass of the Earth. The four largest objects, 1 Ceres, 4 Vesta, 2 Pallas, and 10 Hygiea, make up half the mass of the main belt, with about 30% accounted for by Ceres, 9% by Vesta, 7% by Pallas, and 3% by Hygiea (Fig. 3). For comparison, the total mass of the Trojans is estimated to be one-fifth the mass of the whole asteroid belt, and the total mass of the NEAs is negligible with respect to that of the main belt. Although the main belt contains a vast number of asteroids, the asteroids themselves are spread over an enormous volume of space. As a consequence, and contrary to popular conception, the asteroid belt is relatively empty. Thus, the idea of a spacecraft constantly dodging asteroids belongs only in science fiction movies and video games. In fact, there are too few pebble-sized asteroids distributed at this scale to pose a serious threat to a space mission (Dawn mission, http://dawn.jpl.nasa.gov/mission/journal_11_27_09.asp).

**Naming Asteroids**

The process of naming asteroids is complex. Since the convention was put in place in 1925, an asteroid is given a “provisional designation” before its official “formal designation” is determined. These designations are overseen by the Minor Planet Center, a branch of the International Astronomical Union. Provisional designations are a combination of numbers and letters that designate when during a particular year the asteroid was found. The first four numbers are the year it was discovered, and the following letters (and possibly numbers) indicate when during the year it was found. Formal names of asteroids are given once the official orbit is confirmed. This name consists of a number (giving the order in which it was discovered) and a name (which could be its discoverer, but is often the same as its provisional designation). Example: 101955 Bennu [previously known as (101955) 1999 RQ36]
CELESTIAL MECHANICS

In his seminal work on celestial mechanics, Pierre-Simon Laplace showed that orbital resonances occur when two bodies have orbital periods that are a simple integer ratio of each other. Such resonances may lead to the destabilization of one of the orbits, particularly for small bodies. Within the main belt, objects that have orbital periods in resonance with the orbital period of Jupiter are gradually ejected into different, random orbits with a larger or smaller semimajor axis. For example, at the 4:1 (2.06 AU), 3:1 (2.5 AU), 5:2 (2.82 AU), 7:3 (2.95 AU), and 2:1 (3.27 AU) mean-motion resonances with Jupiter, known as Kirkwood gaps, gravitational perturbations caused by the planet have led to the removal of asteroids from these regions (corresponding to empty zones in FIGURE 4). Another important resonance is the “ν6 secular resonance” between asteroids and Saturn, which is linked to the precession of the perihelion (closest point to the Sun) of the orbit of an asteroid and that of Saturn. This resonance forms the inner boundary of the asteroid belt at around 2.15 AU, with inclinations of about 20° (FIG. 5), and is responsible for delivering asteroids into planet-crossing orbits (see below). Asteroids approaching the ν6 secular resonance have their eccentricity slowly increased until they become Mars-crossers (FIG. 5), at which point they are usually ejected from the asteroid belt due to a close encounter with the gravitational field of Mars. If the “Mars-crossers” fail to interact with Mars, their orbital semimajor axis is gradually reduced and they become NEAs.

Asteroids that are nudged by the gravitational attraction of nearby planets or have significant inclination and eccentricity may collide with other bodies traveling along different orbits. Even if the impact probability is low, collisions between asteroids are not rare on astronomical timescales. Depending on the relative impact velocity between the bodies and on their sizes, collisions result in (1) the fragmentation of a parent asteroid into several large pieces and/or (2) the formation of fine, micron-sized asteroidal dust, which is partly responsible for the zodiacal light we see before sunrises and after sunsets. A collision between large asteroids brings into play both fragmentation and gravitation (see Michel 2014 this issue). The asteroids are partially to totally shattered, and subsequent gravitational attraction between fragments leads to reaccumulation, which finally forms an entire family of large and small objects (see below). Accordingly, most of the smaller asteroids are thought to be piles of rubble held together loosely by gravity (Michel and Richardson 2013; see also Tsuchiyama 2014 this issue). The largest asteroids (those larger than ~100 km), however, are probably primordial objects that were never disrupted (Asphaug 2009).

After almost two centuries of observations, ~600,000 asteroids have been discovered. Sustained accumulation of ground-based spectroscopic data and space mission thermal infrared data have allowed for the physical composition of the main belt to be constrained (Masiero et al. 2011). The composition of an asteroid can be inferred from several parameters: (1) the albedo, or the reflective power of a surface (defined as the ratio of radiation reflected from
the surface to incident radiation upon it, expressed as a percentage; the albedo varies between 0% for a totally absorbing surface and 100% for a perfect mirror); (2) the spectrum of the sunlight reflected by the asteroid surface; and (3) the bulk density of the asteroid. From these observations, we now know that the main belt consists of objects with a great diversity of compositions, with surface reflectances of small bodies revealing carbon-rich, silicate-rich, metal-rich, or basaltic compositions, and in some cases more complex features. Despite such diversity (e.g. Tholen and Barucci 1989), three categories of asteroids dominate the main belt. C-type or carbonaceous asteroids, with a generally low albedo (~5%), represent 75% of the known asteroids; S-type or silicate asteroids, which are relatively bright and have an intermediate albedo, account for 20% of the known asteroids; and M-type, metallic asteroids, as well as other bright objects, account for the rest. Bordering on S-type, V-type asteroids or vestoids have spectra similar to that of 4 Vesta (see McSween et al. 2014). Approximately 6% of main belt asteroids are vestoids. The observed distribution in the main belt suggests that the inner part of the belt is formed preferentially by the highly common S-type asteroids, which orbit nearer to Mars than the 3:1 Kirkwood gap (2.5 AU), while the outer part of the belt is formed by those asteroids orbiting close to Jupiter’s orbit and is dominated by C-type asteroids; M-type asteroids are scattered throughout the central part of the belt (see Cloutis et al. 2014 this issue). Even if the Nice model (Tsiganis et al. 2005; Morbidelli et al. 2005) and the more recent Grand Tack model (Walsh et al. 2011)—that is, models in which the migration of gas-giant planets early in the history of the Solar System scattered the asteroids inward and outward in the Solar System—may explain part of this distribution, the full explanations for such a peculiar distribution of asteroids in the main belt and the small size of the mass in the main belt still remain to be determined. The scarcity of olivine-dominated, metal-free mantle materials in our asteroid observations (Burbine et al. 1996) is also not well understood, particularly if one assumes that complete or near-complete differentiation of pristine chondritic material results in an object with an Fe–Ni core and an olivine-dominated mantle.

In the main belt, several groups of asteroids of different size share similar orbital elements, such as semimajor axis, eccentricity, and orbital inclination. In addition, each group of asteroids is recognized as having similar spectral features within the group. Thus, such asteroids are considered to belong to the same asteroid family. Examples are illustrated in Figure 4. Asteroid families are thought to be the result of the disruption of a single parent body. Following a breakup event, fragments are launched into orbits that are distinct from, but similar to, the orbit of the original parent body. Smaller fragments are typically launched with higher velocity, creating a size-dependent spread in orbital elements that allows for the identification of asteroid families within the belt (see, for instance, Walsh et al. 2013). Several tens of families have already been recognized. Flora, Themis, Eos, Nysa-Eulalia-New Polana, Eunomia, Koronis, and Vesta are some of the most prominent, with each consisting of more than 100 known small bodies (Fig. 4). The boundaries of the families are
somewhat vague because, at the edges, they blend into the background density of asteroids in the main belt (Fig. 4). While the largest families (Eos, Koronis, and Themis) seem to be compositionally homogeneous, interlopers from the background population are frequent in most of the asteroid families. In other cases, observed heterogeneity within families (e.g. the Vestan asteroids) may result from the fragmentation of a differentiated parent asteroid, which may be stripped of its crust, mantle, or iron core (see McSween et al. 2014).

HOW DID METEORITES FROM ASTEROIDS REACH EARTH?

Asteroids are currently thought to be quite mobile during their several-hundred-million-year lifetime inside the main belt (Bottke et al. 2006). Due to asteroid collisions and the Yarkovsky effects (thermal forces changing an asteroid’s semimajor axis over time), main belt asteroids migrate and may end up crossing one of the aforementioned orbital resonances, eventually becoming a planet-crosser, that is, an asteroid whose orbit crosses the orbits of Mars, Earth, Venus, and Mercury (Fig. 5). A main belt asteroid becomes a near-Earth asteroid when its orbit brings it within 1.3 AU of the Sun or within 0.3 AU of the Earth’s orbit. NEAs are grouped into three categories: Atens, representing 8% of the total number of NEAs, with orbital semimajor axes less than 1 AU; Apollos (54% of NEAs), which are Earth-crossing asteroids with orbital semimajor axes greater than that of the Earth (>1 AU), and Amors (37% of NEAs), which have orbital semimajor axes greater than 1 AU. Amors approach the orbit of the Earth but do not cross it; however, most Amors are Mars-crossing asteroids. Collectively, NEAs do not have stable orbits because they evolve rapidly in the Keplerian orbital space due to close encounters with terrestrial planets and resonance with the giant planets. For these reasons, NEAs have short lifetimes, on average only about 10 My (Gladman et al. 2000). NEAs become potentially hazardous asteroids (PHAs) when their orbits are within 0.05 AU (7.5 million kilometers) of the Earth's orbit (known as the Earth minimum orbit intersection distance, or MOID) and when their diameters exceed 100–150 m. Once this happens, there is a greater possibility of colliding with Earth and impacting the surface.

By definition, a meteor is an asteroid that enters the Earth’s atmosphere. Due to their high entry velocity (several kilometers per second), meteors are heated to high temperatures as they are slowed by the atmosphere. This produces a visible path, and the meteor is then known as a fireball or shooting star. If the meteor survives its plunge through the atmosphere and lands on the surface, it is classified as a meteorite. The difference between an asteroid, a meteor, and a meteorite was nicely exemplified on February 15, 2013, when the asteroid NEA 2012 DA14 (45 m diameter) passed within 27,700 km of Earth. On the same day, an unrelated superbolide meteor (NEA Apollo group; D ≈ 15 m) entered the Earth’s atmosphere and descended over the Ural Mountains in Russia. It exploded at altitude in a massive blast captured on cameras, and it produced meteorite fragments that fell in and around the city of Chelyabinsk (Fig. 6). Interestingly, as asteroid NEA 2012 DA14 passed by Earth, its orbital period decreased, moving the asteroid from the Apollo group into the Aten group of near-Earth asteroids (Fig. 5). Thus, this asteroid serves as an example of how the orbital elements of an asteroid might change during its lifetime. As of February 2014, 10576 near-Earth objects (NEOs) have been discovered: 97 are near-Earth comets and 10480 are near-Earth asteroids. Approximately 1450 NEOs are classified as potentially hazardous (source: MPC; see also NASA's NEOWISE).

From these orbital and dynamical arguments, it is believed that most meteorites do indeed come from the asteroid belt and are therefore samples of asteroidal materials (Gounelle 2011). However, several factors bias the population of meteorites arriving on Earth and therefore limit our sampling of the asteroid belt. For instance, dynamical models (Bottke et al. 2000) have shown that the predominant source of NEAs is a narrow zone of the asteroid belt bound by the v6 secular resonance at around 2.15 AU and the 3:1 Kirkwood gap resonance at 2.5 AU (Fig. 5). Therefore, it is quite likely that most meteorites on Earth are samples of the less primitive material of the inner main belt, and are not samples of the outer part of the belt, which is richer in low-albedo, carbonaceous asteroids. The cohesive strength of an asteroid/meteoroid is another important selection factor, which is related to the survivability of impacts in the main belt or collisions in the near-Earth region. The cohesive strength of asteroidal material also makes a great difference when considering its putative delivery to Earth, as evidenced by the frequent preservation of durable iron meteorites but the rare occurrence of fragile carbonaceous chondrites, which are more likely to be reduced to dust (see Elements' Cosmochemistry issue, February 2011).

**Figure 6** On 15 February 2013, an Apollo-group near-Earth asteroid entered the Earth’s atmosphere and became the Chelyabinsk meteor (upper panel), which was captured on cameras over the southern Ural region (Russia). The impact sites of some of the fragments of the Chelyabinsk meteorite have been found near Chebarkul Lake (bottom-left panel; credit to http://en.sia.ru/images/18103/10/181031043.jpg). Meteorite samples were recovered around Chelyabinsk by a Russian scientific group from the Vernadsky Institute of the Russian Academy of Sciences, including Marina A. Ivanova (bottom-right panel), Cyril A. Lorenz, Dmitriy D. Badyukov, Svetlana I. Demidova, Konstantin M. Ryazantsev, and Dmitriy A. Sadilenko.
Although meteorites most likely sample asteroidal materials, linking meteorites to their parent asteroid is a complicated issue. Owing to the lunar missions and more recently to NASA’s Dawn mission to 4 Vesta (see McSween et al. 2014) and JAXA’s Hayabusa mission to the near-Earth asteroid 25143 Itokawa (see Tsuchiyama 2014), we now know that the spectral characteristics of the regolith (Binzel et al. 2004) (the surface material of an asteroid) can be strongly altered by its long-term exposure to space weathering—impacts, solar wind ion implantation, sputtering, and micrometeorite bombardment—changing the surface of asteroids (for example, by mineral amorphization and precipitation of iron metal nanophases; see also Tsuchiyama 2014) so that they appear different from meteorites (Clark et al. 2002; Cloutis et al. 2014). Therefore, it is important to recognize that preferential sampling of Earth-bound materials and space weathering processes introduce biases of unknown magnitude when attempting to link asteroids and meteorites. Ultimately, this limits the usefulness of the meteorite collection, both as a true representation of the asteroid belt (see Goodrich et al. 2014 this issue) and as a proxy for understanding the early history of our Solar System.

**WHY SHOULD WE GO THERE?**

“Greed, fear, and love of knowledge send us to the asteroids,” said Martin Elvis, a senior astrophysicist from the Harvard-Smithsonian Center for Astrophysics (the Smithsonian’s Stars Lecture Series, December 2011), and he is likely right. Most people fear asteroids as a threat to life on Earth (Bottke et al. 2007; McSween 2012). Scientists’ love of knowledge drives them to check out the material our planet grew from, including the oceans; find clues to the origin of life; and, maybe, find exotic materials we cannot make on Earth. And a few visionaries have long argued that the mineral wealth in asteroids is huge. According to John S. Lewis, author of the space-mining book *Mining the Sky*, an asteroid with a diameter of one kilometer would have a mass of about two billion tons and would contain 30 million tons of nickel, 1.5 million tons of metal cobalt, and 7500 tons of platinum. The platinum alone would have a value of more than $150 billion! By 2020, only 19 asteroids will have been visited by spacecraft, while there are millions out there. The time has now come when advanced space engineering and new astronomical knowledge can be combined to make exploring the asteroids possible. Among the missions scheduled to visit asteroids in the near future (described below; Fig. 7), three are targeted to return samples from some of the most primitive carbon- and organic-rich asteroids.

**MISSIONS TO ASTEROIDS**

**Dawn** ([http://dawn.jpl.nasa.gov](http://dawn.jpl.nasa.gov))

During its nearly decade-long voyage, the NASA Dawn mission will study remotely the asteroids 4 Vesta and 1 Ceres, celestial bodies believed to have accreted early in the history of the Solar System. The asteroid Vesta and the recently categorized dwarf planet Ceres have been selected because, while both speak to conditions and processes early in the formation of the Solar System, they developed into two different kinds of bodies. 4 Vesta is a dry, differentiated object with a surface that shows signs of resurfacing. It resembles the rocky bodies of the inner Solar System, including Earth. 1 Ceres, by contrast, has a primitive surface containing water-bearing minerals and may possess a weak atmosphere. It appears to have many similarities to the large icy moons of the outer Solar System. Launched September 27, 2007, Dawn visited 4 Vesta from July 2011 to July 2012 (see McSween 2014) and is now en route to 1 Ceres, with arrival scheduled for February 2015. To carry out its flyby scientific mission, the Dawn spacecraft will carry three science instruments whose data will be used in combination to characterize these bodies. These instruments are a visible-light camera, a visible-light and infrared mapping spectrometer, and a gamma ray and neutron spectrometer. Radiometric and optical navigation will provide data relating to the gravity field and thus to the bulk properties and internal structure of the two bodies.

**OSIRIS-REx** ([http://osiris-rex.lpl.arizona.edu](http://osiris-rex.lpl.arizona.edu))

NASA’s New Frontiers 3 mission will return a sample from the spectral class B Apollo asteroid 101955 Bennu [previously known as (101955) 1999 RO36] in 2023. This potentially hazardous Earth-crossing object is hypothesized to be a carbonaceous asteroid similar to CI or CM carbonaceous chondrites (Campins et al. 2010). The OSIRIS-REx acronym describes the mission objectives: origins, spectral interpretation, resource identification, security, regolith explorer. Central to the mission is the return of 260 g of pristine asteroid regolith for examination by the cosmochemistry and astrobiology communities. By determining the geological provenance of the sample, we (and future generations) will be able to constrain Solar System history in a manner that cannot be fully accomplished with meteorites. The data obtained, including those from the analysis of organics, will be used to test hypotheses on the preaccretion origins of planet-forming materials, the origin of prebiotic compounds, the geological activity that occurred after small-body accretion, and the dynamics of an asteroid that evolves from the main belt to Earth-crossing. Furthermore, the spacecraft instrument suite will permit ground-truthing of orbital and Earth-based telescopic observations. The mission will also constrain the Yarkovsky effect on this asteroid in order to better predict its future orbit and potentially hazardous nature.

**Hayabusa-2** ([http://b612.jspec.jaxa.jp/hayabusa2/e/index_e.html](http://b612.jspec.jaxa.jp/hayabusa2/e/index_e.html))

Following Hayabusa’s successful return of the first asteroid samples to Earth, JAXA is planning another asteroid mission, Hayabusa-2 (2014–2020), which will return samples from the near-Earth carbonaceous-type asteroid (162173) 1999 JU3. Hayabusa-2 has the following scientific objectives: (1) to determine the thermal evolution from planetesimal to near-Earth asteroid, (2) to understand the destruction and accumulation of a rubble-pile body; (3) to identify the diversification of organics through interactions with minerals and water, and (4) to study material evolution in the early Solar System. The basic design of the spacecraft is the same as Hayabusa, but new technologies will...
This proposed sample-return mission will be to a primitive near-Earth asteroid. It was selected in the framework of the European Space Agency’s Cosmic Vision (CV) program as an M3-class mission candidate (for launch in 2022–2024). The final selection will be made in February 2014. The mission will greatly contribute to answering the fundamental CV questions: how does the Solar System work and what are the conditions for life and planetary formation? The target is the primitive potentially hazardous asteroid (314843) 2008 EV5, which offers unique scientific value. The asteroid’s reflectance spectrum hints at an absorption band at 0.48 μm (Reddy et al. 2012), typical of aqueous alteration (Cloutis et al. 2011), implying that the asteroid is a particularly primitive object whose parent body may have accreted in a volatile-rich region of space. Both the spectral behavior of 2008 EV5 and its albedo of about 10–12% are interestingly higher than the albedo of the targets of the OSIRIS-REx and Hayabusa-2 missions, suggest that MarcoPolo-R will sample a more primitive body. MarcoPolo-R will provide a unique opportunity to enhance our knowledge of the nature of a distinct population of primitive bodies. MarcoPolo-R will ensure that European laboratories involved in sample analysis are positioned at the forefront in this new era of sample-return missions. Moreover, the short mission duration (4.5 years) of MarcoPolo-R will bring the time of the sample analysis closer to the expected return times of the JAXA and NASA sample-return missions, allowing Europe to contribute in a timely manner to the international sample-return activities.

ACKNOWLEDGMENTS

M. Delbo, E. Bullock, and T. McCoy are thanked for exciting conversations and for critically reading the manuscript. GL is indebted to the INSU-CNRS since he conducted part of his work as a CNRS delegate. GL was supported in this work by the CNES and by the ANR Shocks 2011 Blanc SIMI 5-6 008-01 grants, specifically to the Henderson Endowment to the Division of Meteorites. This article benefited from insightful reviews by Hap McSween, Travis Tenner, and John Valley. This issue also benefited from the expertise imparted by individual article reviewers Jean-Alix Barrat, Bill Bottke, Tom Burbine, Monica Grady, Vicky Hamilton, Tim McCoy, Ed Scott, Caroline Smith, Jessica Sunshine, and Mike Zolensky. We thank them for their time and assistance. Finally, we would like to express our sincere gratitude to Pierrette Tremblay and John Valley (without whom this issue would not exist) for their time, expertise and patience.

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Spatially-Resolved Mineralogy of Extra-Terrestrial Rocks

FEI’s Automated Mineralogy technology is enabling petrologists to reveal the textures of aqueous alteration phases in CM chondrites.

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Meteorite Murchison 640
Sample and image courtesy of Adrian J. Brearley, University of New Mexico. QEMSCAN® image created by Pieter WSK Botha.
Asteroids are the leftover precursors to the terrestrial planets. Before the first images of them were sent from space, our knowledge of asteroids relied entirely on ground-based observations and meteorite analysis. Spacecraft images revolutionized our knowledge and geological understanding of their physical properties. They also showed us that asteroids are subjected to various kinds of processes and are incredibly diverse in size, shape, structure, composition, and rotational properties. Therefore, space missions remain necessary to enhance our knowledge of the various components of the asteroid population. In addition, numerical modeling is required to interpret spacecraft images and improve our understanding of the physical processes asteroids experience over their lifetime.

Keywords: asteroid, impact, regolith, internal structure

INTRODUCTION

About 4.56 billion years ago, the early Solar System consisted of a rotating disk of gas and dust, called the protoplanetary disk, revolving around the Sun. Planets formed from this disk, and different populations of small bodies, in particular the main belt asteroids between the orbits of Mars and Jupiter, survived as remnants of this era. The process by which dust grew into the first multikilometer-size planetesimals is not entirely understood. However, while the exact mechanism of planetesimal formation and the origin of the primordial asteroid size distribution is still a matter of debate (see, for example, Morbidelli et al. 2009; Weidenschilling 2011), it is clear that planetesimals did form in the inner Solar System. This likely occurred within the first ~5 My of Solar System history.

Once planetesimals grew large enough to gravitationally perturb one another, collisions between bodies on crossing orbits led to the growth of larger planetary embryos and eventually to the formation of planets. According to current models, the asteroid belt that remained at the end of these processes was probably very different from the current main belt; it perhaps contained an Earth mass or more of material in planetary embryos with masses similar to that of the Moon or Mars, as well as tens, hundreds, or thousands of times more bodies like the asteroid 4 Vesta and the dwarf planet 1 Ceres than are present in the main belt today. In addition, the orbits of the planetesimals had relatively low orbital eccentricities and inclinations compared to current values for the asteroid belt. It is during the next stage of evolution that the asteroid belt began to develop to its current state.

This primary architecture of the Solar System shaped a thermal and chemical gradient: solids in the inner part of the disk formed at a temperature high enough to prevent condensation and accretion of volatile species, whereas in the outer region, distant from the proto-Sun, ices and giant gaseous planets formed. In fact, the main belt population represents both a compositional and a temperature gradient that may record this primary architecture, with higher-temperature refractory materials condensing out and forming S-type asteroids in the inner part of the belt and lower-temperature carbonaceous materials and water ice condensing in the outer part, forming C-type asteroids (see later discussion of spectral types). However, recent studies suggest that the lower-temperature carbonaceous material present in the main belt formed in very different locations and then was scattered into the asteroid belt. Evidence of such scattering and radial mixing of bodies comes from both direct measurements and dynamical models (see, for example, Walsh et al. 2011).

High-temperature minerals that formed in the hottest regions of the solar nebula were identified in the samples returned by the Stardust mission (NASA) from the comet 81P/Wild 2, a periodic comet captured only recently from the outer Solar System into its current orbit. This finding resulted in a complete revision of our understanding of early-stage processes in the solar nebula and provided dramatic evidence for extensive radial excursions early on in the solar nebula (e.g. Brownlee et al. 2006). Then, the discovery of planetary systems beyond our own clearly demonstrated that radial excursions also occur at planetary scales; in these systems, giant, gaseous planets are detected very close to their central star, which requires that they moved from their more distant formation regions. Such observations led to increasingly sophisticated numerical modeling, with some models requiring an extraordinary revision of the early history of the Solar System. This is the case of the Grand Tack model, which involves the inward migration of Jupiter and Saturn and their penetration deep into the inner Solar System (down to 1.5 AU for Jupiter) before migrating outwards to their current locations (Walsh et al. 2011). According to this model, the primordial asteroid belt was mostly emptied by the inward migration of Jupiter. On its outward migration, Jupiter scattered some of that material back into the asteroid belt region (predominantly into the inner part of the belt), and, along with Saturn,
the other giant planet, it scattered material formed farther out in the Solar System (beyond ~4–5 AU) into the outer part of the asteroid belt. As a consequence, the inner belt is dominated by material formed in the ~1–3 AU region and the outer belt by material formed beyond ~4–5 AU (Walsh et al. 2011), which would explain the observed distribution of spectral types in the main belt.

