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The Origin and Significance of Antarctic Meteorites

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Abstract

More than 25,000 meteorite specimens have been recovered from Antarctica since systematic collection programs began in the mid 1970's. When properly recovered and curated, these specimens serve as a uniquely representative sample of the extraterrestrial material accreting to our planet, providing our best glimpse of the full lithological and geochemical breadth of the inner solar system. Antarctic meteorite concentrations are intimately linked to variations in climate and ice sheet behavior over the past several million years, with each individual icefield exhibiting distinct and often unique characteristics.

Key words: Meteorites, Antarctic meteorites, Meteorite recovery, Meteorite concentration mechanisms, Meteorite flux, Meteorite statistics, Antarctica, Antarctic climate, Meteorite classification

I. The relationship between Antarctica and meteorites

If you want to catch beasts you don't see every day,
you have to go places quite out of the way.
You have to go places no others can get to.
You have to get cold and you have to get wet, too.
Theodor Seuss Geisel (Dr. Seuss)

History of Discoveries

Meteorites have been a part of Antarctic history since exploration of that continent began in earnest at the turn of the twentieth century. In Antarctica as elsewhere, discoveries were serendipitous and surprising. The first meteorite recovered from Antarctica (about 10 cm across, and fully fusion-crusted) was found by one of Douglas Mawson's

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field parties in 1912, lying on hard snow on the Adelie Coast of East Antarctica (Mawson, 1915). This field party included F.L. Stillwell, a geologist who immediately recognized the rock as a meteorite and studied it in detail after the expedition returned to the civilized world (Bayly and Stillwell 1923).

Systematic scientific exploration of the Antarctic continent is often said to have begun with designation of the 1957 International Geophysical Year. The global focus of that effort resulted in the deployment of extensive international resources in Antarctica and led to a high level of scientific activity in Antarctica that continues to this day. Three meteorites were discovered during geological surveys: Lazarev, an iron recovered in two fragments from the Humboldt Mountains in January of 1961; Thiel Mountains, a pallasite recovered in two fragments in December of the same year; and Neptune Mountains, a single iron recovered from the Pensacola Range in February of 1964. Both Lazarev and Neptune Mountains were discovered on mountain slopes during geological surveys, and were not associated with any obvious glacial processes (Tolstikov, 1961; Turner, 1962; Ravich and Revnov, 1963; Duke, 1965). Thiel Mountains, on the other hand, was a harbinger of the future; the two fragments were found on “hard, irregularly cupped glacier ice” to the northeast of Mount Wrather, associated with morainal debris (Ford and Tabor, 1971). These authors also noted that the association of the specimens with morainal debris implied that they had been transported from their original fall site, and that their weathering state implied that abrasion in the cold, continuous wind of the polar plateau was extremely effective as a local mechanism of erosion. Their observations proved prescient; both processes are now thought to be extremely important components of Antarctic meteorite concentration mechanisms. In fact, the Thiel Mountains pallasite deserves consideration as the first meteorite recovered from an Antarctic meteorite concentration surface (as later recoveries from the region would confirm). Unfortunately, it was the only meteorite located at that time, and thus the concentration at Thiel Mountains would not be recognized until 1982 (Schutt, 1989).

While Thiel Mountains represents the first find from a meteorite stranding surface, there is little ambiguity as to the event that first led to the recognition that meteorite concentrations exist in the Antarctic. On December 21, 1969, Renji Naruse of the 10th Japanese Antarctic Research Expedition (JARE-10) was one of several glaciologists embedding a network of survey stations in the East Antarctic ice sheet to allow the study of glacial movement. As they extended their survey across a blue icefield uphill from the Yamato (Queen Fabiola) Mountains, they found the first of a total of nine meteorite specimens the group would discover that season (Yoshida et al., 1971). The specimens were returned to Masao Gorai, an igneous petrologist and member of the Special Committee on Antarctic Research, Science Council of Japan. Before the field season, Gorai had requested that the party recover “a meteorite or some weird stuff” since he was no longer interested in the more accessible rocks found close to Japan’s Syowa Station (Gorai 1970). Following the field work Gorai was presented with the nine specimens, and his initial analysis (as reported by Yoshida et al., 1971), revealed that they included E, H and L chondrites, a diogenite, and a carbonaceous chondrite, thus representing at least 5 distinct petrographic groups.

The implication of a possible concentration mechanism was immediately recognized by the Japanese. Yoshida et al. (1971) noted two important things. First, they noted that the discovery of several different petrologic types in close proximity to each other “... is a matter of particular interest”. Second, they noted “the movement and structure of (the) ice sheet of the area may account for the concentration of the meteorites". From these observations they concluded that "there may be some other areas ... having a possibility of concentration of meteorites".

These implications were not immediately grasped outside of Japan – those who heard of the Yamato finds generally assumed that they were nine fragments of a shower fall, or did not look beyond the novelty represented by these specimens. Within the Japanese program, however, the finds of the earlier expedition naturally encouraged the follow-up JARE-14 expedition to watch carefully for further specimens. 12 were found in December of 1973, from the same patch of ice above the Yamato Mountains, and from other sites further west (Shiraishi et al., 1976). These finds, together with the 1969 recoveries, were proof enough of a significant concentration, and the JARE-15 expedition subsequently included a field party dedicated to a systematic search for meteorites. Operating in November and December of 1974, that party collected 663 specimens, opening the door to JARE meteorite searches that continue to this day.

At roughly the same time, news of the Yamato finds was making its way to the larger audience of western meteoriticists. A presentation concerning the mineralogy of the 1969 Yamato meteorites at the 1973 meeting of the Meteoritical Society (Shima and Shima, 1973) provided William Cassidy of the University of Pittsburgh with a "eureka" moment; he recognized that these specimens were the vanguard of a potentially huge number of meteorites. Cassidy enthusiastically shared his insight with others, and proposed a US supported search in the Transantarctic Mountains area. The mounting number of meteorite recoveries by the Japanese eventually convinced the United States Antarctic Research Program (now USAP) to begin supporting active searches. The U.S Antarctic Search for Meteorites (ANSMET) program was created in 1975, and during three subsequent Antarctic field seasons (1976–1977, 1977–1978, and 1978–1979) joint US-Japan expeditions explored regions within helicopter range of the large US base on Ross Island, McMurdo Station, recovering 482 meteorite specimens. Both the US and the Japanese meteorite recovery efforts have continued to enjoy great success; as of this writing more than 25,000 specimens have been recovered by these two groups. Using the most recent Catalogue of Meteorites as a reference, it can be estimated that approximately 85% of the world's meteorite collection (by number) originated in Antarctica (Grady, 2000).

Modern Recovery Programs

The successes of these early expeditions engendered increasing demand for new specimens and quickly led well-supported, institutionalized programs of recovery. While the government-supported US and Japanese meteorite programs are by far the largest, several other nations and even non-governmental entities have conducted meteorite collection activities in Antarctica. With a strong backbone of aerial logistics, US expeditions have ranged widely across Antarctica, predominantly in East Antarctica along the Transantarctic Mountains. Field parties of between four and twelve individuals have deployed annually (with one exception) since the 1976–1977 season. Japanese expeditions have been primarily supported by overland expeditions from Syowa Station and thus centered on the Yamato (Queen Fabiola), Sør Rondane and Belgica mountains regions of Queen Maud Land. Typically the Japanese expeditions are on a larger scale (involving more individuals over a longer field season) but occur with less frequency (e.g. Kojima et al., 2000). EUROMET, a consortium of European countries, actively searched for meteorites in the Allan Hills region in 1988-89 and in the Frontier Mountains region in the early 1990's; the Italian National Antarctic Program (PNRA) participated in these searches and conducted their own in 1997, 1999 and 2001 (e.g. Folco et al., 2002). In 1999 and 2000, teams from the People's Republic of China (Chinese Antarctic Research Expedition) recovered meteorites from the Grove Mountains region (Russell et al., 2002). Finally, as of this writing privately funded expeditions (Planetary Studies Foundation) have now made three trips to Antarctica to recover meteorite specimens (Moser, 2002).

The obvious increase in Antarctic meteorite recovery efforts over the past few years has been driven by several forces. Interest in Antarctic meteorites (particularly Martian specimens) grew dramatically as these specimens became one focus of the flourishing new field of astrobiology. This growth in demand for meteorites takes place during a time when interest in Antarctica as a laboratory for environmental and astrophysical research has also increased, in turn leading to strengthened logistical networks providing more routine access to the continent. Currently there are no signs of saturation in demand, in spite of the "flood" of specimens being recovered in northwest Africa. The most probable limiting factor on Antarctic meteorite recovery efforts will be logistical costs.

- Search techniques

While recent technological advances have improved many aspects of Antarctic expeditions, particularly in terms of navigation and communications, the basic methodology used by modern Antarctic meteorite recovery teams has changed little since 1969. Once a meteorite stranding surface has been identified, search strategies typically follow the transect-sampling model in use by natural scientists for hundreds (if not thousands) of years (e.g. Anderson et al., 2001; Melville and Welsh, 2001; Barabesi et al., 2002; Chen et al., 2002; Hammond et al., 2002). Field team members form a line, each member a few to several tens of meters apart depending on the number distribution of rocks to be examined and the method of travel (on foot or motorized vehicle). The team then proceeds across the meteorite stranding surface in a direction perpendicular to this line, examining each rock in their path. After each transect is completed, the team shifts over to cover a new parallel transect. Usually these transects are designed to include significant overlap; transects are also adapted to any local geographical features, hazards, or weather conditions (e.g. wind, sun-angle, and snowcover) that might effect the efficiency of the search. Where terrestrial rock is particularly abundant (such as in a moraine), regions may be physically marked off and repeatedly covered by transects in several directions. During exploratory recovery efforts, single transects may be used as sampling tools to gauge the relative abundance of meteorite specimens.

In spite of the availability of highly technological sensors, currently the most effective meteorite detector for Antarctic meteorite searches is the human eye. The difficult environment of Antarctica demands the highest possible level of efficiency; only the fastest and most energy efficient detector systems make sense. No currently available electronic system can match the human visual system's amazing capacity to rapidly differentiate a scene into its key elements and recognize those elements that are unique or out of place. For areas where the background of terrestrial rock is very low or absent, this innate ability allows field party members to scan enormous areas of blue ice quickly and immediately notice any rocks upon its surface. This ability is limited only by the seeing conditions and the resolution of the human eye, which typically allows a dark, cm-sized meteorite to be resolved at distances of up to 100 meters on the light colored ice (Harvey, 1995). Most field parties routinely recover meteorite specimens much smaller than this; catalogs of Antarctic specimens contain many specimens in the sub-cm size range.

Meteorite recovery tasks become more difficult when terrestrial rocks become abundant. Recovering all the rocks from such areas has been suggested and even tested, but as the density of terrestrial rock increases, collecting everything rapidly becomes impractical and disruptive of the Antarctic environment. For example, in 1997 and 1998 ANSMET marked off a 100×100 m region of the Mare Meteoriticus icefield in the Foggy Bottom region of the Walcott Névé subjectively considered representative of the “average” numerical surface density of rocks. 125 rocks were recovered during this exercise, but no meteorites. This same exercise, when scaled up to the entire Mare Meteoriticus icefield, would require the collection of over 500,000,000 rocks in the <4 g range alone, of which roughly one in 250,000 would be a meteorite. Thus where terrestrial rocks are present some method of sorting meteorites from among other lithologies during recovery must almost always be employed. Ironically, the potential need for a sorting procedure is greatest where its implementation becomes most imposing- such as within a moraine, where only a few grams of meteorite coexist with thousands of tons of terrestrial rock. Again technology has been proposed as a solution to this problem; ANSMET has fielded and tested a variety of instruments from simple metal detectors to a meteorite hunting robot (NOMAD) equipped with multiple sensors and intelligent processing algorithms (Apostolopoulos et al., 2001). In spite of the sophistication of this approach, high technology is unlikely to supplant visual searches for several reasons. First, many technological sensors sort potential specimens in ways antithetical to the value of the Antarctic collection. For example, while metal detectors can be routinely used to locate iron, stony iron and ordinary chondrite meteorites, many of the most scientifically valuable Antarctic meteorites are igneous specimens that bear few ferromagnetic minerals and thus are indistinguishable from terrestrial rocks. Second, while the speed of modern computer processors and robotic systems is growing dramatically, the human mind’s ability to integrate a scene and pick out key elements remains vastly superior. For example, experiments with NOMAD showed that the robot could successfully use optical sensors to locate and identify potential meteorites from among rocks. These tests took place in a very small area chosen because meteorites had been previously located by conventional visual searches by a single experienced individual. In approximately the same amount of time the robot was active, that individual covered nearly 250× of NOMAD’s search area on foot and found nearly 10× more specimens. Finally, there is ample indication that the human visual system is effective even in confusing environments. Of the 5900 specimens recovered from meteorite stranding surfaces in the Walcott Névé region (LEW, QUE, and MAC specimens), all but a few hundred were recovered from regions rich in terrestrial rock. These specimens include many notable samples easily confused with terrestrial rocks, including two Martian specimens, 5 lunar specimens and several rare igneous specimens such as angrites and brachinites. This success is excellent testimony to 10 million years of selective adaptation in the primate visual system- field party members innately build a mental catalog of the local terrestrial rocks, and focus their attention on those that don’t fit that catalog without resorting to conscious effort to categorize all the salient features of each observable lithology.

