Meteorite studies

Meteorite studies: Terrestrial and extraterrestrial applications, 1997

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Meteorites yield a wealth of information concerning Solar System origin, geochemical evolution of primitive parent objects, and irradiation histories of material in space. Since the numerous (approximately 16,000) antarctic meteorites include many of rare or unique types, current extraterrestrial materials research attention focuses on this population. Antarctic meteorites also have the potential for providing unique information on ice-sheet dynamics.

Techniques used for studying extraterrestrial materials are applicable to studies of terrestrial geologic samples, and our analytical capabilities at Purdue have dual purposes. Our research activities involve the acquisition and genetic interpretation of chemical compositional data particularly at trace or ultratrace levels in rocks and other natural materials. Trace elements are especially valuable since a small absolute compositional change produced by some force is magnified into a large relative change.

Analytical capabilities

Our analytical capabilities, previously limited to accelerator mass spectrometry (AMS) for quantifying cosmogenic radionuclides, radiochemical neutron activation analysis (RNAA) for quantifying 15 volatile trace and ultratrace elements, and electron microprobe analysis (in concert with computer modeling) to study compositional changes during igneous processing, have increased.

During the past year, we continued our AMS upgrade (Elmore et al. 1997), acquired a VG Elemental PQ3 inductively coupled plasma mass spectrometer (ICP-MS) and MicroProbe UV laser ablation unit, and a complementary x-ray fluorescence (XRF) system. We are now completing the last of the laboratory renovations housing our RNAA, AMS, ICP-MS, and XRF facilities and their associated chemical preparation areas.

Much genetic information concerning meteorites that we uncovered reflects our statistical capabilities to treat RNAA data using the multivariate statistical techniques of linear discriminant analysis and logistic regression. At the request of the series editors, Wolf and Lipschutz (1995a) reviewed both standard multivariate statistical analysis and our adaptations thereof.

Martian meteorites

Since my last review (Lipschutz 1995), we have studied the 12 Martian meteorites, six of which are antarctic. Our RNAA data for the Martian lherzolite Yamato (Y)-793605 (cf. Mittlefehldt et al. 1997) demonstrate its resemblance to the other two known lherzolites, Allan Hills (ALH) A77005 and Lewis Cliffs (LEW) 88516. Cluster analysis of whole-rock RNAA data for all 12 Martian meteorites, classifies them into the same six groups [shergottites, nakhlites, lherzolites, orthopyroxenite, chassignite, and shergottitelike Queen Alexandra (QUE) 94201] established petrographically and by refractory element data. Apparently, each of these six groups formed in separate igneous chambers in Mars, closed to volatile transfer (Wang, Mokos, and Lipschutz in press).

Having mineral chemistry data for shergottites, Ghosal et al. (in press) used the MELTS program developed here to study their origin. We found that the oxygen fugacity of the shergottite source region was more reducing, 1–4 $\log_{10}$ units lower than others suggested, and that Mars has a more Earthlike mantle than previously proposed. Subsequent *in situ* Martian surface rock analyses by Pathfinder apparently support the latter suggestion.

Ordinary chondrites

In the last year, we published seven studies dealing with ordinary chondrites, five dealing with antarctic samples. In studying igneous inclusions in three antarctic ordinary chondrites by RNAA, we found that troctolitic inclusions from the L6 chondrites Y-75097 and Y-793241 apparently formed from protoliths of nonchondritic composition, whose origin might be nebular or of secondary (parent body) origin. The igneous inclusion from the H5 chondrite Y-794046 was different: it derives from an H chondrite melt that lost approximately 90 percent of its siderophiles and chalcophiles, presumably in immiscible iron–iron sulfide (Fe-FeS) eutectic melt (Mittlefehldt et al. 1995).

Using AMS, we identified an H chondrite from Victoria Land, ALH 88019, having a terrestrial age of 2.03±0.15 million years, essentially twice the age of the previous record-holder, and also reported additional information on its size and irradiation history (Scherer et al. 1997). This long age provides one boundary condition for ice-sheet history in the Allan Hills region of Antarctica.