Although the asteroid belt lost most of its mass during this phase, another bombardment, called the Late Heavy Bombardment (LHB), proposed as the source of the large lunar basins, occurred several hundred million years later. According to the Nice Model, the LHB was caused by a sudden change in the orbits of the giant planets as a result of the gravitational perturbations by an outer disk of planetesimals. While the giant planets were reaching their final orbits, a large amount of material formed beyond the giant planets was injected into the inner Solar System and another fraction of the asteroid belt was dynamically depleted, causing large impacts. The lunar basins provide evidence of these impacts. Several mechanisms have been proposed to deplete the mass of the primordial asteroid belt (possibly in two successive phases) and to cause the dynamical excitation and radial mixing observed today. However, these mechanisms have different implications for the original birth location of asteroids of different types (see for example, O’Brien et al. 2007 and Walsh et al. 2011 for the first depletion phase, and Levison et al. 2011 and references therein for the second depletion phase).

Since this epoch and throughout its history, the asteroid belt has been shaped by collisional processes, such as cratering, disruption, and the generation of new asteroids as collisional fragments. The size-frequency distribution of the main belt is classically fitted with power laws, but it has a wavy shape (i.e. it is not a straight line in a log-log plot; Fig. 1), which is characteristic of a population that has evolved through collisions (see, for example, O’Brien and Greenberg 2003). The specific wavy shape of the size distribution results from the dependence of the strength of a body on its size and the transition between different strength regimes. Asteroids smaller than a few hundred meters are held together mainly by material strength and are expected to become weaker with increasing size due in part to the distribution of flaws within them; larger bodies are affected more by gravitational forces and become stronger with increasing size (e.g. Holsapple et al. 2002).

As a reference, the number of asteroids larger than 1 km is estimated at about one million in the main belt (Fig. 1). Bottke et al. (2005) found that the current asteroid size distribution arose fairly early in the history of the asteroid belt. Once the belt was dynamically depleted and reached roughly its current mass, there was little further evolution of the size distribution, and hence Bottke et al. (2005) referred to it as a “fossil” size distribution. In its current state, collisions still occur in the asteroid belt, albeit at a reduced rate. The most obvious evidence for this is the formation of asteroid families, which are groups of asteroids whose members share similar orbital and taxonomic properties, suggesting that each of these families was formed by the disruption of a large parent body.

The collisional lifetime of bodies larger than a few tens to hundreds of kilometers in diameter is longer than the age of the Solar System, suggesting that most are likely to be primordial, while smaller bodies are probably collisional fragments. The exact size above which a body is more likely to be primordial is somewhat model dependent. Binzel et al. (1989), from the study of light curves, suggested that this transition occurs at a diameter of ~125 km. However, as this is a statistical measure, some smaller asteroids may still be primordial and some larger ones may have broken up in the past. Roughly 20 asteroid families have formed from the breakup of parent bodies larger than ~100 km in diameter (e.g. Bottke et al. 2005) over the last 4 billion years or so. In contrast, however, several hundred bodies currently exist in the 100 km size range, and most of these are likely to be primordial.

Despite our current understanding of how planets and small bodies formed and of how the asteroid belt evolved, we do not know much about the physical properties of asteroids. Such knowledge is fundamental for testing the validity of these scenarios and to extrapolate them to the future. Indeed, asteroids are subjected to various kinds of stresses (e.g. impacts, shaking) during their history. Their responses to these stresses depend on their physical properties. In turn, the processes that asteroids undergo during their history modify those properties. In order to achieve a more accurate picture of these bodies and their evolution, we need more information on their physical properties and we have to understand (1) how these properties influence the way they respond to different processes and (2) how these processes affect the properties.

**PHYSICAL PROPERTIES OF ASTEROIDS**

**Knowledge from Ground-Based Observations**

Asteroids are faint in the sky because they are small and only reflect sunlight from their surface. Therefore, knowledge of their physical properties from ground-based observations remains very limited.

One kind of information that can be obtained using optical telescopes is the visual magnitude of the asteroid. This is then converted into the absolute magnitude (the visual magnitude that it would have if it were at 1 AU from both the Sun and the observer), which gives a rough indication of the asteroid’s size. Optical telescopes also provide light-curve measurements; collected over sufficient time, these allow the determination of the rotational period and possibly the pole orientation, and also permit a rough estimate of the object’s shape.

![Cumulative size distribution of main belt asteroids](image-url)
Rotational periods have been determined for more than 1500 asteroids. Asteroid spin periods have a wide range, from several days to less than a minute for some small near-Earth asteroids (e.g. Pravec and Harris 2000). Spin periods are possibly related to the strength properties of the object. For bodies less than about 10 km in diameter, even a small amount of strength allows much more rapid spins than purely gravitational binding. This is the case of the so-called fast rotators. Analytical estimates suggest that even small amounts of strength or cohesion in a gravitational aggregate can render rapidly spinning small bodies stable against disruption. This interpretation implies that such bodies do not necessarily need to be fully cohesive or monolithic to survive with a fast rotation, but they cannot be pure cohesionless rubble piles either (Holsapple 2007).

On the other hand, the spin rates of all bodies larger than about 10 km in diameter are limited to periods greater than about 2 h. This observation has been interpreted as evidence for a rubble pile (or gravitational aggregate) structure. This interpretation is actually flawed because the tensile strength of a monolithic body decreases with its size, and therefore in this size range (greater than several kilometers) the strength is so small that it does not permit higher spin rates than would be allowed for pure gravitational aggregates. Therefore these bodies may well be rubble piles, but their observed spin limits do not require it (see Holsapple 2007).

The spectral properties of an asteroid provide information about its composition. Visible-light to near-infrared spectroscopy has been used to place asteroids into multiple taxonomic classes based on the characteristics of their spectroscopic signature at different wavelengths (e.g. DeMeo et al. 2009). Asteroids of taxonomic type S (with a visual albedo \( p_v \approx 0.15 \) on average) are preferentially situated in the inner main belt. They are several times brighter than C-type asteroids (with a visual albedo \( p_v \approx 0.05 \) on average), which are mainly located in the outer main belt, and have distinct silicate absorption bands. S-type asteroids are probably made of similar materials to those of the most common meteorites, the ordinary chondrites, which are moderately evolved but unmelted chondritic rocks. In fact, the analysis of particles from the S-type asteroid Itokawa, successfully returned by the Japanese Hayabusa mission in 2010, shows that the particles came from materials like those in thermally metamorphosed LL-group ordinary chondrites and that the spectrum of Itokawa has been reddened by space weathering as a result of the exposure of its surface to micrometeorites and solar wind. The complete taxonomy of asteroids is obviously more complex and includes numerous subgroupings, such as the B, C, P, and D types, all of which correspond to dark, reddish asteroids. These asteroids are presumably made of the same materials as the most primitive meteorites, the carbonaceous chondrites, which include complex organic molecules, silicate minerals, and reduced iron and other metals. About 60% of the C-class asteroids, at heliocentric distances between 2.5 and 3.5 AU, are thought to have undergone some kind of aqueous alteration process (Barucci et al. 1998). D-type asteroids are particularly red at long-infrared wavelengths, may be rich in organic compounds, and have no clear relation with any kind of meteorite, with the possible exception of the Tagish Lake meteorite. A distinct class called M was originally thought to correspond to metallic fragments originating from differentiated planetary cores. However, mid-infrared spectroscopy (Rivkin et al. 2000) showed that the mineralogy of some M-type asteroids likely corresponds to hydrated silicate and not metal. So, our understanding of composition based solely on spectral observations remains limited and uncertain. The information provided by spectral observations tells us only about the first few micrometers of the surface and does not necessarily allow us to determine a possible overall heterogeneity.

Mid- to thermal-infrared observations, along with polarimetry measurements, are probably the only data that give some indication of actual physical properties. Measuring the heat flux of an asteroid at a single wavelength gives an estimate of the dimensions of the object; these measurements have lower uncertainty than measurements of the reflected sunlight in the visible-light spectral region. If the two measurements can be combined, both the effective diameter and the geometric albedo—the latter being a measure of the brightness at zero phase angle, that is, when illumination comes from directly behind the observer—can be derived. In addition, thermal measurements at two or more wavelengths, plus the brightness in the visible-light region, give information on the thermal properties. The thermal inertia, which is a measure of how fast a material heats up or cools off, of most observed asteroids is lower than the bare-rock reference value but greater than that of the lunar regolith; this observation indicates the presence of an insulating layer of granular material on their surface (Harris 2005). Moreover, there seems to be a trend, perhaps related to the gravitational environment, that smaller objects (with lower gravity) have a small regolith layer consisting of coarse grains, while larger objects have a thicker regolith layer consisting of fine grains. However, the detailed properties of this regolith layer are poorly known from remote observations. Moreover, the relation between thermal inertia and surface roughness is not straightforward, so one needs to interpret the thermal inertia with caution.

Finally, when an object comes close enough to Earth that detailed radar observations can be performed, a radar shape model can be produced. This allows one to probe some of the details of the body’s surface properties, such as the potential presence of craters or large boulders (Fig. 2). The Arecibo Observatory in Puerto Rico, with a 305 m diameter dish, and the 70 m steerable dish at the Goldstone Observatory in California have been used with great success to obtain detailed images and dynamical information about near-Earth objects, as well as to characterize main belt asteroids (see, for example, Ostro et al. 2002). In addition, the great accuracy of the astrometry provided by radar observations allows for highly refined determinations of the orbital and rotational dynamics of an asteroid, which is crucial for assessing its risk as a threatening object.
Knowledge from Space-Based Observations

Surface Properties

Ground-based observational programs, such as the Catalina Sky Survey (www.lpl.arizona.edu/css, University of Arizona), have been responsible for the discovery of the greatest number of asteroids, and they complement space-based programs. However, in principle, space-based observatories should detect a greater number of objects because a larger portion of sky is seen from space and because the atmosphere is absent. For example, the WISE space observatory took millions of infrared images. NEOWISE, the asteroid-hunting portion of the WISE survey, observed more than one hundred thousand asteroids in the main belt, in addition to at least 585 near-Earth objects (Mainzer et al. 2012). The Spitzer telescope has also observed more than 700 near-Earth asteroids (NEAs) (Trilling et al. 2010). From these observations, it was possible to estimate the sizes of most of these asteroids. However, such observations cannot tell us very much about the properties of the asteroids’ surfaces, such as the size distribution of the grains that compose the regolith, as well as the regolith’s depth, angle of repose, cohesion, and porosity. This information, as well as the detailed surface morphology/topography and distributions of craters and boulders on an asteroid’s surface, can only be obtained by in situ investigations or sample-return space missions.

So far, only three space missions have been devoted to investigating asteroids from orbit, namely, the NEAR-Shoemaker mission (NASA), which orbited the 34.4 x 11.2 x 11.2 km size near-Earth asteroid 433 Eros (Fig. 2) for one year in 2000–2001; the Hayabusa mission (JAXA), which visited the 535 x 294 x 209 m NEA 25173 Itokawa (Fig. 2) for 3 months and successfully brought a sample back to Earth; and the Dawn mission (NASA), which investigated 4 Vesta, the second-largest asteroid at 530 km diameter, during one year in 2011–2012 (see McSween et al. 2014 this issue). Several other missions have performed asteroid flybys (e.g. the NASA Galileo and the ESA Rosetta missions), which are not discussed here due to space limitation, but they have contributed greatly to our current understanding of asteroids.

While Eros and Itokawa belong to the same S taxonomic class, their spacecraft-imaged surfaces show two drastically different worlds (Fig. 3). Eros’s surface consists of a layer of regolith composed of very fine dust, with an estimated depth between 10 and 100 meters. Itokawa’s surface contains both smooth and very rough areas and is covered by a layer of regolith whose average depth is estimated to be a few tens of centimeters. This layer is composed of unconsolidated gravels, which are typically piled on each other without being buried by fines (Miyamoto et al. 2007). The finest observed particles are centimeter-sized pebbles and are concentrated on smooth terrains.

If gravity is the discriminator, then Itokawa would be expected to be as different from Eros, geologically, as Eros is from the Moon (Asphaug 2009). This may explain their different geological properties despite their similar spectral type. On the other hand, both objects share an apparent lack of small craters compared with the number expected from their impactor flux histories. This lack of craters is interpreted as possible evidence of seismic shaking during small impacts, which can cause the regolith to move and erode small features (Miyamoto et al. 2007; Michel et al. 2009). A low-gravity environment can thus make small objects more sensitive to small events.

So far, we do not have this level of detail for the surface of any dark, carbonaceous asteroid. These asteroids are believed to be the most primitive ones, and they dominate the population of the main belt (most of them reside in its outer part). The only images of a C-type object that we have are those of the 53 km diameter main belt asteroid 253 Mathilde, obtained during the NEAR mission flyby in 1997. They show five craters larger than 20 km, undisturbed by each other, which suggests that low-density asteroids (1.35 g/cm³ for Mathilde) have a great ability to survive energetic impacts. These images, which were received with great surprise, opened an entire area of research regarding energetic impacts onto porous targets.

In summary, asteroid surfaces are very diverse, and each rendezvous or flyby with an asteroid has helped to improve our geological understanding of granular mechanics, landslides, earthquakes, faulting, and impact cratering.

Future missions devoted to these small bodies will provide a great science return, and it is likely that some of our assumptions will need to be reconsidered.

Internal Structure

The internal structure of asteroids is inferred only from indirect evidence: bulk densities measured by spacecraft, the orbits of natural satellites in the case of asteroid binaries (Merline et al. 2002), and the drift of an asteroid’s orbit due to the Yarkovsky thermal effect. A spacecraft near an asteroid is perturbed enough by the asteroid’s gravity to allow an estimate of the asteroid’s mass. The volume is then estimated using a model of the asteroid’s shape. Mass and volume allow the derivation of the bulk density, whose uncertainty is usually dominated by the errors made on the volume estimate. These measurements indicate that dark bodies have a bulk density (typically about 1.0–1.3 g/cm³; see, for example, Yeomans et al. 1997) that is lower than that of the bright asteroids (typically about 2.0–2.7 g/cm³; see, for example, Abe et al. 2006).

The internal porosity of asteroids can be inferred by comparing their bulk density with that of their assumed meteorite analogues (Britt and Consolmagno 2000). Despite the small number of statistics from this comparison, it is clear that the interior of an asteroid generally has some degree of porosity. However, dark asteroids seem to be more porous (>40%) than bright ones. The nature of this porosity is unclear. Microscopic porosity is characterized by pores sufficiently small that their distribution can be assumed to be uniform and isotropic at the considered
scale. In this case, the pore is typically smaller than the thickness of the shock front resulting from an impact. A rock like pumice has such microporosity. Macroscopic porosity, on the other hand, is characterized by pores whose sizes are such that the medium can no longer be assumed to be homogeneous and isotropic at the scale of the object. This porosity corresponds to large voids in an otherwise nonporous rock. While macroporosity may explain the difference in density between S-type asteroids and their meteorite analogues (ordinary chondrites), some microporosity may be needed to explain the lower bulk density of C-type asteroids.

Unfortunately, we do not have any direct evidence of the kind of porosity inside an asteroid, even in the cases of asteroids for which the density has been estimated. For instance, is Mathilde microporous, in the manner of cometary dust balls, as has been proposed to explain Mathilde’s giant craters (Housen and Holsapple 2003)? Then, despite its possible microporosity, is Mathilde cohesive, as one might expect for microscale grain structure? Or does Mathilde, and the other primitive asteroids with comparable densities, possess huge voids, as one would expect from collisional disruption and reaccumulation of major fragments (Michel et al. 2001)? And at what size should asteroids be monolithic bodies (even with microporosity) rather than gravitational aggregates?

These questions do not have any clear answers yet, and only space missions aimed at probing the internal structure of an asteroid (for instance, by using radar tomography or by performing a seismic experiment) will provide them.

Knowledge from Numerical Modeling and Experiments

Collisions

Asteroids are continually involved in collisions. The outcome of these events depends on the physical properties of the colliding bodies, and the properties are, in turn, modified by these events. The collisional process is not fully understood, because we must still rely on poorly known asteroid-fragmentation physics. Nevertheless, numerical modeling of asteroid collisions has given results consistent with observations and has allowed us to make inferences about the physical properties of asteroids. Numerical simulations of the collisional disruption of large asteroids, including the fragmentation of the asteroid and the gravitational phase during which the fragments interact due to their mutual attraction, have successfully reproduced the formation of groups of asteroids sharing similar orbital and taxonomic properties (i.e. asteroid families) (Michel et al. 2001). The results showed that after a large asteroid is fragmented into small pieces by the impact of a projectile, subsequent gravitational reaccumulation of some of the fragments typically happens and leads to the formation of an entire family of large and small objects, whose properties are similar to those of the real family used as a comparison (Fig. 4). Moreover, in the models, all large family members (fragments larger than a few hundred meters) are made of gravitationally reaccumulated blocks (these bodies are called rubble piles or gravitational aggregates). This conclusion has great implications because it suggests that a large number of asteroids, in particular those originating from the disintegration of a larger body as a result of a collision, are rubble piles formed by reaccumulation.

Most objects larger than 125 km are likely to be primordial. Although most of them have probably been affected by small collisions that occurred repeatedly, they did not experience catastrophic disruption and reaccumulation. Smaller bodies are thus probably more thoroughly shattered and are more porous than larger primordial bodies. This is consistent with the low bulk densities measured for some asteroids and has implications for their collisional lifetime and for the preparation of mitigation strategies aimed at deflecting a potentially dangerous asteroid.

Other Surface Processes

All observed bodies are covered with some kind of regolith. Knowledge about processes such as landslides, seismic shaking, and cratering can be used to infer the physical properties of asteroid surfaces observed by spacecraft. For instance, during impact-induced shaking, a form of segregation in granular material called the “Brazil nut effect” takes place, with the larger particles moving to the top. On asteroids, thorough shaking by nondisruptive collisions may activate the Brazil nut effect. This effect could thus contribute to the presence of large boulders on the surface of small asteroids like Itokawa (Miyamoto et al. 2007), although a recent study proposed that these boulders are the direct outcome of the reaccumulation that formed Itokawa (Michel and Richardson 2013). Nevertheless, the...
mechanism driving the Brazil nut segregation on asteroids is still under debate. Itokawa has long lost any internal heat capable of driving convection, which is a possible driving force for segregation. Ashphaug (2007) suggested that the energy source was a granular thermal input associated with impacting meteoroids. However, new experiments in a parabolic flight environment have shown that gravity plays an active part in granular convection by tuning the frictional forces and that convective flow turns off under zero-gravity conditions (Murdoch et al. 2013). Therefore, a weak gravitational acceleration will likely reduce the efficiency of particle size segregation, and it is not clear yet whether the Brazil nut effect, if driven by convection, can be effective in a low-gravity environment such as that on Itokawa. However, it is likely that particle segregation does occur even in the reduced-gravity environment found on asteroid surfaces, but the process may require much longer timescales than would be needed in the presence of a strong gravitational field. This example demonstrates that we need more knowledge about the dynamics of regolith in low-gravity environments if we are to understand asteroidal surface properties and their evolution. This information is also necessary for designing efficient tools for human or robotic space missions to asteroids.

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PERSPECTIVES

Ground- and space-based observations of asteroids have already allowed us to increase tremendously our knowledge of their physical properties, and they have shown us how diverse asteroids are in terms of size, shape, and surface properties. However, we do not have any details yet on their internal structure, and our understanding still relies on numerical models that need further testing. Moreover, although meteorites are fragments of asteroids, we are not sure if they are representative of the material composing the most primitive asteroids (especially the dark ones), and the only way to make the link between our meteorite collection and asteroids in space is to return samples to Earth (Libourel and Corrigan 2014 this issue).

Moreover, a particularly interesting and hazardous body, the 325 m diameter NEA 99942 Apophis, will come within 32,000 km of Earth in 2029. This might be an excellent opportunity for a space mission to determine its internal structure. Returning samples from different NEAs and probing their interiors using various techniques (e.g. radar tomography, seismic experiments) will give new insights into the physical properties of these leftovers from planet formation. 

ELEMENTS
Establishing Asteroid– Meteorite Links

Edward A. Cloutis1, Richard P. Binzel2, and Michael J. Gaffey3

Asteroids are arguably the most accessible remnants of building blocks of the early Solar System and an essential piece of the terrestrial planet–formation puzzle. Determining their compositions and physical properties can provide important and otherwise unobtainable information concerning the origin, structure, and dynamic history of the Solar System, as well as insights into the sources of materials from which the terrestrial planets were constructed. Our understanding of the compositional structure of the asteroid belt and of individual asteroids has advanced significantly since the 1970s. Strong associations between asteroids and meteorites are emerging thanks to multitechnique observations, the synthesis of observations and modeling, in situ measurements, and sample-return missions.

KEYWORDS: asteroids, meteorites, Solar System evolution

INTRODUCTION

Understanding the origin and evolution of the Solar System is a fundamental scientific endeavour. Our planet, whose geology we are most familiar with because it is directly accessible to us, does not retain a readily readable record of its origins. Four and a half billion years of geological processes have largely obliterated this early record. To better understand the origin and early history of our planet and Solar System, we need to include information from outside the Earth.

Meteorites, which seemingly come to us for “free,” can provide this crucial window into our origins. Meteorites come in different varieties, enabling us to sample different parts of the Solar System and different times in its evolution. The vast majority of meteorites originated from small parent bodies (asteroids); a small fraction of recovered meteorites (a few dozen of the tens of thousands of recovered meteorites) originated from the Moon and Mars (http://curator.jsc.nasa.gov/anmtet/mmc/index.cfm), and possibly comets. A major shortcoming, which confirms the fact that nothing comes for “free,” is that using meteorites to understand Solar System evolution is hampered by our lack of knowledge about their provenance. As on Earth, a rock with known spatial context is much more valuable than one collected at random. Thus, although we can date the formation of meteorites and often reconstruct their dynamical history, a priori knowledge of where these events occurred is lacking.

IMPORTANCE OF ASTEROID–METEORITE LINKS

If we can relate specific meteorites to either specific parent bodies or regions of space, we can start to address a range of important questions, such as:

- What kinds of dynamical processes operated in the early Solar System? (See Michel 2014 this issue.)
- What kinds of heating processes operated in the early Solar System? In other words, what controls the fact that meteorites range from fully primitive to highly evolved (completely differentiated)? (See Fig. 1.)
- What in situ resources are available on asteroids that could be economically exploited or used to facilitate extended human presence in space?
- What kinds of impact hazards does the Earth face? Asteroid composition and structure will determine what impact-mitigation strategies may be most effective.

The answers to these questions fall outside the scope of this article. However, to better understand Solar System history and begin to answer these questions, we need to study the when, where, and how of meteorite evolution. In this article, we focus on the where.

WHAT WE KNOW ABOUT ASTEROIDS

Our knowledge of asteroids dates back to 1801, with the discovery of the first main belt asteroid, 1 Ceres4. Over the ensuing years, many more asteroids were discovered, with the current inventory of discovered asteroids now numbering in the hundreds of thousands (www.minorplanetcenter.net). As the discoveries mounted, so too

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4 Upon discovery, asteroids are given an alphanumeric preliminary designation, which is replaced by a purely numeric catalog number when the orbit becomes precisely known. Once assigned a permanent number, a name can be proposed.
have the physical observations that have yielded notable milestones in understanding the geology of asteroids. Some examples follow.

- The first indications that the asteroid belt is geologically diverse came in the 1920s with the discovery of color differences among asteroids (Bobrovnikoff 1929).


- The first large-scale taxonomic studies, whereby asteroids were categorized into different spectral or color groups—suggestive of both mineralogical diversity and compositional groupings—emerged in the late 1970s and early 1980s (e.g. Bowell et al. 1978).

- The ability to firmly constrain or establish the surface mineralogy of spectrally distinctive asteroids began in the 1970s and was extended to more asteroids in the 1980s (e.g. Cruikshank and Hartmann 1984).

- Spectroscopic surveys of large numbers (hundreds) of asteroids began in the late 1970s (Zellner et al. 1985) and were expanded during the subsequent decades to include more asteroids, more detailed spectral resolution, and greater wavelength coverage (e.g. Xu et al. 1995; Burbine and Binzel 2002). Also during this period, Earth-based radar observations were used to determine shape, spin, and thus the history of asteroids.

- The mineralogical/spectral diversity across the surfaces of specific asteroids (e.g. Gaffey 1997) and within taxonomic groups (Gaffey et al. 1993) was discovered, and we acquired the ability to derive, or at least constrain, the surface mineralogy of spectrally distinctive asteroids (1990s).