Another proposed sorting strategy is “high-grading”; specifically targeting recoveries on achondrites and the other unusual specimens that are of the most interest to science and ignoring more mundane discoveries such as small ordinary chondrites (Harvey and Cassidy, 1998). Some amount of this has occasionally taken place during short reconnaissance searches, when unique specimens are encountered by sheer chance, time is limited and any recoveries that do take place must be prioritized. While high-grading offers the potential to preferentially recover those specimens currently most in demand, the potential for losing interesting specimens is very high, particularly if those picking up the meteorites have little expertise (as is often the case with meteorites being recovered in Northwest Africa). Rare specimens are not always easily recognized from among other meteorites; the differences in their lithologies may be subtle at the hand-specimen level of examination, or fusion crust may hide their interior. Many unusual specimens in the existing Antarctic collections were not recognized as unusual in the field; witness ALH84001, originally classified as a diogenite and reclassified as a Martian orthopyroxenite nearly ten years later (Mittlefehldt, 1994). It is also not clear that searching specifically for rare specimens would significantly reduce the amount of time it takes to find them, given that the geographical distribution of meteorites on each icefield shows no distinction among meteorite types. Visiting each specimen for even the most cursory examination is the major logistical cost, and with actual collection times that are short the value of high-grading decreases. Subsequently most meteorite recovery teams try to restrict high-grading during field recoveries, collecting everything that is clearly a meteorite, or has the potential to be a meteorite, and accepting some level of "false positives".

- Collection and curation

Antarctic meteorite specimens were recognized as much more pristine chemically than most finds from the civilized continents, and the US and Japanese programs worked quickly to establish collection and curation protocols. These protocols, while not strict or enforced in any legislative sense, have been recognized to be of immense value; Antarctic meteorite collection protocols have become the *de facto* standard for meteorite recovery efforts in many locales. A unique feature of these protocols is that they do more than preserve specimen integrity; they can also insure early, unbiased access to the samples by members of the international planetary materials community. As of this writing, the US governmental agency responsible for activity in the Antarctic is actively discussing enforceable regulations regarding meteorite protection (Anonymous, 2002).

When an Antarctic meteorite has been located, the typical procedure is as follows. Upon discovering a meteorite, several field team members converge on the find site. All contact with skin, clothing, or "dirty" implements is avoided while location of the find is accurately determined (currently using GPS technology) and the specimen is photographed *in situ*. Each specimen is assigned a unique field identifier and distinguishing characteristics of the find (size, visible fusion crust, characteristic fractures, nearby fragments, contact with snow or terrestrial rocks, accidental human contact, etc.) are carefully noted. The sample itself is placed into a clean plastic collection bag that is then sealed and kept under ambient conditions. Note that while efforts are made to avoid introducing anthropogenic contamination, the specimens have typically been immersed in the Antarctic environment for thousands of years; "terrestrial" contamination is unavoidable.

After recovery in the field, Antarctic meteorites are usually kept frozen until they can be thawed under controlled dry conditions to minimize interaction with liquid water. Curatorial facilities for Antarctic meteorites differ in scope, with the United States (at NASA's Johnson Space Center (JSC) in Houston, Texas and Smithsonian Institution in Washington DC) and Japanese programs (at NIPR Headquarters, in Tokyo) supporting high-level facilities. The handling of newly recovered ANSMET specimens serves as a good example. After arrival at JSC, the bags containing specimens are opened and thawed to room temperature under flowing dry nitrogen. Samples are subsequently stored in glove boxes, either in normal atmosphere (for ordinary chondrites) or nitrogen (for rarer specimens). Using the field notes to prioritize the order of examination, curatorial staff carefully crack open each sample, documenting each split of the specimen and preparing a macroscopic description. This description then serves as a guide the next stage of characterization. For most ordinary chondrite specimens, Fe/Mg ratios determined for loose olivine and pyroxene grains to help determine type and petrographic grade. For rare specimens such as achondrites or carbonaceous chondrites, thin sections are prepared and a more detailed initial characterization is performed. In exceptional cases, specimens may be analyzed for oxygen isotopic composition to help determine their parentage; however, efforts are made to limit the characterization of specimens to only the data needed for accurate publication of their classification.

These initial classifications are typically published (twice yearly for the US collection) in the form of a newsletter distributed within the international planetary materials community (e.g. Kojima, 2001; Allen, 2002). Interested researchers are invited to request specific samples from the curatorial facility at no charge; in most cases, samples of individual meteorites are made available within a year of their recovery.

• Concentration mechanisms

The distribution of meteor radiants and meteorite falls across the Earth's surface shows only minor variation with latitude, primarily because gravitational focusing by our planet overwhelms the original orbital inclination of incoming projectiles (e.g. Whipple, 1950; Halliday, 1982). Researchers have long been aware that natural processes and conditions influence the detectable abundance of extraterrestrial material on the surface of the Earth (e.g. Nordenskjöld, 1875; Murray and Renard, 1891; Fredriksson and Gowdy, 1963), but most suggested that the primary factors behind the geographical distribution of meteorite finds are the density of human traffic and specimen survival (e.g. Farrington, 1904; Brown, 1960; Hughes, 1982). Subsequently, the recovery of meteorites from polar regions was considered as "impossible" as their recovery from the ocean bottoms (Wetherill, 1976). In this context, the discovery of Antarctic meteorite can rightfully be considered a paradigm-shifting event, proving that concentrations of extraterrestrial material in the form of meteorites can reach very high levels under specific conditions and within constrained geographical regions as a result of natural processes (Yoshida et al., 1971; Huss and Wilson, 1973; Yanai, 1978; Whillans and Cassidy, 1983). These regions are characterized by stable, old surfaces where slow or negative rates of terrestrial accumulation allow the extraterrestrial component to be exaggerated. Typically they also have low weathering rates and background materials that bear little visible resemblance to meteoritic lithologies.

These conditions are often present in deserts of various kinds, and the East Antarctic ice sheet is no exception. But while the first-order concept of East Antarctica as a desert with commensurate meteorite concentrations is easy to appreciate, it is also simplistic-the physical processes active on this ice sheet are vastly different than those active in temperate localities. A better understanding of Antarctic meteorite concentrations requires consideration of a variety of factors, some brutishly strong and others diabolically subtle.

- Geography

Glaciologists typically divide large continental icesheets such as that in East Antarctica into two distinct zones. The interior of the ice sheet is considered an accumulation zone, where snow falling over time is compressed into ice flowing outward under its own weight. At the periphery of the ice sheet is a broad, distinct ablation zone, where precipitation still falls but loss mechanisms dominate. Ice is lost within the ablation zone through a variety of processes including calving of icebergs, melting, sublimation and physical abrasion (Benn and Evans, 1998). Because ablation typically exposes deep, relatively bubble-free layers of the ice sheet, the ice sheet surface in such areas is often snow-free ice of a beautiful blue color, and the term "blue ice area" or BIA has come into common usage (Bintanja, 1999). Meteorite concentrations in Antarctica have invariably been found on expanses of blue ice, or intimately associated with them. Blue ice areas are commonly visible in satellite imagery and aerial photography, and reconnaissance for new meteorite recovery sites usually starts with a survey of available imagery (Lucchitta, 1987).

Although the presence of blue ice seems to be a prerequisite for meteorite concentrations, the vast majority of blue ice areas harbor no concentrations at all. In East Antarctica, most blue ice areas occur at the periphery of the ice sheet (within a few tens of km of the sea), on fast-moving outlet glacier surfaces or on the terminal surfaces of valley glaciers. Searches of such areas for meteorites have been conducted on several occasions and (as of this writing) no meteorite concentrations have been found. In contrast, blue ice areas that harbor meteorite concentrations are almost always significantly inland, near the "front range" where plateau ice flowing out and down from the center of the continent first interacts with major mountain ranges. These meteorite-bearing blue ice areas are highly localized areas of ablation (the combined ice loss processes of sublimation, melting and abrasion) found well within the traditional accumulation area of the ice sheet- many meteorite-bearing blue ice areas are literally surrounded by snowfields where precipitation is actively accumulating today. Thus the known meteorite-bearing icefields represent regions of anomalous ablation, which in turn suggests either anomalous ice flow, or climatic conditions, or both (Harvey et al., 2001).

Not only are meteorite-bearing blue icefields anomalous in terms of siting, they are also nearly insignificant in extent compared to continental icesheets. Most meteorite-bearing blue ice areas are smaller than a few 100 km^2 in area, although the massive Yamato icefields are nearly an order of magnitude larger at 4000 km^2. Bintanja's (1999) estimate that blue ice areas make up approximately 1% of the 1.8×10^7 km^2 East Antarctic ice sheet surface is generous; given that only a very small percentage of blue ice areas bear meteorites, most meteorite stranding surfaces are vanishingly small and highly localized when compared to broader ice sheet phenomena such as glaciers, domes and ice shelves.

Of the four main settings for blue ice areas recognized by Takahashi et al. (1992) and Bintanja (1999), three have been related to meteorite concentrations:

1) Immediately adjacent to, and on the interior, ice sheet (plateau) side of nunataks or mountains, such as at the Yamato Mountains;
2) Immediately adjacent to, and on the downhill (lee) side of front range nunataks or mountains, such as at the Frontier Mountains;
3) Surrounding major ice scarps, with or without exposed morainal material, such as the Elephant Moraine icefields.

For simplicity, in later sections of this paper we will refer to these key settings as uphill, downhill and overflow, respectively. Many meteorite recovery sites contain regions exhibiting more than one of these settings, and some contain all three (e.g. the Meteorite Hills icefields – see Fig. 1). However, while recognition of these key settings has improved the rate of discovery of new meteorite concentration sites over the years,

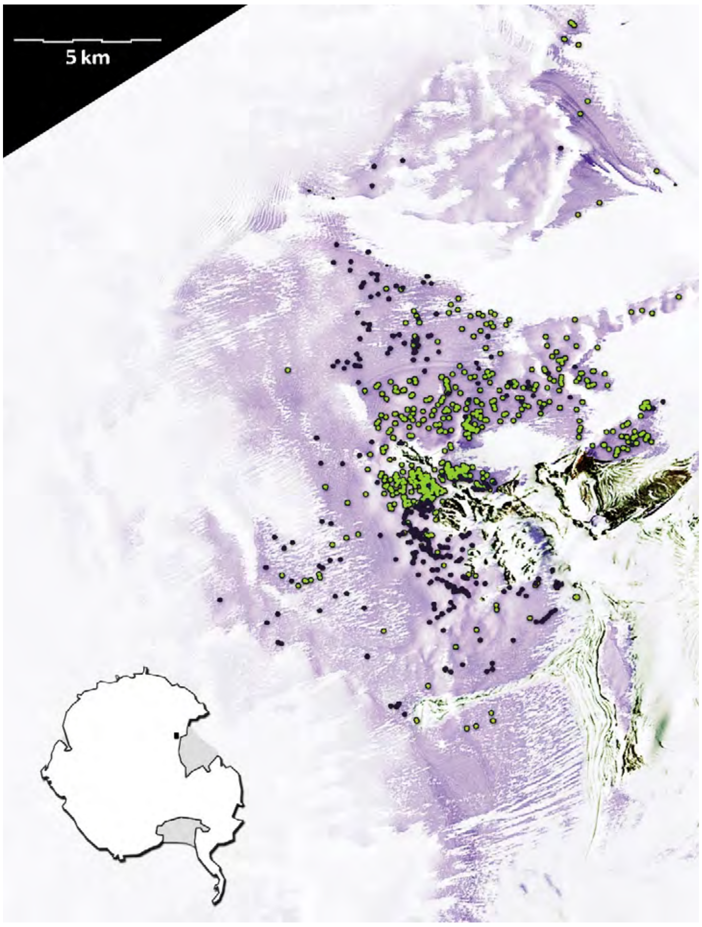


Fig. 1. LANDSAT 7 image of the Meteorite Hills icefields with meteorite finds from several field seasons superimposed. The East Antarctic ice sheet is toward the left, while the Meteorite Hills are the series of exposed nunataks in the central Transantarctic Mountains ranging from the center of the image to the lower right. The large snowfield to the right is the upper reaches of the Darwin Glacier. Crevasses and streamlines show that while ice in the southern sections of the stranding surface is moving toward the northeast, in the northern sections ice is diverting around the exposed nunataks to merge with the Darwin Glacier flowing toward the southeast. Southern sections of the Meteorite Hills icefields occupy the "uphill" setting typical of conveyor-belt style stranding surfaces such as the Allan Hills, while northernmost sections are in the "overflow" setting with a streaming moraine, and several small icefields immediately east of the Meteorite Hills occupy the "downhill" setting (see text). Continental outline of Antarctica in lower left shows location of region in Transantarctic Mountains (black rectangle). LANDSAT image courtesy USGS; meteorite locations provided by J. Schutt.

only a modest percentage of these selected blue ice areas harbor significant concentrations of meteorites. Meteorite concentrations are obviously complex natural phenomena whose existence depends on a variety of factors including ice flow, ablation and several others, as follows.

- Glacial movement

The key settings listed above suggest that there is an important relationship between the retardation of ice flow by bedrock barriers and the presence of meteorite concentrations. Many theories regarding the role of ice flow in the production of meteorite concentrations have been put forward, and most agree on the basic principles put forward early on (e.g. Yanai, 1978; Nagata, 1982; Whillans and Cassidy, 1983). These models suggest that as the East Antarctic ice sheet flows toward the margins of the continent, meteorites randomly located within the volume of ice are transported toward the ice sheet margin. Where mountains or subsurface obstructions block glacial flow, diversion of ice around or over an obstruction reduces horizontal ice movement rates adjacent to the barriers and creates a vertical (upward) component of movement. If local mechanisms for ice loss (ablation) exist at such sites, an equilibrium surface will develop according to the balance between ice supply and loss, and the cargo of meteorites is exhumed on a blue ice surface. The result is a conceptual “conveyor belt” bringing meteorite-bearing volumes of ice from the interior of the continent to stagnant or slow-moving surfaces where ice is then lost and a precious cargo is left as a lag deposit. Cassidy et al. (1992) provide an excellent overview of how this model has been adapted to several Antarctic stranding surfaces.

