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Contributions to International Polar Year Science

Igor Krupnik, Michael A. Lang,
and Scott E. Miller
Editors

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Antarctic Meteorites: Exploring the Solar System from the Ice

Timothy J. McCoy, Linda C. Welzenbach, and Catherine M. Corrigan

ABSTRACT. The collection of meteorites from the Antarctic plateau has changed from a scientific curiosity to a major source of extraterrestrial material. Following initial meteorite recoveries in 1976, the U.S. National Science Foundation, the National Aeronautics and Space Administration (NASA), and the Smithsonian Institution formed the U.S. Antarctic Meteorite program for the collection, curation, classification, and distribution of Antarctic meteorites, which was formalized in 1981. The Smithsonian provides classification and serves as the long-term curatorial repository, resulting in explosive growth of the Smithsonian meteorite collection. After 30 field seasons, more than 80% of the Smithsonian collection now originates from Antarctica. In addition to curation and classification, Smithsonian staff provide administrative leadership to the program, serve on field expeditions, and provide specimens for outreach and display. Given the relatively pristine state and ancient terrestrial ages of these meteorites, they provide perhaps our best sampling of the material in our solar system. Meteorites from the Moon were first recognized among the Antarctic meteorites in 1981, as was the first martian meteorite the next year. In 1996, debate erupted about evidence for past microbial life in an Antarctic martian meteorite, and that debate spurred the launch of two rovers to explore Mars. Among meteorites thought to have originated on asteroids, ingredients for ancient life may have survived much higher temperatures than previously envisioned during early planetary melting and differentiation. The ongoing collection of Antarctic meteorites will enrich the scientific community and Smithsonian Institution in specimens and knowledge about our solar system.

METEORITES FROM ANTARCTICA

Serendipitous finds of meteorites from Antarctica were documented as early as 1912 (Adelie Land), and several such finds occurred in the early 1960s as scientific investigations in Antarctica increased (Lazarev, 1961; Thiel Mountains, 1962; Neptune Mountains, 1964). In 1969, with the recovery of nine meteorites in the Yamato Mountains by Japanese glaciologists, meteorites went from being mere curiosities to becoming a focus of exploration. While most accumulations of multiple meteorites represent a single fall that broke up in the atmosphere and showered an area with stones, this discovery suggested a unique concentration mechanism. These nine meteorites represented six different types, including two rare chondrites (primitive meteorites formed in the solar nebula) and a diogenite

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(a rock formed by melting on the surface of an asteroid) (Shima and Shima, 1973).

The concentration mechanism (Figure 1) is tied to the 12 million km^2 of Antarctic ice sheet, which acts as an ideal catchment area for fallen meteorites (Harvey, 2003). As the East Antarctic ice sheet flows toward the margins of the continent, its progress is occasionally blocked by mountains or obstructions below the ice. In these areas, old, deep, blue ice is pushed to the surface, carrying the meteorites along with it. Strong katabatic winds cause massive deflation, removing large volumes of ice and preventing the accumulation of snow on the stranded deposits of meteorites. The end result is a representative sampling of meteorite falls.

Of additional significance is the terrestrial residence time of these rocks. Antarctic meteorites record terrestrial ages ranging from tens of thousands to two million years (Welten et al., 1997) and yet are less weathered than meteorites found in temperate climates. The newly fallen meteorites are quickly frozen and preserved into the thickening ice sheet, reducing the amount of weathering and contamination. The relatively pristine state of the samples allows studies that were previously difficult or impossible. The lack of weathering also means that much smaller meteorites survive and thus provide a broader sample of the material in our solar system.