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**FIGURE 1** Images of the interior surface of various meteorites. (A) The Allende CV3 carbonaceous chondrite, a primitive carbonaceous meteorite containing organic material, chondrules (melted droplets of preexisting minerals—round objects in the image); carbonaceous chondrites have been linked to various dark-asteroid classes. (B) The Seymchan pallasite, a differentiated meteorite or impact melt containing large grains of olivine in a metallic matrix; pallasites have been linked to A-class asteroids. (C) The Odessa differentiated iron meteorite showing the Widmanstätten pattern indicative of slow cooling; iron meteorites have been linked to M-class asteroids. (D) The Norton County aubrite, a high-temperature, highly reduced, differentiated meteorite; aubrites have been linked to E-class asteroids. (E) The NWA 869 L4-L6 ordinary chondrite breccia; darker regions are fragments of a carbonaceous chondrite, likely added as a result of an impact. Scale bars are in millimeters.
Programs such as the Sloan Digital Sky Survey (www.sdss.org) and the NEOWiSe Space Infrared Survey (http://neo.jpl.nasa.gov/programs/neowise.html) carried out large-scale surveys of asteroids (thousands to hundreds of thousands) at a few wavelengths.

Ground-based, telescopic spectral analysis predicted the LL ordinary chondrite composition of asteroid 25143 Itokawa (Binzel et al. 2001; the asteroid’s original designation was 1998 SF36). Successful sample return by the Hayabusa mission gave ground-truth confirmation of the LL chondrite class (Tsuchiyama 2014 this issue).

The earliest large-scale surveys suggested that the asteroid belt is radially stratified, with the presumed highest-temperature asteroids at the smallest heliocentric distances and the least altered asteroids farthest out. Since then, we have greatly refined our understanding of asteroidal mineralogical diversity and are strengthening mineralogical–spectroscopic linkages.

Some meteorites can be traced to specific regions in space or specific parent bodies. Sky-scanning cameras can detect meteorites entering the Earth’s atmosphere as fireballs and we can back-calculate their orbits (e.g., Halliday et al. 1978). We were also fortunate recently to detect and study an asteroid prior to its encounter with Earth (2008 TC3) and then recover pieces of the asteroid (Goodrich et al. 2014 this issue).

Although Earth- and space-based investigations can help us constrain asteroid surface compositions, there is no substitute for having a sample of known provenance in hand. Recently we directly sampled the near-Earth asteroid Itokawa (Tsuchiyama 2014). Asteroid sample-return missions are also scheduled for later in this decade (OSIRIS-REx, Hayabusa-2).

Compositional studies of meteorites indicate that they originated from at least many tens of distinct parent bodies (Keil 2000). It also appears that our meteorite collection is not representative of the compositional diversity of the asteroid belt (Burbine et al. 2002). A number of meteorite types must have formed in association with other types that have not yet been found. This is likely due to the biases and selection effects that are associated with the mechanisms that deliver meteorites from the asteroid belt to the Earth (e.g. Burbine et al. 2002). There are a number of asteroids whose mineralogy is reasonably well understood but for which we have no representatives in our meteorite collections (e.g. 44 Nysa, 349 Dembowska); conversely, there are meteorites for which we have no obvious parent body (e.g. GRA 06128/9). Complicating the determination of asteroid–meteorite links is the fact that the delivery of meteorites to Earth from the main asteroid belt is normally a multistep process with various biases (Michel 2014).

WAYS OF INVESTIGATING ASTEROIDS

We have a multitude of ways of investigating asteroids and forging asteroid–meteorite connections. Each method has advantages and limitations, and some methods can provide information on both physical properties and composition. Techniques that have been applied to the study of asteroids and that reveal something about physical properties (usually in conjunction with some constraints on composition) include gravitational interactions, stellar occultations, Earth-based radar imaging, optical and radar polarimetry, the acquisition of rotational light curves, and thermal-infrared observations. The derivable physical properties include size, shape, density, surface texture, presence or absence of regolith, rotation rate, and porosity. For most asteroids, one or a few of these parameters have been determined, leading to at least some constraints on physical and/or compositional properties. As the number of observational techniques applied to an asteroid increases, our understanding of an asteroid’s physical structure necessarily improves.

Asteroid compositional determinations are also possible via multiple techniques. The major ways in which compositional properties can be determined or constrained include density determinations or constraints by gravitational interactions or radar observations, radar reflectivity to constrain metal content, elemental analysis using gamma ray or neutron detection, the measurement of a magnetic field (if present), optical polarimetry, reflectance spectroscopy, thermal emission spectroscopy, direct imaging, and dynamical correlations. As with the methods that can be used to constrain physical properties, these observational techniques probe asteroids to different depths and at different spatial scales, providing types of information that complement one another. Sample return provides the capstone of our understanding of asteroid–meteorite connections (Fig. 2).

FORGING ASTEROID–METEORITE LINKS

By combining the results of multiple techniques, a more robust picture of an asteroid’s properties emerges. Among the properties of interest, internal structure and composition are, not surprisingly, the most intractable. Different techniques probe asteroids to different depths, so any near-surface variations that may exist, such as those due to space weathering, are potentially recognizable. For example, apparent variations in the mineralogy of asteroid 433 Eros can largely be reconciled by invoking various surface-modification processes and the different interrogation depths of the instruments aboard the NEAR spacecraft (McCoy et al. 2001). Sending appropriately equipped spacecraft to asteroids also helps forge asteroid–meteorite links (Fig. 2).

Reflectance spectroscopy is the most widely applied asteroid-characterization technique. Many asteroids have reflectance spectra that seem to lack diagnostic absorption features. However, there are indications that what we believe to be spectrally bland asteroids may in fact have weak diagnostic absorption features that can be detected with high signal-to-noise observations (e.g., Vilas and Gaffey 1989). As data quality improves and other kinds of observational data become available, traditional asteroid taxonomic classes (such as the M class) may include...
mineralogically diverse bodies, ranging from primitive (wet) to evolved (dry) (Rivkin et al. 2000), thus increasing our ability to distinguish different materials.

A further issue that complicates establishing links is the dynamic nature of the asteroid belt. Once formed, asteroids do not serenely orbit the Sun, untouched. They are subject to various events and conditions: impacts over a range of sizes and energies, orbital perturbations, solar wind and galactic cosmic ray bombardment, the vacuum of space, and temperature excursions. Polymict breccias and the presence of xenoliths are the norm rather than the exception. Thus, when viewing an entire hemisphere of an asteroid, as is done for Earth-based observations, we are likely observing a diversity of terrains, both physically and compositionally. This further complicates our ability to relate a few grams of meteoritic material, which managed to survive a perilous journey to Earth, to a parent body exposed to the space environment.

The availability of meteorites and samples of known provenance (such as the Hayabusa samples from Itokawa and the Almahata Sitta samples from 2008 TC3) is proving to be extremely valuable as we continue to establish asteroid–meteorite links. Although Itokawa samples yielded a previously predicted result (Binzel et al. 2001), the much more complex characteristics of the Almahata Sitta meteorite have demonstrated that, in other cases, samples can be more complicated than what is predicted from telescopic data. By combining asteroid observational data with models of asteroid orbital evolution and surface modification, as well as with meteorite data such as ejection and exposure ages, we are beginning to fill in the details on how we can better reconcile asteroid and meteorite observations. Our view of asteroids is also becoming more nuanced, with evidence pointing to these bodies having optically (and mineralogically) complex surfaces (FIGS. 3, 4). The Dawn mission to Vesta is providing strong evidence of mixing of different meteorite types at large scales (McSween et al. 2014 this issue), complementing evidence of mixing of similar meteorite types at microscopic scales (Chou et al. 1976).

EXAMPLES OF ESTABLISHED ASTEROID–METEORITE LINKS

One of the first asteroid–meteorite links to be established was between 4 Vesta and howardite-eucrite-diogenite meteorites (McCord et al. 1970). Initially, their spectroscopic similarity was deemed dynamically dubious owing to the apparent lack of a plausible pathway from Vesta to the Earth. The discovery of the Vestia family of asteroids (or “Vestoids”; Binzel and Xu 1993) extending from Vesta to resonance delivery zones solidified the link. This link has stood the test of time and been confirmed by the in situ results provided by the Dawn mission to this asteroid (McSween et al. 2014). The return of samples from Itokawa by the Hayabusa mission (Tsuchiyama 2014) cemented the relationship between Itokawa and LL chondrites that was predicted prior to the spacecraft’s launch. These are by far the strongest and most accepted asteroid–meteorite links, and they demonstrate the value of asteroid sample return and detailed spacecraft observations, and the capability of successful mineralogical interpretations by Earth-based observers.

Other links are less certain, and their reliability is often a function of an asteroid’s “uniqueness.” For example, as a group, the E-class asteroids are bright, and either they are spectrally featureless or they possess an absorption feature that is probably associated with the rare mineral oldhamite (CaS). Their brightness and the presence of oldhamite eliminate the possibility that these asteroids contain more than trace amounts of ferrous iron–bearing or opaque minerals. Only the aubrite achondrites satisfy these criteria. Asteroid Steins, an E-class asteroid, has high albedo, consistent with achondrites, but shows a prominent oldhamite-like absorption feature, suggesting that it represents a type of achondrite not represented in our meteorite collections, that is, an achondrite with a high-temperature, low-oxygen-fugacity mineral assemblage (Keller et al. 2010).

Another example is the strong link between A-class asteroids and olivine-rich meteorites, such as brachinites and pallasites. This association is based on a unique and diagnostic absorption feature exclusively attributable to ferrous iron–bearing olivine (Cruikshank and Hartmann 1984). At the other extreme, the Tagish Lake meteorite, a rare carbonaceous chondrite, has been associated with D-class asteroids; both Tagish Lake and D-class asteroids have reflectance spectra that are very dark in the visible-light region, becoming brighter toward the near-infrared, and they exhibit no recognizable absorption bands in their reflectance spectra (Hiroi and Hasegawa 2003). In other cases, such as the C-class asteroids, the lack of diagnostic spectral features suggests that this class may encompass multiple meteorite types and include compositionally diverse objects.

Meteorite-asteroid links can be enhanced when observational data are combined with other lines of evidence, such as the location of asteroids near “escape hatches” for delivery to Earth, clusters of meteorite exposure ages, and the spectral uniqueness of parent bodies. By building an internally self-consistent picture for specific asteroids, we can begin to home in on potential parent bodies for specific classes of meteorites. Such multidisciplinary approaches provide the strongest linkages. Multiple criteria have been used to link asteroid 6 Hebe and the H-type ordinary chondrites (Gaffey and Gilbert 1998), and 4 Vesta and the howardite-eucrite-diogenite suite of achondrites (McSween et al. 2014).

There are also abundant cases of asteroids for which no plausible meteorite analogues have been identified. These mostly include a number of the low-albedo, spectrally
featureless asteroids. Such spectrally featureless asteroids are assigned to the C spectral class and include a number of taxonomic subgroups that differ on the basis of their overall spectral shapes. Some recently identified asteroids exhibit absorption features diagnostic of ferrous iron-bearimg spinel, and although spinel is present in a number of primitive carbonaceous chondrite meteorites, the inferred overall mineralogy of these asteroids is unlike that of any known meteorite (Sunshine et al. 2008). Interestingly, meteorites can sometimes be made to match asteroids, at least spectrally, by subjecting them to laboratory treatments, such as heating (Hiroi et al. 1996), further suggesting that the terrestrial meteorite collection is an incomplete representation of asteroid diversity.

It is worth reiterating that the terrestrial meteorite collection is not representative of the asteroid belt (Burbine et al. 2002). There are undoubtedly numerous asteroids and even asteroid taxonomic classes for which we have no recognized meteorites. The most numerous meteorites in our collections, the ordinary chondrites, are plausibly linked to only a small subset of characterized asteroids. Their dominance in current fall statistics may be attributable to relatively recent breakups of a few favorably placed parent bodies, as proposed for the asteroid Gefion and the L chondrites (Nesvorný et al. 2009). Underrepresentation is further hampered by ongoing uncertainties about how the space environment can affect the appearance of asteroids.

**SPACE WEATHERING**

Our long-standing inability to find good optical spectral matches between the most common meteorite types (ordinary chondrites) and their presumed parent bodies (expected to reside within the traditional 8 taxonomic class), as well as the large spectral differences between lunar regolith and rocks have made us realize that the exposure of asteroidal surfaces to the space environment can dramatically change their optical properties. This would result in a surface that is not representative of the bulk asteroid, potentially hiding expected meteorite parent bodies from view. The plethora of processes that can occur at the asteroid–space interface are collectively termed “space weathering” and include devolatilization/desiccation, solar wind implantation, sputtering, radiation damage, micrometeorite impacts, and thermal cycling (Hapke 2001). These are in addition to processes that may operate in the interior of asteroids, such as heating and aqueous alteration, as well as other processes such as impact-induced seismic shaking, rotationally induced movements of material towards the equator, and tidal stresses during planetary encounters (Binzel et al. 2010).

How space weathering operates on asteroidal surfaces is an area of active research. It appears to work in different ways on different asteroids (Gaffey 2010). A number of tentative explanations have been advanced to account for differences in perceived asteroid space weathering. Recent results from the Dawn mission to Vesta indicate that this body exhibits a style of space weathering quite different from that seen on other airless bodies (Pieters et al. 2012). There are likely multiple factors that can affect the style of space weathering. These include:

- **Heliocentric distance.** This is likely the most important control on space weathering as it determines the solar wind density, impactor velocity, and the spatial density of potential impactors (higher in the main asteroid belt than near the Earth’s orbit).

- **Size.** Larger asteroids will provide a bigger target for potential impactors and will attract or perturb nearby asteroids (gravitational focusing) and will have greater ability to retain regolith.

- **Surface composition.** Different materials will have different susceptibilities to space weathering. For example, the production of nanophase iron, which is an important modifier of the optical properties of the lunar regolith, requires an Fe-bearing target.

- **Magnetic field.** The presence of a remnant magnetic field, such as may be present on Vesta (Fu et al. 2012), can deflect the solar wind, leading to less space weathering by processes associated with the solar wind.

- **Orbital inclination.** This may play a secondary role, determining the spatial density of potential impactors, such as dust lanes in the main asteroid belt.

- **Date since the last major resurfacing relative to the time required for weathering or reweathering.** An asteroid’s surface can be “reset” by a major resurfacing event such as a large impact or intense seismic shaking. If the space weathering timescale is as short as 10⁶ years (Vernazza et al. 2009), then surfaces young enough to appear “fresh” or “unweathered” are understandably rare since large-scale impacts occur, on average, on timescales greater than 10⁹ years.

Variations in the appearance of space weathering on different asteroids likely reflect differences in the relative contributions of the same set of processes (Gaffey 2010). As an example, micrometeorite impacts on the lunar surface occur with an average speed that is a factor of ~4 greater than in the main asteroid belt. This could effectively lead to more impact melting on the Moon than on asteroids, where average speeds are lower.

Asteroidal-type space weathering, even though it affects many spectral properties, does not affect some that can be used to determine properties like the pyroxene/olivine ratio and mafic silicate composition, properties that can be used to discriminate ordinary chondrites from primitive or fully differentiated achondrites. Our understanding of space weathering, at least for near-Earth asteroids, has improved with the return of a regolith sample from Itokawa (Tsuchiyama 2014). Many, if not most, of Itokawa’s mineral grains examined to date show evidence of space weathering, most notably in the form of nanophase iron and iron sulfides in the outer rind. Given our understanding of how nanophase iron and iron sulfides affect reflectance spectra, the spectral mismatch between Itokawa and LL chondrites can be largely resolved.
Some aspects of space weathering that can impact our ability to forge meteorite–asteroid linkages are still not well understood. For example: Does space weathering preferentially concentrate or deplete specific phases? What is the effect of space weathering on the composition of organic molecules and water-bearing minerals and on the distribution of fine-grained opaque minerals? Can space weathering “sandblast” metallic surfaces or grains? To answer these questions, a combination of work on samples recovered from the uppermost surfaces of asteroids, laboratory studies, and theoretical modeling is required.

**REFERENCES**


Bobrovnikoff NT (1929) The spectra of asteroids and 9 coauthors (2010) Earth-crossing orbits, and how similar or different are main belt and near-Earth asteroids? What processes have affected asteroids since their formation?

**ASTEROIDS AND THE ORIGIN OF THE TERRESTRIAL PLANETS**

Remnants of the building blocks of the terrestrial planets are likely still present in the asteroid belt. As knowledge of the compositional diversity of asteroids and the compositional structure of the asteroid belt and near-Earth asteroids improves, we will be able to better address questions such as: Which models of Solar System evolution (some of which include large radial excursions of the giant planets) are consistent with compositional zonations in the main asteroid belt (Michel 2014)? Could the main asteroid belt have provided all the building blocks for the formation of the terrestrial planets? Where are the remnant building blocks of the terrestrial planets currently located? How do asteroids from the main belt evolve such that they develop Earth-crossing orbits, and how similar or different are main belt and near-Earth asteroids? What processes have affected asteroids since their formation?

**THE FUTURE**

Our ability to establish meteorite-asteroid linkages continues to improve, and the strongest connections are made when multiple observational techniques and dynamical models are combined to develop an internally consistent picture. Significant advances will be made by targeting sample-return missions to representatives of key asteroid taxonomy classes, such as the C spectral group, for which our understanding of composition is tenuous. The OSIRIS-REx asteroid sample-return mission is an important step in this direction. It will acquire both a regolith sample, to better understand how space weathering affects dark asteroids, and a bulk sample, which will help us relate the uppermost regolith to its overall composition. Future observations of asteroids using multiple techniques will gradually improve our view of the origin, structure, and composition of these important building blocks of our Solar System.
The small (~4 m) asteroid 2008 TC3 was discovered and predicted to hit Earth within ~19 hours. Photometric data and a reflectance spectrum were obtained. The asteroid fragmented at ~37 km altitude above Sudan. Approximately 700 centimeter-sized fragments were recovered and constitute the meteorite Almahata Sitta. It is a unique meteorite breccia, consisting of ~50–70% ureilite materials, plus samples of nearly every major chondrite group. The reflectance spectrum of 2008 TC3 is closest to that of F-class asteroids, not previously associated with any meteorite type. 2008 TC3/Almahata Sitta records a complex history of fragmentation, migration, and reaccretion of materials in the Solar System.

Keywords: asteroids, meteorites, 2008 TC3, Almahata Sitta, ureilites, reflectance spectra, chondrites

THE DISCOVERY OF ASTEROID 2008 TC3

On October 6, 2008, the small asteroid that was subsequently named 2008 TC3 was discovered by Richard Kowalski of the Catalina Sky Survey at Mt. Lemmon Observatory in Tucson, Arizona, USA. The discovery was reported to the Minor Planet Center in Cambridge, Massachusetts, where it was soon realized that this asteroid was on a trajectory to hit the Earth. The news spread quickly around the world, and both professional and amateur astronomers began to track and study this soon-to-be meteoroid. Steve Chesley of the Jet Propulsion Lab in Pasadena, California, calculated the asteroid’s orbit and predicted that it would impact the Earth over northern Sudan about 19 hours after the time of its discovery. In the ensuing hours before impact, its orbit was determined very precisely, photometric data (measuring its brightness) were collected, and a reflectance spectrum of the asteroid was obtained.

Early in the morning on October 7, 2008, eyewitnesses along the Nile River near Wadi Halfa and at Train Station 6 in the Nubian Desert of Sudan saw the fireball that resulted when 2008 TC3 hit the Earth’s atmosphere. The US government’s weather satellite Meteosat 8 first detected the bolide (a term for an especially bright fireball) at an altitude of ~65 km. A few seconds later, at ~37 km above the Earth, the atmosphere created pressures of up to 1 MPa on the rock, causing it to shatter into fragments in a series of explosions. Meteosat 8 observations in mid-infrared channels detected two dust clouds in the atmosphere (Fig. 1a).

resulting from the explosions (Borovička and Charvát 2009). No significant dust deposition was observed below about 33 km, and no meteorites were expected to survive (Jenniskens et al. 2009).

THE SEARCH FOR METEORITES

Nevertheless, based on the asteroid’s trajectory and predicted geographic coordinates of its impact with the atmosphere, it was possible to outline a footprint for any potential rock fragments reaching the ground (Borovička and Charvát 2009). However, initial searches for meteorites in this area were not successful. Possibly the main reason that this initial prediction of the fall area was off-target is that the asteroid shattered much higher in the atmosphere than expected based on fireballs associated with ordinary chondrites, making the predicted geographic coordinates of its impact incorrect. In December 2008, Peter Jenniskens of the SETI Institute (Mountain View, California) and Muawia Shaddad of the University of Khartoum, Sudan, teamed up to try again. Based on eyewitness accounts, dust-train observations, atmospheric factors (winds), and the new geographic coordinates of the asteroid’s impact with the atmosphere, they refined the predicted fall area and led a team of 45 students and staff from the University of Khartoum on an organized search (Fig. 1b). The first meteorite was found a few hours after the search began. Three more organized search campaigns were carried out in 2008 and 2009, involving international astronomers and meteoriticists in addition to the students and staff of the University of Khartoum. More than 600 individual meteorite fragments were collected during these searches, over an area of about 7 × 30 km. Further search activities recovered additional samples, 80 of which were classified at the University of Münster (Bischoff et al. 2010a, b, 2012, 2013; Horstmann et al. 2012). All these fragments were small, ranging from ~0.2 to 400 g in mass. Collectively they are considered to be a single meteorite named Almahata Sitta, which means “Station 6” in Arabic (Fig. 1c). Almahata Sitta is the first meteorite derived from a known asteroid, that is, an asteroid that was tracked and studied by astronomical methods before it hit the Earth. In particular, it is the first meteorite observed to originate from a spectrally classified asteroid. The importance of this meteorite for linking asteroid classes with meteorite classes (see Cloutis 2014 this issue) was immediately recognized by planetary scientists.
ALMAHATA SITTA: THE SAMPLES

Based on their physical, chemical, and mineralogical properties, the samples collected from the Almahata Sitta meteorite strewn field are remarkably heterogeneous (Fig. 2). The first sample studied petrologically and chemically (sample #7, which had a mass of 1.5 grams) was identified as a ureilite (see Box 1) on the basis of its oxygen isotopes (Fig. 3) and carbon-rich composition, as well as several other distinguishing mineral and bulk-chemical features (Jenniskens et al. 2009). It was also recognized to be a polymict ureilite (a relatively rare type) because it consisted of welded-together clasts of a variety of ureilite types. In addition, it was atypical even for a polymict ureilite because it was unusually porous. About 10–25% of this sample consists of pores (Fig. 2a) lined with euhedral to subhedral crystals of olivine that may have been deposited from vapors (Jenniskens et al. 2009; Zolensky et al. 2010). This feature had not previously been seen in a ureilite. On the basis of studies of this one sample, Almahata Sitta was classified as an anomalous polymict ureilite (Jenniskens et al. 2009).

As additional samples of Almahata Sitta were studied, it became apparent that many of the pieces of rock collected from this meteorite were not like sample #7, but rather were fragments of typical main-group ureilites with different mineral and oxygen isotope compositions (Bischoff et al. 2010b; Rumble et al. 2010; Zolensky et al. 2010). In addition, the Almahata Sitta samples included a variety of chondritic lithologies (Bischoff et al. 2010a, b, 2012; Zolensky et al. 2010; Horstmann et al. 2010, 2012; Rumble et al. 2010; Kohout et al. 2010). These samples were identified as chondrites on the basis of their mineralogy and oxygen isotope compositions (Fig. 3), which are quite distinct from those of ureilites. The first analyses of short-lived cosmogenic radionuclides of two of these chondritic samples demonstrated that they were part of the Almahata Sitta meteorite shower (Bischoff et al. 2010a). Based on analysis of the magnetic susceptibility of 60 samples from the strewn field, Kohout et al. (2010) estimated that half of their studied samples could be non-ureilitic. Thirty chondrites (~40%) were found among the 80 samples examined at the University of Münster (Bischoff et al. 2010a, b; Horstmann et al. 2010, 2012). In addition,

**Box 1**

**Chondrites and Achondrites** – Meteorites are divided into two major categories based on their bulk-chemical compositions and textures: differentiated and undifferentiated. Chondrites, which constitute more than 80% of the current meteorite flux, are undifferentiated. They have bulk compositions that closely match the composition of the Sun, with the exception of a few highly volatile elements. They are interpreted to represent the most primitive Solar System materials available. Achondrites are silicate-rich (in contrast to iron and stony-iron meteorites) differentiated meteorites. They are rocks that experienced igneous processing on their parent asteroids. Unlike chondrites, some achondrites resemble terrestrial igneous rock types.

**Ureilites** – These are the second-largest group of achondrites (Mittlefehldt et al. 1998). They are coarse-grained ultramafic rocks, consisting mainly of the minerals olivine and pyroxene, and are thought to represent the residual mantle of a partially melted asteroid. One of the distinguishing characteristics of ureilites is their high abundance of carbon. The carbon is mostly in the form of graphite, but diamonds occur as well. Ureilites are also characterized by their oxygen isotope compositions, which set them apart from any other group of achondrites. Mineral and oxygen isotope compositions are very homogeneous within each ureilite, yet vary greatly among samples. Ureilites are divided into different types, or lithologies, based on these differences. About 5% of known ureilites are polymict breccias, thought to be samples of regolith formed on a ureilitic asteroid (Goodrich et al. 2004).