This “conveyor-belt” model actually incorporates two distinct meteorite concentration mechanisms, both of which reduce the volume of the ice substrate. Continued precipitation gradually buries surface snow and compresses it into ice at depth; typically this transition occurs at about 50 meters (Benn and Evans, 1998). Snow itself is of very low density, and conversion to ice typically reduces the vertical dimension of a given stratigraphic sequence by a factor of 10× or more. As a result, a volume of deep glacial ice represents a much larger accumulation time than the same volume of surface snow, and thus contains a concentrated meteorite sample. Simple delivery of surface snows from one site to another does not concentrate meteorites; but the delivery of deep glacial ice through upward movement by the “conveyor-belt” models is a true concentration mechanism.

- Ablation/sublimation

The second concentration process implicit in “conveyor-belt” models is a continuation of the theme of reducing ice volume, but taken to the extreme through physical loss of ice. In principle, the simple loss of ice through ablation should be enough to produce a meteorite concentration regardless of ice flow or volumetric conversion of snow to ice (Nishio et al., 1982). As ablation removes surface snow and ice it leaves behind any meteorites those surface layers contained; over time continued ablation will therefore remove many layers and leave a surface with meteorites representing all the years of accumulation the lost layers represent.

The main ablative processes present at meteorite stranding surfaces are sublimation (conversion of ice directly into atmospheric moisture) and abrasion (physical reduction of the surface through the grinding action of wind-blown snow and ice particles). Melting, which is the most important process for most ablation regions worldwide, does not appear to be an important process at high-altitude meteorite sites; a few meteorite stranding surfaces show ephemeral melt ponds, but these are rare and always associated with moraine or bedrock exposures (Harvey, 1989; Bintanja, 1999). Both sublimation and abrasion are driven by the strong katabatic winds of the East Antarctic ice sheet. The atmosphere above the high altitude interior of the ice sheet is separated from warmer, more humid coastal regions by a circumpolar jet stream, resulting in an isolated mass of cold, dry air that cools further through radiative cooling. Small perturbations of this dense air mass periodically send it rolling down the slope of the ice sheet as gravity-driven katabatic winds. Meteorite-bearing blue ice areas are typically well exposed to these katabatic winds by virtue of their location at the margin of the interior plateau of the ice sheet. Automated weather station data suggest that these sites consistently experience winds over 80 km/hr for weeks each year, with gusts of over 200 km/hr not uncommon (Stearns et al., 1993). Furthermore, many Antarctic meteorite stranding surfaces are located in regions where katabatic winds converge, significantly enhancing their effect (Cresswell, 1988). High local wind speeds and turbulence-driven gusts over the blue ice mean that enormous amounts of snow and ice can be entrained and transported (Bintanja, 1999). This effectively blocks accumulation by new precipitation or horizontal snowdrift.

The relative importance of abrasion and sublimation are not well known, and the balance between these two processes is likely to shift with the seasons. Sublimation is clearly important and the better observed process, since it is at its strongest during the constant daylight of the austral summer, and thus has been both measured and observed. Blue ice has a significantly lower albedo than snow or bubbly white ice and thus can be warmed significantly. Blue ice has been observed to sublimate at rates as high as 5 cm per day when katabatic winds are low, air temperatures are relatively high, and the sky is clear (Annexstad, 1982; Whillans and Cassidy, 1983; Faure and Buchanan, 1991; Delisle and Sievers, 1991; Bintanja and Van den Broeke, 1995). At meteorite stranding surfaces, annual sublimation rates are dominated by these few days of exceptional activity. On several occasions field workers have been able to watch cm-sized meteorites become exposed during a few days of exceptionally calm and sunny weather. Sublimation is much less important during the winter months because at extremely cold temperatures both the moisture capacity of air and the enthalpy of sublimation for ice are low. Faure and Buchanan (1991) estimated that winter ablation rates were 5x slower than summer rates; Bintanja et al. (1998) had similar results from a study of the Scharffenbergbotnen BIA in Queen Maud Land.

The importance of abrasion to the overall mass balance of blue ice areas is less well known. Yanai (1978), Williams et al. (1983) and Orheim and Lucchitta (1990) have all suggested that abrasion can be a powerful process on blue ice areas. This process would be most important in winter, when wind speeds are dramatically higher, and its effectiveness on erosion of exposed bedrock is well documented (e.g. Anderson, 1986). But harsh conditions and limited research efforts mean that wintertime abrasion on BIAs has yet to be observed or quantitatively measured, and some authors discount the process. Bintanja (1999) considered wintertime abrasion as a way to explain annual ablative loss that could not be accounted for by sublimation measurements (nearly 50% of the yearly total), but ice surface textures compelled him to reject its significance. While the magnitude of the effect of wintertime abrasion on the blue ice surface is currently unclear, its effect on the meteorites is more obvious, as will be discussed in a later section.

The possibility that ablation can act as the sole or dominant process behind meteorite concentrations has been discounted by some authors, who note that the number of specimens recovered from some icefields far exceeds any reasonable estimates based on known influx or ablation rates (e.g. Cassidy et al., 1992). In addition, the ice movement aspects of the "conveyor belt" model have been of more frequent interest to glaciologists because of their relevance to larger scale studies, while the local nature of ablation studies limits their possible significance on the scale of the ice sheet (e.g. Annexstad, 1982; Hamilton and Whillans, 1996). But within combined models, the perception that ablation is less important than ice movement seems to be changing as icefield studies increase in resolution. Recent studies of the occurrence of meteorite concentrations at the Lewis Cliff Ice Tongue and Frontier Mountains icefields show that ice movement rates are very low where concentrations are highest, suggesting "conveyor belt" delivery is currently a very minor component compared to ice loss through ablation (Harvey and Schutt, 1998; Folco et al., 2002). This makes sense in light of well-documented climatic changes that have drastically reduced the thickness of the East Antarctic ice sheet, particularly at its margins, since the last glacial highstand roughly 20,000 years ago (e.g. Anderson et al., 2002). The deflation of the ice sheet surface and redirection of ice flow resulting from climate change may be directly responsible for the meteorite concentrations we see today. Thus while ablation alone cannot account for most meteorite concentrations, it may be an exceptionally powerful force in some settings.

- Direct infall

As noted earlier, blue ice areas qualify as "stable" surfaces by the standards of meteorite accumulation areas found on other continents. For most East Antarctic blue ice surfaces, the most important terrestrial sediment is snow falling at rates around 10 cm (liquid water equivalent) per year. At meteorite stranding surfaces, however, this precipitation is ephemeral, because the katabatic winds quickly entrain and remove the snow, leaving little or no accumulation (Takahashi et al 1992; Bintanja, 1999). Aeolian deposition of terrestrial rock fragments are of limited significance, occurring only in highly localized regions where portions of meteorite stranding surfaces are located downwind of bedrock or morainal exposures. In the absence of fluvial processes, macro- and microfauna, anthropogenic activity, and surface materials other than snow, surface gardening processes are insignificant. Furthermore, the most energetic process prevalent on blue ice surfaces (ablation) is one of slow net loss of ice from the surface. Thus meteorite-bearing blue ice areas are "stable" in that the surface is old and relatively unchanging, allowing the thin rain of extraterrestrial material to accumulate.

Like ablation, surface stability can in principle serve as the singular or dominant factor behind the existence of a meteorite concentration. The presence of a stable ice surface will allow accumulation of meteorites through direct infall even in the absence of ablation or in-ice meteorite delivery processes. This is the situation prevalent at meteorite stranding surfaces in temperate deserts, and there is no reason to doubt it would work for ice surfaces as well. Huss (1990,1991) carefully tested this hypothesis for the meteorite stranding surfaces in the Allan Hills region, comparing the observed mass frequency distribution of meteorites from these icefields to the expected accumulation by direct infall over time. He suggested that direct infall was the most important factor producing the observed meteorite distribution on these icefields; other factors, including ice movement and ablative volume loss, were included in the model but at modest values. Unfortunately, his model was preliminary and incorporated a number of assumed values based on limited field observations and small data sets. For example, his model is highly dependent on the number of specimens of different sizes recovered, and thus on the relatively completeness of recovery efforts for a given icefield. Systematic recovery had barely begun on some of the icefields examined in his study, and subsequent recovery totals exceed his estimates for the total number of specimens by a factor of 5 or more for several icefields. As in considerations of ablation acting alone, the total number of meteorites found on these icefields suggests more meteorites than can be easily accommodated by direct infall. In spite of these shortcomings, Huss (1990) deserves recognition for developing the first of a new generation of Antarctic meteorite concentration models, recognizing that glacial “conveyor belts” need not be the dominant factor producing all Antarctic meteorite concentrations, and that the processes that dominate may differ from icefield to icefield.

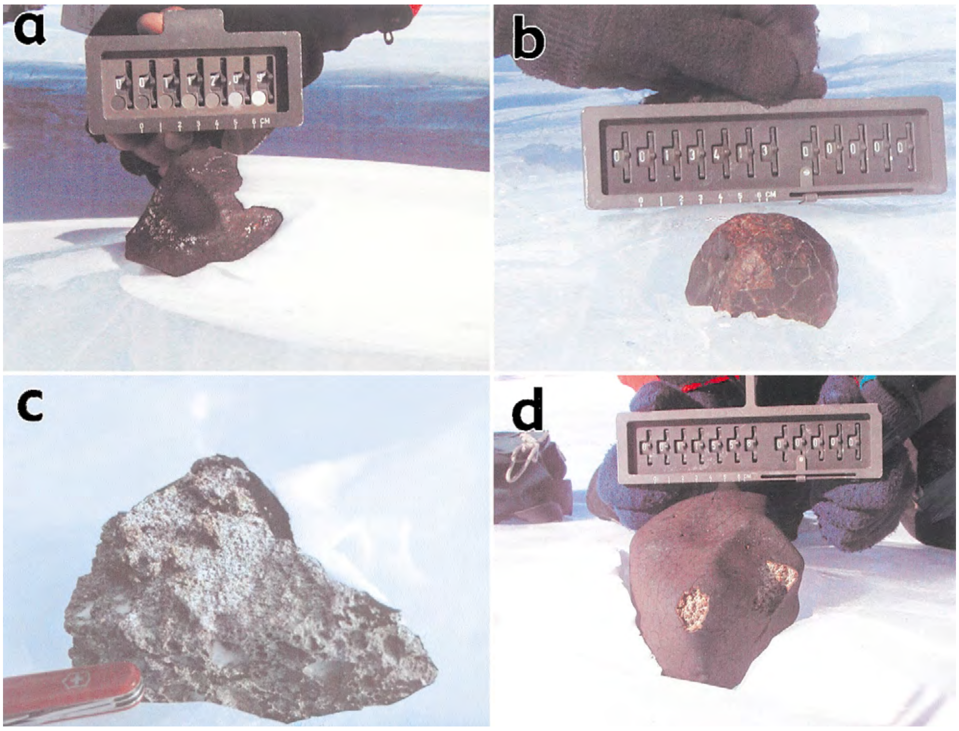


Fig. 2. Field portraits of meteorites *in situ* illustrating various types of weathering. a) MIL 99304, an H5 chondrite from the Miller Range, showing a downwind snow pendant and significant development of bright white evaporites along cracks in an otherwise fully fusion crusted specimen. b) MET 00461, an L6 chondrite from Meteorite Hills, showing bleaching of fusion crust along cracks in the fusion crust. Note the sculpting of the ice around the meteorite and its level compared to the local ice surface. c) HOW 88401, a large, brecciated eucrite. This specimen has experienced severe abrasive erosion by the strong katabatic winds prevailing from the lower left in this photo. All fusion crust has been removed from this side, and less resistant clasts and mineral grains have been plucked or eroded away. In contrast, the rear of the meteorite exhibits continuous fusion crust. d) MET 01003, an L chondrite from Meteorite Hills. The fusion crust of this specimen is uniformly cracked on the cm scale; weathering has removed some sections to reveal intense iron oxide staining around oxidizing metal grains. Like many Meteorite Hills specimens, it sits within a sublimation cavity below the local ice surface.

Loss mechanisms

Ablation, direct infall and glacial movement are the key natural forces increasing the number of meteorites found on some blue ice areas. There are other forces affecting the number of meteorites recoverable from a meteorite stranding site, some of which actively reduce the number of meteorite specimens that will be found. Weathering, redistribution by the wind, sinking in the ice and the vagaries of human searches all can significantly alter the number of recoverable meteorites.

- Weathering processes

The cryogenic environment of Antarctica has long been cited as a significant factor behind meteorite concentrations, since it greatly reduces weathering rates and preserves samples far longer than is seen in temperate meteorite stranding surfaces. Bland (2001) compared the oxidation state of ordinary chondrites from the Allan Hills region and from hot deserts and found that, in spite of their greater terrestrial age, the Antarctic specimens were significantly less oxidized. He estimates that Antarctic meteorite weathering rates are approximately 3 orders of magnitude slower than rates for meteorites in hot deserts; and given that even the oldest Antarctic meteorites are only 2 orders of magnitude older than their hot desert counterparts, he postulates that the rate at which Antarctic meteorites are completely destroyed by weathering is so low that few are missing from modern collections.

Although the slow rate of weathering means that Antarctic meteorites of a given age are much less weathered than their hot desert counterparts, signs of both chemical and physical weathering are found in all but a very small subset of samples, including rust halos, missing or fractured fusion crust and surface evaporitic "druse" (Fig. 2). On the observational scale used for the US collection, less than 4% of the ANSMET collection have been assigned to weathering class "A" (least weathered) and even cursory examination of these specimens shows that most exhibit some level of oxidation, fracturing and/or evaporite development. Field observations (mostly anecdotal) have revealed something of the conditions prevalent during alteration of Antarctic meteorites. Meteorites often are seen to have pendants of ice or snow adhering to their surfaces, particularly on the downwind side. Another telling observation is that meteorites typically exhibit little or no snowcover within a day or two following significant snowfalls (a few cm or more), suggesting that snow was melting or sublimating directly on the specimens. Several experiments have been done that measure the interior and exterior surface temperature of rocks sitting on the ice of meteorite stranding surfaces (Schultz, 1986; Friedman, unpublished, Harvey and Moog, unpublished). These experiments demonstrate that while ice surfaces rarely get above –15° C and air temperatures rarely reach –5° C, rock temperatures can spike as high as +10° C (Fig. 3).