To test effects of weathering on RNAA data for antarctic ordinary chondrites, we obtained Fe^{3+} data (using Mössbauer) for 33 antarctic H4-6 chondrites for which we already had RNAA data. Using multivariate statistical techniques, we found no significant dependence of composition on weathering (Wolf and Lipschutz 1995b). Thus, highly significant compositional difference between falls and antarctic H4-6 chondrites with terrestrial ages of 50,000 years or more suggests that the Earth's sampling of H chondrite source objects has varied on the 50,000-year scale (cf. Wolf and Lipschutz 1995c). Based on multivariate statistical analysis of RNAA data, Lipschutz, Wolf, and Dodd (1997) demonstrate that 13 H4-6 chondrites that fell in May 1855–1895 and 17 H4-6 chondrites that fell in September and October 1812–1992 can be distinguished compositionally from 33 random falls of H chondrites between 1773 and 1970 (Wolf et al. 1997). Identification of these two meteoroid streams demonstrates source variations on the hundred-year scale (cf. Lipschutz et al. 1997).

We obtained RNAA and mineral-chemical data for igneous regions in seven, nonantarctic, ordinary chondrites: an H5, H6, two L5, and three L6 (Yolcubal et al. 1997). Use of the MELTS program indicates that igneous regions in six chondrites derive from melting of chondrite types like their hosts and provide detailed information on their metamorphic and magmatic histories. The igneous region in the L6 chondrite Chantonnay, however, apparently derives from an H chondrite source. Only the L6 chondrite Chico evidenced volatile loss; heating involving the other six was short-lived, closed-system, or both.

Carbonaceous chondrites

We have revisited the idea that surfaces of C, G, B, and F asteroids represent thermally metamorphosed material excavated from the interiors of these asteroids by comparing the ultraviolet, visible, near infrared, and 3-micrometer (μm) reflectance spectra of seven selected C, G, B, and F asteroids with spectra from 29 carbonaceous chondrites and artificially heated samples (Hiroi et al. 1996). Twelve of these (including three thermally metamorphosed ones) are antarctic. Relationships between the various spectra produce results suggesting that the larger asteroids represent heated inner portions of even larger bodies. Thus, common CI and CM chondrites may derive from the lost outer portions of these bodies, which escaped extensive, late-stage heating episodes (Hiroi et al. 1996).

A paper describing the petrology of the known CM chondrites, most of which are antarctic, is currently being revised in the light of reviewers' comments (Zolensky et al. 1997). As previously found from RNAA data, CM chondrites not only exhibit petrographic characteristics traditionally defined as type 2 according to the traditional chondritic classification, but extend even to type 1, while filling in the putative hiatus between them (Zolensky et al. 1997).

Ureilites

Finally, Sinha, Sack, and Lipschutz (1997) reported microprobe data for eight antarctic ureilites and used previous empirical data to determine conditions during which ureilite smelting occurred. We found that these eight igneous rocks derive from three or more disconnected parent regions:

- I—equilibrated at 1100–1070°C at 50 kilometers (km) depth or more;
- II—equilibrated at 1230±15°C at 50 km depth or more; and
- III—equilibrated at 1200±15°C in near-surface regions.

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Meteorite recovery and reconnaissance in the Allan Hills–David Glacier and Darwin Glacier regions, 1996–1997

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The region north and west of the Allan Hills has been a prolific source of meteorites since meteorite concentrations were first discovered there in 1976. Recent search efforts have concentrated on the Elephant Moraine icefield, a large [30×15-kilometer (km)] group of blue-ice areas approximately 40 km west of Reckling Peak (figure 1). These icefields, like those to the east at Reckling Moraine, take the form of a series of steps downward from south to north. As indicated by the presence of local superglacial moraines (not associated with exposed bedrock), these steps probably correspond to local thinning of the icesheet as it passes over submerged barriers.