**Breccias** – A breccia is a rock consisting of fragments derived from an earlier generation of rock(s) and consolidated into a new clastic rock, typically (in the case of meteoritic breccias) by shock metamorphism. The most common types of meteorite breccias include monomict, polymict, and regolith breccias (Bischoff et al. 2006). In monomict breccias, both matrix and clasts are derived from the same primary rock type, whereas in polymict breccias, lithified fragments of various types, origins, and/or compositions coexist. Regolith breccias derive from the upper surface of a parent body (and therefore contain solar wind-implanted gases).
Variety of lithologies among samples of the Almahata Sitta meteorite. (A) Scanning electron microscope image of a porous area of ureilite sample #7. The pores contain crystals of FeO-rich olivine and pyroxene, along with metal spherules and botryoidal troilitte. Courtesy of Mike Zolensky (NASA JSC). (B) Light microscope (crossed polars) image of coarse-grained, pyroxene-rich sample MS-MU-005, which resembles many main-group ureilites. (C) Cut surface of the EL chondritic breccia MS-179, which contains different types of EL chondrite lithologies embedded in a fine-grained matrix of EL chondritic material. (D) Unique sample MS-CH (Horstmann et al. 2010), which is similar to R chondrites but with unusual properties.

Based on hand-specimen properties, Shaddad et al. (2010) estimated that about 20–30% by mass of the samples in the University of Khartoum collection are non-ureilitic. Never before had pieces of several different meteorite types been collected from the same fall. Approximately 100 samples have so far been classified on the basis of mineralogical, chemical, and oxygen isotope properties. However, since this represents only ~15% of all samples collected, there is no guarantee that the studied samples give a representative picture. It is possible that additional new lithologies will be found among the petrologically unstudied samples.

Based on the main data sets currently available (Zolensky et al. 2010; Bischoff et al. 2010b; Horstmann et al. 2012), the most abundant Almahata Sitta samples are compact (dense, not porous), main-group ureilite lithologies with various olivine/pyroxene ratios, mineral compositions, and grain sizes (Fig. 2b). Coarse-grained (up to several millimeters), olivine-rich ureilite fragments are dominant. There are also many coarse-grained, pyroxene-rich ureilite fragments, typically with grain sizes significantly less than 1 mm (Fig. 2b). The second most abundant lithology can be described as a fine-grained, porous ureilite type, mainly composed of 10–30 µm sized olivine and pyroxene grains in a granoblastic mosaic texture, with abundant opaque phases, such as metal, sulfides, and carbon polymorphs. This texture is similar to what is seen in some shock-melted main-group ureilites (e.g. Warren and Rubin 2010). These fine-grained fragments are often quite dark or have dark areas due to the high abundances of metals, sulfides, and carbon phases. The grain sizes of olivine and pyroxene are not always homogeneous throughout these fragments; some (such as sample #7) contain areas with larger crystal sizes. Surprisingly, in some Almahata Sitta samples, sulfide and metal are the dominant constituents, which is not the case in any previously known ureilite. These samples have been described as “metal-sulfide assemblages with enclosed ureilite portions” (Bischoff et al. 2010b), indicating their affinity to the ureilite lithologies. One sample with ureilite oxygen isotope characteristics is an andesite, possibly derived from the crust of the ureilite parent body (Bischoff et al. 2013). So far, no achondritic lithologies other than ureilites have been found among Almahata Sitta samples.

Among the chondritic Almahata Sitta samples, enstatite (E) chondrites are the most abundant (see Box 2). They are similar in overall abundance to the fine-grained, porous ureilites. Samples of both E chondrite subgroups (EL and EH) have been encountered, with the EL subgroup being dominant. For both subgroups, individual samples of various petrologic types (e.g. EL3, EL4, EL5, EL6) occur, and these are indistinguishable from previously known E chondrites. Some of the E chondrites are heavily brecciated and shock-darkened, and may contain shock-melted metal–enstatite assemblages. The complex EL chondritic breccia MS-179 (Fig. 2c) contains clasts of different types of EL chondritic lithologies (EL3–5) embedded in a fine-grained, clastic matrix that is only loosely cemented (Horstmann et al. 2012).

**Box 2 Chondrites**

There are 4 major chondrite classes defined on the basis of mineralogical, textural, and isotopic properties. **Ordinary chondrites** are the most abundant group and are subdivided based on their Fe concentration and metal abundance into three subgroups (H = high-iron; L = low-iron; LL = low-Fe, low-metal). **Enstatite (E) chondrites** contain minerals that formed under highly reducing conditions (e.g. Si-bearing metals, graphite, sinitite [Si2N2O]), enstatite with very low FeO). Based on their bulk-compositional Fe/Si ratios, they are subdivided into the EL (low-Fe) and EH (high-Fe) subgroups. **Carbonaceous chondrites** are subdivided into 8 major subgroups (CI, CM, CO, CV, CK, CR, CH, CB) based on their mineralogy, texture, and chemical/isotopic composition. Typically, they have higher abundances of fine-grained matrix than the other chondrite groups, leading to a darker appearance in hand specimen and thin section. **Rumuruti (R) chondrites** are olivine-rich rocks (commonly breccias) with distinct oxygen isotope compositions. Their olivine has mostly high FeO contents (FeO>40), indicating formation under highly oxidizing conditions.

**Petrologic Type**—Although chondrites and their constituents are considered to be “relatively pristine” Solar System materials, their parent bodies have experienced some secondary processes, such as hydrothermal alteration and metamorphism. Annealing has modified different components of chondrites to different degrees. This effect is described by the petrologic types 3–6: Type 6 chondrites have undergone a high degree of thermal metamorphism, whereas type 3 chondrites show no or only minor modification. If pristine Solar System material reacted with water, distinct minerals may have formed (e.g. phyllosilicates, magnetite, carbonates). The degree of aqueous alteration is defined by petrologic types 1 and 2, with the type 1 chondrites showing the highest degree of aqueous alteration.
Oxygen isotope compositions of 34 Almahata Sitta samples with typical R chondrites (Bischoff et al. 2011). R chondrites but has higher abundances of metal compared to other known F-class asteroids (see next section), a (a measure of the reflectivity of the surface of a body) in rocks from a small asteroid are dependent on both the elements that are produced on the surface and near-surface samples. Cosmogenic nuclides are isotope compositions of certain elements in the meteorite samples. Cosmogenic nuclides are isotopes of certain elements that are produced on the surface and near-surface of rocky bodies by interaction of cosmic rays with atoms in the rock. The concentrations of cosmogenic nuclides in rocks from a small asteroid are dependent on both the depth in the asteroid and the density of the overlying material through which the cosmic rays had to pass. Using this technique, Welten et al. (2010) determined the average density of asteroid 2008 TC₃, to be approximately 1.7 g cm⁻³. This density is much lower than the densities of many of the Almahata Sitta meteorite samples. For example, the compact, main-group ureilite samples have densities of 3.0–3.3 g cm⁻³ (Welten et al. 2010; Shaddad et al. 2010). Therefore, the asteroid on the whole must have had an average porosity of ~50%. Such high porosity suggests that the asteroid was very weak (low tensile strength), which would explain why it exploded at such a high altitude in the atmosphere (Borovička and Charvát 2009). In other words, 2008 TC₃ was far from being a solid rock. Instead, it consisted mostly of fine-grained, highly porous matrix material, weakly cementing a small fraction of isolated, centimeter-sized fragments of denser rocks that became the fallen meteorites.

These data also tell us that the vast majority of the material in 2008 TC₃ was lost, probably as fine dust dispersed in the Earth’s atmosphere. Assuming that the asteroid was a sphere 1.8 m in radius, with an average density of 1.7 g cm⁻³, it would have had a total mass of ~41 tons. For comparison, the total mass of fallen material was estimated to be ~39 ± 6 kg, based on the areal density of recovered meteorite mass (Shaddad et al. 2010). This implies that ~99% of the asteroid’s mass was not recovered. Most of this material was probably the fine-grained matrix material in which the more coherent rock fragments were embedded. What did this lost material consist of? We turn to the reflectance spectrum of 2008 TC₃ to address this question.

**THE REFLECTANCE SPECTRUM OF 2008 TC₃ AND ASTEROID–METEORITE CONNECTIONS**

The reflectance spectrum of 2008 TC₃ (Fig. 5) is most closely matched by the spectra of F-class asteroids (Jenniskens et al. 2009) in the Tholen asteroid taxonomy (Tholen and Barucci 1989). F-class asteroids are rare, comprising only about 1% of all bodies in the main asteroid belt. Along with the C, B, and G classes, they fall in the broader C group of asteroids, which are thought to be related to carbonaceous chondrites. F-class asteroids are similar in spectrum to B-class asteroids such as 1999 RQ₃₆, the target of the OSIRIS-REx mission. The two are not always easy to distinguish from one another, but often appear as distinct groups in photometric color plots (i.e. plots of U-B vs. B-V, where U, B, and V are the brightnesses in different filters). Until the discovery and impact of 2008 TC₃, F-type asteroids were not suggested as the source of any known meteorite types. Thus, it was particularly surprising when the first sample of the Almahata Sitta meteorite turned out to be a ureilite, since ureilites had previously been suggested to come from S-type asteroids (Gaffey et al. 1993). However, considering the great lithological diversity and the loosely consolidated structure of the asteroid, the meaning of the asteroid’s reflectance spectrum must be considered carefully. It seems clear that this spectrum does not represent a single, coherent rock, and it may be very different from the reflectance spectrum of the original ureilite parent body.

The reflectance spectrum of 2008 TC₃ can be compared to laboratory-obtained spectra of Almahata Sitta rock samples in the same spectral range in order to shed light on what the asteroid spectrum represents. One such study was carried out on rock chips and powders of 11 Almahata Sitta samples, of which 10 were ureilite and one was an ordinary chondrite (Hiroi et al. 2010). The spectra of the ureilite samples were consistent with those of previously studied ureilites (Cloutis et al. 2010), with low reflectance due to high carbon and metal contents.
and spectral features indicating various olivine/pyroxene ratios. The spectrum obtained for the ordinary chondrite sample was distinct from the spectra of the ureilites and similar to those of H chondrites. Various combinations of these sample spectra were then compared to the spectrum of the asteroid. This comparison indicated that mixtures dominated by ureilite rock chips could reproduce the main features of the asteroid spectrum, namely, the relatively flat visible-light spectrum and the weak near-ultraviolet and 1 µm band absorptions (Fig. 5). This is consistent with ureilite material dominating the surface of the asteroid, but seems to suggest that little of this material was in the form of fine-grained regolith (Hiroi et al. 2010). The latter is surprising, given the inference that the asteroid consisted of ~99% fine-grained material. On the other hand, only a few combinations of Almahata Sitta sample spectra have been examined, and these include only two of the many different meteorite types that are present. The degree to which these other types—in particular, the E chondrites, which constitute a significant fraction of the collection—are reflected in the asteroid spectrum is unknown. Thus, it is not yet possible to draw any firm conclusions about the nature of the ~99% of unsampled material in 2008 TC3.

Comparing the spectrum of 2008 TC3 and Almahata Sitta samples with that of main belt asteroids suggests the Nysa-Polana asteroid family as a possible source of 2008 TC3 (Jenniskens et al. 2010; Gayon-Markt et al. 2012). This family is located at low inclination next to the 3:1 resonance with Jupiter, a powerful route for delivering material to near-Earth space. Furthermore, it is a complex family, consisting of various subgroups and asteroids of different spectral types. The Polana group is primarily F-class, the asteroid Nysa itself is E-type, and most of the rest of the Nysa group is S-type (these S-types are sometimes referred to as the Mildred family). This diversity of material in a small dynamical region may be tied to the origin of 2008 TC3 and Almahata Sitta. The discovery of Almahata Sitta has raised the possibility that some asteroid spectral types do not correspond to single meteorite types, but rather to complex mixtures of types.

**THE IMPACT OF ASTEROID 2008 TC3 AND THE ALMAHATA SITTA METEORITE**

The advent of asteroid 2008 TC3 was a remarkable event, for many reasons. It demonstrated how effectively scientists around the world can work together to track Earth-approaching asteroids and how quickly they can mobilize resources to study unpredictable arrivals. It led to the rapid deployment of an international team that recovered over 600 fragments of the freshly fallen meteorite. It provided the first “data point” definitely linking an asteroid spectral type with a meteorite type. And it brought us an extraordinary new type of meteorite.

Ureilites are an enigmatic group of achondrites (Mittlefehldt et al. 1998). For this reason, new ureilites bringing potentially new information about their petrogenesis are always welcome. Fresh falls are particularly valuable because the metallic minerals in ureilites are susceptible to terrestrial weathering and can lose the information they hold about their extraterrestrial formation in a very short time on the Earth’s surface. The early realization that Almahata Sitta was polymict made it even more important because polymict ureilites can contain rock types from the ureilite parent body that are not represented as individual meteorites in the world’s collections. However, compared to previously known polymict ureilites (Goodrich et al. 2004; Downes et al. 2008), Almahata Sitta probably has a much higher ratio of matrix to clasts, is much less coherent, and has a higher proportion of highly shocked material. Furthermore, Almahata Sitta has a much larger component of non-ureilitic material (at least among the clasts), possibly as much as 50%, compared with <1% in previous polymict ureilites. Perhaps Almahata Sitta should not even be classified as a ureilite, but rather as a unique meteoritic breccia.

The closest analog to Almahata Sitta among previously known meteorites is the complex breccia Kaidun (Zolensky and Ivanov 2003). Unlike Almahata Sitta, Kaidun fell (in 1980) as a single, coherent chunk of rock, weighing ~1 kg,
Several groups of researchers (Bischoff et al. 2010a, b; Herrin et al. 2010; Jenniskens et al. 2010; Hartmann et al. 2011) have hypothesized that a ureilite daughter body accumulated material from diverse chondritic impactors to become the parent asteroid of 2008 TC₃ (Fig. 6). Where and how the various stages of this evolutionary scenario occurred, and the details of the many processes involved, are actively being explored and will probably be debated for some time to come.

CONCLUDING REMARKS

The discovery of 2008 TC₃ and the fall of Almahata Sitta have given us a unique opportunity to link astronomical observations of an asteroid to fragments of that asteroid (i.e., meteorites) collected on the ground. Thus, it has provided an important data point for mapping asteroid–meteorite connections. However, the connection is not always straightforward. Asteroid 2008 TC₃/Almahata Sitta has heightened our awareness that many near-Earth asteroids could be loosely consolidated breccias on a whole-body scale, and could even be polymeric (Herrin et al. 2010; Popova et al. 2011). It has also led to speculation that polygenetic objects could be a common vehicle for simultaneous delivery of meteorites of different types to Earth (Herrin et al. 2010; Popova et al. 2011). Perhaps the complex sequence of events that resulted in Almahata Sitta (e.g. Fig. 6) is not commonplace. However, even if that is the case, it is often the anomalies that provide the most useful information, and further studies to understand the history of this unique meteorite will reveal important new clues to Solar System processes.

ACKNOWLEDGMENTS

We thank the editors of Elements for inviting us to write this article. We also thank (in alphabetical order) William Hartmann, Marian Horstmann, Peter Jenniskens, Marek Kozubal, Bob Reedy, Petr Scheirich, and Mike Zolensky for enlightening discussions and/or providing material for this article. We greatly appreciate helpful reviews received from Caroline Smith, Edward Scott, and guest editors Cari Corrigan and Guy Libourel. We thank Thomas Clark for editorial assistance. The work of C.G. and D.O.B. was supported by NASA grants NNX12A184G and NNX12AH74G. The work of A.B. was partly supported by the DFG within the SPP 1385.
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Most asteroids are collisional rubble from eons past, and few of them have survived intact. Vesta, the second most massive asteroid, is the only differentiated, rocky body in this category. This asteroid provides a unique view of the kinds of planetesimals that accreted to form the terrestrial planets. We know more about this asteroid than any other, thanks to its recently completed exploration by the orbiting Dawn spacecraft and studies of the ~1000 meteorites derived from it. The synergy provided by in situ analyses and samples has allowed an unparalleled understanding of Vesta’s mineralogy, petrology, geochemistry, and geochronology.

Vesta—outside and in

Asteroid Vesta, once called the smallest terrestrial planet (Keil 2002), is a leftover planetary building block. It was recently imaged, analyzed, and mapped from orbit by the Dawn spacecraft mission (described in Box 1).

Vesta has an average diameter of 510 km and a mean density of 3456 kg/m³ (Russell et al. 2012). Although the body is massive enough to have assumed a spherical shape, it is conspicuously out of round, a consequence of a huge impact basin (Fig. 1) near its south pole (Schenk et al. 2012). This basin, called RheaSilvia, has a diameter almost equal to that of Vesta. RheaSilvia is superimposed on an older crater, Veneneia. The combined impacts excavated deeply enough to expose the Vestan mantle (Jutzi et al. 2013; McSween et al. 2013). The RheaSilvia event launched a host of multikilometer-sized bodies that are still orbitally linked to Vesta—the Vesta family, or “Vestoids” (Binzel and Xu 1993). Dislodged samples of the Vestoids have migrated into nearby resonances—“escape hatches” from which they were perturbed into Earth-crossing orbits to eventually become meteorites.

Vesta is covered with a regolith of impact-comminuted igneous rocks and pocked with hundreds of craters. However, no lava flows or other volcanic constructs are recognizable (Jaumann et al. 2012). Steep slopes are everywhere on Vesta, complicating our understanding of its geomorphology.

Modeling of Vesta’s gravity and shape reveals its dense heart—an iron metal core 220 km across (Russell et al. 2012). The catastrophic RheaSilvia impact should likely have destroyed Vesta, but its metallic skeleton may have aided the asteroid’s survival. The effects of RheaSilvia, though, are hard to miss. A girdle of ridges and troughs that encircles the equator (Buczkowski et al. 2012) is thought to be a result of seismic reverberations from the core, and a thick blanket of ejecta extends outward from the basin to cover the southern half of the asteroid (Schenk et al. 2012).

Keywords: Vesta, asteroid, HED meteorites, differentiation, impact

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4 The names of Vestan features follow a Roman naming convention; RheaSilvia is named after the mother of Rome’s founders, Romulus and Remus.
VESTA SAMPLES—HED METEORITES

Four decades ago, McCord et al. (1970) identified Vesta as the likely parent body for the igneous howardite-eucrite-diogenite (“HED”) meteorites, based on their spectral similarities. Eucrites are comprised of plagioclase plus pyroxene and are commonly subdivided into fine-grained volcanic (basaltic eucrite) and coarse-grained plutonic (cumulate gabbroic eucrite) varieties (FIG. 2). Diogenites are ultramafic rocks formed through accumulation of crystals of orthopyroxene (pyroxenite) or orthopyroxene plus olivine (harzburgite) (FIG. 2). One mostly olivine cumulate (dunite) obviously linked to diogenites has also been described. Most eucrites and diogenites are breccias and represent regolith materials. These breccias can be monomict (containing clasts of a single lithology) or polymict (containing clasts of both basaltic and cumulate eucrite, or of multiple diogenite units). If both eucrite and diogenite clasts are present, the meteorite is a howardite. There is a continuum between polymict eucrites, howardites, and polymict diogenites, making the distinction somewhat arbitrary. The co-occurrence of these different rock types within breccias supports the idea that they formed on a common parent body. The oxygen isotope compositions of most HEDs also lie on the same 16O–17O–18O mass-fractionation line (Greenwood et al. 2005), taken as a geochemical fingerprint of their parent asteroid. Descriptions of the petrology and geochemistry of these meteorites abound, and are most recently reviewed by McSween et al. (2011).

The crystallization ages of basaltic eucrites, determined from radiogenic isotopes (87Rb–87Sr, 147Sm–143Nd, 207Pb–206Pb), are ~4.5 billion years (numerous references in McSween et al. 2011). The measured ages of plutonic diogenites and cumulate eucrites tend to be slightly younger, likely reflecting slower cooling through the isotope blocking temperatures. The decay products of short-lived radionuclides (26Al, 53Mn, 182Hf) are also found in HED meteorites, further confirming their ancient ages and the rapid differentiation of their parent body.

![Perspective view of the topography of Vesta’s south pole region, showing the huge Rheasilvia impact basin. Elevations, relative to the average Vesta surface, are indicated by coloration and demonstrate that this basin significantly affects the asteroid’s overall shape. This view was compiled by the Dawn Science Team from Framing Camera images.](image1)

![Photomicrographs (crossed polars) of (left) basaltic eucrite, composed of ferroan pyroxenes and plagioclase; (center) cumulate eucrite, composed of magnesian pyroxenes and plagioclase; and (right) diogenite, composed of orthopyroxene and, locally, olivine. Scale bars are 2.5 mm.](image2)
Despite the association of eucrites and diogenites in breccias, the petrogenetic relationships between them are not well understood. An early model explaining eucrites as partial melts and diogenites as solid residues (Stolper 1977) has mostly been supplanted by magma-ocean models that explain diogenites as cumulates and eucrites as residual liquids (e.g. Righter and Drake 1997; Greenwood et al. 2005; Mandler and Elkins-Tanton 2013). Asteroid-wide melting is suggested by rapid heating through decay of $^{26}$Al. However, models indicate highly efficient melt removal from asteroid mantles, so that only a few percent of magma might be present at any particular time, possibly preventing formation of a magma ocean (Wilson and Keil 2012). For a body the size of Vesta, eruptions directly to the surface via dikes would be mechanically difficult; instead, large magma chambers would likely form in the subsurface, and flows could erupt episodically from these chambers (Wilson and Keil 2012; Mandler and Elkins-Tanton 2013). The varied trace element patterns in diogenites are consistent with their derivation from separate magma chambers (Shearer et al. 1997; Mittlefehldt et al. 2012), and geochemical trends in basaltic eucrites may require multiple magmas and complex processes within the crust (Barrat et al. 2007).

**VESTA’S COMPOSITION AS MEASURED BY DAWN**

Comparing the reflectance spectra of Vesta, as measured by a visible–infrared spectrometer (VIR) (De Sanctis et al. 2012a), with the spectra of HEDs provides a means of identifying surface lithologies. Figure 3 shows a plot of the center positions of the 1 $\mu$m and 2 $\mu$m absorption bands (henceforth called B1 and BII) in well-characterized HED meteorites measured in the laboratory; these bands vary with pyroxene composition and abundance. The boxes in Figure 3 serve as a spectral classification, and a contoured, global cloud of Vestan spectral pixels measured by Dawn’s VIR spectrometer is also shown. The greatest concentration of Vestan pixels corresponds to howardite or cumulate eucrite. Howardite, representing the regolith, is the more likely interpretation. The eucrite and diogenite boxes in Figure 3 are not completely populated by Vesta data. This presumably reflects the large spatial resolution of VIR data (~700 m/pixel at the altitude where global mapping occurred). Mixing of eucrite with diogenite, or vice versa, is apparently common at this scale on Vesta, pulling spectra towards the center of the plot.

Vesta’s global weight ratio of Fe/Si and Fe/O, determined by GRaND (Prettyman et al. 2012), also identifies HED-like compositions (Fig. 4). In this diagram, howardite and diogenite provide the best match for Vesta data. Other meteorite types mostly plot outside the Vesta data ovals.

A VIR global map (De Sanctis et al. 2012a), using the classification in Figure 3, distinguishes areas dominated by howardite, eucrite, and diogenite (Fig. 5). Eucrite mostly occurs in heavily cratered, ancient crust near the equator, and diogenite is concentrated in the southern hemisphere. A global map of GRaND-measured variations in neutron absorption (Prettyman et al. 2012), which relate to the different element abundances in eucrites and diogenites, is illustrated in Figure 6. Although the spatial footprint of GRaND is large (~300 km), these data confirm the distributions of HED lithologies determined by VIR spectra.

The measured depletions of siderophile (metal-loving) trace elements (Righter and Drake 1997) and paleomagnetic indications of a former magnetic dynamo (Fu et al. 2012) in eucrites are evidence for a metal core in the HED parent asteroid. Compositional models of the interior of the HED parent body, constructed from the meteorite compositions, predict a metallic core with a mass fraction of 15–20% (Righter and Drake 1997). This compares favorably with the ~18% mass fraction of Vesta’s core determined by Dawn (Russell et al. 2012).
VESTA’S CHRONOLOGY AND IMPACT HISTORY

The ages of Vesta’s surface units, derived from the density of craters, are 3 to 4 billion years (Marchi et al. 2012). These are minimum ages, because the surface has become effectively saturated with craters, so that new craters destroy older ones. The ~4.5-billion-year crystallization ages of eucrites, and especially the former presence of short-lived radionuclides, reveal that Vesta melted and differentiated earlier, within the first several million years of Solar System history. However, somewhat younger ages for diogenites and cumulate eucrites indicate a protracted cooling history lasting perhaps 50 million years.