Under these conditions, any ice or snow clinging to rock surfaces will liquefy and interact with the specimen both chemically and physically. As a solvent, reactant and catalyst, water mobilizes active cations and allows chemical weathering to proceed. It also can produce mechanical effects; rock temperatures oscillate above and below 0° C, promoting freeze-thaw fracturing. Even in the warmest, calmest conditions, however, the extremely dry atmosphere of the Antarctic plateau dramatically limits the existence of liquid water, and only within a meteorite's interior pore spaces is it likely to remain stable for any significant period (Gooding, 1986).

The presence of fusion crust has interesting effects on both chemical and physical weathering processes. Fusion crust is non-porous, and thus serves to encapsulate the meteorite and protect the interior from liquid water. However, it is also an excellent collector of solar energy, thus promoting the melting of any ice or snow in contact with the rock, and as a glass it tends to fracture during rapid cooling. In addition, the higher chemical diffusion rate typical of glass means it can hydrate and dehydrate much more quickly than most silicate minerals. Hydrated glasses are in turn mechanically weaker and less protective against mechanical weathering. Once the fusion crust is pierced, capillary action can draw water into the interior. These holes can also create directional flow between sites of moisture absorption and highest evaporative loss, producing a net suction that draws water through the rock from a moisture source. Even though the conditions needed to wet a meteorite may occur only a few days of a year, partial fusion crust produces a variable microclimate within the interior of specimens that can exaggerate the effects of weathering.

- Chemical weathering

Only a small subset of types (CM, CI and CK carbonaceous chondrites) show significant evidence for equilibration with liquid water and oxidizing conditions prior to their arrival at the earth's surface in Antarctica; for the remainder, the presence of terrestrial water, CO_2 and O_2 quickly leads to a number of reactions in spite of relatively slow weathering rates. One of the most visible weathering reactions is the production of "rust" (an amalgam of Fe oxides, hydroxides and other phases) from meteoritic metal (Fe-Ni

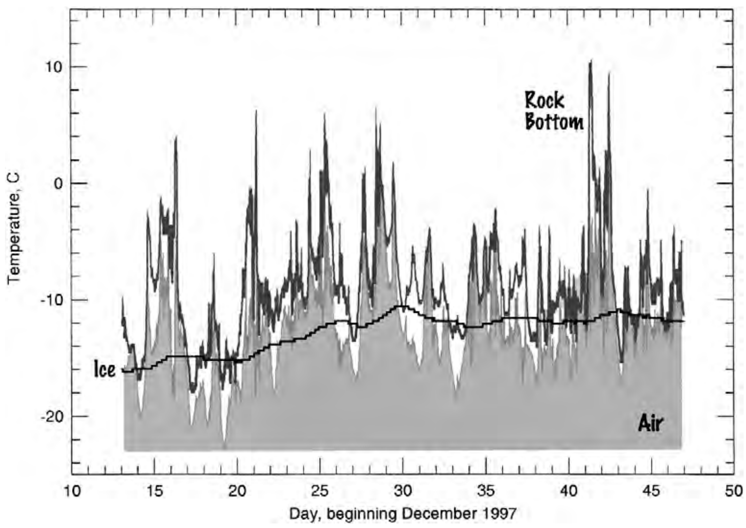


Fig. 3. Temperatures on and around a 1 kilogram dolerite cobble placed on the Mare Meteoriticus icefield. Thermocouples were affixed 10 cm down in the ice, on the bottom of the rock where it was in contact with the ice, and in the air at 1 m height above the ice surface. Higher air temperatures are highly correlated with the lack of cold katabatic winds; rock temperatures correlate directly to air temperatures with significant additional heat production due to warming from solar radiation. The response of the ice to these thermal pulses is highly moderated by its massive volume, delaying peaks by a day or more.

alloys) through reactions with water. These reactions are electrochemical in nature; as Fe^0 goes into solution and converts to Fe^{+2}, the free electrons produced reduce O_2 or H^+ ions to form hydroxyl radicals (OH^-), that in turn recombine with Fe to form a variety of oxides including akaganeite, goethite, maghemite and lepidocrocite. Chlorine scavenged from the terrestrial environment or meteoritic chlorapatite plays a critical role as a catalyst; the high ionic strength of Cl^- means that it rapidly diffuses to the reaction surface of the metal, where it reduces the oxide, removing it as a protectant and subsequently increasing the rate of corrosion (Buchwald and Clarke, 1989). The sporadic availability of liquid water common for Antarctic meteorites apparently promotes the process; Cl is only very slowly flushed from the rock and therefore can repeatedly catalyze reactions over time (Buchwald, 1990).

The sporadic availability of water also promotes formation of evaporites, which along with rust are the most visible indicators of weathering on Antarctic meteorites. Evaporitic Mg and Ca carbonates and sulfates such as nesquehonite, hydromagnesite, gypsum and epsomite commonly form as vein fillings and/or as surface efflorescences (Velbel et al., 1991). While evaporites are typically visible on the surface of around 5% of meteorites, with higher percentages common at warmer, low altitude stranding surfaces, spectroscopic studies suggest that some level of evaporite formation is almost ubiquitous. Isotopic studies have shown that the source of water and CO_2 is terrestrial, while mass balance and element ratio studies have shown that meteoritic minerals are the source of major active cations (Mg, Ca, K, Na, P, S). As with rust formation, the sporadic nature of liquid water availability plays a key role. Mobile cations are not physically removed from the meteorite; instead they are redeposited in fractures and exterior surfaces (Nobuyoshi et al., 1997). Antarctic meteorite chemical weathering is thus a “slow leak” system, with mobilization and gradual loss of active chemical species, in contrast to the more open system seen in most other weathering processes.

Less visible signs of Antarctic chemical weathering are also important to meteoritic studies. Gooding (1986) differentiates “metallic” rust and evaporites from “sialic” rust produced by oxidation of Fe^{+2} from mafic silicates. Most studies of sialic weathering products have identified them only as minor “clay mineraloids” or simply “clay minerals”, but the results are consistent with expected weathering products such as iddingsite, saponite, serpentine, chlorite and montmorillonite (e.g. Gooding, 1986; Miyamoto et al., 1992; Noguchi et al., 1999). Studies of minor and trace elements have suggested that mobile elements including the REE’s, B, Ba, Ce, Co, Cr, Cs, Cu, Nd, Ni, Rb, Sm, Sr, Zn, and Cs may have been redistributed and/or leached away by the repetitive “boom and bust” cyclic style of Antarctic weathering processes. It has also been suggested that the chemical highway runs in both directions; enrichments in U, Se, Hg and many other elements in meteorites have been attributed to leaching from nearby terrestrial sources (Dreibus et al., 1986; Jovanovich and Reed, 1987; Delisle et al, 1989; Scherer et al., 1992; Krähenbühl et al., 1998).

Most studies of chemical weathering of Antarctic meteorites have considered reactions that take place while the rock is exposed on the ice surface; however, it is clear reactions begin much earlier. For those meteorites that are incorporated into the East Antarctic ice sheet shortly or immediately after falling, encapsulation in snow and ice generally creates a benign, low energy-setting for the meteorite. However, the few (6) meteorites recovered while still encased in ice all exhibit obvious signs of chemical weathering, some fairly severe (e.g. Gow and Cassidy, 1989; Harvey and Score, 1991). This suggests that meteorites may have a secret weathering history prior to arrival at a meteorite stranding surface including exposure before burial, in-ice weathering, or multiple exposures at the surface (Cassidy et al., 1992). The relative transparency of blue ice and snow, and the near "black body" behavior of meteorites, allows them to absorb significant amounts of solar radiation at depths up to several meters, which can subsequently promote production of liquid water and weathering (Harvey and Score, 1991).

- Physical weathering

Exposure at a meteorite stranding surface subjects the typical meteorite to a more variable, energetic environment than would be seen while encapsulated in ice. In winter, the high winds and cold temperatures mean that exposed meteorites experience significant mechanical abrasion by saltating snow and ice particles. As previously noted, no quantitative data are available on winter abrasion rates at blue ice areas. However, field observations of large meteorites (unlikely to move in the wind) show many suffer significant erosion on the upwind side with much less weathering on the downwind side (Fig. 2c). During the short-lived warmth of summer, the importance of abrasion diminishes while the importance of freeze-thaw fracturing increases. As is the case in chemical weathering, the infiltration and flow of water through rock can be considered the primary, most active agent responsible for these processes. Adhering snow and ice crystals provided by snowfall, saltation, hoarfrost and the ice surface all can contribute liquid H_2O to the meteorite; and when this liquid refreezes, the volume change associated with the transition to solid ice forces fractures to grow and widen. The physical forcing of fractures then results in fragmentation of the meteorite. Temperature measurements suggest that meteorites may go through about a dozen short-duration thaw cycles during a typical Antarctic summer, with duration and temperature dependent on meteorite size as well as meteorological conditions (Fig. 3). The rate at which meteorites are completely disrupted by these physical processes is unclear, but is probably much slower than typically seen in more temperate climates where high-density aeolian debris is present and freeze-thaw cycles are more frequent.

- Wind redistribution

The combined action of physical and chemical weathering causes fragmentation of meteorites, reducing the size of larger specimens and increasing the number of specimens of smaller sizes. The katabatic winds prevalent at Antarctic meteorite stranding surfaces then play two roles: acting as a redistribution force, and an agent of specimen loss. A number of empirical studies have been conducted to gauge how specimens might be moved or lost on meteorite stranding surfaces. Most have taken the form of a "rock race", where specimens of known mass are positioned along a starting line that runs perpendicular to prevailing winds, and subsequent revisits to the site allow scientists to track their changing positions (e.g. Schutt et al., 1986; Folco et al., 2002). These studies show that specimens massing a few 10's of g are routinely set in motion by the wind, some moving several 10's of meters before stopping while others are blown entirely off the icefield. Even fairly large rocks can be moved; Folco et al. (2002) report 7 m of movement in four years for a 171 g specimen. These results agree well with theoretical models of meteorite movement. Using data from Antarctic automated weather stations and aeolian movement threshold models, Harvey (1995) estimated that there is a 50% probability that rocks weighing between 64 and 80 g will move in any typical year. The same study suggests that rocks in the < 10 g range are virtually certain to move in a typical year, and given that most icefields extend no more than a few km in the direction of prevalent winds, meteorites are likely to be removed from an icefield on short timescales. Luckily, natural traps exist to slow this loss process. Blue ice surfaces are not perfectly smooth on the centimeter-scale; they exhibit ripples and "sun-cup" textures produced when turbulence at the ice surface produces unequal sublimation (Bintanja, 1999). This surface texture slows the progress of saltating meteorites, particularly those smaller in dimension than the amplitude of the local ripples or sun cups. Field observations suggest that relatively soft and porous snow bridges in crevasses also trap saltating meteorites (Delisle and Sievers, 1989). As these crevasses wax and wane with the seasons, they may either release the meteorites to the wind or re-entomb them deep within the ice sheet. Similarly, ephemeral snow patches on the blue ice surface can trap meteorites, and as the snow is transported or ablated away the specimens are released. The most significant trap for saltating meteorites is rough, hard crystalline snow (firn) on the downwind edge of the blue ice area. Most blue ice areas are separated from surrounding snowfields by a border of firn representing intermediate levels of ablation; where this firn border is exposed on the downwind edge, a concentration of smaller meteorites and meteorite fragments is often found. These meteorites are thought to have been transported across the relatively smooth icefield by the wind and become trapped by the rough firn upon arrival. While the size of such specimens is typically small, and terrestrial aeolian debris is sometimes included, recovery efforts from firn can be of significant value; one region searched by ANSMET in 1994–1995 (informally called "Footrot Flats") yielded more than 350 specimens, including two distinct lunar meteorites. Such concentrations are not only of value for the specimens themselves- they also serve as a subjective measure of the meteorite concentration to be found upwind.

Many icefields (particularly those in the uphill and downhill settings) have a downwind border made up of morainal material. These complex mixtures of terrestrial bedrock and glacial debris also serve as traps for meteorites undergoing aeolian transport, and while they represent obvious difficulties for recovery efforts, moraine searches have proven rewarding at many sites. At the informally named "Main Foggy Bottom" icefield of the Queen Alexandra Mountains, roughly 50% of the specimens recovered came from a large moraine immediately downwind of the ice; and most of these specimens came from within a few meters of the upwind edge of this moraine. A similar situation was found at a site near the Lewis Cliff Ice Tongue, where the informally named "Meteorite Moraine" yielded 312 specimens during short visits over many seasons.

At some icefields morainal material is exposed at upwind or interior locations; typically this material has then been widely dispersed by the wind, producing everything from a uniform background of terrestrial rock on the ice to actively saltating "rock dunes" (e.g. Folco et al., 2002). The most important effect on meteorites in such regions is an increased difficulty in meteorite detection, particularly if the background terrestrial material is dark in color and non-uniform in size and shape. The importance of such search losses will be discussed in more detail in a later section.

In summary, the wind has an appreciable effect on meteorite concentrations. As an abrasive agent it promotes the fragmentation of larger specimens. As a redistribution force it keeps small and intermediate specimens in motion on seasonal timeframes and concentrates meteorites in downwind traps. As a loss mechanism it removes the smallest meteorites from the icefield by either driving them into surrounding snowfields or moraines where they may be lost, or into crevasses where they may be re-interred into the ice.

- Sinking

Another potential loss mechanism for meteorites is sinking through the ice. Rocks are significantly denser than ice; they warm easily in the sun and under appropriate conditions will sink toward the bottom of the ice sheet. This is fairly common in typical blue ice areas sited on the margins of icesheets or alpine glaciers, and the term “cryoconite” has been used in reference to the columnar water or ice-filled holes left in the wake of the sinking rock. Cryoconite holes are much less common under the conditions prevalent at meteorite-bearing blue ice areas; the cold, dry conditions mean that rocks warm less and the ice itself is colder and stiffer. Nagata (1982) constructed a first-order model of the sinking process under these conditions and concluded that only very large and dense meteorites (irons larger than 1 m in diameter) are likely to sink at rates that could result in their loss.