The exposure of blue ice near Elephant Moraine, although extensive, is not fully continuous, and the concentration of meteorites varies dramatically from place to place. An extensive reconnaissance of the area during the 1987–1988 field season resulted in practical subdivisions of the Elephant Moraine icefield into local, smaller bare ice areas, identifying those with significant meteorite concentrations for future systematic searching (figure 2). One of these areas, an icefield unofficially named "Meteorite City" (76°14'S 156°35'E), was the focus of meteorite recovery efforts during the 1996–1997 season by the Antarctic Search for Meteorites (ANSMET) team. The 1987–1988 reconnaissance, and a subsequent short visit in 1990–1991, indicated that the surface of this icefield contained significant numbers of meteorites. Other local icefields were also to be visited for reconnaissance purposes. Our party was put into the field on 20 November 1996 via LC-130 Hercules aircraft, approximately 12 km west of Griffin Nunatak (figure 1). Group members included Laurie Leshin, Sara Russell, Rene Martinez, Guy Consolmagno, and the authors.

From this put-in site, the field party traversed to the Elephant Moraine region and set up camp on the border of the Meteorite City icefield. After an initial orientation period allowing field party members to become familiarized with the region and proper meteorite identification and collection techniques, systematic searching commenced. After some early successes, search efforts were significantly hampered by abundant new snow and high winds, greatly reducing the effectiveness of searches. Eventually the high winds did remove the new snow and systematic searching once again became profitable. By season's end (27 December), 334 meteorites had been recovered and approximately 50 percent of the Meteorite City icefield had been systematically searched.

Midseason (5 December) two members of our party (Schutt and Russell) were transported via Twin Otter to the Meteorite Hills (79°40'S 155°36'E) at the west end of the Dar-

Meteorite finds from the 1996–1997 ANSMET program

Icefield	Ordinary chondrite	Achondrite	Carbonaceous chondrite	Stony iron	Iron	Unknown	Total
Meteorite City	306	5	17		1	5[a]	334
Other local areas	17	1					18
Meteorite Hills	36	1				1	38
Mount DeWitt	2						2
Total	361	7	17	0	1	6	392

[a]Includes at least one lunar specimen.