Like other bodies in the Solar System, Vesta was struck by careening, massive bolides in the period from 4.1 to 3.5 billion years ago. This period of high impactor flux, sometimes called the “late heavy bombardment,” is thought to have resulted from gravitational stirring of the asteroid belt when the giant planets migrated inward or outward to their present orbital positions. This bombardment is revealed by a number of peaks among the 40Ar–39Ar ages of eucrite breccias, and these peaks represent a series of age-resetting events.

Rheasilvia, the most prominent feature on Vesta, is ~1.0 billion years old as determined from crater counting and therefore is considerably younger than the rest of the asteroid’s surface (Marchi et al. 2012). This age is consistent with the ages of the Vestoids, the orbits of which would have been scrambled if they had been launched from Vesta much earlier.

VESTA’S SURPRISING SOIL

Although howardite covers most of Vesta’s surface, it is not the most abundant type of HED meteorite. The Rheasilvia impact excavated much more material from the deep crust and mantle than from the veneer of regolith on the surface. A prediction that the regolith might have a globally homogenized composition (Warren et al. 2009) was not born out, as Figures 5 and 6 show that the proportions of eucrite and diogenite in howardite terranes vary considerably. Although a few exotic components have been found in howardites, such as potassium-rich glasses suggested to represent a highly fractionated component analogous to lunar KREEP (Barrat et al. 2009), none has been detected at Dawn mapping scales.

Another surprise was GRaND’s discovery of hydrogen in the regolith (Prettyman et al. 2012). Broad regions of the surface contain >400 μg/g H (Fig. 7), an abundance that cannot be explained by solar wind implantation, as on the Moon. The hydrogen-rich regions have low albedo and exhibit a 2.8 μm absorption in VIR spectra, which is attributable to OH in phyllosilicate minerals (De Sanctis et al. 2012b). In hindsight, this discovery should not have been a surprise. Howardites commonly contain foreign clasts of carbonaceous chondrite meteorites (Fig. 7), which are largely composed of OH-bearing serpentine and clays. Laboratory spectra of eucrites mixed with a few percent carbonaceous chondrite (which would give bulk hydrogen contents like those measured by GRaND) provide an excellent match with the spectra of these dark regions (Reddy et al. 2012).

Solar irradiation and micrometeorite bombardment have altered the spectrum of lunar soil—a process called space weathering. The spectral changes result from the production of nanoscale iron metal particles, which subdue absorption bands and modify the continuum slope. On Vesta, space weathering takes a different form. Although the albedo of the Vestan surface exposed by recent impacts changes over time, its spectrum does not show the characteristics of nanophase iron (Pieters et al. 2012), and this mineral is virtually absent from howardites. Vesta’s location so far from the Sun, where impact velocities are lower, and possible shielding of cosmic rays by its remnant magnetic field (Fu et al. 2012) may account for this difference in soil mineralogy.

**FIGURE 5** Global map of the distribution of terrains dominated by eucrite, diogenite, and howardite on Vesta, based on VIR spectra from De Sanctis et al. (2012a). The dashed and dotted lines represent the limits of the Rheasilvia and Veneneia impact basins, respectively.
SUMMARY
Coupling the petrologic, geochemical, and geochronologic information afforded by laboratory studies of HED meteorites with the geologic context provided by Dawn’s orbital exploration of Vesta allows an understanding of this unique, antique asteroid—the kind of objects that accreted to form our own planet. Its early differentiation and magmatic evolution, violent collisional history, and interaction with the space environment are all imprinted on its surface and written in its rocks. Asteroid Vesta now joins the Moon and Mars as astronomical objects that have been transformed into geologic worlds.

ACKNOWLEDGMENTS
We gratefully acknowledge the efforts of the Dawn Operations and Science Teams (CT Russell, Principal Investigator) and reviews by T. J. McCoy and J. A. Barrat. This work was supported by NASA’s Discovery Program through contracts to UCLA (HYM) and the Jet Propulsion Laboratory (THP), and by the Italian Space Agency (MCD).

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Do You Think Ions Like Queuing Up?
Asteroid Itokawa: A Source of Ordinary Chondrites and A Laboratory for Surface Processes

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The Japanese spacecraft Hayabusa returned samples from the surface of an asteroid (near-Earth S-type asteroid 25143 Itokawa) for the first time in human history. This article describes the results of the initial analysis of the mineralogy, micropetrology, and elemental and isotopic compositions of regolith particles from Itokawa measuring 30–180 μm in diameter. The results show a direct link between ordinary chondrites and S-type asteroids. The regolith particles provide evidence of space-weathering rims and grain abrasion, and the information obtained has elucidated various processes on the airless surface of Itokawa, such as the impact of small objects, grain motion, and irradiation by solar wind.

Keywords: Hayabusa mission, regolith, space weathering, solar wind, impact, S-type asteroids

HAYABUSA: SAMPLE-RETURN MISSION

The spacecraft Hayabusa of the Japan Aerospace Exploration Agency (JAXA) arrived at the near-Earth S-type asteroid 25143 Itokawa in September 2005 and made remote sensing observations of the asteroid (Fujiwara et al. 2006). Fine particles on Itokawa’s surface were recovered and successfully returned to Earth in June 2010. This material was the first sample recovered from an asteroid and returned to Earth. Furthermore, Itokawa’s surface was only the second extraterrestrial surface to have been sampled (the first being the Moon’s, which was sampled by the Apollo and Luna missions, e.g. Heiken et al. 1991). A preliminary examination of these samples was carried out in Japan in 2011 (Nakamura et al. 2011; Nakamura et al. 2012), and more detailed investigations are now being performed in laboratories around the world.

Asteroids are small celestial bodies in our Solar System that have not grown to planets, and thus hold valuable information about conditions during the formation of the Solar System. It is known from images acquired by spacecraft that the surfaces of relatively large asteroids (a few tens to a hundred kilometers in size), such as asteroid 433 Eros (Veverka et al. 2001), are roughly similar to the Moon’s surface. They are covered with sand-sized particles, called regolith, formed mainly by crushing of material during the impact of celestial objects onto the asteroids, and they have a large number of impact craters. In contrast, Itokawa is a small asteroid (535 × 294 × 209 m) with low gravity and thus a low escape velocity (~0.2 m/sec) (Fujiwara et al. 2006). Observations by the Hayabusa spacecraft revealed that its surface morphology is different from that of larger asteroids: the surface is mostly covered by boulders, with a maximum size of about 50 m, and in some areas by regolith (Fig. 1a). The porosity of Itokawa is estimated to be about 40% based on its low bulk density (1.9 g/cm³). The presence of a large number of boulders and the high porosity imply that Itokawa is a rubble-pile asteroid that was formed by the early collisional breakup of a preexisting large parent body followed by the reagglomeration of a small fraction of the original fragments (Fujiwara et al. 2006).

It has long been accepted wisdom that most meteorites originate from asteroids, as demonstrated by orbital determinations from observed meteorite falls (Cloutis et al. 2014 this issue). Primitive meteorites called chondrites constitute more than 80% of observed meteorite falls. They are divided into three major classes based on chemical composition: ordinary, carbonaceous, and enstatite chondrites. As discussed below, Itokawa materials are thought to represent ordinary chondrites. Ordinary chondrites comprise three groups, H, L, and LL, which vary in the amounts and forms of iron they contain. “Ordinary” refers to their prevalence; they constitute 74% of observed meteorite falls. Another criterion for chondrite classification is rock texture, which correlates with metamorphic or alteration history (petrologic type). Increasing thermal metamorphism corresponds to types 3 to 6, while increasing hydrous alteration is observed in types 3 to 1.

The composition of asteroids has been estimated by comparing their reflectance spectra in visible to near-infrared light with those of meteorites. Ground-based telescope observation (Binzel et al. 2001) and remote sensing images obtained by the Hayabusa spacecraft (Abe et al. 2006) indicated that the materials on S-type asteroid Itokawa are probably similar to thermally metamorphosed LL chondrites belonging to petrologic type 5 or 6 (i.e. LL5 or LL6). However, the spectral features of S-type asteroids and ordinary chondrites do not exactly match: the reflectance of the asteroids in the shorter-wavelength (blue) region is lower than that of the meteorites (Cloutis et al. 2014). It has been determined that such spectral darkening and reddening occurred on the Moon by “space weathering” (e.g. Heiken et al. 1991), and similar phenomena are expected on the surfaces of asteroids. Itokawa samples allow a direct validation of the relation between asteroid observations and meteorite samples, and they can also be compared with lunar regolith. Thus, in addition to providing information about composition, Itokawa regolith...
samples can be studied to understand surface processes on an asteroid, such as regolith formation, micrometeorite bombardment, and irradiation by cosmic rays. Exotic materials, including organic-rich matter provided by impacts on the asteroid’s surface, might also be included in the samples. The returned samples from Itokawa are ideal for such examination because they come from a known source and they have experienced minimal contamination from the Earth’s atmosphere and organic materials.

**SAMPLE COLLECTION AND CURATION**

In the original sampling plan, a bullet was to have been shot from the spacecraft into Itokawa’s regolith at the time of spacecraft touchdown on the surface, and particles were then to have been collected and placed in a sample capsule (Yano et al. 2006). Unfortunately, no bullets were shot during the two touchdowns and only a limited number of small particles were recovered in the two sample catchers, A and B, which correspond to the second and first touchdowns, respectively (Figs. 1A, B) (Nakamura et al. 2011). The sample capsule was opened at JAXA’s curation facility.

In total, more than 2000 returned particles have been identified by preliminary elemental analysis to date, and more remain to be identified. Two methods were used to obtain sample particles (Nakamura et al. 2011). The first involved sweeping the inner wall of sample catcher A with a Teflon spatula. However, most of the particles collected on the spatula were too small (less than 10 μm) to be safely handled without losing them. The other method was to collect particles that fell from sample catchers A and B onto a silica glass plate after physically tapping the catcher. Larger particles (maximum size about 300 μm) were safely picked up from the quartz plates (these are called “tapping samples”).

**SAMPLE ANALYSIS**

Sixty-eight particles 30–180 μm in size from the tapping samples (64 and 4 particles from sample catchers A and B, respectively) (Fig. 1C) were allocated to researchers for initial analysis. The total volume of 48 particles examined by X-ray microtomography was approximately 4×10^6 μm³, corresponding to a sphere about 200 μm in diameter or 15 μg in mass (Tsuchiyama et al. 2013a).

It was important to prepare a systematic sample-analysis program, where different analyses were made grain by grain, to obtain as much information as possible from the small amount of tiny particles. The 68 particles were divided into two groups for analysis. One group followed an analytical protocol designed for the characterization of space weathering, noble gases, and carbonaceous and organic materials, while minimizing contamination. For the analysis of space weathering, ultrathin sections were made across the surfaces of twelve particles mainly using an ultramicrotome in a purged nitrogen atmosphere to avoid oxidation of Fe nanoparticles, and these were examined by transmission electron microscopy (TEM) (Noguchi et al. 2011, 2013). The isotopic compositions of noble gases in three particles, which were handled in a nitrogen-purged atmosphere, were measured by laser ablation mass spectrometry (Nagao et al. 2011). The surfaces of five particles were examined nondestructively by micro-Raman and micro-infrared spectroscopy to seek carbonaceous materials possibly present on the surfaces (Kitajima et al. 2011). These particles were then rinsed with a small amount of dichloromethane/methanol solution, and the extracts were examined using high-precision liquid chromatography to seek amino acids or using time-of-flight secondary ion mass spectrometry (TOF-SIMS) to analyze other organic compounds, including a search for polycyclic aromatic hydrocarbons (Naraoka et al. 2012). Neutron activation analysis of one particle was done after the rinse to determine major and minor element abundance (Ebihara et al. 2011). The residual samples from all of the above treatments, except for those analyzed for noble gases, were then added to the mainstream analytical protocol described below.

Particles of the mainstream group, including the remaining portion of the 48 particles, were sequentially examined by progressively more destructive analytical methods (Nakamura et al. 2011; Tsuchiyama et al. 2013a). First, synchrotron radiation (SR)–based microtomography was used to obtain three-dimensional structures of the Itokawa grains (Tsuchiyama et al. 2011, 2013a). This was followed by SR-based X-ray diffraction (XRD) to identify mineral phases (Nakamura et al. 2011). The use of microtomography together with XRD for nondestructive analysis is one of the key features of the Hayabusa preliminary examination strategy involving sequential studies. The three-dimensional mineral distribution, together with the external shape of each particle, provides critical information concerning where a particle should be cut to ensure that the subsequent destructive analyses examine the best areas of the minerals exposed in the cross sections of these small particles. Then, the particles were polished or sectioned by an ultramicrotome or a focused ion beam (FIB). Ultrathin sections were analyzed by TEM to examine the micro- and nanostructures (Nakamura et al. 2011, 2012). The polished cross sections of the particles were examined using an optical microscope and a field-emission scanning electron microscope (FE-SEM) (Zolensky et al. 2012), and the chemical compositions of minerals were measured using an electron probe microanalyzer (EPMA) (Nakamura et al. 2011). Subsequently, oxygen and magnesium isotope compositions of minerals together
with some minor element compositions were determined using secondary ion mass spectroscopy (SIMS) (Yurimoto et al. 2011a, b). The surface nanomorphologies of eight particles were also observed by FE-SEM before sectioning (Matsumoto et al. 2012).

Five different particles were independently studied by another examination team (Nakamura et al. 2012). First, the surface nanomorphologies of these particles were observed by FE-SEM, and then the particles were sectioned using FIB. The FIB sections were observed using an optical microscope and FE-SEM; the elemental and oxygen isotope compositions of minerals were measured by EPMA and SIMS, respectively.

**WHAT WAS LEARNED FROM THE SAMPLE ANALYSES**

**Materials on Itokawa's Surface**

A list of minerals identified in Hayabusa samples (Nakamura et al. 2011) is shown in Table 1, and typical particle cross sections are shown in Figure 2. The isotopic compositions of minerals can give information about their formation and later history. The oxygen isotope compositions of Hayabusa samples are different from those of terrestrial materials and are consistent with those of LL chondrites (Table 1), although the possibility of an LL chondrite affinity cannot be excluded by the isotope ratios alone (Yurimoto et al., 2011a). Subsequently, more accurate data on the oxygen isotope compositions showed that the Itokawa particles resemble equilibrated LL chondrites (Nakashima et al. 2013).

The mineral assemblage of the Itokawa samples is consistent with that of ordinary chondrites. The chemical compositions of minerals fall within the compositional range of LL chondrites (Table 1) (Nakamura et al. 2011; Nakamura et al. 2012). The modal abundances of minerals are also consistent with LL chondrites (Table 1) (Tsuchiyama et al., 2011, 2013a). Slight differences of the mineral abundances between the Itokawa sample and LL chondrite might be due to a statistically insufficient amount of Itokawa sample. Based on the abundances and the chemical compositions of minerals, the bulk density (3.4 g/cm²; Tsuchiyama et al. 2011, 2013a) and the bulk chemical composition (Nakamura et al. 2011) were obtained. The Fe/Sc and Ni/Co ratios are consistent with those of ordinary chondrites. Depletion of Ir, which may be the result of condensation in the early solar nebula before chondrite formation, was also noted (Ebihara et al. 2011).

The above results clearly show that the materials making up Itokawa's surface correspond to ordinary chondrites, in particular LL chondrites. This provides the first direct link between asteroids and meteorites based on sample analysis.

**Itokawa's Parent Body**

About 90% of the Itokawa particles examined exhibit triple junctions at the boundaries between coarse silicates (Fig. 2a) or almost monomineralic features (Fig. 2c, d); the particles show an almost homogeneous chemical composition of minerals, indicating that they have been thermally annealed, and thus they are similar to LL5 and/or LL6 chondrites (Nakamura et al. 2011; Tsuchiyama et al., 2011, 2013a). The maximum temperature estimated from the chemical compositions of an equilibrated Itokawa mineral pair of Ca-poor and Ca-rich pyroxenes is about 800°C. If a small body like Itokawa was heated to 800°C, even its interior would have cooled very fast. Based on a heating model calculation using the extinct nuclide 26Al as a heat source, the original Itokawa parent body radius should have been larger than 20 km (Nakamura et al. 2011) (Fig. 3). The remaining Itokawa particles (~10%), which are made up of fine silicate grains and have more heterogeneous chemical compositions, are similar to LL4 chondrites (Fig. 2b). Such less-equilibrated material should have formed near the original parent-body surface. A relative age determination, using the 26Al–26Mg isotope system, indicates that the maximum age of thermal metamorphism is 4.562 billion years (Yurimoto et al. 2011b).

Some of the Itokawa particles have minerals with impact shock features (Zolensky et al. 2012). Optical microscope observations suggest mild impact at the S2 meteorite shock stage, which corresponds to a shock pressure of 5–10 GPa. It is not yet known how these features are related to impacts on the Itokawa parent body and/or to Itokawa's formation.

**Surface Processes on Itokawa**

Examination of regolith particles from Itokawa provides valuable information on surface processes that cannot be obtained from existing meteorites. The shape distribution of Itokawa particles with respect to their three axial ratios is not statistically different from that of fragments formed by high-speed impact in laboratory experiments, indicating that the Itokawa particles resulted from mechanical disaggregation, primarily as a response to impacts (Tsuchiyama et al. 2011, 2013a). The particle size distribution has a cumulative log slope of about −2, which is more gradual than that of boulders (about −3), indicating a lower abundance of 10–100 μm particles than of millimeter- to centimeter-sized regolith particles (Tsuchiyama et al. 2011, 2013a); this conclusion is consistent with the close-up image of regolith taken by the Hayabusa spacecraft (Fig. 1a) (Yano et al. 2006). This size distribution may be explained by smaller particles having higher ejection velocities and thus higher loss rates as a result of impacts.
on Itokawa. In contrast, abundant submillimeter-sized fragments in regolith are observed on larger bodies such as the Moon (Heiken et al. 1991).

The surfaces of regolith particles can be regarded as an interface with the space environment, where the impacts of small objects and irradiation by the solar wind and galactic cosmic rays have been recorded (Fig. 3). Two kinds of surface modification have been recognized on Itokawa particles. One is the formation of space-weathering rims: thin layers of amorphous silicates a few to 80 nm in thickness contain a large amount of iron-rich nanophase (FIG. 4A) (Noguchi et al. 2011, 2013). The presence of the nanophase is the cause of the reddening and darkening of the reflectance spectrum, known as space weathering (FIG. 4C). In contrast, abundant submillimeter-sized fragments in regolith are observed on larger bodies such as the Moon (Heiken et al. 1991).

The other observed surface modification that has taken place on Itokawa grains is grain abrasion (Tsuchiyama et al. 2011, 2013b). The edges of Itokawa particle surfaces observed by microtomography are usually angular (FIG. 2C), while faint or no steps were observed on rounded surfaces (FIG. 2D). Similar features were also observed with higher resolution by FE-SEM; sharp steps formed by fracturing were observed on angular surfaces (FIG. 5A), while faint or no steps were observed on rounded surfaces (FIG. 5B) (Matsumoto et al. 2012). These results indicate that some mechanically crushed fragments were abraded later. The degree of rim development due to space weathering is not related to the abrasion (Tsuchiyama et al. 2013b). Thus, the abrasion process can be regarded as a different type of space weathering with a longer timescale, and should be called “space erosion.” This abrasion may be the result of grain migration, which is caused by seismic waves repeatedly reflecting off the surface of Itokawa after impacts (Tschiyama et al. 2011). Release profiles of solar noble gases from Itokawa particles are consistent with grain motion in the regolith layer, and observed He losses suggest preferential abrasion of the space-weathering rim from the particle surfaces (Nagao et al. 2011).

Galactic cosmic rays can reach much deeper levels (several tens of centimeters below the surface) in an asteroid. However, no measurable cosmic ray–produced Ne was detected beyond experimental errors (Nagao et al. 2011).

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Abbreviation</th>
<th>Formula</th>
<th>Crystal system</th>
<th>Mineral abundance (wt%)</th>
<th>Chemical composition</th>
<th>Oxygen isotope composition, (\delta^{18}O_{SMOW} (%e))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olivine</td>
<td>Ol</td>
<td>(Mg,Fe)(_2)SiO(_4)</td>
<td>Orth</td>
<td>67.2</td>
<td>(\delta^{18}O_{SMOW} = -0.52%e)</td>
<td></td>
</tr>
<tr>
<td>Low-Ca pyroxene</td>
<td>LPx</td>
<td>(Mg,Fe)(_2)SiO(_3)</td>
<td>Orth, Mono</td>
<td>18.1</td>
<td>(\delta^{18}O_{SMOW} = -0.52%e)</td>
<td></td>
</tr>
<tr>
<td>High-Ca pyroxene</td>
<td>HPx</td>
<td>(Ca,Mg,Fe)(_2)SiO(_3)</td>
<td>Mono</td>
<td>2.6</td>
<td>(\delta^{18}O_{SMOW} = -0.52%e)</td>
<td></td>
</tr>
<tr>
<td>Plagioclase</td>
<td>Pl</td>
<td>(Na,Ca)Al(Al,Si)(_2)Si(_2)O(_8)</td>
<td>Mono, Tri</td>
<td>8.5</td>
<td>(\delta^{18}O_{SMOW} = -0.52%e)</td>
<td></td>
</tr>
<tr>
<td>Tropolite</td>
<td>Tr</td>
<td>FeS</td>
<td>Hex</td>
<td>2.9</td>
<td>(\delta^{18}O_{SMOW} = -0.52%e)</td>
<td></td>
</tr>
<tr>
<td>Kamacite</td>
<td>Kam</td>
<td>(\alpha)(Fe,Ni)</td>
<td>Cub</td>
<td>0.0</td>
<td>(\delta^{18}O_{SMOW} = -0.52%e)</td>
<td></td>
</tr>
<tr>
<td>Taenite</td>
<td>Tae</td>
<td>(\gamma)(Fe,Ni)</td>
<td>Cub</td>
<td>0.5</td>
<td>(\delta^{18}O_{SMOW} = -0.52%e)</td>
<td></td>
</tr>
<tr>
<td>Chromite</td>
<td>Chm</td>
<td>FeCr(_2)O(_4)</td>
<td>Cub</td>
<td>0.1</td>
<td>(\delta^{18}O_{SMOW} = -0.52%e)</td>
<td></td>
</tr>
<tr>
<td>Apatite</td>
<td>Cp(^f)</td>
<td>Ca(_5)(PO(_4))(_2)(F,Cl,OH)</td>
<td>Hex</td>
<td>0.1</td>
<td>(\delta^{18}O_{SMOW} = -0.52%e)</td>
<td></td>
</tr>
<tr>
<td>Merrillite</td>
<td>Cp(^g)</td>
<td>Ca(_5)NaMg(PO(_4))(_2)</td>
<td>Tri</td>
<td></td>
<td>(\delta^{18}O_{SMOW} = -0.52%e)</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Cub: cubic, Hex: hexagonal, Orth: orthorhombic, Mono: monoclinic, Tri: triclinic
\(^b\) Data from Tsuchiyama et al. (2013a)
\(^c\) Data from Nakamura et al. (2011)
\(^d\) From Yurimoto et al. (2011a)
\(^e\) Data from Nakamura et al. (2011)
\(^f\) Measurements of terrestrial olivine from San Carlos and plagioclase from Miyake-jima (theoretically, \(\delta^{18}O_{SMOW} = 0\) )
\(^g\) Measurements of terrestrial olivine from San Carlos and plagioclase from Miyake-jima (theoretically, \(\delta^{18}O_{SMOW} = 0\) )
\(^h\) Apatite and merrillite are abbreviated together as Cp (Ca phosphate)
This result permits estimation of the upper limit of the residence timescale of grains in the regolith layer, namely, about 8 million years. This is much shorter than the nominal exposure ages of over 400 million years for mature lunar regolith (Wieler 2002). The short duration of cosmic ray exposure and solar wind implantation indicates that the loss of surface materials from this small asteroid with low gravity through impacts occurred at a rate of several tens of centimeters per million years (Fig. 3) (Nagao et al. 2011). Submicrometer-sized impact craters were observed on the surface of one grain (Fig. 5c) (Nakamura et al. 2012). They may have been created by the impact of high-speed secondary nanoparticles produced by the impact of an object into Itokawa’s regolith. Tiny, flattened glass objects, which seem to be melt splash (Fig. 5d) (Nakamura et al. 2012; Matsumoto et al. 2012), probably also formed as a result of small-scale impacts. Large-scale melting features, such as the agglutinates found in lunar regolith, have not yet been observed among the Itokawa samples (Tsukiyama et al. 2011). This can be explained by the differences between the mass and representative impact velocities for asteroids and the Moon (about 5 km/sec and over 10 km/sec, respectively).