ANTARCTIC METEORITE PROGRAM

The Japanese began regular collecting expeditions to the Antarctic in 1973, collecting a modest 12 meteorites. In 1974, they returned hundreds of meteorites. During this same period, University of Pittsburgh meteorite scientist Bill Cassidy submitted three proposals to the National Science Foundation (NSF) to fund a U.S. expedition to find other suitable areas of meteorite accumulation. When word of the Japanese success finally reached the NSF, after it had rejected the three previously submitted proposals, support was granted for a 1976–1977 expedition. Cassidy was joined by Ed Olsen (Field Museum, Chicago) and Keizo Yanai (National Institute for Polar Research, Tokyo) to search in areas accessible by helicopter from McMurdo Station to Allan Hills. Nine specimens were found that season. These early days of Antarctic meteorite collection are wonderfully recounted in Cassidy (2003). The meteorites were curated by Olsen

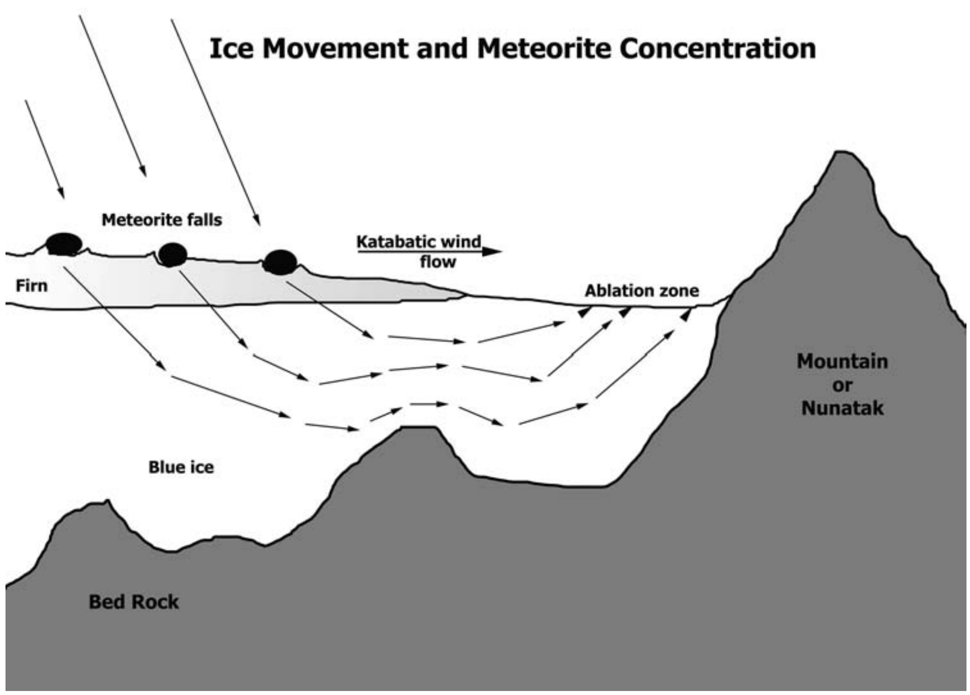

FIGURE 1. Diagram illustrating the mechanism by which Antarctic meteorites are concentrated in specific locations . See text for description of this process.

at the Field Museum, and pieces were distributed in an ad hoc fashion to the research community.

Despite the modest numbers for this joint U.S.–Japanese team, it was clear that this was merely the tip of the iceberg and that large numbers of meteorites from the cleanest environment on Earth were soon to be recovered in Antarctica. An ad hoc committee was convened on 11 November 1977 in Washington, D.C. The meeting included representatives of NSF (Mort Turner), the field party (William Cassidy), the Smithsonian Institution (SI, Brian Mason of the Natural History Museum and Ursula Marvin of the Astrophysical Observatory), National Aeronautics and Space Administration (NASA, Don Bogard of Johnson Space Center and Bevan French of NASA headquarters), and the scientific community (including Jim Papike) (Antarctic Meteorite Working Group, 1978). This meeting produced "a plan for the collection, processing, and distribution of the U.S. portion of the Antarctic meteorites collected during 1977-78" (Antarctic Meteorite Working Group, 1978:13). However, much of the groundwork for this system of interagency cooperation (which ultimately was formalized as the three-agency agreement between NASA, NSF, and SI) and distribution of samples was laid before the meeting. Brian Mason (Smithsonian Institution, personal communication, 2004) recounted a conversation with Mort Turner where the opinion expressed was that meteorites collected by U.S. field expeditions should properly become U.S. government property. It was agreed that NASA would provide short-term curation modeled on, but less rigorous than, standards for lunar rock curation, while the Smithsonian would assume responsibility for classification and long-term curation and storage.