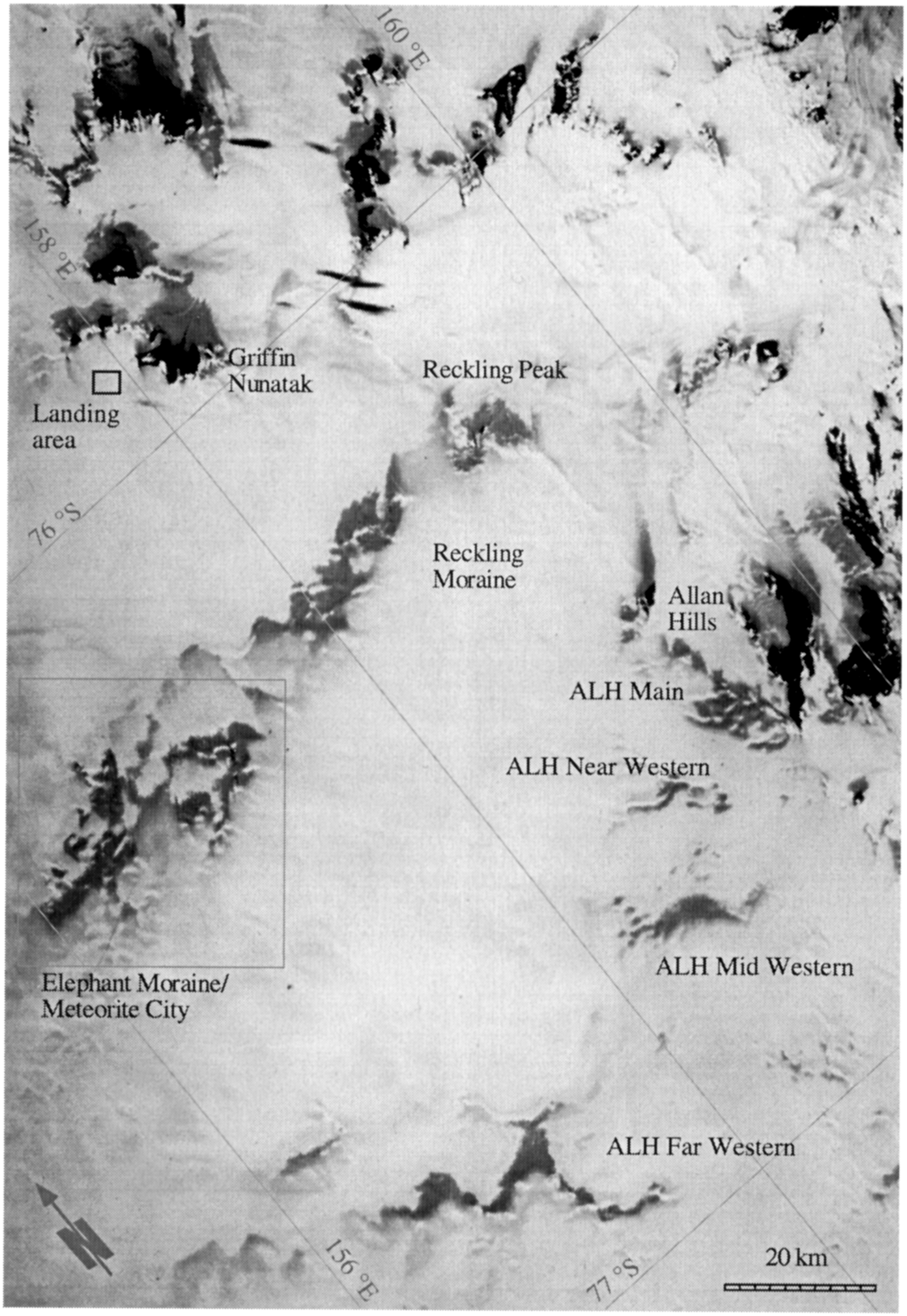

Figure 1. The Allan Hills/Elephant Moraine Area, Antarctica, visited by ANSMET during the 1996–1997 field season. All icefield names are informal designations and unoffical.

win Mountains, in the Darwin Glacier region. This region had been previously visited by a helicopter-based reconnaissance party during the 1978–1979 season, resulting in the recovery of 28 meteorites; however, only a small portion of the icefield was visited and the full extent of the concentration was not known. The 1996–1997 reconnaissance team spent 7 days traveling across the area on snowmobiles and recovered 38 specimens,confirming the presence of a significant concentration and its geographical extent. Systematic searching of the Meteorite Hills icefield is planned for a future season. Reconnaissance in the Meteorite City area included trips to the Texas Bowl, which had been systematically searched in 1987–1988 and 1990–1991 yielding over 1,200 specimens, and the Shooda Bin, a bowl-shaped icefield that exhibited many promising characteristics when examined remotely. The very small number of specimens found in the large area represented by the Shooda Bin (5 total) illustrates, however, how incomplete our understanding of meteorite concentration mechanisms really is.

By season's end a total of 390 meteorites had been collected; 334 from Meteorite City, 38 from Meteorite Hills, and 18 from other areas of the Elephant Moraine icefields. Although the weather limited our systematic searching efforts, several unusual specimens were recovered, including at least one lunar specimen (table). Future seasons of work in this region will be required to complete systematic searching of this important meteorite concentration. Two additional meteorite specimens were collected by representatives of another science project, from bare ice areas around Mount DeWitt (77°12'S 159°50'E).