SUMMARY AND FUTURE OUTLOOK

Figure 3 illustrates Itokawa’s history and regolith evolution as elucidated from a preliminary examination of the returned samples. This history is summarized as follows: (1) Formation of the Itokawa parent body, which was larger than 20 km in diameter and composed of LL chondrite materials. (2) Thermal metamorphism (up to about 800°C), probably slightly less than 4.562 billion years ago. (3) Catastrophic impact and formation of the rubble-pile asteroid Itokawa by reaccumulation of some fragments. (4) Formation of regolith by impacts of small objects, with selective escape of the finest-scale particles. (5) Implantation of solar wind into the uppermost particle surfaces and formation of space-weathering rims with a timescale of ≈10^3 y. (6) Grain abrasion, probably due to seismic-induced particle motion, with time periods significantly longer than 10^3 y. Processes (5) and (6) might have been repeated. (7) Final escape of particles from the asteroid by impact within the past 8 million years.

As the size and amount of the collected Itokawa samples are very limited, some basic information has not yet been obtained. For example, we do not know the absolute formation age of Itokawa material. The nature of the catastrophic impact on the parent body is not well understood, nor is the age of this impact, which corresponds to Itokawa’s formation age. We have not found any unmetamorphosed chondritic materials (LL3 chondrites) that might have been present on the surface of the original parent asteroid. The cause of grain abrasion should be confirmed. It will be critical to make comparisons with the lunar regolith by analyzing particles from each body using the same methods, which will eventually lead to a comprehensive understanding of surface processes on airless bodies.

It is expected that exotic materials that originated from other celestial bodies and fell on Itokawa are included in the Hayabusa samples. Carbonaceous materials, including...
organic materials, are being actively sought but have not been detected thus far (Kitajima et al. 2011; Naraoka et al. 2012). The safe handling of tiny grains less than 10 μm across is difficult at present. Unique materials may be present in these tiny particles.

We do not completely understand how the Hayabusa spacecraft collected the samples without shooting a bullet. Three sampling mechanisms are possible (Tsuchiyama et al. 2011): (1) ejection by impact with the sampler horn, (2) levitation by electrostatic interaction among charged particles, and (3) ejection by thruster jets from the ascending (or descending) spacecraft. Some of these mechanisms might have caused the fractionation of particle sizes and/or mineral abundances. As all the particles analyzed show solar noble gas implantation and space-weathering rims, they must have been sampled from the outermost surface of the asteroid. More detailed analysis may elucidate the mechanism.

The detailed-analysis phase for Hayabusa samples started in mid 2012. The analysis team looks forward to many new discoveries and to sharing them with the scientific community and the world.

ACKNOWLEDGMENTS

I thank the Hayabusa project and sample curation teams at JAXA. I am also grateful to members of the preliminary examination team and research facilities that gave opportunities for the sample analyses.

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NEAR-SHOEMAKER AT EROS: THE FIRST DETAILED EXPLORATION OF AN ASTEROID

Larry R. Nittler

On 14 February 2000, a small robotic probe entered orbit around the asteroid 433 Eros to undertake a groundbreaking mission aimed largely at clarifying the relationships between asteroids in space and meteorite samples collected on Earth. The Near Earth Asteroid Rendezvous (NEAR) mission (Cheng et al. 1997) was the first in NASA’s line of “faster, better, cheaper” Discovery planetary missions. Launched on 17 February 1996, the NEAR spacecraft (later renamed NEAR-Shoemaker2 in honor of pioneering astrogeologist Eugene Shoemaker) collected images and spectra during a ~1200 km flyby of asteroid 253 Mathilde in 1997 (Veverka et al. 1999). The Eros orbit insertion on Valentine’s Day 2000, appropriate for a mission to a body named for the Greek god of love, began a successful year of data collection by a suite of scientific instruments, culminating in a controlled descent and gentle landing on the asteroid’s surface on 12 February 2001. The mission ended two weeks later, just over 5 years after launch.

As an S-class asteroid, Eros is typical of the most abundant asteroids of the inner main belt, which are postulated to be progenitors of the ordinary chondrites (OCs). However, as a Mars-crossing Amor asteroid (perihelion distance of 1.133 AU), Eros was reachable by a relatively low-cost spacecraft. The geological, mineralogical, and geochemical data obtained by NEAR from Eros support the relationship between S-class asteroids and OC meteorites (McCoy et al. 2002) and laid the groundwork for the recent successes of Hayabusa and Dawn in their investigations of 25143 Itokawa and 4 Vesta (Tsuihjima 2014 this issue; McSween et al. 2014 this issue).

GEOLGY

Eros is a potato-shaped body, roughly 35 km long by 10 km across, marked by impact features large and small and a huge number of boulders (Fig. 1). Its inferred bulk density of 2.7 g/cm³ (Veverka et al. 2000) is too high for it to be a rubble pile and suggests rather that the asteroid is a coherent body, but with significant porosity due to large-scale fracturing from impacts. The NEAR magnetometer detected no hint of a magnetic field, consistent with Eros being a primitive, undifferentiated object. NEAR returned more than 160,000 images of Eros acquired at a variety of resolutions and under different lighting conditions. These images revealed abundant features, including grooves and ridges, depressions, crater chains, and rectilinear craters, and showed the asteroid to be covered by a thick layer of fragmental debris (regolith).

Particularly interesting was the discovery of deposits known as “ponds” (Robinson et al. 2001). These are smooth deposits that have infilled many craters and depressions, crater chains, and rectilinear craters, and showed the asteroid to be covered by a thick layer of fragmental debris (regolith). Particularly interesting was the discovery of deposits known as “ponds” (Robinson et al. 2001). These are smooth deposits that have infilled many craters and depressions (Fig. 1c). They are possibly due to pre-eruptive movement of extremely fine regolith material via electrostatic levitation and thus might represent a physical fractionation of material by size across the surface. Based on the final images returned by the spacecraft during its controlled descent, it is believed that NEAR’s landing site was in fact in one of these dusty ponds. More recently, Hayabusa discovered similar ponds on Itokawa (Yano et al. 2006), suggesting that they are a common asteroidal feature.

MINERALOGY

Reflectance spectroscopy is a widely used tool for inferring mineralogical information from rocky planets, including asteroids. Particularly useful are near-infrared spectral absorption features (bands) at wavelengths around 1 and 2 microns arising from the common Fe-bearing silicate minerals olivine and pyroxene. Data from the Near-Infrared Spectrometer onboard NEAR both confirmed ground-based measurements indicating the presence of the 1- and 2-micron bands and revealed a remarkable degree of mineralogical uniformity across the surface (McFadden et al. 2001; Bell et al. 2002). The nature of these spectral features (e.g. band centers, band area ratios) depends on the relative amounts of olivine and pyroxene as well as on the composition of the minerals, and analysis of the Eros data indicates a silicate composition similar to (but not unique to) that of OC meteorites. However, as commonly seen in ground-based observations of S-asteroids, the near-infrared reflectance spectrum of Eros is considerably redder, that is, it has a more steeply increasing slope at longer wavelengths, compared to laboratory measurements of OCs. This discrepancy is generally attributed to “space weathering,” the alteration of the optical properties of the surface materials due to bombardment by radiation and micrometeoroids.

CHEMICAL COMPOSITION

NEAR carried two instruments designed to directly determine the chemical composition of Eros: the X-ray Spectrometer (XRS) and the Gamma Ray Spectrometer (GRS). XRS detected fluorescent X-rays emitted from surface atoms of Mg, Al, Si, S, Ca, Cr, and Fe (<100 μm depth) under solar X-ray bombardment, and GRS detected gamma ray emission from the top tens of centimeters due to natural radioactive decay (40K) or to interactions with galactic cosmic rays (O, Mg, Si, Fe). XRS acquired its best data during several solar flares, periods of enhanced solar X-ray emission, when it was sampling regions across the asteroid. GRS did not obtain interpretable signals during orbit. However, following NEAR’s controlled descent, GRS was fortuitously in an ideal orientation to carry out surface measurements, and the mission was extended a week to obtain high signal-to-noise gamma ray data at the landing site.

For most of the elements measured by either XRS or GRS (in particular Mg/Si, Al/Si, and Ca/Si ratios and K abundance), Eros’s surface was found to have a composition most consistent with that of OC meteorites (H, L, and LL chondrites; Fig. 2), compared to other types of asteroidal meteorites (Trombka et al. 2000; Evans et al. 2001; Nittler et al. 2001). The Fe/Si ratio was also found to be consistent with OCs. However, the values measured by the two instruments did not agree with each other, with the XRS measurements indicating high (H chondrite-like) iron contents and the GRS showing lower (L- or LL-like) ones (Fig. 2). This difference is not fully understood. It may reflect a systematic uncertainty in one or both of the measurement techniques, not taken into account in the analysis methodology (Okada 2004). Alternatively, it may indicate a local difference in Fe/Si at the NEAR landing site, where the GRS measurement was made, compared to the larger-scale XRS measurements. The latter possibility could be explained by a physical separation of Fe metal grains from finer-grained silicate material during
the formation of the pond deposit on which NEAR most likely landed. In any case, the range of measured Fe/Si ratios is consistent with undifferentiated, chondrite-like compositions.

A major surprise of NEAR geochemical measurements was the discovery that the surface of Eros is highly depleted in sulfur; the XRS-derived S/Si ratio is an order of magnitude lower than that of meteorites (Fig. 2c). Two possible explanations were originally suggested to explain this strongly nonchondritic composition (Trombka et al. 2000). First, the space weathering processes invoked to explain the red slope of Eros’s near-infrared reflectance spectrum (micrometeoroid and/or ion bombardment) could in principle also preferentially remove surface S, relative to less volatile species. If so, the observed S depletion would be essentially a surface regolith effect, and the bulk of Eros could have OC-like S/Si ratios. Alternatively, Trombka et al. (2000) pointed out that the first melt to form when chondritic material is heated is rich in S, so the observed S depletion could instead reflect a limited amount of partial melting and melt separation in a mainly undifferentiated body. In this case, Eros might represent a type of “primitive achondrite” akin to some known meteorite groups (McCoy et al. 2000), rather than an OC-like body. Icarus 184: 338-343

**REFERENCES**


Foley CN and 6 coauthors (2006) Minor element evidence that asteroid 433 Eros is a space-weathered ordinary chondrite parent body. Icarus 184: 338-343


Noguchi T and 17 coauthors (2011) Incipient space weathering observed on the surface of Itokawa dust particles. Science 333: 1121-1125


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**FIGURE 2** Element weight ratios on Eros (green ellipses) compared to laboratory data for meteorites (Nittler et al. 2004). (A) Mg/Si versus Al/Si, both determined by XRS. (B) Ca/Si (XRS) versus Fe/Si (XRS and GRS). (C) Cr/Fe versus S/Si, both determined by XRS. For a strong S depletion, Eros’s surface is most consistent with the composition of ordinary chondrite (H, L, LL) meteorites. The OC-like Cr/Fe ratio argues for a space weathering explanation for the low S/Si ratio. XRS data are from Trombka et al. (2000), Nittler et al. (2001), Foley et al. (2006), and Lim and Nittler (2009); GRS data are from Enos et al. (2001).
NEW METEORITICAL SOCIETY COUNCIL

A new Council will take office in January 2015, with Mike Zolensky as president and Monica Grady as past president. The Nominating Committee (Gretchen Benedix, William Bottke, Denton Ebel, Matthieu Gounelle, David Kring, and Hiroko Nagahara, chair) prepared the slate of candidates listed below. The Council has affirmed that this slate was selected in accordance with the Society’s Constitution and Bylaws.

The new vice president of the Society will be Trevor R. Ireland of the Australian National University. Michael K. Weisberg of Kingsborough Community College and the American Museum of Natural History will be the new secretary, and Candace Kohl, of Del Mar, California, will be our new treasurer.

The following councilors will return for a second term: Jay Melosh (Purdue University), Larry R. Nittler (Carnegie Institution of Washington), Maria Schönbrücher (ETH Zürich), and Yoshi Yurimoto (Hokkaido University). In addition, four new councilors will begin their first term: Alexander N. Krot (Hawaii Institute of Geophysics and Planetology), Keiko Nakamura-Messenger (NASA-Johnson Space Center), François Robert (Muséum National d’Histoire Naturelle, Paris), and Caroline Smith (Natural History Museum, London).

REPORT A FIREBALL FROM YOUR SMARTPHONE!

Phil Bland of Curtin University and colleagues have developed a smartphone app that allows anyone to report a fireball sighting from anywhere in the world. The app was designed to capture data of sufficient quality to create a “crowd source, smartphone, fireball network.” It is downloadable for free and intended to be easy and fun to use. The observer simply points the smartphone at the point in the sky where the fireball started, clicks, and then points and clicks again at the point where the fireball ended. The app also allows the input of a variety of other data.

With enough observations, Bland hopes to be able to determine a trajectory for the fireball and send that information back to the observer with a message that the rock that made the fireball came, perhaps, from the outer asteroid belt, or that it was a chunk of a comet.

The app is available for both iOS and Android, and can be found by searching for “fireballs in the sky” on app stores. Bland invites users of the app to let him know if they have any problems or suggestions for improvement.

PHOTOS WANTED FOR SOCIETY WEBSITE

Alex Ruzicka, chair of the Membership Committee, would like to receive interesting pictures for the home page of the website. Eye-catching pictures of interest to the general public are especially welcome. E-mail: Ruzickaa@pdx.edu.

JOIN THE METEORITICAL SOCIETY – RENEW YOUR MEMBERSHIP

You can join the Meteoritical Society or renew your membership online at http://metsoc.meteoriticalsociety.net. Please renew your membership by March 31, 2014; after that date, a $15 late fee will be assessed.

ANNUAL MEETING SCHEDULE

2014 September 8–12, Casablanca, Morocco; www.metsoc2014casablanca.org
2015 July 27–31, Berkeley, California, USA
2016 August 7–12, Berlin, Germany
2017 Dates to be announced; Albuquerque or Santa Fe, New Mexico, USA
FROM THE PRESIDENT

Dear Members of the DMG,

Balloting for the new Council and committee members of the DMG closed at the end of November. I would like to thank all of the 363 DMG members who sent me their postal ballots. The ballots were counted on December 16, 2013, by S. Jung (DMG Council member) and two other DMG members. The results of the elections are as follows, with the number of votes in parentheses:

VICE PRESIDENT for 2014 and designated PRESIDENT for 2015–2016
François Holtz (299)

TREASURER (2014–2015) – Gerhard Franz (293)

ADVISORY COMMITTEE
(2015–2016) – Cristina Maria Pinheiro De Campos (104)

NEWS EDITOR Geot and ELEMENTS (2014–2015) – Klaus-Dieter Grevel (263)
VICE DGK LIAISON OFFICER (2014–2015) – Jürgen Schreuer (252)

VICE CHAIRPERSONS 2014 and designated CHAIRPERSONS 2015–2016 for the following sections:

CHEMISTRY, PHYSICS, AND CRYSTALLOGRAPHY OF MINERALS
Volker Presser (48)

GEOCHEMISTRY
Stefan Weyer (106)

PETROLOGY AND PETROPHYSICS
Wolfgang Bach (102)

APPLIED AND ENVIRONMENTAL MINERALOGY
Stefan Stöber (59)

COMMITTEES FOR 2015–2016

ABRAHAM-GOTTLOB-WERNER MEDAL – Hans Keppler, Monika Koch-Müller, Gregor Markl, Klaus Mezger, Carsten Münker, Wolfgang Schmahl (282)

VIKTOR-MORITZ-GOLDSCHMIDT PRIZE – Friedhelm von Blankenburg (177), Marcus Nowak (172), Andrea Koschinsky-Fritsche (147), Heinz-Günter Stosch (180)

GEORG-AGRICOLA MEDAL – Cornelia Boberski, Herbert Pöllmann, Thomas Holzapfel, Hans-Joachim Kleebe, Klaus Nickel (267)

TEACHING AND UNIVERSITY AFFAIRS for 2014–2015 – Lutz Hecht, Peter Schmid-Beurmann, Burkhard Schmidt, Roland Stalder (271)

I congratulate the newly elected members of the DMG Council and also thank all resigning Council members for their efforts and commitment to the DMG. I wish you all the best for 2014 and hope to see you at the annual DMG meeting in Jena.

Yours sincerely,

Astrid Holzheid, DMG President

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A PRIMARY SCHOOL MEETS MINERALOGY

In the spring of 2013, a lively debate about public relations in mineralogy started in the DMG forum. The main points were: How can we explain to the world that mineralogy is important? How can we attract attention in the public sphere? What is a good public relations strategy for mineralogy? At this point, the Horizontereignis Limited nonprofit company and the Department of Mineralogy at the Free University of Berlin started a project called “The Alchemists and the Philosopher’s Stone,” which was targeted at the Geißenweide primary school in Berlin-Marzahn. What for? The idea was that children have no prejudices against science or others fields. They just do what they like and they just like what they like. If it is possible to demonstrate to these children the absolutely wonderful world of mineralogy, they will tell their parents and friends. Hopefully, in this way we can start to open the minds of these people. And the next time they hear or read about mineralogy, maybe they won’t turn away or turn the page but remember what happened in school.

The three-day project took place in June 2013 with 15 pupils aged 10 to 12 years. We started by visiting the mineral collection of the Free University Berlin. (FIG. 1). From the moment we left the school, the children started picking up little stones from the street, wanting to identify them. At the FU, we showed them some selected minerals and taught them how they could identify them themselves. Afterwards we chose fantastic mineral aggregates and let the children do the identifying. No problem for these smart kids! Then, we inspected the same minerals under the microscope. How fascinated the children were about how colorful rocks can be. They detected twins and figured out that they change if you turn the microscope stage, and the colors do too. On our way back to school, the children were now able to identify their street rocks by themselves.

On the second day we learned about the necessity of minerals and thus of mineralogists. The children were absolutely free to read up on websites and books, and to select a special mineral to present. In group work they designed a poster about their respective topic and presented it in front of the class. The selected topics were: gemstones, healing stones, and minerals in mobile phones (FIG. 2). Also on this day, we grew crystals (to have something to show at home) and, as an example of what minerals are used for, we started to produce our own paint pigments out of minerals.
On the third day, we explained that mineralogy is not only mineralogy. It is also chemistry and physics and mathematics and more. We started with mathematics and brought some paper crafts of different crystal systems. The task was to figure out how to make a 3-D model out of the paper and determine which mineral the distinct model could represent. In parallel, the “chemistry lab” was opened, and the children finished painting their colors from the previous day and gave the crystal paper models a perfect mineral color (Fig. 3).

Finally – the big presentation of the project in front of the school and the parents. On the afternoon of the third day, the children had to present their project as part of the garden party of the school. And they did so with great pride! They explained to everybody everything they had learned about minerals. They showed pictures and posters and made PowerPoint presentations, and they let the parents and other children tinker with a paper crystal system.

What was the result of this project? During the party, a lot of parents came up to us and thanked us for these three days. The children were totally fascinated and went home talking about nothing but minerals. The kids asked us to work at their school forever, and the school invited us to define more projects for the next school year. But the question is always about money. So, one school in Berlin is now infected with mineralogy fever. Let’s see how to feed and spread this fever in the future.

Cornelia Meyer (conny@horizontereignis.de)  CEO of Horizontereignis gUGe

INTERNATIONAL YEAR OF CRYSTALLOGRAPHY – 2014

In July 2012, the General Assembly of the United Nations adopted the resolution that 2014 would be the International Year of Crystallography, 100 years after the award of the Nobel Prize for the discovery of X-ray diffraction by crystals. The SFMC participates actively as a member of the steering committee for the “International Year of Crystallography in France – AICr2014,” notably in the organisation and promotion of the celebratory events in France. Many events (conferences, exhibitions, crystal-growing competition, and others) are scheduled throughout the year and throughout France. Information about these events and others can be found on the website www.aicr2014.fr/.

The “Matériaux 2014” conference will be held in Montpellier in November 2014. The deadline for abstract submission is April 7, 2014. Information is available on the website www.materiaux2014.net/.

LES MÉTÉORITES 2 / DES MÉTÉORITES PRIMITIVES AU SYSTÈME SOLAIRE

In October 2013, the journal Le Règne Minéral (www.leregnemineral.fr) published its second special issue (100 pages in French) devoted to meteorites and aimed at a wide but scientifically oriented audience. While the first one dealt with differentiated meteorites, this new issue explores the world of chondrites and the small Solar System bodies from which they originate. It contains a general introduction and monographs on two special French meteorites (the Orgueil CI and the latest French fall, Draveil). A whole chapter is devoted to chondrite groups, their possible relationships and significance, and how to identify them. Individual chondritic components are then explored (chondrules, CAIs, matrix, presolar grains, metal), as well as parent-body transformations. The remaining chapters are devoted to the atmospheric phenomena associated with meteorite falls, to chondrite parent bodies and to the early Solar System. In addition to numerous diagrams and tables, the book is illustrated with ~150 new pictures of meteorites and meteorite sections. The authors of the twenty chapters are meteoritists, physicists and astrophysicists from various public research institutions and universities, mostly in France, but also in the US and Germany. This handsome and well-documented volume should prove a valuable resource for both students and colleagues working in related fields who wish to learn more about chondrites.

MINTEM 2014

The third school on the theme “Transmission Electron Microscopy in Mineralogy” organized by the SFMC, will be held at the University of Lille on 3–7 November 2014. The number of participants is limited to 12. The school will interest graduate students, post-docs and researchers. For more information and registration, go to the website http://uemet.univ-lille1.fr/Animation/MinTem.php.
are usually for applicants who are scientifically independent and have 7 and 12 years earlier. The deadline in 2014 is in May. Advanced Grants up to €2 million and are for scientists who have finished their PhD between 2 and 7 years earlier. The deadline in 2014 is in May. Advanced Grants have no age restriction and can be up to €2.5 million. Significant additional “start-up” funds can also be requested within all 3 grant types when the researcher originates from outside the EU.

In Horizon 2020 it will be mandatory for all publications arising from ERC grants to be open access either through the publisher or through an open access repository 6 months after publication.

Proposals are evaluated by 25 panels, which cover different subject areas. In the first review round, the panel evaluates the proposal based on the researcher’s track record and a 5-page synopsis of the project. Successful projects enter a second round where the full proposal, which includes a 15-page research project, is sent out for external review. The overall success rate has varied between 9 and 14% in recent years. For the geosciences, the most relevant panel is PE10, Earth System Science, although PE9, Universe Sciences, which includes planetary science, may be also relevant. To date approximately 3% of funded Starter Grants were from PE10, with a slightly higher proportion for funded Advanced Grants. This means that if you order the panels in terms of how many grants they have funded, the Earth science panel is near the bottom of the list. It would be interesting to track down why this is so; are Earth science reviewers harsher than those in other fields?

Daniel Frost (University of Bayreuth)

Note: While every effort has been made to ensure the accuracy of information, all facts, figures, and dates should be checked at the relevant EU portal website, which is currently http://erc.europa.eu/sites/default/files/document/file/ERC_Work_Programme_2014.pdf.

FUNDING OPPORTUNITIES – THE EAG ON THE ERC

With a 75% increase in budget over the last funding round, the European Research Council (ERC) appears to be a clear winner in Horizon 2020, the European Union’s funding programme for 2014–2020. ERC grants have proved popular with researchers, judging by the number of applications, because they provide a high level of funding through a relatively short proposal and are implemented with comparatively little red tape. Here we examine the various ERC schemes and look at how they will change in Horizon 2020.

Since its inception in 2007, the ERC has given out €7.5 billion through the funding of 4000 individual research grants, split between the domains of physical sciences & engineering, life sciences, and social sciences & humanities. This money has funded approximately 7000 PhD students and 9000 post-docs Europe-wide over the last 7 years. This is a significant amount of funds that suddenly appeared on the landscape. Rather than developing out of a pre-existing strategy, the ERC was brought into existence as a way of stimulating innovative groundbreaking research in Europe. In contrast to many other types of EU or national funding schemes, ERC grants have no predetermined priorities and are assessed purely on merit. The guide for reviewers makes clear that proposals should be addressing challenges that are beyond the state of the art, and a recurrent catchphrase in ERC literature is high risk / high gain. ERC funding is evidently aimed at inspiring a more adventurous level of research that would not necessarily be funded by the more conservative national funding agencies. ERC grants also stand out in comparison to other EU funding strategies in that they are not increasingly tied to wider initiatives and to industrial collaboration.

Applicants for ERC grants can be of any nationality, although the research must be conducted at a host institution in an EU or associated member state over a period of up to 5 years. There are three main types of grants aimed at different career stages, each with one submission deadline per year. Starting Grants can be up to €1.5 million and are for researchers who completed their PhD between 2 and 7 years earlier. The deadline in 2014 is near the end of March. Consolidator Grants can normally be up to €2 million and are for researchers who finished their PhD between 7 and 12 years earlier. The deadline in 2014 is in May. Advanced Grants are usually for applicants who are scientifically independent and have a recent research track record and profile which identifies them as leaders in their respective field(s) of research. Advanced Grants have no age restriction and can be up to €2.5 million. Significant additional “start-up” funds can also be requested within all 3 grant types when the researcher originates from outside the EU.