The collection effort evolved into what is now known as the Antarctic Search for Meteorites (ANSMET). Thirty full seasons have now been completed with the recovery of more than 16,000 meteorites—more than were collected over the entire Earth in the previous 500 years. The field party grew from three members initially, with six to eight members during much of its history, and peaked at 12 members split between two field parties, with one supported by NASA with the specific objective of increasing the collection of martian meteorites. The NSF Division of Polar Programs, with decades of experience in exploring the harsh Antarctic environment, provides support for the ANSMET. Currently, the ANSMET program is run by Ralph Harvey, an associate professor at Case Western Reserve University. Each year, teams of four to eight scientists work together collecting meteorites in remote field locations for about six weeks during the austral summer (November–January). Their primary goal is to recover a complete and uncontaminated sampling of meteorites. Systematic searches are conducted as a series of 30-m-wide parallel transects by snowmobile on areas of snow-free blue ice. If the concentration is high, transects by snowmobile are replaced by searching on foot, ensuring the recovery of meteorites as small as 1 cm in diameter. Many stranding surfaces are large enough to require several seasons in the same area.

It is interesting to note that as the program evolved, the number of meteorites recovered changed dramatically. Starting with 11 meteorites in 1976, ANSMET averaged ~200 meteorites per year from 1976 to 1984, before ramping up to an average of nearly 600 meteorites from 1985 to 2001. This average is remarkable given the cancellation of the 1989 field season due to logistical problems and the intentional exploration of areas with greater and lesser numbers of meteorites to average out the curatorial workload from year to year. During 2002–2006, an average of more than 900 meteorites was recovered each year, including two seasons of 1200+ meteorites.

The astounding success of the Antarctic meteorite programs of the United States and Japan have spurred a number of other efforts, including those from Europe (EUROMET) (Folco et al., 2002) and China (Lin et al., 2002). Indeed, a few privately funded expeditions have actually recovered meteorites in Antarctica. These events caused the Antarctic Treaty Organization to encourage member countries to take measures to protect this valuable scientific resource. The U.S. government, through the NSF, responded by implementing a federal regulation (45 CFR 674; National Science Foundation, 2003) that codified, for the first time, collection and curatorial standards used by the U.S. Antarctic Meteorite Program. It is important to note that other national governments and government consortia (e.g., EUROMET) adhere to similar standards, although each has standards adapted to their unique situation.

SMITHSONIAN'S ROLE IN THE U.S. ANTARCTIC METEORITE PROGRAM

While the Smithsonian's role has primarily been in classification and curation, it has been greatly strengthened by the participation of several SI staff in the field efforts over the years (Figure 2). Ursula Marvin of the Smithsonian Astrophysical Observatory, who played a pivotal role in both the initial formation and long-term management of the program over the next three decades, was the first Smithsonian participant in 1978–1979 and returned in 1981–1982, joined by Bob Fudali of the Division of

FIGURE 2. Linda Welzenbach collects an achondrite meteorite at Larkman Nunatak during the 2006–2007 ANSMET field season.

Meteorites, a long-time associate of Cassidy. Subsequently, Fudali (1983–1984, 1987–1988), meteorite collection managers Twyla Thomas (1985–1986) and Linda Welzenbach (2002–2003, 2006–2007), and postdoctoral fellows Sara Russell (1996–1997) and Cari Corrigan (2004–2005) served on the ANSMET field parties.