Field observations suggest that the potential loss of meteorites through sinking is small but not vanishingly so, as Nagata (1982) suggested. At particularly cold, windy sites meteorites are occasionally found on short pedestals, suggesting that the rate of ice loss from the surface exceeds the potential sinking rate for these specimens. However, at warmer, more protected sites some meteorites have been found in relatively deep cups in the ice (depth approaching the full diameter of the rock), and on more than one occasion the surrounding cup was partially filled with liquid water or clear regelated ice (Fig. 2b). These observations suggest that local climate plays a large role in whether a meteorite will remain at the ice sheet surface or sink. Harvey and Moog (unpublished) created a thermodynamic model to examine the conditions required for the initiation of sinking that incorporates solar heating of a meteorite specimen, losses from radiative cooling, convective cooling and conduction into the ice. Preliminary results suggest that if winds are light and air temperatures are above –10 °C, average-sized meteorites can establish an equilibrium temperature many tens of degrees warmer than surrounding air and ice in only a few hours when winds are light. This energy can be sufficient to melt quantities of ice equal to the volume of the specimen on similar timescales to produce a net downward motion of the meteorite. These results match up well with the empirical studies of meteorite heating (e.g. Schultz, 1986) and suggest that sinking will occur if the melting rate exceeds the surface sublimation rate. Whether or not the meteorite sinks in an air-filled cavity or a water-filled one is dependent on local relative humidity, and the depth to which the specimen sinks is controlled by diminishing radiative gains, evaporative heat loss and decreasing ice temperatures. The larger the rock mass, the deeper the rock can melt before reduced solar illumination and increased thermal contact with deeper, colder ice create a new equilibrium that stops the downward plunge.

These results suggest a complex feedback between climate conditions and meteorite sinking rates. Many key variables in the model (such as air and ice temperatures, solar illumination, relative humidity, wind speed and sublimation rates) vary in a manner suggesting meteorite sinking is likely only at lower altitudes and latitudes. Furthermore, most of the variables in question vary at different rates and reach extreme values on just a few days of the year, while geography can produce highly localized microclimates. Thus the model in its current form has limited predictive power, suggesting that sinking will be a factor for blue ice areas only in more clement settings. Field observations provide indirect evidence for the altitude/meteorite loss link; most meteorite stranding surfaces lie above 2000 m and rarely show any evidence for melting, while the most abundant evidence for melting is seen at sites below 1500 m in altitude, where meteorite stranding surfaces are much less common.

- Search losses

A final loss mechanism for consideration is the failure to detect meteorites during searching. This loss mechanism is effectively a resolution problem, dependent on size distribution of the target meteorites, the sensitivity of the typical detector (the human eye) and the spacing with which it is deployed. As in the case of wind losses discussed previously, estimating the efficiency of systematic searching presents a very tractable modeling problem; we look for dark, relatively large objects on a plane of limited area. Meteorite searches usually involve a series of transects of a suspected collection area, with a definite spacing between searchers and systematic coverage of an entire region. Many empirical models exist for analogous searches, such as those used to estimate whale populations in the ocean, weeds in fields, tortoises in the desert and other spatially difficult targets (e.g. Anderson et al., 2001; Melville and Welsch, 2001; Barabesi et al., 2002; Chen et al., 2002; Hammond et al., 2002). Because the ability to detect a target is controlled by angular dimensions rather than true size, acuity defines an inverse geometric relationship between the size of an object and the distance at which it is visible; i.e., the farther away something is, the harder it is to see. Assuming a power-law distribution of meteorites randomly distributed within transects and the use of standard ANSMET field protocols (e.g. partially overlapping transects, complete coverage of the stranding surface), Harvey (1995) developed a theoretical model for search efficiency and ran numerous computer simulations incorporating visual acuity, search spacing, and surface roughness. Using values for these variables derived from ANSMET fieldwork (transect width ~30 m, surface roughness ~10 cm, typical human visual acuity ~2 minutes of arc), results suggest that a cut-off exists at about 8 g; specimens above this mass have a low probability of being missed, while the probability of losing smaller specimens increases dramatically as size decreases below this 8 g cutoff. In spite of this rapid increase, the probability of finding even the smallest specimens is never zero, because it may lie directly in the center of the search transect. Simulations run using this model suggest that the loss of small meteorites due solely to search inefficiencies should run at about 1% of the total number of specimens predicted by power laws. However, given that many small meteorite specimens have almost certainly been removed by the wind before any search is conducted, this value may have little meaning.

The described model considers only the ideal case of a uniform surface free of snow or confusing terrestrial lithologies, both of which are clearly an issue. Snow and terrestrial rock are typically highly localized on blue ice surfaces, affecting some areas and not others. As noted previously, terrestrial rock acts like camouflage, making it difficult for field workers to distinguish target lithologies from background. While this effect can be quantified for simple cases (e.g., Anderson et al., 2001) the complex nature of mixed geological materials such as glacial moraines brings human skill and judgment into play at a high level, making search losses difficult to gauge except subjectively.

The effect of snow is more one of obscuration than filtering; even shallow snowfalls can cover or reduce the exposed area of the majority of specimens within a search transect. Furthermore, snow offers the particular problem of variability in both time and space. Some percentage of almost every blue icefield is covered with snow of a variety of ages, with some patches frozen hard to the ice surface and others moving freely in the wind. Thus its effect on a search can differ dramatically not only from one place to another but also from day to day. On several occasions ANSMET field parties have repeated searches over a specific area because of changing snow coverage, and as many as 10% more specimens have been recovered. As with terrestrial rock density, the loss of meteorite specimens due to snow coverage is hard to treat quantitatively; field observations give us only anecdotal evidence of its magnitude. Improving recovery efficiency in snow covered or morainal areas would be costly in terms of personnel time or advanced sensors, and with uncertain return is unlikely to be pursued in the immediate future.

An evolved picture of meteorite stranding surfaces: It is clear from the studies discussed so far that models for Antarctic meteorite concentrations focusing on single dominant processes will be much less realistic than those incorporating the full range of processes now known to be active. Incorporating this variation means that a generic model is less specific; it serves less well as a detailed description of any individual site. But this variability gives the model much broader application to the growing range of sites being explored, and serves a better template for future detailed study of individual sites. The key considerations are as follows.

1) Meteorite stranding surfaces are highly localized: Most of the first-order models of meteorite concentrations were attempts to adapt large scale (continental ice sheet), steady-state processes to phenomena that are constricted geographically and may be variable on short time scales. Meteorite-bearing blue icefields are sites of confined, highly localized ablation embedded deep within the accumulation zone, far from its margins or terminus. This is clear evidence that they deviate substantially from the generic large-scale mechanisms portrayed by early "conveyor-belt" models, where high-volume directional flow from interior accumulation regions to distal ablation regions is the norm. Furthermore, while meteorite stranding surfaces seem to be limited to few unique high-altitude topographic settings where ice flow velocity is significantly diverted and/or diminished, the observed variation around these "norms" increases as more icefields are discovered. Individual meteorite stranding surfaces commonly differ from each other in terms of ablation rates, iceflow and accumulation history as much as they differ from large-scale regional norms for these processes. Such variations are not confined to comparisons between icefields; meteorite concentration levels differ dramatically from site to site within individual icefields, particularly the larger examples. In summary, individual meteorite stranding surfaces are places where small-scale geography and microclimate factors have driven ablation and iceflow rates away from regional norms, and regional considerations are of baseline value only. Understanding a specific meteorite concentration thus requires an understanding of bedrock geometry, iceflow rates, ablation rates and other factors that may be entirely unique to this individual site, while subsets of this data may prove inadequate or misleading.

2) Reduction of ice sheet volume is a key factor: If a penultimate broad scale phenomenon is to be invoked as a driving force behind meteorite concentrations, climate change may be a better choice than ice sheet dynamics. All meteorite stranding surfaces seem to share a basic trait-ice loss by ablation exceeds ice input by horizontal flow. But rather than treat these two mechanisms as distinct, they should be considered as closely linked symptoms of the broad deflation of the East Antarctic ice sheet surface since the last glacial highstand about 20,000 years ago (Delisle, 1993). As the volume of the ice sheet has diminished, mountains at its periphery became an increasingly significant barrier to flow and drainages were significantly reorganized. While major outlet glaciers would experience relatively little restriction, many other drainages would essentially lose their outlets, resulting in dramatic changes to local iceflow direction and velocity and increasing the relative importance of ice loss through ablation. Submerged bedrock protrusions with minimal effect on surface topography and iceflow became much more significant barriers, retarding and redirecting flow.

A corollary to this consideration is that most meteorite stranding surfaces are currently far from equilibrium; they are a response to continuing reduction in ice sheet volume rather than a response to stable conditions. Furthermore, they should be considered ephemeral on geologic timescales. While meteorite stranding surfaces seem invariant over the timescale of human exploration, we are only now exploring whether this is actually true; and field observations (admittedly subjective) suggest that snow-cover on many blue icefields has increased over the last 20 years. In summary, the longer-term history of a specific site may be fundamentally important in understanding why a concentration exists there. Models for most individual meteorite stranding surfaces must be consistent with continual ice volume loss and surface deflation over the past 20,000 years, and episodic ice loss and gain over the past several million years.

3) "Stranded" ice instead of "conveyor belts": As more and more meteorite-bearing blue ice areas have been discovered, it has become apparent that horizontal iceflow rates at some can be phenomenally low. Such sites represent an end-member in the continuum of iceflow conditions, places where horizontal outflow has essentially ceased and inward iceflow velocities are orders of magnitude slower that that seen on the larger regional scale. The most recognizable of these sites are in the "downhill" setting and bear some resemblance to a shallowly sloping alpine glacier, flowing downhill from snowfields adjacent to the polar plateau with constrictions at their sides and significant morainal development at their terminus. Others are subtler and offer no immediately obvious clues to their existence; places where a stranded ice body frozen to its bed remains nearly immobile next to moving ice. Stranded ice may be separated from moving ice only by a diffuse shear zone and may be expressed at the surface as a blue ice valley within a larger ablating area. Such sites presumably were well supplied with incoming ice in the past, but continual reorganization of iceflow since the last glacial highstand has eventually cut off their source. By definition, such sites are no longer a part of local ice streams, therefore derailing any significant "conveyor belt" meteorite delivery process. With losses from ablation and sublimation exceeding the rate of inflow, ongoing loss of ice volume and surface deflation are the driving force behind any meteorite concentrations that might be present. Unfortunately, stranded ice sites can only be distinguished by high-resolution, long-term studies of ice movement and bedrock topography; only rarely are they visible in photographs as regions of crossing streamlines (Fig. 4). However, the mechanism has previously been proposed for sections of one important icefield (The Allan Hills Main Icefield) and suggested for another (the Lewis Cliff Ice Tongue) (Delisle et al., 1991; Cassidy et al., 1992). In a later section we will explore the latter case in detail.

One important feature of stranded ice sites is their potential to be very old, much older than ice from continuously moving parts of the ice sheet. Having been cutoff from the majority of existing ice sheet flow, volume is sacrificed to ablation until the ice body disappears. If ablation rates are moderate and the volume of the ice body in question is significant, stranded ice areas have the potential to produce significant meteorite concentrations as ice volume is lost over time. That such old ice exists is not in question-stranded ice in the Dry Valleys of McMurdo Sound with ages approaching 8 million years are known (Sugden et al., 1995). These ice bodies represent stranded ice, formerly a part of a major drainage system, that are nearly 20× older than the oldest ice in the currently flowing parts of the ice sheet (Petit et al., 1999). Meteorites with terrestrial ages exceeding 3 million years (roughly two orders of magnitude older than the mean terrestrial age for Antarctic meteorites) have been recovered from the periphery of the Allan Hills and Lewis Cliff sites, strengthening the suggestion that these sites contain stranded ice (Welten et al., 1997; Nishiizumi et al., 2000).

Fig. 4. Oblique (side-looking) aerial photograph showing remarkably clear stream lines on a glacial tongue flowing through a gap in the Colbert Hills between Coalsack Bluff and Mt. Sirius, about 15 km east of the Lewis Cliff Ice Tongue (the aircraft position and viewing angle are shown on Fig. 5). Crossing streamlines in the center of the photograph strongly suggest that diminishing ice flow has stranded ice along the margin of the moraine to the right. (USGS aerial photograph TMA1344(133) F31).

4) Decoupled and transitory mechanisms; or, changes over time: It may seem contradictory to suggest that meteorite stranding surfaces are primarily due to deflation over the preceding 20,000 years while also suggesting that several sites have ice and meteorites much older than this. However, the solution to this paradox is to consider the modern period within the longer-term history of the ice sheet. Ice core studies suggest that climate-forced changes in ice volume along the high-altitude margin of the East Antarctic ice sheet are a common occurrence over the past 500 ka, with the current reduction in ice sheet volume simply the latest in a long, complex series of volumetric responses to climate change (Petit et al 1999; Anderson et al., 2001). Furthermore, while longer-term (100 ka) trends and periodicity show up in ice core data, the "saw tooth" pattern superimposed on these trends demonstrate abrupt variability over shorter intervals, often reversing and/or accelerating trends on nearly human timescales of a few tens of years (Severinghaus and Brook, 1999). Longer-term records suggest this variability extends further into the past, probably throughout the existence of the ice sheet (e.g. Marchant et al., 1993). In essence, the altitude of the East Antarctic ice sheet interior is changing continuously, rising and falling as average temperature and precipitation rates vary, with both rate and direction of change only occasionally visible on human timescales.