In Horizon 2020 it will be mandatory for all publications arising from ERC grants to be open access either through the publisher or through an open access repository 6 months after publication.

Proposals are evaluated by 25 panels, which cover different subject areas. In the first review round, the panel evaluates the proposal based on the researcher’s track record and a 5-page synopsis of the project. Successful projects enter a second round where the full proposal, which includes a 15-page research project, is sent out for external review. The overall success rate has varied between 9 and 14% in recent years. For the geosciences, the most relevant panel is PE10, Earth System Science, although PE9, Universe Sciences, which includes planetary science, may be also relevant. To date approximately 3% of funded Starter Grants were from PE10, with a slightly higher proportion for funded Advanced Grants. This means that if you order the panels in terms of how many grants they have funded, the Earth science panel is near the bottom of the list. It would be interesting to track down why this is so; are Earth science reviewers harsher than those in other fields?

Daniel Frost (University of Bayreuth)

Note: While every effort has been made to ensure the accuracy of information, all facts, figures, and dates should be checked at the relevant EU portal website, which is currently http://erc.europa.eu/sites/default/files/document/file/ERC_Work_Programme_2014.pdf.
Our 50th Anniversary Annual Meeting in Urbana-Champaign was a success! Joe Stucki and the other members of the 2013 Local Organizing Committee combined anniversary-themed sessions with thoughtfully defined thematic and general sessions, and included well-planned social activities and field trips, all centered on an accessible, effective, and historically significant venue for clay science. This combination drew the usual diversity and high quality of CMS-member scholarly presentations, and attracted registrants in numbers not seen since the early days of the recent economic downturn. Perhaps highly successful CMS annual meetings are a sign of emerging and continuing improvement in the larger economy!

By the time this issue of Elements arrives in your physical and virtual mailboxes, it will be only a few months until our next annual meeting, to be held on May 17−21 in College Station, Texas, USA. Visit the 2014 meeting website (see the ad below) to see the broad range of exciting sessions Youjun Deng and the 2014 Local Organizing Committee have assembled around the theme “Everything is Big: From Nanoparticles to Planets.” Make your plans now to join in the scholarship and networking of our multidisciplinary clay science community.

Best wishes,

Michael Velbel (velbel@msu.edu)
President, The Clay Minerals Society

NOMINATIONS SOUGHT FOR CMS AWARDS

The CMS gives four awards at its annual meetings. See the CMS website at www.clays.org for a description of the awards and an overview of the nomination process. The nomination deadline for the 2015 awards is March 31, 2014.

STUDENT RESEARCH GRANTS AND TRAVEL AWARDS

The research grant program is designed to provide partial financial support (up to $3000) to graduate students pursuing master’s and doctoral research in clay science and technology. The travel grant program provides graduate students with partial financial support to attend the annual meeting of the Clay Minerals Society and present the results of their research. All student members of the Clay Minerals Society are eligible for the travel grant program. See the CMS website, www.clays.org, for more information. The application deadline is March 31, 2014.

REYNOLDS CUP 2014

The 7th biennial Reynolds Cup competition for quantitative mineral analysis is now open. Information about the competition, including guidelines and the names of previous winners, can be found at www.clays.org/SOCIETY%20AWARDS/RCintro.html. The competition is free for all to enter; however, persons who are not members of the CMS are encouraged (but not obliged) to become members (see www.clays.org/MEMBERSHIP/MemberRates.html for details).

You can register your interest in the contest by sending an e-mail mentioning the subject “Reynolds Cup 2014 registration” to rc2014@ethz.ch. Registration e-mails must include the following information: name, institution/organization, shipping address (must work for DHL/Courier delivery), phone number (for delivery), and e-mail address.

About 90 sets of samples will be available for distribution. Each set comprises three samples of approximately 4 g each composed of mineral mixtures commonly found in clay-bearing rocks and soils. Sets of samples will be distributed in the order of registration. Samples are expected to be dispatched on January 20, and the deadline for the submission of results is March 31, 2014. The top three contestants with the most accurate results will be announced at the 51st annual meeting of the Clay Minerals Society (May 17−21, 2014). Only the names of the top three contestants will be published. The names of the other participants will remain strictly confidential.

Because of the popularity of the Reynolds Cup and the enormous amount of work put into its preparation, potential participants are strongly encouraged to plan ahead and only request samples if they are sure they can complete the analysis and return results to the organizers by the due date. Those who request samples and do not send in results or fail to return the samples unopened well before the due date will not be eligible to participate in future Reynolds Cups.

We look forward to your participation!

Michael Ploetze, Reynolds Cup 2014 organizer
UPCOMING IAGC MEETINGS

10th International Symposium on the Geochemistry of the Earth's Surface (GES-10)
“BETWEEN ROCKS AND SKY: EARTH’S CRITICAL ZONE”

August 18–22, 2014
Collège des Bernardins, Paris
www.ipgp.fr/GES10

The next Geochemistry of the Earth’s Surface meeting (GES-10) will be held in the Collège des Bernardins in Paris, France, on August 18–22, 2014. GES-10 will emphasize Critical Zone cutting-edge research at all scales, from elementary processes to global biogeochemical cycles.

The GES meeting will be a small-size, friendly meeting (<200 attendees) featuring a limited number of invited oral presentations and extensive poster sessions. Invited oral presentations will be held in the morning, and poster sessions will occupy the afternoons. A half day is scheduled for exploring the Quartier Latin, in the footsteps of Vernadsky and Marie Curie. Social events will include wine tasting (the blood of the Critical Zone) and a relaxing, convivial banquet. Prior to the meeting, a field trip will be held in France.

GES is a good format for students to meet established scientific leaders, and the participation of early-career scientists is particularly encouraged. Partial support will be available to help students attend and present their work.

Contact and information:
Jérome Gaillardet (gaillardet@ipgp.fr)

BIOGEOMON 2014
8th International Symposium on Ecosystem Behavior

July 13–17, 2014
University of Bayreuth, Germany
www.bayceer.uni-bayreuth.de/biogeomon2014/
Abstract submission deadline: April 4, 2014

The focus of BIOGEOMON is the biogeochemistry of forest and natural ecosystems as influenced by anthropogenic and environmental factors. We invite empirical and modeling studies on fluxes and processes related to the turnover of major and trace elements at ecosystem, watershed, landscape, and global scales.

Themes:
1. Long-term trends in the functioning of ecosystems
2. Environmental controls on fluxes and processes in ecosystems
3. Fluxes between the atmosphere and ecosystems
4. Below-ground turnover of C and nutrients in forest soils
5. Linking biodiversity and biogeochemistry
6. Biogeochemistry of wetlands
7. Dissolved organic matter in ecosystems and at the interface with the hydrosphere
8. Trace element biogeochemistry
9. Critical unknowns in the cycling of P in forest and wetland ecosystems
10. Links between the N cycle and other elements
11. Weathering and chemical processes as keys to ecosystem functioning
12. Restoration and rehabilitation of ecosystems

The conference will be hosted by the Bayreuth Center of Ecology and Environmental Research (BayCEER).
The Japan Association of Mineralogical Sciences and the Clay Science Society of Japan are coorganizing a traveling exhibition of splendid crystals. The specimens on display were selected from the mineral collection of the late Professor Ryuji Kitagawa of Hiroshima University (1949–2009), who had the cherished desire to show people, especially children and youths, the wonders of geomaterials. Most of the specimens were collected by Professor Kitagawa himself from outcrops and mine faces in many countries. The exhibition started last May at the Hiroshima Children’s Museum and has been open to the public at the Nakatsugawa Mineral Museum, the National Museum of Nature and Science in Tokyo, the Fossa Magna Museum in Itoigawa, and the Kiseki Museum of World Stone in Fujinomiya. The exhibition is now at the Natural History Museum and Institute, Chiba, as a part of the IYCr2014 Promotion and Recognition Activities in Japan. The exhibition will continue traveling to the Tohoku University Museum in Sendai, the Toyohashi Museum of Natural History, the Kujimura Museum, the Yamanashi Jewelry Museum, the Nagoya City Science Museum, the Ehime Prefectural Science Museum, the Toyama Science Museum, and others. We hope that the exhibition will give future mineralogists the opportunity to develop an interest in minerals.

Ritsuro Miyawaki
National Museum of Nature and Science, Japan

Yasuyuki Banno
Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Japan

JOURNAL OF MINERALOGICAL AND PETROLOGICAL SCIENCES
Vol. 108 no. 6, December 2013

Original articles
- Middle Paleozoic greenstones of the Hangay region, central Mongolia: Remnants of an accreted oceanic plateau and forearc magmatism — Ganbat ERDENESAIHAN, Akira ISHIWATARI, Demberel OROLMAA, Shoji ARAI, Akihiro TAMURA
- Crystal structure of hydroxybastnasite-(Ce) from Kamihouri, Miyazaki Prefecture, Japan — Kiyonori MICHIBA, Ritsuro MIYAWAKI, Tetsuo MINAKAWA, Yasuko TERADA, Izumi NAKAI, Satoshi MATSUBARA
- Takanawait-(Y), a new mineral of the M-type polymorph with Y(Ta,Nb)O4 from Takanawa Mountain, Ehime Prefecture, Japan — Daisuke NISHIO-HAMANE, Tetsuo MINAKAWA, Yukikazu OHGOSHI

Letters
- Petrology and phase equilibrium modeling of spinel-sapphire-bearing mafic granulite from Akarui Point, Lutizow-Holm Complex, East Antarctica: Implications for the P-T path — Shunki IWAMURA, Toshiaki TSUNOGAE, Mutsumi KATO, Tatsuya KOIZUMI, Daniel J. DUNKLEY
- Blue cathodoluminescence related to defect center in smithsonite — Hirotsugu NISHIDO, Masato MAKIO, Nobuhiro KUSANO, Kiyotaka NINAGAWA
- Spectroscopic determination of the critical temperatures and pressures of H2O, CO2, and C2H3OH — Chizu SEKIGUCHI, Nobuo HIRANO, Atsushi OKAMOTO, Noriyoshi TSUCHIYA

INVITATION TO THE JAPAN GEOSCIENCE UNION MEETING
We are pleased to inform you that the annual Japan Geoscience Union Meeting 2014 will be held from April 28 to May 2, 2014, at Pacifico YOKOHAMA, Kanagawa, Japan. More than 40 international sessions will be held. The abstract deadline was February 12, 2014. More information is available at the following link: www.jpgeu.org/meeting_e/

INVITATION TO THE ASIA OCEANIA GEOSCIENCES SOCIETY 11th ANNUAL MEETING 2014
The Asia Oceania Geosciences Society (AOGS) was established in 2003 to serve the geosciences community in Asia and Oceania. Since its inception, the focus of the society has been to promote the geosciences and their applications for the benefit of humanity, not only in the Asia–Oceania region but also all over the world. In this light, the society’s primary activity is to organize an annual conference and exhibition in June/July/August for five days. The AOGS 2014 Annual Meeting will be held in Sapporo, Japan, from July 28 to August 1, with an expected attendance of 3500 participants. The abstract deadline was February 11, 2014. More information is available at the following link: www.asiaoceania.org/aogs2014.
The Association of Applied Geochemists (AAG) and SGS are pleased to announce that Pim van Geffen has won the 2013 SGS-AAG Student Paper Prize. This prize is awarded for the best paper published by a student in the AAG’s scientific journal Geochemistry: Exploration, Environments, Analysis (GEEA), on work performed as a student and published within three years of graduation; the work must address an aspect of exploration or environmental geochemistry related to the mining industry. Pim’s winning paper is based on research that he undertook for his PhD at Queen’s University, Ontario, Canada.

His award-winning paper is entitled “Till and vegetation geochemistry at the Talbot VMS Cu-Zn prospect, Manitoba, Canada: implications for mineral exploration” and was published in 2012 in GEEA (vol. 12, p. 67-88). It was coauthored by Kurt Kyser, Christopher Oates, and Christian Ihlenfeld. The abstract of the paper follows:

The Proterozoic Talbot VMS occurrence in the Flin Flon–Snow Lake terrane is buried under more than 100 m of Palaeozoic dolomites and Quaternary glacial till. Structurally controlled anomalies of Zn, Cu, Ag, Pb, Au, Mn, Hg, Cd, Co, Bi and Se in the clay fraction of till thickness profiles indicate upward element migration from the buried volcanicogenic massive sulfide mineralisation and near-surface charnko-related deposition. Principal component analysis and molar element ratios indicate that separation of the <2 µm clay fraction reduces chemical heterogeneity and increases trace-element yield relative to the <250 µm fraction of the till. The greatest anomalies occur at or below 30 cm depth and over faults, suggesting that elements were deposited in the till after upward migration through structures. The ratio Zn/Al in the <250 µm fraction can be used as a proxy for Zn in the clay fraction, producing high-contrast anomalies that these anomalies are related to organic carbon in the clay fraction. Humus, moss and black spruce bark are of limited use for exploration in this environment, because they accumulate atmospheric Pb and Cd, most likely from the Flin Flon smelter at 160 km NW. Black spruce tree rings that formed before smelter operations commenced indicate Zn and Mn anomalies in an uncontaminated sampling material. Much of the initial vertical migration of elements to the surface at the Talbot prospect was driven by upward advection of groundwater through fractures in the dolomite, resulting from a combination of subsurface karst collapse and remnant hydrostatic pressure during glacial retreat.

Pim received a $1000 cash prize from SGS, a two-year membership in the AAG, our journal GEEA and newsletter Explore, and a certificate of recognition at the International Applied Geochemistry Symposium held last November in Rotorua, New Zealand.

The AAG would like to thank SGS for, once again, generously supporting this prize.

David R. Cohen (d.cohen@unsw.edu.au) Chair, AAG Student Paper Competition Committee

RECENT ARTICLE PUBLISHED IN EXPLORE


Soil geochemistry is widely used for Au exploration as a first-pass evaluation of a prospective area; however, specific mechanisms for the formation of soil anomalies in transported overburden are not well understood. In particular, assessing the mobility and bioavailability of metals under natural conditions requires the development and evaluation of new tools. Diffusive gradients in thin films (DGT) technique is a method for measuring the mobility of metals in soils, but has not previously been assessed for geochemical exploration. The DGT technique presents several advantages for measuring element concentrations in soils, namely that DGT pre-concentrates metals via diffusive transport through the soil solution; induces resupply from elements bound to the solid phase; has very good sensitivity, especially when deployment times are extended; does not significantly alter the soil either chemically or physically; and has been demonstrated to behave analogously to plant roots for a number of trace metals. In this study, we applied the DGT technique for a range of elements, not including Au, to auriferous soil transects obtained from two Australian prospects, both of which are covered by transported overburden. The results of DGT-measured concentrations were compared with porewater concentrations at these two prospects (see Figure).

Andrew Lucas (lucasa04@student.uwa.edu.au) The University of Western Australia, Australia

A call for laboratory support...

The Association of Applied Geochemists (AAG) invites analytical laboratories to participate in pairing their analytical facilities with student projects to develop emerging geochemists and their science. The AAG Education Committee is seeking analytical laboratories to offer in-kind support to students in terms of analysis, while receiving acknowledgement on AAG’s website and in the Association’s EXPLORE newsletter.

“If your laboratory is interested in learning more about this program, please contact the Chair of AAG’s Education Committee, Erick Welland Erick_Welland@fmi.com

“Today’s students are tomorrow’s clients”
WELCOME ADDRESS BY BERNARDO CESARE, SIMP PRESIDENT 2014–2015

Dear friends and colleagues,

Let me first express the gratitude of SIMP and my personal recognition to Past President Giuseppe Cruciani, who served the Society with a relentless dedication that will be hard to match.

In Italy, mineralogy and petrology, and scientific research in general, suffer from a “split personality” that varies depending on the point of observation. From the outside, the point of view of most readers of Elements, and considering research outcomes and achievements in science, Italian mineralogy in the wide sense is alive and well: the number, impact and citations of papers are high and increasing. The same holds for our involvement in activities at the international level, where numerous Italian colleagues are chairs or members of panels, editorial boards, and organizing committees, or are prize awardees. In recognition of such international relevance, SIMP has been chosen to host the European Mineralogical Conference in 2016.

The situation changes when observed from the inside. It is sad for me to reiterate what my predecessors outlined on these pages two and four years ago: a tragic perspective for Italian research and a sense of importance among scientists. Not only are we facing a drastic and increasing cut of funds, we are also, and more importantly, seeing a decrease in human resources. Given our good scientific productivity, low resources imply that Italians carry out very cost-effective research (as outlined in the ANVUR-VQR 2013 reports). However, low resources also bring seriously into question the survival of the geosciences in Italy! The next two years will be fundamental for redesigning Italian Earth sciences, and SIMP will do its best to achieve a better coordination of societies, and to build the common commitment that is key for improving the visibility and importance of the geosciences in public policy and understanding.

I see a few priorities for SIMP, including organizing a lively and vigorous congress in September 2014, jointly with the Italian Geological Society, and reinvigorating a sense of belonging among members, especially the youngest researchers and students. In the meanwhile, we want to increase our efforts with DMG, SEM, and SFMC aimed at improving the status of the European Journal of Mineralogy among the major international journals.

That is surely enough for my two-year mandate, and I will do my best to accomplish these goals.

Bernardo Cesare, University of Padova
SIMP President 2014–2015

INTERNATIONAL ECLOGITE CONFERENCE

The 10th International Eclogite Conference (September 2–10, 2013; www.iec2013.unito.it) took place at Courmayeur, Aosta Valley, Italy. It included a three-day meeting, with oral and poster sessions, and pre-, syn-, and post-conference field excursions (see the conference report in the December 2013 issue, page 475). The 10th IEC was organized by the Petrology Research Group at the Department of Earth Sciences of Torino, in cooperation with the corresponding research group at the Institute of Geological Sciences, University of Bern, Switzerland. The University of Torino, SIMP, the Italian Geological Society, and the Italian Earth Sciences Federation sponsored the conference. The

For information: info@geoscienze2014.it
A belated happy New Year to all readers.

2013 was a busy publishing year for the Mineralogical Society. Three volumes appeared in the EMU series, DHZ was published. We had extra issues in both Mineralogical Magazine and Clay Minerals at no extra cost to the reader! 2014 continues in the same vein, starting with the latest (eighth) ‘Cambridge Diagenesis’ special issue of Clay Minerals.

DHZ History

On 27 November, the Society held a launch event to mark the publication of the third edition of Introduction to the Rock-Forming Minerals by Deer, Howie and Zussman. A speech by Prof. Jack Zussman was recorded and has been placed on YouTube. Watch it at www.minersoc.org/DHZ.html/.

Copies of DHZ continue to be available from the Society’s online bookshop (www.minersoc.org), through the MSA and from the Geological Society (London). Orders may also be placed through Amazon.

Call for Nominations for Society Medals

The deadline for nominating a colleague for a Society medal for 2015 is 25 April 2014. Please visit the awards page on the Society website (www.minersoc.org) for details on how to make a nomination.

The next ‘School’ being organized by the European Mineralogical Union, on the theme “Planetary Mineralogy,” will be held in Glasgow, UK, from 25 August to 3 September 2014. Topics and invited speakers include:

- Planetary interiors – Wim van Westrenen
- Lunar geology – Mahesh Anand
- Meteorite parent bodies – Josep Trigo-Rodríguez
- Early Solar System solids – Ian Sanders
- Noble gas chemistry – Julia Cartwright
- Isotopic analysis – Jutta Zipfel
- Terrestrial impacts – Alex Deutsch
- Shock metamorphism – Mark Burchell
- Organic in primitive meteorites – Laurent Remusat
- Micrometeorites – Luigi Folco

The Society will co-publish a volume in the EMU Notes in Mineralogy series to accompany the School, and this will be available from the Society bookshop by late summer. More information about the School is available at http://emuschool2014.org/.

British Zeolite Association Annual Meeting

Registration and abstract submission for the 2014 meeting of the British Zeolite Association are now open. The meeting website, complete with registration links, is at www.chem.gla.ac.uk/bza2014/.

ERES – European Rare Earth Resources Meeting

This, the first ERES meeting, will take place in Milos Island, Greece, on 4–7 September 2014. Topics to be covered include:

- REE importance for Europe (supply and demand issues)
- REE exploitation policy issues
- REE occurrences in Europe
- REE processing
- REE urban mining and recycling
- Environmental impacts

Further information is available at http://eres2014.conferences.gr/.

PPV@10 – A meeting for the 10th anniversary of the discovery of post-perovskite

A series of papers published in 2004 reported the discovery of a post-perovskite phase transition in the MgSiO3 system that dominates the mineralogy of Earth’s lower mantle. This discovery acted as a catalyst for research into the properties and behaviour of the lowermost mantle where the phase transition explains a raft of previously unexplained observations. To mark the tenth anniversary of this event, and to explore the questions that remain, we are arranging a two-day interdisciplinary meeting “ppv@10” at the University of Bristol in June 2014. Further information, including registration details, can be found online at www1.gly.bris.ac.uk/ppv/.

EMU NOTES IN MINERALOGY SERIES

Did you know the Society has now co-published seven titles in the EMU Notes in Mineralogy series? Read more about each of the titles and place an order at www.minersoc.org/EMU-notes/EMU-notes.html.
The Petrology Group of the Mineralogical Society of Poland held its 20th anniversary meeting on October 17–20, 2013, in Niemcza, Poland. The Petrology Group was established in 1993 thanks to Professor Alfred Majerowicz of the University of Wrocław. Jacek Puziewicz, known as Puzon (“Trombone”) and at the time a young scientist, was elected chair of the group. At the beginning of the 1990s, the number of Polish researchers in petrology was around 70. They were not often in contact with each other and there was no tradition of regular meetings. So Trombone proposed that the Petrology Group organize an annual meeting. The idea was simple: bring the people together and give those at the beginning of their career the opportunity to present their work to a gathering of all Polish petrologists. The first meeting was held in Trzebieszowice in the Sudetes in 1994 and attracted about 40 participants, but no proceedings book was prepared. The lively discussions and perfect social atmosphere were an indication that Petrolology Group meetings had a chance to work. The break came in 1995 in Kowary: the number of participants was still 40, but all Polish academic centers where petrology was being taught were represented. The first proceedings book was published.

The meetings between 1994 and 1999 were held in the Sudetes and all were organized by Trombone’s group. Since financial support was nonexistent or minimal and the participants had to cover all the costs, the meetings were held in relatively cheap places like rustic hotels, inns, and recreation centers. The 1995 meeting in Kowary was remarkable because the heating in the hotel was out of order for two days, which is a problem in Poland in October. All the participants crowded into a small cafeteria in the underground and consumed liquid calories, which eventually gave them the courage to go to their cold rooms and get some sleep. The meetings were always located outside large towns and all participants were housed in a single hotel, which enabled an intense evening social life—as important to our meetings as the scientific sessions. During the first meetings the number of participants stabilized at about 60, and this number continues to the present. An important watershed in the history of Petrology Group meetings occurred in 1999 when the meeting language was changed from Polish to English, an initiative of Jack Puzewicz (resulting in one of the thinnest proceedings books!). After the first “English” meeting, the psychological barrier was broken and the first foreign participants started to come. The first non-Sudetes meeting was held in Osieczany in 2000 and was organized by Marek Michalik (Jagiellonian University, Cracow). Since then the meetings have been held in various places in Poland, always with some foreign participants who are attracted by the leading topic or a field trip. The 20th meeting of the Petrology Group was again organized by Trombone and his coworkers and attracted over 70 participants. The scientific program showed a broad spectrum of petrological research, from studies of deep-seated plutonic igneous rocks to environmental and industrial matters. The diversity of topics is reflected by the talks of the invited speakers: Hubert Bril (University of Limoges, France)—“Solid speciation studies—a tool to assess potential release of ‘heavy metals’ from contaminated mining and industrial sites”; Theodoros Ntaflos (University of Vienna, Austria)—“Geochemical and petrological constraints on the origin of the Earth’s lithospheric mantle beneath the back-arc environment in northern and easternmost Russia”; Ewa Slaby (University of Warsaw, Poland)—“Numerical simulation of magma mixing, from macro- to microscale”; and Brian Upton (University of Edinburgh, Great Britain)—“Mesoproterozoic continental rifting, alkaline magmatism, long-term lithospheric memories, and mantle plumes.” The meeting ended with a half-day field trip to see igneous rocks near Niemcza (Cenozoic alkaline volcanic rocks, Variscan basement granodiorites) and the environmental problems related to lateritic Ni-ore exploitation and smelting in an abandoned mine in the small serpentinite massif of Szklary.