While the collection effort was shared by many, the classification of Antarctic meteorites has been largely the responsibility of two individuals, Brian Mason and Tim McCoy. Mason volunteered his services during the formative stages of the program, and it would be hard to have found a more perfect individual to undertake the challenge of classifying thousands of individual meteorites. During his tenure at the American Museum of Natural History in New York and subsequently at the Smithsonian Institution, Mason had examined virtually every type of meteorite known, pioneered the use of mineralogical data in the classification of meteorites in his seminal 1963 paper (Mason, 1963), and, when faced with an unusual Antarctic meteorite, could quickly recall other similar meteorites he had examined during his long career. During his long tenure with the ANSMET program, Mason would go on to classify more than 10,000 individual meteorites, including a considerable number of Japanese meteorites during a visit to the National Institute of Polar Research in 1982. McCoy was hired in large part because of his experience and interest in classification of and research on Antarctic meteorites and has overseen classification, with the help of Welzenbach and a cadre of students and postdoctoral fellows, of more than 5,000 meteorites.

After macroscopic descriptions are completed at NASA's Johnson Space Center, a small chip is sent to the Smithsonian for classification. In the earliest days of the program, a thin section was prepared for every meteorite, and mineral compositions were measured using the electron microprobe. As the numbers of meteorites ramped up between 1984 and 1988, it became clear that this laborious, time-consuming technique was producing an unacceptably large backlog of meteorites awaiting classification. Mason saw a need for a quicker technique to separate and classify the myriad of equilibrated ordinary chondrites. In 1987, he returned to a technique he had successfully applied in the 1950s and early 1960s—oil immersion. The rapid determination of the composition of a few olivine grains from each meteorite then became and remains the method by which 80%–90% of all U.S. Antarctic meteorites are classified.

Unequilibrated ordinary, carbonaceous, and enstatite chondrites and achondrites are sent for thin section preparation, along with some meteorites that cannot be confidently classified due to brecciation, shock, or severe weathering. The Smithsonian's Antarctic thin-section library now contains over 5,000 thin sections, and ~200 new sections are prepared each year. Mineral compositions (olivine and orthopyroxene for most chondrites; olivine, pyroxene, and plagioclase for achondrites) are determined using the JEOL JXA-8900R electron microprobe. The Smithsonian prepares brief descriptions, tables of data, and digital petrographic images that are published in the *Antarctic Meteorite Newsletter* (Satterwhite and Righter, 2006), which is also posted on the Web. Antarctic iron meteorites, which are found at very modest rates, are permanently transferred. The Smithsonian has unique capabilities for processing iron meteorites and handles all processing, curatorial, and classification of irons. For more than 30 years, the responsibility for the description and curation of Antarctic meteorites fell to Roy S. Clarke Jr., whose specialty in the metallography of iron meteorites and oversight of the non-Antarctic collection made him an ideal choice. While all meteorites are classified, the Smithsonian's major task is identifying those specimens that are of particular interest to scientists and that would be worthy of further study. Figure 3 illustrates the results of these efforts, indicating the number of samples recovered, the total number of meteorites, and the subset of meteorites that are not equilibrated ordinary chondrites. The number of meteorites recovered increased steadily from an average of ~300 (1977–1984) to greater than 1,000 per year (2002–2006) as collecting techniques improved and field parties grew in size and number. The number of samples was sometimes greater than the number of meteorites due to the collection of a small number of terrestrial rocks mistaken for meteorites. The number of the most scientifically interesting specimens, those other than equilibrated ordinary chondrites (e.g., unequilibrated ordinary chondrites, carbonaceous and enstatite chondrites, achondrites, and irons), remained constant at ~50/year. (The sharp dip in 1989 was due to a cancelled field season.) The apparent disconnect between the number collected and those of greatest scientific interest is due to the occurrence of meteorites that break up in the atmosphere and possibly shower local areas with thousands of individual fragments. While most scientific studies focus on the small subset of the most interesting specimens, the collection as a whole still offers clues to ice movements related to concentration mechanism and the influx of meteoritic material to Earth over time (Harvey, 2003). Only through systematic collection and classification of all the meteorites can these latter studies be undertaken.