The magnitude of these changes differs significantly between the interior of the ice sheet and its margins. In accumulation regions at the center of the ice sheet, altitude changes are thought to be minimal because the lower flow rates associated with colder ice are balanced by lower accumulation rates; similarly, in warmer periods higher accumulation rates are balanced by faster flow. The result is that the effects of climatic change are seen most strongly at the terminus of the ice sheet, where dropping temperatures may result in ice shelves thickened by a thousand meters and extended many hundreds of kilometers past current values (Denton and Hughes, 2000). By virtue of their location at the high altitude margin of the ice sheet, meteorite stranding surfaces are subjected to moderated ice volume changes over time, probably measured in terms of a few 100 meters or less. Changes on this scale are sufficient to produce alteration in drainage velocity and direction by increasing or decreasing the effectiveness of barriers to iceflow, but within mountainous terrain whose relief is often measured in thousands of meters, the effects remain localized.

One of the most important implications for meteorite stranding surfaces is that the relative importance of various concentration mechanisms may change dramatically over time. Mechanisms such as conveyor belt delivery need not be simultaneous with ablation; the two can be decoupled as a localized area transitions from slow but continuous flow at glacial highstands to stranded, rapidly deflating conditions at another time. Stranding surfaces do not have to be old or in continuous operation to have lots of meteorites; they only need to deflate old ice that is periodically delivered. With this in mind, a surface that is only a few thousand years old can easily contain a high concentration of meteorites, some 3 orders of magnitude older than the surface itself.

The result is a concept of meteorite stranding surfaces as ephemeral products of local and relatively short-lived glacial phenomena; but such stranding surfaces may have existed periodically in these settings throughout the history of the ice sheet. The icefields we see today, therefore, are likely to be a mixture of sites, some of which were "flushed" by increased iceflow during the last glacial highstand, and others where flushing was incomplete or minimal. High-altitude barriers to iceflow such as the Transantarctic Mountains act as a dam with many spillways of varying height; and as the East Antarctic

Ice sheet floods and wanes, ice pulses course through some gaps and not others. For meteorite stranding surfaces, the result may be a very complex stratigraphy; with many ages of ice welded together and meteorites with terrestrial ages from a series of intervals including, but not necessarily limited to, the modern deflationary period. The concept of periodic flushing and reactivation of meteorite icefields in not new; Cassidy et al. (1992) speculated that some meteorites may undergo repeated cycles of exposure and exhumation as ice flow conditions change over time, and sequential storage of meteorites has been suggested by the work of Delisle (1995) and Welten (2000). The full complexity that such behavior implies, however, is only now beginning to be grasped; ideally, we may some day be able to examine chronologically discrete groups of specimens recovered from within a single icefield.

An example: Icefields of the Walcott Névé: Geomorphological constraints and a relatively long history of study make the Walcott Névé an excellent place to examine this evolved view of meteorite concentration mechanisms in a variety of settings. The Walcott Névé is a broad snowfield in the front range of the Transantarctic Mountains immediately north of the headwaters of Beardmore Glacier. Surrounded by the Queen Alexandra Range to the east, Goodwin Nunataks and a ridge informally named “Foggy Bottom” to the south, the Lewis Cliff on the west, and the Colbert Hills to the north, the Walcott Névé forms a gigantic, emergent cirque roughly 60 km across. Plateau ice enters the névé from the southwest, cascading over the southern end of Lewis Cliff, or through gaps surrounding Goodwin Nunataks, and exits into the Bowden Névé and the Law glacier to the north. The altitude of the ice sheet surface in the Beardmore region is thought to be about 200–400 m lower now than during the last glacial highstand – thus the setting is one of reduced ice inflow due to a number of emergent barriers (Denton and Hughes, 2002).

The Walcott Névé and its periphery are the home to more than a dozen meteorite bearing blue ice areas, including the important Lewis Cliff Ice Tongue and South Lewis Cliff Icefields (where 1870 LEW specimens have been recovered), Foggy Bottom and Goodwin Nunataks icefields (where more than 3400 QUE specimens have been recovered), and MacAlpine Hills icefields (where nearly 750 MAC specimens have been recovered) (Fig. 5). These various icefields occupy the full range of settings previously described as important for meteorite recovery. Two of them are of particular interest as examples of icefields where changing ice levels and stranded ice are implicated, as follows.

1) The Lewis Cliff Ice Tongue: The 3×8 km Lewis Cliff Ice Tongue (LCIT) was the first Walcott Névé site to be examined in detail, and more than 1300 meteorite have been recovered from this exposed ice since it was first discovered in 1985. The LCIT runs northward along the bottom of the Lewis Cliff, resembling a shallowly sloping alpine glacier in form, with a wide terminal moraine sequence separating it from the Law Glacier (Fig. 6). The ice tongue has upper and lower sections separated by a steep, crevassed and predominantly snow-covered scarp approximately half way down its length. Incipient terminal moraines can be seen forming on the lower ice tongue at several intervals along its length. Among the most obvious observations is that the numerical density of meteorites is dramatically higher along the western side of the LCIT. Terrestrial rock is also more common on the west side, although no attempt was made to

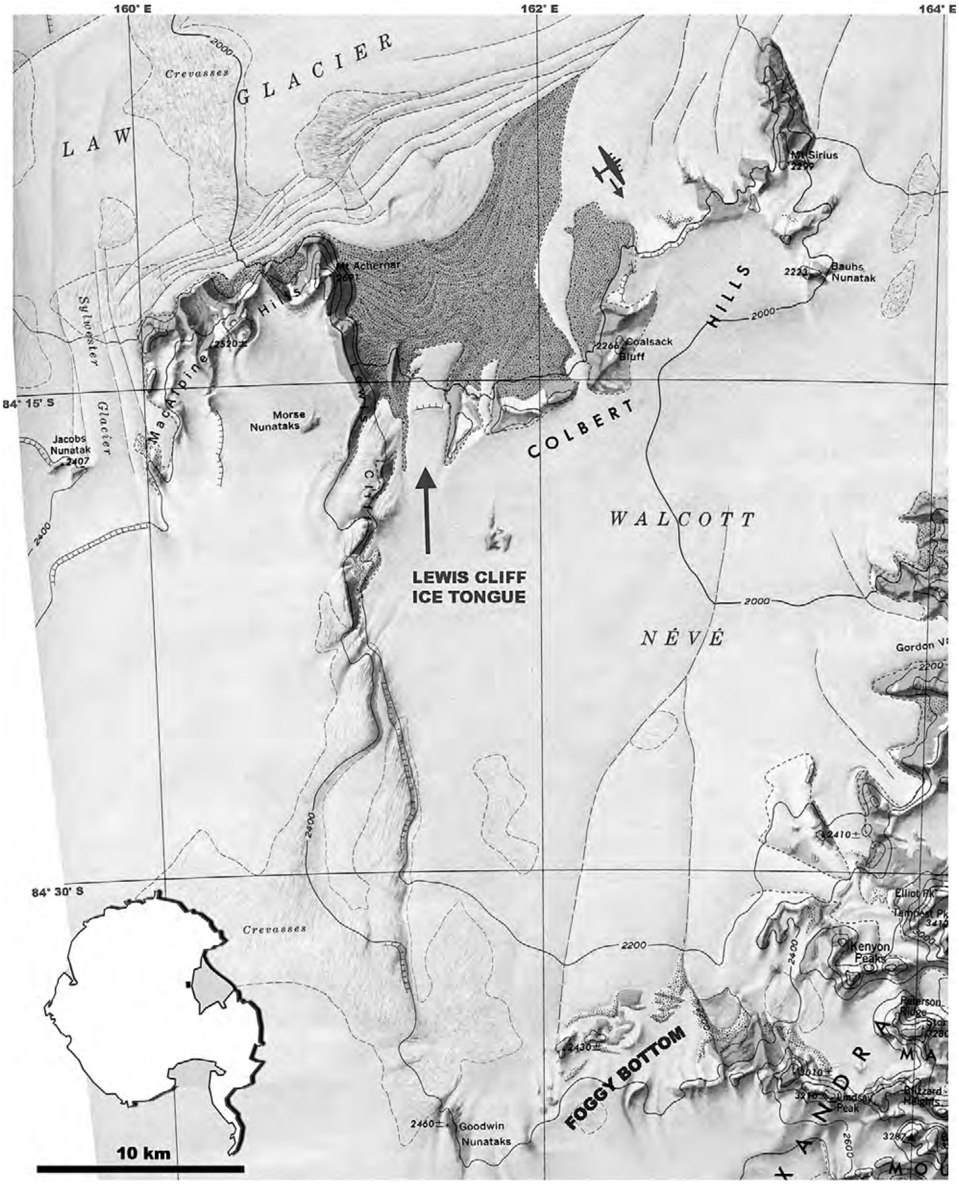


Fig. 5. Map of the Walcott Névé, central Transantarctic Mountains, Antarctica. Lewis Cliff forms the western border of the Névé, while the Colbert Hills and Queen Alexandra Range form the north and southeast borders. The unofficially named Lewis Cliff Ice Tongue in the north and Foggy Bottom region in the south are discussed in detail in the text, and located as shown. An outline of Antarctica shows the location of the Walcott Névé on the continent, and an aircraft silhouette shows the position and look angle for the aerial photograph in Fig. 4. (USGS *Buckley Island* quadrangle, 1:250,000 Reconnaissance Series, SV 51-60/3, revised 1988).

quantitatively determine its numerical density. The predominant katabatic winds direction is straight down the ice tongue (from south to north), suggesting that the distinction is not due to wind-induced movement of samples toward the west. Prominent color bands and streamlines visible in aerial photography and on the ground run lengthwise down the LCIT and serve as a natural demarcation between the higher meteorite density west and lower density east sides of the ice tongue. Furthermore, on the lower ice tongue these

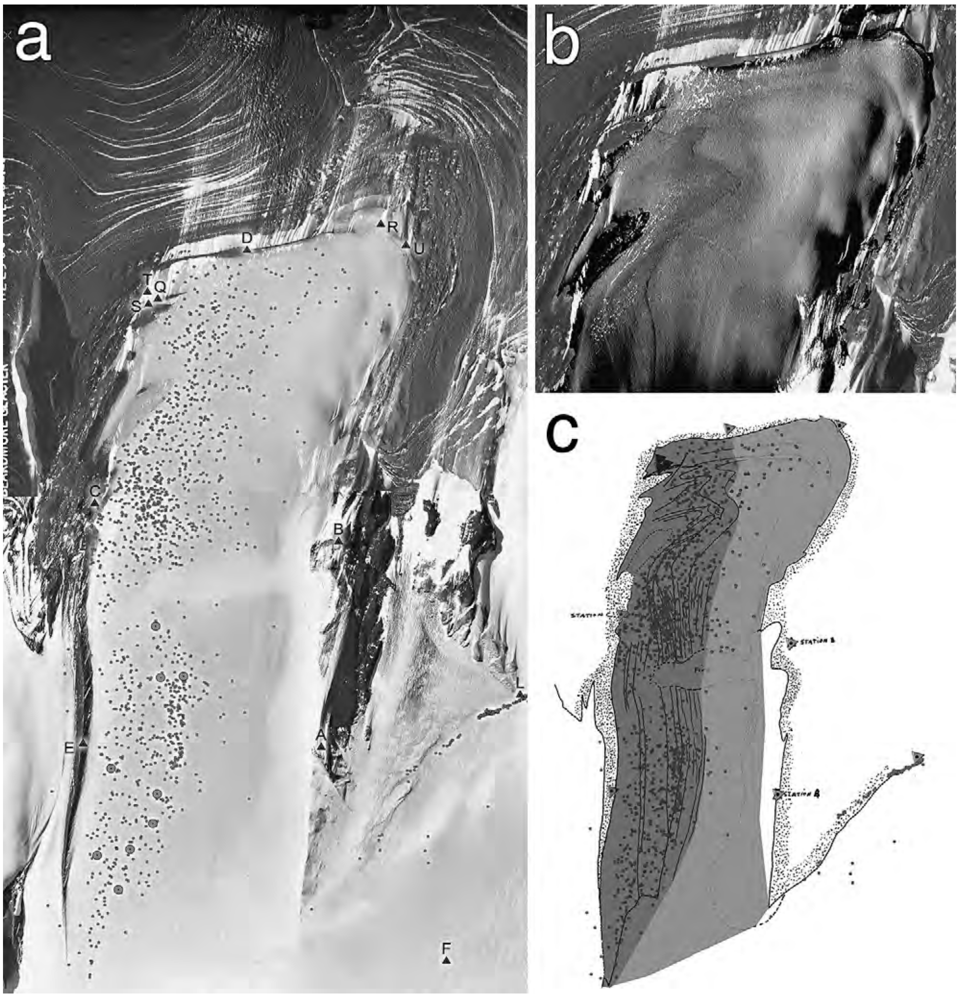


Fig. 6. The Lewis Cliff Ice Tongue (LCIT). a) Mosaic of vertical aerial photographs of the LCIT showing meteorite distribution. Triangles and circles are survey stations. b) Enlargement of the northern end of the LCIT that has been contrast enhanced. The west side of the LCIT shows a series of curving and dead-ending streamlines; a prominent dark streamline separates the east and west sides. c) A sketch of LCIT streamlines identified from airphotos and ground evidence, from Cassidy et al., 1992. The grayed region shows the region of the LCIT used to calculate ice loss volumes in Harvey and Schutt (1998). The darker sub-region represents a proposed stranded area used for comparisons in section II of this paper.

streamlines can be seen to cross in several areas, strongly suggesting that the LCIT ice along the western side is stranded. The most eastern prominent streamline serves as a suggested boundary between an older body of stranded ice on the west and younger, faster flowing ice on the east. Ice movement and oxygen isotope data both support this hypothesis; ice on the western side is moving very slowly and has strongly negative, "old and cold" $d^{18}O$ values while ice on the eastern side is moving more quickly and has relatively "warmer" values 8–10 per mil higher (Grootes 1989; J. Schutt, unpublished data). The geomorphology of the moraines surrounding the ice tongue also support this scenario. Individual morainal ridges (each representing distinct past positions of the terminus of the ice tongue) suggest that along its western boundary the LCIT has receded from a "maximum" position only a few hundred m further north. Along its eastern side, however, these same morainal ridges suggest the LCIT spread several km further to the north and east, occupying an additional horizontal area nearly equal to what is currently exposed on the lower ice tongue.