Jacek Puziewicz (Wrocław University)
PRESIDENT’S LETTER

Ongoing Business

My nearly two months in the role of president have taught me how fortunate we are as members of MSA to have such dedicated people working behind the scenes, both at the office in Chantilly and spread more widely. The job of running a learned society is becoming ever more complex, with challenges that range from dealing with new US Government legislation to publishing in the age of ‘open access’ and rapidly advancing communication technologies. I see MSA not only rising to these challenges but, in many cases, providing leadership for the larger communities of which we are part.

The developments touched on in my last President’s Letter continue to move forward. In particular, we hope soon to formalise our collaborations with some of our European ‘sister’ societies through memoranda of understanding. These will lead to regular discussions aimed at both raising awareness of our existing activities and at exploring the possibilities of joint meetings and publications. We are also very much raising awareness of our existing activities and at exploring the possibilities of joint meetings and publications. We are also very much involved in an ongoing debate about the archiving of large bodies of data and the possibility of some form of (electronic) journal associated with such data. It is early days as yet, although this field is moving ahead very rapidly.

I also have some other new developments to mention in this letter. One is concerned with setting up a series of meetings that we are initially entitling ‘workshops’. These would be half- or one-day events with a handful (perhaps only one, two or three) invited speakers and focusing on a ‘hot topic’. The target audience would be students and early-career scientists. There would not be any new publications involved, but we might consider making the workshops more widely available via electronic media. These workshops would be very different from our short course program, which involves the considerable costs of a residential course and the complications of concurrently producing the Reviews in Mineralogy and Geochemistry volumes (which are very detailed, authoritative and comprehensive publications). Workshops should appeal to a different audience from that attending short courses or, indeed, attending a thematic session at a conference such as the GSA Annual Meeting.

Another development concerns the MSA website. The current site functions very well and enables members or enquirers to get ready access to the information they need. However, as our ‘shop window’ it is appropriate that we periodically give it a fresh look, and that is what is happening at the moment, thanks to the sterling efforts of our webmaster and executive director. This is definitely a case of ‘watch this website.’

David J. Vaughan (david.vaughan@manchester.ac.uk) 2014 MSA President

NOTES FROM CHANTILLY

- MSA will use electronic balloting for its 2014 election of MSA officers and councilors. The slate of candidates follows. President: Steven B. Shirey, Carnegie Institution of Washington; vice president (one to be selected): Carol D. Frost, University of Wyoming, and Rebecca A. Lange, University of Michigan; treasurer: Howard W. Day, University of California–Davis; councilors (two to be selected): Barry R. Bickmore, Brigham Young University; Abby Kavner, University of California–Los Angeles; Matthew J. Kohn, Boise State University; and Donna L. Whitney, University of Minnesota. Andrea Koziol continues in office as secretary. Continuing councilors are Isabelle Daniel, Kirsten P. Nicolaysen, Edward S. Drew, and Wendy Panero.

- Ore Microscopy and Ore Petrography, by James R. Craig and David J. Vaughan, is available at the “Open Access Publications” link on the MSA home page. Also available are the Guide to Thin Section Microscopy, by Michael M. Raith, Peter Raase, and Jurgen Reinhardt; Teaching Mineralogy, by John B. Brady, David W. Mook, and Dexter Perkins II (editors); and Carbon in Earth, by Robert M. Hazen, Adrian P. Jones, and John A. Baross (editors). These publications are made freely available by the authors, a funding organization, or MSA. MSA will host additional open access publications about mineralogy, crystallography, petrology, and geochemistry of interest to its membership. If you have a publication you would like to post on this site, please contact the MSA business office.

- All 2012 and 2013 MSA members have been contacted by mail, electronically, or both about renewing their membership for 2014. If you have not renewed your MSA membership, please do so. If you have not received a notice by the time you read this, please contact the MSA business office. You can also renew online at any time.

J. Alex Speer (jaspeer@minsocam.org) MSA Executive Director

NOMINATIONS Sought FOR MSA AWARDS

- The Roebling Medal (2015) is MSA’s highest award and is given for eminence as represented by outstanding published original research in mineralogy.

- The Dana Medal (2016) recognizes continued outstanding scientific contributions through original research in the mineralogical sciences by an individual in the midst of their career.

- The Mineralogical Society of America Award (2015) is given for outstanding published contribution(s) prior to the 35th birthday or within 7 years of the PhD.

- The Distinguished Public Service Medal (2015) is presented to an individual who has provided outstanding contributions to public policy and awareness about mineralogical topics through science.

- Society Fellowship is the recognition of a member’s significant scientific contributions. Nomination is undertaken by one member with two members acting as cosponsors. Form required; contact the committee chair or visit MSA’s home page.

Submission requirements and procedures are on MSA’s home page: www.minsocam.org. Nominations must be received by June 1, 2014.
THE MINERALOGICAL SOCIETY OF AMERICA

2015 GRANTS FOR

Research in Crystallography
from the Edward H. Kraus Crystallographic Research Fund
with contributions from MSA members and friends

Student Research in Mineralogy and Petrology
from an endowment created by MSA members

Selection is based on the qualifications of the applicant; the quality, innovativeness, and scientific significance of the research as judged from a written proposal; and the likelihood of success of the project. There are five US$5000 grants, with the restriction that the money be used in support of research. Application instructions and online submission are available on the MSA website, www.minsocam.org. Completed applications must be submitted by June 1, 2014.

NEW TITLE: REVIEWS IN MINERALOGY & GEOCHEMISTRY

Volume 77 – Geochemistry of Geologic CO2 Sequestration
Editors: Donald J. DePaolo, David R. Cole, Alexandra Navrotsky, and Ian C. Bourg


Geochemicals and applications in geologic CO2 sequestration technology involve the effects of fluid flow combined with chemical, thermal, mechanical, and biological interactions between fluids and surrounding geologic formations. Complex and coupled interactions occur both rapidly, as the stored material is emplaced underground, and gradually, over hundreds to thousands of years. The long sequestration times needed for effective storage, the large scale of GCS globally necessary to significantly impact atmospheric CO2 levels, and the intrinsic spatial variability of subsurface formations provide challenges to both scientists and engineers. A fundamental understanding of mineralogical and geochemical processes is integral to the success of GCS. Large-scale injection experiments that will be carried out and monitored in the next decade will provide a unique opportunity to test our knowledge of fundamental hydrogeology, geochemistry, and geomechanics.

For a description and to order online, go to www.minsocam.org.

PLANETARY PUBLICATIONS FROM MSA

MINERALOGICAL SOCIETY OF AMERICA AND GEOCHEMICAL SOCIETY SHORT COURSE ANNOUNCEMENT

Environmental Geochemistry, Mineralogy, and Microbiology of Arsenic
15–16 June 2014 (after Goldschmidt 2014)
Miner’s Foundry, Nevada City, California. USA


For a description and a table of contents of these books and to order online, visit www.minsocam.org or contact the Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110, USA; phone: +1 (703) 652-9950; fax: +1 (703) 652-9951; e-mail: business@minsocam.org.
As it does in alternating Januaries, New Year’s Day in 2014 saw the changing of the guard at the Geochemical Society. I am sure you will all join me in expressing thanks to Rick Carlson for his extraordinary vision and energy in moving the Society forward during his 2012–2013 presidency, and we count on being able to continue to draw on his insight and expertise in his new role as past president. Profound thanks are also due to Sam Mukasa, who was past president in 2012–2013, as he steps down from the GS executive after 6 successful years of leadership. We welcome and extend our congratulations to the new GS vice president, Laurie Reisberg (president-elect for 2016–2017), and 5 new Board members, Anton Eisenhauer (secretary), Katherine Freeman (OGD chair), Hilairy Hartnett (OGD secretary), Tomoki Nakamura (director), and Chris Hawkesworth (director), who are joining the 2014 GS Board for the first time. As the new president for 2014–2015, I am looking forward to working with the whole team.

Along with new faces, the Geochemical Society has several historic milestones to celebrate this year and next. December 4, 2013, marked the 100th anniversary of Frederick Soddy’s publication in Nature that is widely credited for formally introducing the terms isotopes and isotopic elements because they occupy the same place in the periodic table; this idea was supported by earlier work by Van der Broek (from a Nature publication on November 27). See more on Soddy’s landmark publication, and the subsequent response from an always lively Ernest Rutherford, at www.nature.com/physics/looking-back/soddy/index.html.

Intriguingly, December 4 has been, since medieval times, the festival of St. Barbara, the patron saint of geologists, miners, and all those who work with stone. If you feel so inclined, send in your write-in ballots and we’ll see if we can get ourselves a patron saint of isotopes!

In the coming year, preparations will be underway for the 2015 celebration of the 60th anniversary of the Geochemical Society and the 25th Goldschmidt Conference (which, while inaugurated in 1988, has been held annually only since 1994). The pre-party (tailgater for you football fans) will begin with the 24th Goldschmidt on June 8–13, 2014, in Sacramento, California! For information, go to http://goldschmidt.info/2014/.

The chairs of the International Program Committee, Dominique Wets and Adina Paytan, are working closely with the Local Organizing Committee, led by Paul Renne, Isabel Montanez, Charlie Alpers, and Lisa Hammersley, to ensure that the California Goldschmidt in Sacramento delivers the high-quality, diverse, and exciting international science you have come to expect from the meeting, coupled with expanded opportunities in student and early-career mentoring, the ability to submit two abstracts as presenting author (only one as a possible oral presentation), a state-of-the-art venue for sessions, meetings and exhibits, superb locations for field trips, and a lively social program in the center of historic California’s gold and wine country. The state capital and also the oldest incorporated and sixth-largest city in California, Sacramento’s founding population of indigenous peoples, Spanish explorers, Chinese immigrants, pioneers, and gold-seekers developed the settlement at the confluence of the American and Sacramento rivers. This strategically located city was the hub of the first transcontinental railroad, and before that the western end of the Pony Express—a western heritage that can still be explored in the restaurants and bistros of historic Old Sacramento (pictured), a short walk from the conference venue and hotels. The Governor’s Mansion, Crocker Art Museum, Memorial Auditorium, and State Capitol buildings and parkland (pictured) adjacent to the conference center provide opportunities to extend the conference beyond the walls and enjoy the city. In addition to official conference field trips, informal side trips to Napa (60 minutes), San Francisco (90 minutes), Tahoe (2 hours), and Yosemite (3 hours) will beckon to delegates.

California begins here! Join us in this historic location as Goldschmidt 2014 continues its role as science and community catalyst, on the cusp of its second quarter century.

Barbara Sherwood Lollar, GS President
GS WELCOMES NEW OFFICERS AND VOLUNTEERS

On January 1, 2014, Barbara Sherwood Lollar (University of Toronto) took up the mantle as Geochemical Society president. She will serve after Richard Carlson (Carnegie Institution of Washington), who remains on the Board as past president. Joining the 2014 Board of Directors are six new members: Vice President Laurie Reisberg (CRPG), Secretary Anton Eisenhauer (GEOMAR), OGD Chair Katherine Freeman (Penn State University), OGD Secretary Hilairy Hartnett (Arizona State University), Director Tomoki Nakamura (Tohoku University), and Director Chris Hawkesworth (University of St. Andrews).

Five committees also welcome new members. Jeremy Fein (University of Notre Dame) and Andrew Davis (University of Chicago) join the 2014 Joint Publications Committee; Erik Hauri (Carnegie Institution of Washington) and Takeshi Kakegawa (Tohoku University) join the 2014 Nominations Committee; Elisabeth Sikes (Rutgers University), Hilairy Hartnett (Arizona State University), and Josef Werne (University of Pittsburgh) join the 2014 OGD Executive Committee; Pratigya Polissar (Columbia University) joins the 2014 OGD Best Paper Award Committee; and James Brenan (University of Toronto) and Li-Hung Lin (National Taiwan University) join the 2014 Geochemical News editors.

For a full list of officers and volunteers please visit www.geochemsoc.org/society/committeesandpersonnel/.

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Sacramento, California
8 – 13 June 2014
goldschmidt.info/2014

Early Registration Deadline
8 April 2014
OBITUARY

Dorian G. W. Smith (1934–2013)

Dorian G. W. Smith was born in London, England, in 1934. After his schooling, he did national service with the Royal Air Force in the UK and Germany, kindling an interest in flying which later led to a pilot’s license. He then studied at University College London before moving to the University of Alberta for his MSc. His timing was excellent: while in Edmonton, thousands of meteorites fell nearby at Bruderheim, and he helped to collect them. These samples became the nucleus of the University of Alberta’s meteorite collection, which he was to curate later. He returned to the UK for his PhD at Cambridge, graduating in 1963. He worked as a demonstrator (sessional lecturer) in mineralogy at Oxford University for three years, where he received an MA by decree in 1964.

In 1966, he became a professor in the then Department of Geology at the University of Alberta, where he was to spend the rest of his career. He taught mineralogy, established the electron microprobe lab, and became the curator of the mineral and meteorite collections. His research included K/Ar dating, clay mineralogy, meteoritics, X-ray spectroscopy, microanalysis, and computer applications. He was very active in meteoritics in Canada, sitting on national committees and leading an expedition to the Devon Island ice cap in the Arctic to locate meteorites. He traded samples of Bruderheim and other meteorites with collections worldwide, helping to establish a collection of international importance. His development of microprobe microanalytical techniques increased his interest in the identification of minerals. This led to the development, over many years, of an extensive mineral-properties database and software for the identification of minerals (MinIdent), which is still used at academic institutions and mining companies throughout the world. He was closely associated with the Mineralogical Association of Canada. He organized the first MAC short course with published notes, which became a cornerstone of the Association, and later held a number of positions within MAC, including president in 1978–1979.

As he approached retirement in 2000, he devoted more time to the Subcommittee for Unnamed Minerals (SCUM as he liked to call it) of the IMA Commission on New Minerals, Nomenclature and Classification, where he helped develop the code names for unnamed minerals. He also spent a great deal of time maintaining and adding to the MinIdent mineral-properties database. The last upgrade was just a few weeks before his death and contained almost a million data items. His attention to detail was legendary and ensured the quality of all that he did.

After “retirement,” he bought a house in Brittany and lived as a “reverse snowbird”—summers in France and winters in Edmonton. He returned to France briefly, before he died in Scotland in the company of his family in June 2013.

Michael Higgins, Université du Québec à Chicoutimi

At their annual meeting in Winnipeg, the Geological Association of Canada and the Mineralogical Association of Canada held the symposium “Earth Materials, Petrological and Geochemical Processes (in Honour of Frank C. Hawthorne).” The symposium was organized by Elena Sokolova and Norman Halden. The photograph shows the keynote speaker, the iconic Bob (“ionic radius”) Shannon, with Elena Sokolova and Frank Hawthorne.

Hot off the press!
Order your copy TODAY at www.mineralogicalassociation.ca
CALENDAR

2014


April 6–9 AAPG 2014 Annual Convention & Exhibition, Houston, TX, USA. Web page: www.aapg.org/meetings


April 27–May 2 European Geosciences Union General Assembly 2014, Vienna, Austria. Web page: www.eGU2014.eu


May 10–15 Hot Topics in Contemporary Crystallography, Šibenik, Croatia. Web page: www.hazu.hr/kristallografia/HotTopics

May 17–21 51st annual meeting of The Clay Minerals Society (CMS), College Station, TX, USA. Web page: https://csm2014.tamu.edu


May 24–28 American Crystallographic Association Meeting, Albuquerque, NM, USA. Web page: www.americalas.org/content/pages/main-annual-meetings


May 26–31 Accretion and Early Differentiation of the Earth and Terrestrial Planets (ACCRETE), Nice, France. Web page: www.accrete.uni-bayreuth.de/page=workshops


June 15–19 11th International GeoRaman Conference, Saint Louis, MO, USA. E-mail: alanwill@levée.wustl.edu; web page: www.georaman2014.wustl.edu

June 30–July 4 Asteroids, Comets, Meteors, Helsinki, Finland. E-mail: acm-2014@helsinki.fi; web page: www.helsinki.fi/acm2014

June 30–July 4 30th SEGH (Society of Environmental Geochemistry and Health) Conference, University of Northumbria, Newcastle, UK. Web page: www.segh.net/events/segh-conference


July 14–18 Eighth International Conference on Mars, Pasadena, CA, USA. Web page: www.hou.usra.edu/meetings/8thmar2014


August 2–7 IUMAS-6 held in conjunction with Microscopy & Microanalysis 2014, Hartford, CT, USA. Web page: www.iumas6.org


August 5–7 First Meeting of the IAGC Urban Geochemistry Working Group, Columbus, OH, USA. Web page: www.iagc-society.org/UG.html

August 5–12 23rd Congress and General Assembly of the International Union of Crystallography, Montreal, Canada. Website: www.iucr2014.org

August 10–14 248th ACS National Meeting & Exposition, San Francisco, CA, USA. Web page: www.acs.org

August 18–23 Geochemistry of the Earth’s Surface (GES-10), Paris, France. Web page: www.ipgp.fr/GES10

August 19–22 14th Quadrennial IAGOD Symposium, Kunming, China. Website: www.14iagod.org


September 1–5 21st General Meeting of the International Mineralogical Association (IMA2014), Johannesburg, South Africa. E-mail: info@ima2014.co.za; web page: www.ima2014.co.za

September 6–10 31st International Conference on Ore Potential of Alkaline, Kimberlite and Carbonatite Magmatism, Antalya, Turkey. Website: http://alkaline2014.com

September 4–7 ERES – European Rare Earth Resources Meeting, Milos Island, Greece. Web page: http://eres2014.conferences.gr


September 9–13 Cities on Volcanoes 8, Yogyakarta, Indonesia. E-mail: info@citiesonvolcanoes8.com; website: www.citiesonvolcanoes8.com

September 10–12 Joint SGI-SIMP Meeting, Milano, Italy. E-mail: segreteria@scimpi.net; web page: www.geosci2014.it

September 10–12 Planet Formation & Evolution 2014, Kiel, Germany. Web page: webpages1.tphysik.uni-kiel.de/-kiei/2014/main

September 16–19 3rd Mid-European Clay Conference (MECC2014), Dresden, Germany. Website: www.mecc2014.de

September 21–24 The 92nd Annual Meeting of the German Mineralogical Society (DMG), Jena, Germany. Website: www.dmg2014.de

October 12–16 MS&T’14: Materials Science & Technology Conference and Exhibition, Pittsburgh, PA, USA. Web page: www.dmg2014.de

October 19–22 Geological Society of America Annual Meeting, Vancouver, BC, Canada. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings

October 20–24 Short Course “Introduction to Secondary Ion Mass Spectrometry in the Earth Sciences”, Potsdam, Germany. Web page: www.giz-potsdam.de/MSIMS

November 17–22 5th International Maar Conference, Queretaro, Mexico. Web page: maara2014.geociencias.unam.mx


November 30–December 5 MRS Fall Meeting & Exhibit, Boston, MA, USA. Web page: www.mrs.org/fall2014


2015


July 5–10 Euroclays 2015, University of Edinburgh, UK. E-mail: stephen.hillier@hutton.ac.uk; web page: www.minersoc.org/euroclay.html


August 8–14 Geoanalysis Conference, Leoben, Austria. Web page: www.geoanalysis.info

August 16–20 250th ACS National Meeting & Exposition, Boston, MA, USA. Web page: www.acs.org

August 16–21 2015 Goldschmidt Conference, Prague, Czech Republic. Web page: www.geochemsoc.org/programs/goldschmidtconference

August 23–28 29th Meeting of European Crystallographic Association (ECMS2015), Rovin, Croatia. Web page: ecms29.earcnovs.org

August 24–27 SGA 13th Biennial Meeting, Nancy, France. E-mail: sga-2015@univ-lorraine.fr

September 9–11 8th European Conference on Mineralogy and Spectroscopy (ECMS2015), Rome, Italy. Details forthcoming

September 20–25 8th Hutton Symposium on Granulite-Related Rocks, Floriánopolis, Brazil. Web page: www.hutton8.com.br

October 4–8 MS&T’15: Materials Science &Technology Conference and Exhibition, combined with ACRS 117th Annual Meeting, Columbus, OH, USA. Details forthcoming

November 1–5 Geological Society of America Annual Meeting, Baltimore, MD, USA. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings

2016


August 27–September 4 35th International Geological Congress, Cape Town, South Africa. Website: www.35igc.org

The meetings convened by the societies participating in Elements are highlighted in yellow. This meetings calendar was compiled by Andrea Kozioł (more meetings are listed on the calendar she maintains at http://homepages.udayton.edu/~akozio1/meetings.html). To get meeting information listed, please contact her at Andrea.Koziol@notes.udayton.edu.
The brown hill in the middle is Klokken, with layering dipping from right to left. Beyond, glaciers lead up into the Inland Ice, the vast ice sheet that covers most of Greenland and continues for 2400 km to the north.

Klokken can be reached only by helicopter (Fig. 1), so visits are not cheap. Exposure is good, because it is scoured of plant life by violent föhn winds that blow from the Inland Ice. I’ve now been there nine times, including three one-day visits for field workshops with 20+ participants. I’m not getting any younger and had rather given up hope of returning, but I had the great pleasure to visit again in 2013 as part of a small group with interests in the rheology of magmas and crystal mushes. I first went there in 1971, with one research-student companion, with the task of mapping the intrusion for the Geological Survey of Greenland. We had some handwritten notes from an early reconnaissance visit, in Danish, which we didn’t speak, so it was really a step into the unknown. We were set down by a huge SH-60 helicopter, put up our tents, had a cup of tea, and strolled up the nearest hillside. Very soon we encountered our first black swan (Fig. 2).

In 1971, the thinking about layered igneous rocks was dominated by the work of Wager and Deer on the Skaergaard intrusion, much further north on the east coast of Greenland. There, graded layers are arranged so that denser minerals (olivine and pyroxene) are concentrated at the base and low-density plagioclase feldspar is concentrated at the top. Sorting by density, under the influence of gravity, was the white swan of igneous layering in gabbroic intrusions. In Klokken the density sequence is inverted. The white rock at the bottom of Figure 2 is composed mainly of parallel tablets of alkali feldspar (specific gravity 2.6) giving it a strong igneous lamination; the dark, mafic rock at the top is largely made of the iron pyroxene hedenbergite (3.6). In some layers (Fig. 3) the density range is even larger, with iron olivine, fayalite (4.4), and magnetite (5.2) forming the top of the layer. This ‘inversely graded’ modal layering is unique to Klokken. It occurs repeatedly and can be traced laterally around a central focus towards which it dips at roughly 35°. In syenites elsewhere on Earth, layering is normally graded, in gabbros, Klokken is truly the black swan of mineral layering.

Another type of black swan has glided into Figures 3 and 4. About 85% of the Klokken layered series is composed of the coarse-grained laminated syenite with its enigmatic inversely graded layering (Fig. 2). The remaining 15% is composed of discontinuous layers, of variable thickness, of relatively fine-grained ‘granular’ syenite, the brown rock at the top of both figures. The grain size in these layers increases downwards. The feldspathic laminated syenite and granular syenite have nearly the same compositions (they are composed mainly of similar alkal feldspars), but the olivine and pyroxene tell an interesting story. All the pyroxenes and olivines in the laminated syenites and modal layers are very iron-rich and vary little with stratigraphic position. In the granular layers these minerals change in composition systematically, more magnesian at the top, iron-rich at the bottom. This downward mineral evolution is the hallmark of a sequence of rocks formed in a chill zone at the roof of a magma chamber, another celebrated feature of the Skaergaard intrusion. It seems that in Klokken, sheets of syenite in the chill zone became detached from the roof of the magma chamber and sank gently down like giant pancakes onto a crystal mush of laminated syenite.

Yet another black swan in Figure 3 is the irregular, lobate interface between the olivine-rich rock and the granular syenite, with upward-pointing flame-like structures. If you know anything about clastic sedimentary rocks, you may be reminded of load structures. Throughout Klokken, at most interfaces between granular and laminated syenites, I can’t thank enough Marian Holness and Llewellyn Pilbeam, from Cambridge, and Madeleine Humphreys, now at Durham, for their tolerance and invigorating companionship during this trip.

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including their inversely graded layers, there are load structures, often on a scale that far outshines those in sedimentary rocks (Fig. 4). Load structures have been recorded in a few other layered intrusions, but none approach the size or splendour of those at Klokken. Again, it is the density relationships that qualify these structures for black swan status. In sedimentary rocks, load structures form where a dense bed rests on a less dense one. As we see them now, the syenite types in Figure 4 have very similar densities, with the upper rock very slightly the more dense, but in Figure 3 the lower rock is much denser. And yet there are load structures...! Throughout the intrusion the size of the load structures depends inversely on the density contrast, but the lower unit is often the denser.

Afi cionados of igneous layering will be gritting their teeth because, for brevity, I have been guilty of considerable oversimplification here. Crystal supply, crystal size, crystal nucleation and growth rates, liquid density and viscosity, temperature and water vapour pressure, all changing with time, are among the factors that will have contributed to the formation of these unique structures2. If my comrades from last summer have their way, Klokken may become tomorrow’s white swan in the field of magma rheology.

Ian Parsons
University of Edinburgh


PARTING QUOTE

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