The other major obligation of the SI in the U.S. Antarctic Meteorite Program was serving as the long-term curatorial facility for specimens (Figure 4). In 1983, the SI opened its Museum Support Center in Suitland, Maryland. This state-of-the-art collections facility is centered on four pods (football-field-sized buildings ~50 feet (~15 m) high)

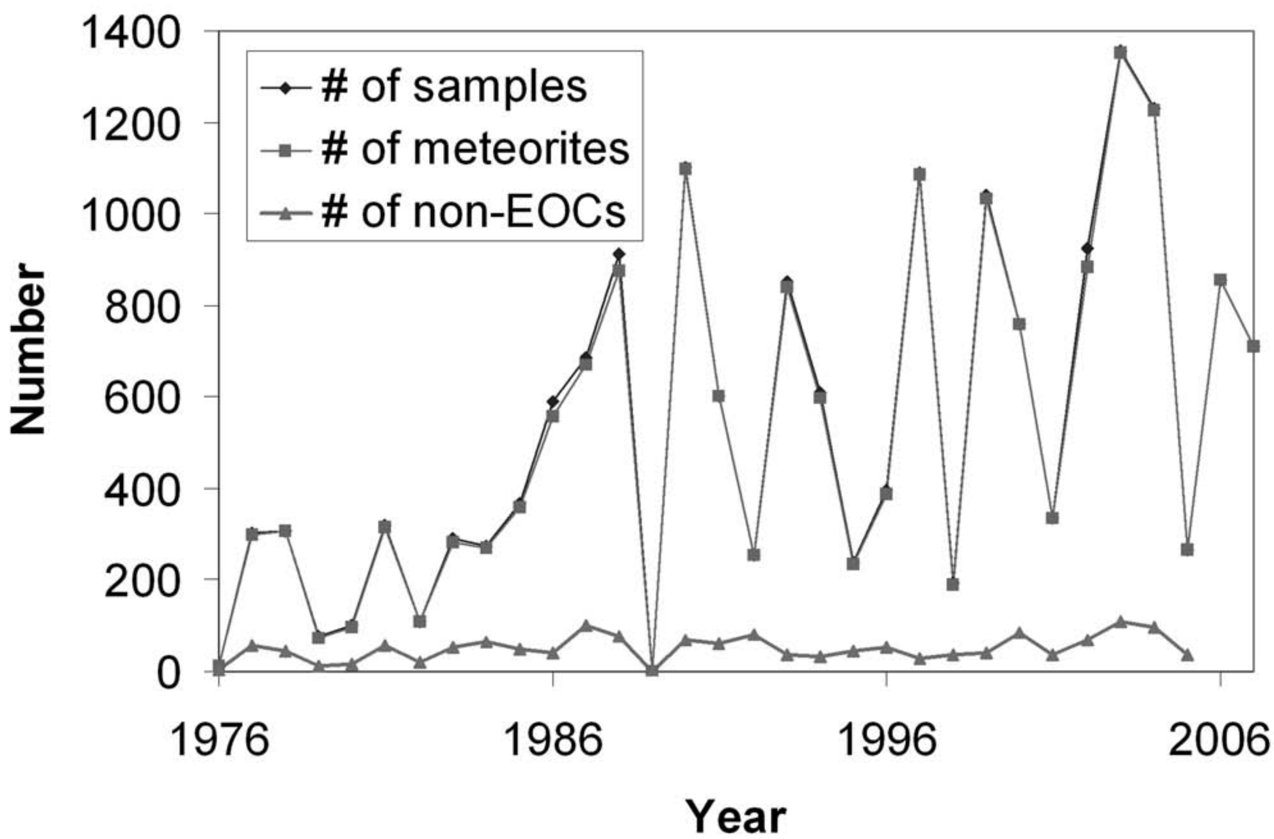

FIGURE 3. The number of samples and recovered meteorites and those meteorites that are not equilibrated ordinary chondrites (EOCs) from 1977 to 2007.