Taken together, these observations suggest that the body of ice currently lying along the western side of the LCIT has become isolated from faster flowing, younger ice along the eastern side of the ice tongue. This in turn suggests the following sequence of events since the last glacial highstand. At its highest stand, plateau ice entering the Walcott Névé from the plateau probably flowed actively northward along Lewis Cliff through the gap between the Cliff and the Colbert Hills to the east, joining the Law Glacier roughly 30 km further west than it does today. At that time the confluence of the two ice streams was

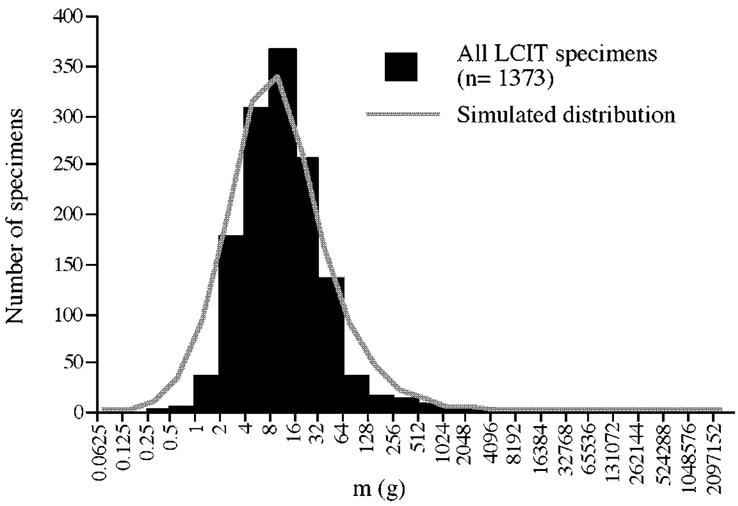


Fig. 7. Comparison between the size distribution of meteorite specimens from the Lewis Cliff Ice Tongue and a simulated distribution from Harvey and Schutt (1998). The height of the bars (and line) represent the number of meteorites recovered within a given mass range (bin), with each bin doubling in size toward the right. The simulated distribution is the predicted abundance assuming the loss of approximately 10 km^3 of highly compressed ice through deflation over the past 20,000 years. That ice was assumed to contain a meteorite distribution based on the influx rate of Halliday et al. (1996), modern accumulation rates and a 10:1 compression ratio within deep glacial ice, with influx continuing throughout the deflationary period. Search and wind losses were also included in the study, but no continual delivery by conveyor-belt mechanisms was assumed.

probably marked by a simple medial moraine streaming northeast from Mt Ackernar (then a small nunatak) at the crest of Lewis Cliff. As regional deflation of the ice sheet surface began, the Lewis Cliff and the Colbert Hills became more effective barriers to iceflow, and the medial moraine where the ice streams once joined became a terminal moraine for the newly separated LCIT and other ice pendants leading from the Névé northwards. Continued deflation led to continual retreat of the LCIT and Law Glacier to their current surfaces, leaving a series of moraines concentric around their former meeting point. At some time in this sequence, regions of the western side of the LCIT became progressively stranded, with continuing flow being diverted to the eastern side of the ice tongue. The current surface thus represents 200-400 meters of deflation since the much higher ice surface level prominent at the last glacial high stand (Cassidy et al., 1992; Denton and Hughes, 2002). While all of the meteorites found on this surface were originally brought in by ice movement and exposed by ablation, the much higher concentrations along the western side of the LCIT owe their existence to this massive loss of ice on a stranded surface.

Simple models of meteorite concentration processes have provided some validation of the proposed scenario. Harvey and Schutt (1998) simulated the LCIT as an appropriately-sized box with ice flowing into the southern end and leaving at variable rates either by flow out of the northern end or lost at the top surface through ablation. Meteorites arrived at the box surface in two ways; delivered by iceflow and later exhumed by sublimation, and accumulating through direct infall. With an abundance of variables (including all the meteorite delivery and loss mechanisms discussed in this paper) and a dearth of measured constraints, the model offers no unique solutions; but its results suggest that even a complete cut-off of “conveyor belt” ice delivery 20,000 years ago is capable of producing the observed concentration where ablation and direct infall are moderate and continuous (Fig. 7).

2) The Foggy Bottom/Goodwin Nunataks region: The most numerically productive icefields of the Walcott Névé lie at its southern end, along an east-west extension of the Queen Alexandra Range informally called “Foggy Bottom”. The Goodwin Nunataks serve as the westernmost exposed end of this extension, separated from the Foggy Bottom ridge by a shallowly sloping chute of ice a few km across. Blue ice is extensive on both the southern (uphill) and northern (downhill) sides of both sites, and several different concentration mechanisms are in play. Glaciological data for the Foggy Bottom/Goodwin Nunataks region are more limited than for the Lewis Cliff Ice Tongue; a single ice movement network was installed in 1994 and remeasured once a little more than 3 years later, and no ice chemistry or ice thickness studies were conducted. In spite of this, the existing broad scale data strongly suggest that stranded ice plays a key role for the icefields in a downhill setting. Fig. 8 shows a RADARSAT image of the Walcott Névé with an inset of the Foggy Bottom/Goodwin Nunataks region, with ice movement vectors and the names of key icefields superimposed. Two ice streams originating on the plateau are clearly visible; the Sylvester Glacier diverting northward around Mt. Ackernar of Lewis Cliff to join the Law Glacier flowing eastward, and an un-named ice stream cutting across the Névé from the southwest to northeast. Admittedly less clear than those seen on the Lewis Cliff Ice Tongue, crossing streamlines are still evident along the western side of the Mare Meteoriticus icefield (hereafter called “the Mare”), suggesting the un-named ice stream is bypassing the adjacent icefields to the east. Radar-dark icefields are prominently visible on either side of this ice stream, which serves as a sharp terminator for the Mare. Velocity vectors show that the ice is moving relatively quickly right at the border between the un-named icestream and the Mare, but velocities fall dramatically as one moves eastward into the interior of the Mare and onward to the Tail's End icefields. With measured horizontal velocities that are vanishingly small and no clear input of ice (being cut off from the ice stream by a shear zone), the Mare and Tail's End icefields in the downhill setting of the Foggy Bottom region fit the definition of meteorite concentrations on stranded ice.

In contrast, horizontal ice velocities on the uphill side of Foggy Bottom are much more consistent with classic conveyor-belt processes that have been heavily modified by the wind. Ice flow and winds are both primarily from the south, with horizontal ice flow velocities diminishing northward to insignificance as one moves toward the exposed ridge-like assemblage of nunataks that make up Foggy Bottom. This ridge acts as a nearly complete barrier to further iceflow, and only a shallow gap on its eastern side allows some ice to cascade over the ridge and form a pendant ice tongue with a series of moraines at its terminus (the Footrot Flats/Scoraine Moraine area). The reduced ice flow velocities have led to enhanced ablation and the exposure of blue ice in the last few kilometers as the ice approaches the ridge from the south (Fig. 9). The ice surface slopes gently northward until the last few hundred meters, where it steepens dramatically to form an escarpment (crevassed in places) and then shallows again as it meets moraines bordering the nunataks.

The distribution of meteorites on the various icefields of Foggy Bottom echo the dichotomy between stranded ice on the downhill Mare and Tail's End icefields, and heavily wind-altered conveyor belt concentrations on the uphill Foggy Bottom icefields. While a few larger meteorites were found widely scattered out on the more southerly uphill areas of blue ice, the vast majority of the meteorite finds on the uphill side have been associated with moraines, most within a band marking the moraines bordering the nunataks. A secondary "band" of meteorites a few hundred meters to the south marks the bottom of the previously mentioned steep slope. Although there are some notable exceptions, the vast majority of meteorites finds in aeolian traps have been small (Fig. 10).

Some of these wind-driven assemblages on the uphill side are notable. The previously described pendant ice tongue on the eastern side of Foggy Bottom provides almost 5 km of continuous blue ice exposure sloping downhill and very close to the prevailing katabatic wind direction. Moraines at the terminus of this ice tongue have evidently served as aeolian traps, and have yielded many hundreds of finds. One astonishing aeolian trap (Footrot Flats) is not a moraine but rather a gently sloping patch of very hard, rough snow (firn) in a larger snowfield. Modestly sized at about 100 m wide and 600 m long, this rough snow surface is much more resistant to abrasion and sublimation than the blue ice, and through friction alone has trapped an amazing number and diversity of specimens. 343 meteorite specimens have been recovered over the years, including two distinct lunar specimens (one of which was the first meteorite found at the site), suggesting an average linear spacing between distinct finds of less than 15 m. As is consistent with an aeolian origin, the vast majority of these specimens are 10 g in mass or smaller; the largest was 99.5 g.

Meteorite concentrations on the Mare show the effects of aeolian transport as well, though these are modest by comparison to the uphill settings. Both the Mare and Tails End icefields are littered with small (<2 g) terrestrial rock fragments, apparently blown off of the Foggy Bottom ridge and distributed downwind. Moraines at the foot of the Foggy Bottom ridge also contribute terrestrial rock to these icefields; notably the large,

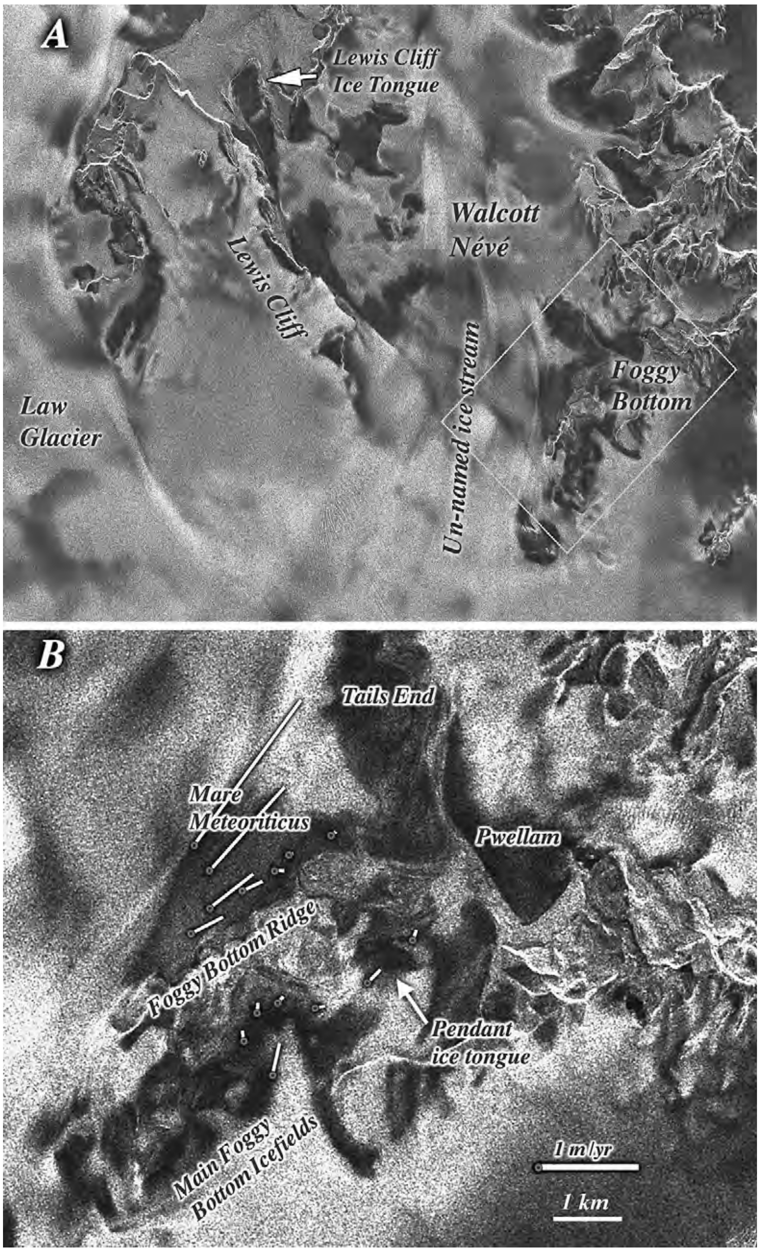


Fig. 8. RADARSAT images of the Walcott Névé and Foggy Bottom area. Blue ice is an inefficient reflector of radar wavelengths and thus shows up dark in these images. Neither image has been corrected for the oblique viewing angle, so scale bars are approximate. A) Full resolution image showing the Walcott Névé with key meteorite regions and ice streams. Box shows area enlarged in Fig. 8B. B) Close-up of the Foggy Bottom region rotated so north is "up". Labels show names of local icefields and features mentioned in the text. Grey dots mark the position of survey stations, with proportional bars showing the direction and velocity of ice movement.

lambda-shaped "Tail" moraine that streams several km northward into the Walcott Névé. However, there is no association between moraines, aeolian redistribution and meteorite concentrations on these downhill icefields. The only recognizable wind concentration is a string of finds marking the downwind firn edge along the northwestern border of the Mare (Fig. 9). The highest numerical density occurs in a region affectionately called "the Maelstrom", where several hundred paired LL5 fragments were recovered in a region several hundred meters on a side and elongated in the predominant wind direction. This presumably is the central region of the strewn area for this shower fall. Another high density region is somewhat linear along the southwestern border of the Mare, marking a shallow basin where the southern end of the Mare borders the nunataks. This numerical