At the end of the regular season, two field party members (Harvey and Schutt) made a short series of day trips into the McMurdo Dry Valleys via helicopter. The purpose of these trips was to explore the possibility that ancient bedrock platforms in the region might harbor recognizable meteorite concentrations, mimicking those found in dry deserts from other parts of the world such as the Nullarbor Plain in Australia and the Libyan Desert. Such concentrations typically are found where sediment is actively being removed from a surface, enhancing the relative contribution of meteorites from space; however, erosion must not be so active as to actively destroy the meteorites. Meteorites had previously been recovered from bedrock in Antarctica; the most notable of these were the many Derrick Peak specimens collected in 1979, which represented a shower of iron meteorites. These finds, however, represented isolated random falls rather than a true concentration. Our efforts focused on identifying regions where predominant rock type was sedimentary and light in color to make meteorite recognition easier. Regions of the Asgard and Olympus ranges were overflown, as well as Mount Fleming, the Taylor Valley, the Beacon Valley, and the Miers Valley regions. Landings and extensive searches were conducted at promising locations on the Nussbaum Reigel and Cirque 3 of the Asgard Range, but no specimens were found. A few promising sites remain to be examined; but, in general, it seems regions of suitable age and bedrock composition are simply not big enough to represent a significant collection of meteorites.

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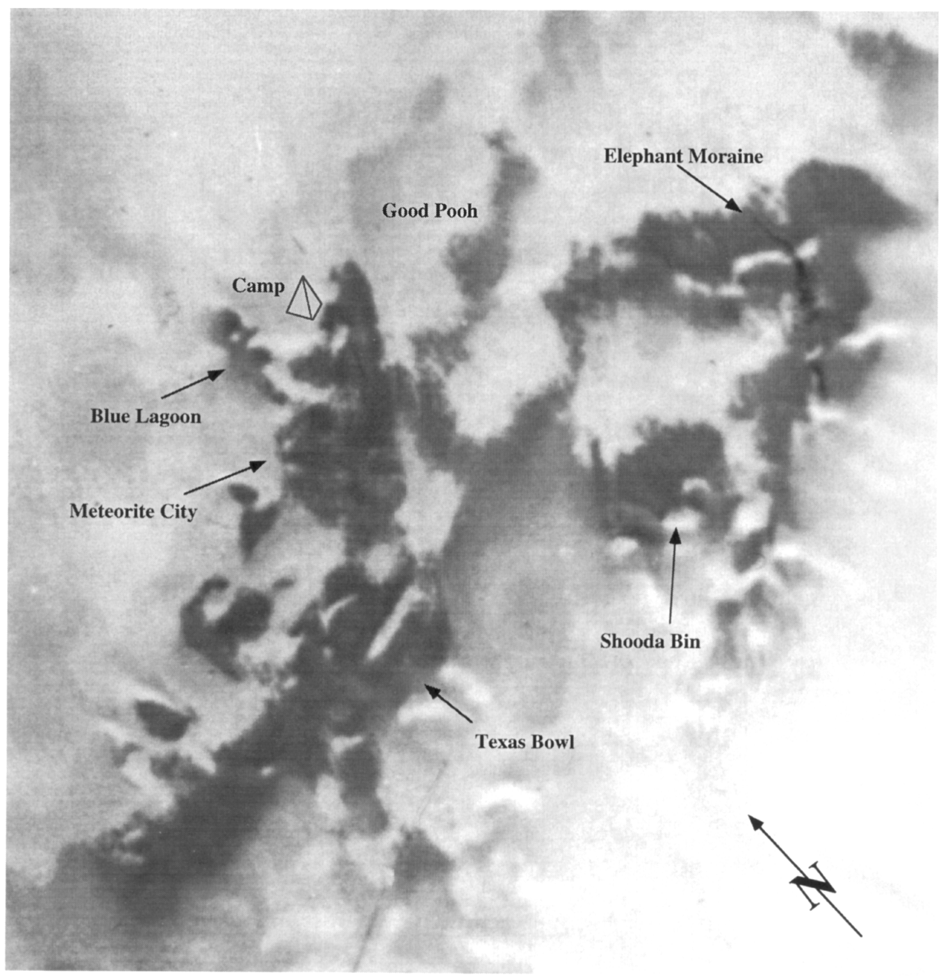

Figure 2. Elephant Moraine area, showing unoffical icefield names. Image is approximately 35 km across.