FIGURE 4. Meteorite storage laboratories at the Smithsonian Museum Support Center in Suitland, Maryland, modeled on the facility used for lunar rocks at NASA's Johnson Space Center. The water- and oxygen-free nitrogen gas in the cabinets keeps meteorites from oxidizing and free from contamination by environmental pollutants such as organic compounds, heavy metals, and salts, which could reduce the scientific value of the specimens. Photo by Chip Clarke, SI.

connected by a corridor of offices and laboratories. Shortly after this facility opened, planning began for building what became essentially a duplicate of the dry nitrogen storage facility for Antarctic meteorites at Johnson Space Center in Houston, and the new museum storage facility opened in the fall of 1986. The first significant transfer (126 specimens) of Antarctic meteorites to the Smithsonian occurred in 1987. Regular annual transfers from Johnson Space Center to the museum began in 1992, and the flow of meteorites increased tremendously in 1998. At that point, the Meteorite Processing Laboratory at Johnson Space Center was essentially full, and the subsequent influx of newly recovered meteorites necessitated the transfer of large numbers of specimens to the SI. By the end of 2004, more than 11,300 individual specimens had been transferred to the museum. When coupled with the chips and thin sections used for the initial classification, Antarctic meteorites now represent more than 80% of named meteorites in the Smithsonian collection and more than 70% of all specimens. These percentages alone demonstrate the spectacular impact of the Antarctic Meteorite Program on the Smithsonian's meteorite collection.

During the 30 years of the U.S. Antarctic Meteorite Program, Smithsonian personnel have fulfilled a number of other roles. The program is managed by a three-member Meteorite Steering Group with representatives from NASA, NSF, and the Smithsonian. Recommendations on sample allocations are made by the Meteorite Working Group, a 10-member panel that also includes members of the academic and research communities. Smithsonian personnel from both the Natural History Museum and the Astrophysical Observatory have actively participated or led these committees throughout the history of the program. Additionally, the Smithsonian provides selected samples of Antarctic meteorites for exhibits throughout the world, including meteorites on display at the Crary Science and Engineering Center in McMurdo Station, perhaps the southernmost display of Smithsonian objects.

SCIENTIFIC VALUE OF ANTARCTIC METEORITES

While the U.S. Antarctic Meteorite Program has had a dramatic influence on the size of the Smithsonian meteorite collection, it is the information that these priceless samples hold that is of greatest benefit. While listing the full range of scientific discoveries is beyond the scope of this paper, we list a few examples.

Brian Mason and Smithsonian volcanologist Bill Melson published the first book-length treatise on Apollo 11 samples in 1970 (Mason and Melson, 1970), and Mason remained involved in the study of lunar samples through the end of the Apollo Program. In 1982, Mason described the Antarctic meteorite ALH A81005 as containing clasts that "resemble the anorthositic clasts described from lunar rocks" (Mason, 1983). From his earlier work, Mason knew this was the first lunar meteorite but presented his findings in a typically understated manner so as not to undercut the considerable research that would be forthcoming. Today, we recognize more than three dozen distinct lunar meteorites. A remarkable feature of these meteorites is that they commonly exhibit very low abundances of the radioactive element thorium. In contrast, the area sampled by the Apollo missions on the equatorial near side of the Moon typically has elevated thorium concentrations indicative of the thin crust and extensive volcanism that occurred in that region. For this reason, lunar meteorites are thought to represent a much broader representative sampling of the lunar surface and are the subject of intense scrutiny as the U.S. plans for a return to the Moon (Korotev et al., 2003).

The realization that lunar meteorites had been launched by impacts from the surface of the Moon and escaped the heating that many predicted would melt them completely reinvigorated debate about whether certain meteorites actually originated on Mars. This debate was largely settled in 1981, when Don Bogard and colleagues at Johnson Space Center showed that gases trapped inside impact melt pockets in the Antarctic meteorite EET A79001 matched those measured in the martian atmosphere by the Viking lander. These samples, now numbering several dozen, provide the only materials from Mars that we have in our laboratories. Although they lack geologic context, study of these rocks has posed many of the questions driving Mars exploration. This was never more true than when McKay et al. (1996) argued that ALH 84001 contained evidence of past microbial life in the form of distinctive chemical, mineralogical, and morphological features. Although the result has been vigorously debated for over a decade, it is clear that this single paper reinvigorated NASA's Mars Exploration Program. The founding of the NASA Astrobiology Institute and the launch of the Mars Exploration Rovers Spirit and Opportunity, which continue to operate after three years on the surface of Mars and on which the senior author is a team member, were spurred in part by the idea that ancient life may have existed on Mars. It is truly remarkable that a modest program of collecting meteorites—the poor man's space probe—prompted the initiation of major research and spacecraft efforts!

Among the significant advances in meteoritics within the last decade, one of the most noteworthy is the recognition of meteorites that are intermediate between the primitive chondrites formed as sediments from the solar nebula and achondrites that sample differentiated bodies with cores, mantles, and crusts, like Earth. These meteorites, termed primitive achondrites, experienced only partial melting and differentiation, after which the process was halted. These meteorites may offer our best clues to how our own planet differentiated. While such meteorites have been known for more than a century, they were few in number and largely viewed as curiosities. The vast numbers of meteorites recovered from Antarctica have pushed these meteorites into prominence, as major groupings have emerged. Among these meteorites, one is truly remarkable. Graves Nunatak (GRA) 95209 contains metal veins that sample the earliest melting of an asteroid as it began to heat up more than 4.5 billion years ago (McCoy et al., 2006). These veins record a complex history of melting, melt migration, oxidation-reduction reactions, intrusion into cooler regions, cooling, and crystallization. The single most remarkable feature of this meteorite is the presence of millimeter-size metal grains that contain up to a dozen graphite rosettes tens of micrometers in diameter. Within a single metal vein, carbon isotopic compositions ($\delta^{13}C$) can range from -50 to $+80‰$. These graphite grains formed not in the parent asteroid during melting but during nebular reactions. This isotopic heterogeneity is even more remarkable when we consider that a single millimeter-sized metal grain within this meteorite has a greater carbon isotopic heterogeneity than all the natural materials on Earth. Despite extensive heating, this asteroid did not achieve a homogeneous carbon isotopic composition. In a very real way, this sample gives us a glimpse into the processes that occurred in the solar nebula during the birth of our solar system as well during the heating, melting, and differentiation of our Earth.

CONCLUSIONS

The meteorite collection and the insights provided by the influx of a tremendous number of Antarctic meteorites continue to enrich the Smithsonian collections and offer opportunities for research among its staff. Much of the current emphasis is in the burgeoning field of astrobiology. Understanding the fate of carbon during the differentiation of planets forms another link in understanding this fundamental element from its birth in other stars to the role it plays today in biologic evolution. Scientists at the Smithsonian use these meteorites to ask fundamental questions that they then set about answering through participation in spacecraft missions to the Moon, Mars, asteroids, and comets. Rather than supplanting meteorites as a major source of information, samples returned from these bodies will make Antarctic meteorites more scientifically valuable as they continue to provide the framework as we continue to ask and answer the questions of our solar system's birth, evolution, and destiny.

ACKNOWLEDGMENTS

This paper reports the results of an effort shared by hundreds of individuals over three decades. These include the members of the meteorite search teams, the curatorial teams at Johnson Space Center and the Smithsonian Institution, the administrative support at NASA, the National Science Foundation, and the Smithsonian, and the efforts of thousands of scientists who have studied Antarctic meteorites. Among these, Don Bogard (NASA Johnson Space Center), Ursula Marvin (Smithsonian Astrophysical Observatory), and Bill Cassidy (University of Pittsburgh) have given us insights over the years into the formative stages of the U.S. Antarctic Meteorite Program. Our current partners in the curatorial and collection efforts Ralph Harvey (Case Western Reserve University), John Schutt (ANSMET), Kevin Righter (NASA Johnson Space Center), and Cecilia Satterwhite (Jacobs) have been particularly helpful, as have our colleagues at the Smithsonian, Brian Mason, Roy S. Clarke Jr., and the late Gene Jarosewich, who preceded us in these efforts and have been unfailingly supportive. We dedicate this paper to our colleague Gene Jarosewich, who never wavered in his enthusiasm for meteorites.

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