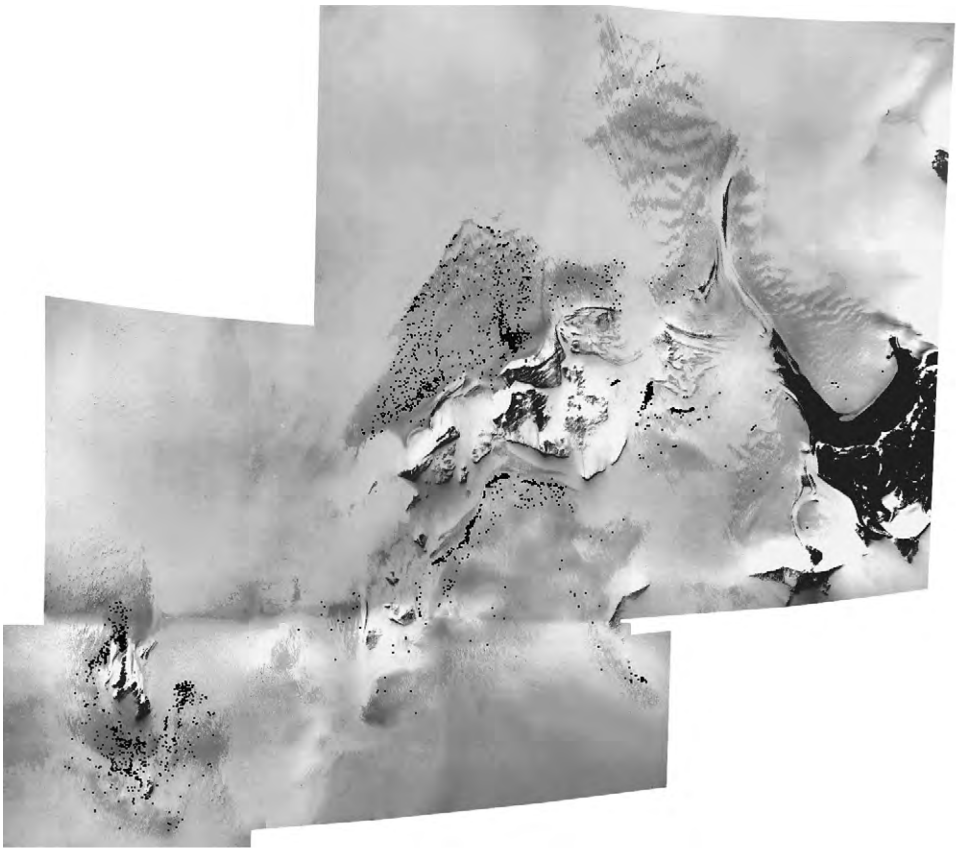


Fig. 9. Mosaic of aerial photographs of Foggy Bottom / Goodwin Nunataks region with meteorites superimposed. The photographs have been geo-corrected to remove view angle effects, and some color correction has been done to reduce vignetting and film processing artifacts. On the southern (uphill) side of the exposed nunataks, meteorites are thinly scattered on blue ice, but highly concentrated on downwind firn edges, moraines and other aeolian traps. In contrast, icefields on the northern (downhill) side of the nunataks show more widespread distributions. The sharp termination of meteorite finds against the western border of the Mare Meteoriticus is a wind-driven concentration along the downwind firn edge. Other groupings seen on the Mare are of unknown origin but often contain a large proportion of individuals from the previously mentioned shower falls.

concentration is probably due to gravity-driven sliding rather than the wind, given that the Mare surface slopes downward toward the south (into the wind) in this region.

Like the Lewis Cliff Ice Tongue, the meteorite concentrations on the Foggy Bottom icefields can best be explained as a product of localized changes in iceflow since the last glacial highstand. Unlike the Lewis Cliff region in the northwest of the Walcott Névé, where the highest peak (Mt. Ackernar) lies more than 200 meters above the altitude of the surrounding plateau, the highest peaks in the Foggy Bottom region are currently only a few tens of meters higher than the ice sheet. This suggests that the Foggy Bottom ridge was a much less effective barrier to northward flow at the last glacial highstand, when local ice levels were thought to be 200–400 meters higher. Under these conditions, the Foggy Bottom ridge probably was a subsurface obstruction to ice flow, marked by an escarpment and local blue ice. Under these conditions the region could still have been an active "conveyor-belt"-style meteorite concentration site, such as those currently existing at the Allan Hills Far Western or Elephant Moraine icefields. But as the ice surface retreated and the highest peaks of Foggy Bottom emerged, they gradually became a more and more effective barrier to direct northerly flow. As this process continued, ice on the downhill side of the Foggy Bottom ridge became increasingly isolated as the icestreams feeding the Walcott Névé diverted to the west. During this period, the Tail moraine developed, first as a small medial moraine marking the border between the icestream to the east and west, and growing to today's boundaries as deflation continued. Continuous but diminishing delivery of ice to the uphill region would allow a classic conveyor-belt style meteorite stranding surface to develop against the absolute barrier represented by the Foggy Bottom ridge, while the region of stranded, massively deflating ice in the downhill regions would increase in size both westward and eastward around the Tail moraine.

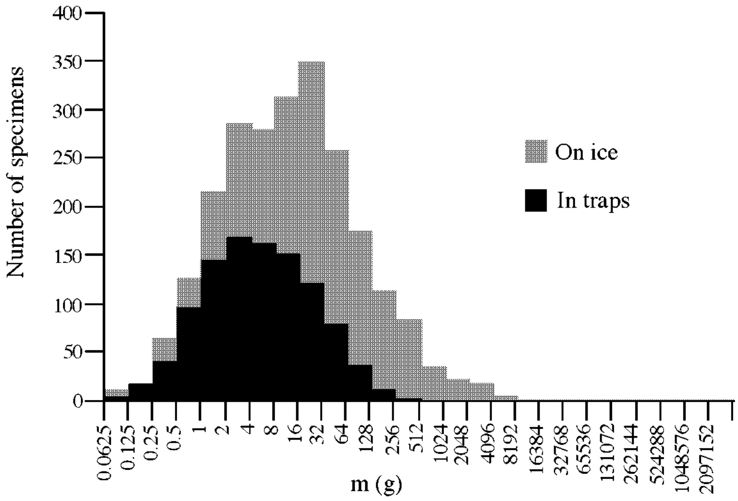


Fig. 10. Size distributions of meteorites from Foggy Bottom. The larger curve with the higher mean mass represents meteorites found on ice; the smaller curve represents meteorites from aeolian traps, including Footrot Flats, Scoraine Moraine, RB Moraine, Lunch Moraine, and the main Foggy Bottom moraine. Note that the on-ice distribution is skewed, with a tail toward larger sizes, while the aeolian meteorites show a more symmetrical distribution.

II. Significance: Antarctic meteorites as samples of the meteoritic complex

Introduction

Although its origins as a recognizably scientific pursuit are more than 200 years old (e.g. Chladny, 1794), in many ways meteoritics is still a youthful science. Many of its publications are descriptive, devoted to the basic petrography and chemistry of new finds, and discussions of their place within a growing catalog of lithologies. That meteoritics retains a footing in a primarily descriptive phase is evident given that individual specimens still routinely force significant changes to our developing understanding of solar system materials and processes (most recently Tagish Lake; Brown et al., 2000).

The sheer number of meteorite specimens recovered from Antarctica has been a significant influence in the maturing of meteoritics, increasing the number of known specimens by roughly an order of magnitude. But the numbers alone are a poor indicator of how important Antarctic specimens have been to meteoritics. Many individual Antarctic finds are either fragments of falls or parts of shower falls, making up a significant but poorly known proportion of the collection. Estimates of the Antarctic "falls to finds" ratio vary dramatically; from roughly 1:1 to 1:10 (Scott, 1989; Graham and Annexstad, 1989; Lindstrom and Score, 1995; Ikeda and Kimura, 1992; Benoit and Sears, 2000). This pairing problem is unlikely to ever be resolved-tackling it comprehensively would require tens of thousands of repetitive petrological and geochemical analyses on relatively mundane specimens. Furthermore, it may not be solvable; not all specimens are paired, and pairing of some specimens may always be ambiguous given that the inherent geochemical and petrological variability of some common planetary materials is simply not known.

A more practical indicator of the significance of Antarctic meteorites is how they have influenced the growth of planetary materials research. Antarctic meteorites rival the Apollo lunar specimens in their impact on planetary materials research while new specimens continue to arrive yearly. Illustrating the importance of Antarctic meteorites, the recently published book *Planetary Materials* (Papike, 1998) is a comprehensive survey of research on extraterrestrial materials, running over 1000 pages. Of the 435 individual meteorites listed in the index to this book, 38% (167) were collected in Antarctica. Similarly, GeoRef, the comprehensive online bibliography of Earth Sciences, lists 2852 publications in the category of "petrology of meteorites" over the past five years; nearly 10% of these (241) refer to a single Antarctic meteorite (ALH84001).

Another key factor in the widespread scientific use of Antarctic meteorites has been the rapidity and efficiency with which samples of the Antarctic meteorites make their way into the world's research facilities. The vast majority of Antarctic finds (>99.5%) have been made available for research purposes, free of charge, through government-supported curatorial programs. This is a pleasant contrast to meteoritic specimens recovered from the "civilized" continents, whose high value to private collectors has often created an inverse relationship between the scientific importance of a specimen and the amount of material available to science.

Perhaps the most significant factor contributing to the importance of Antarctic meteorites is the "completeness" of this sample – how well it represents the full range of materials falling to Earth. The Antarctic collection represents a relatively unsorted and unaltered sample of what has fallen to Earth, with individual icefields representing varying time spans that can reach a million years or more. The Antarctic finds are thus an excellent complement to the witnessed modern falls – the latter representing a relatively unsorted snapshot of what is falling to Earth today, and the former representing a larger but unknown number of fall events integrated over a much longer timescale. The Antarctic meteorites provide a new sample of the flux of extraterrestrial materials falling to Earth, and an expanded catalog of known planetary materials, including those that fall only rarely on historical scales.

Understanding of the significance of the Antarctic finds requires comparisons among the various meteorite collections and estimates of the extraterrestrial flux. These comparisons demand careful consideration of the unique characteristics of individual meteorite collections (e.g., Antarctic finds, witnessed falls, non-Antarctic finds) and individual meteorite stranding surfaces. Antarctic finds come from individual icefields that vary in age, recovery conditions and recovery standards (depending on who did the collecting). Witnessed falls span a much shorter time range and offer an "instantaneous" view of the population of incoming meteorites, almost completely unsorted by type and size, over a large but poorly defined area. Non-Antarctic finds are often highly skewed toward more durable and recognizable meteorite types; but some, like those systematically collected by experienced meteoriticists in dry deserts, can retain the characteristics needed to be good samples of the incoming meteorite population.

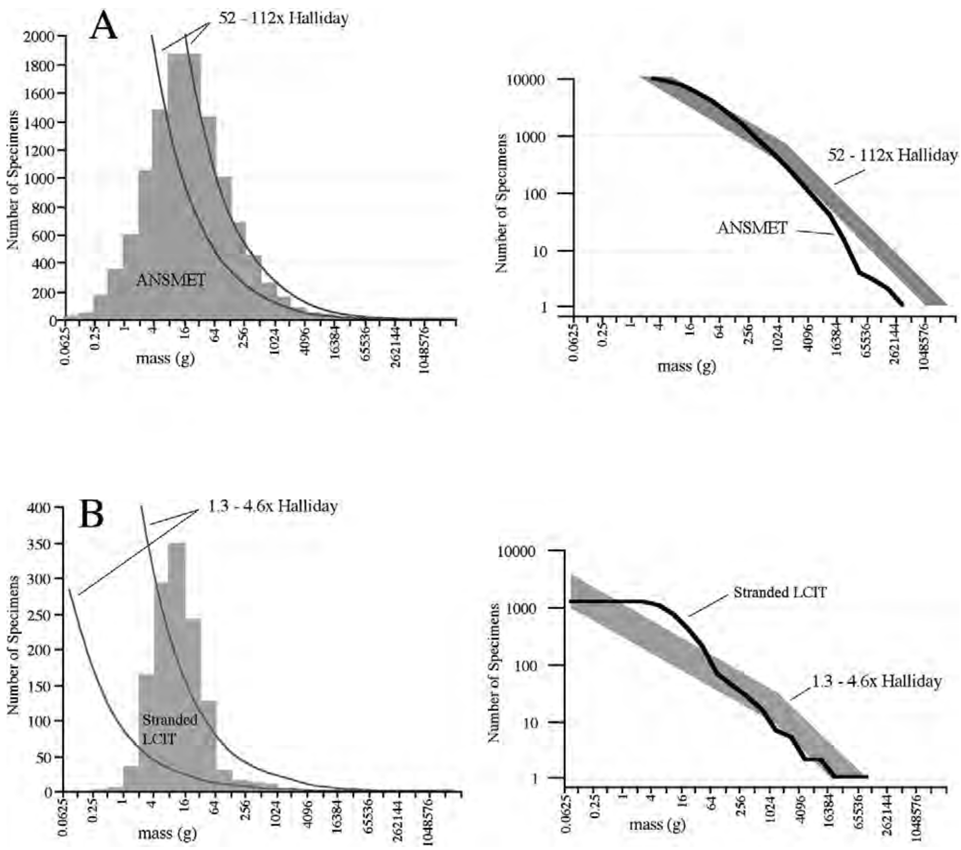
When exploring the importance of Antarctic meteorites as a whole and making comparisons between the various meteorite collections, we will limit ourselves to a few chosen sub-samples whose characteristics are well understood. Among the larger Antarctic meteorite collections, the ANSMET meteorites are an excellent and representative sub-sample, consisting of slightly less than half of all recovered Antarctic specimens (as of this writing, more than 12,500 specimens totaling over 2600 kg) with nearly complete characterization and consistent recovery standards over time. Because the all-ANSMET sample contains specimens from several icefields where systematic collection is not yet complete, we will also consider sub-samples from individual ANSMET icefields, serving as samples of the meteoritic complex integrated over much smaller geographical ages and time spans but with the absolute minimum of sorting effects. We will use an updated version of the witnessed modern falls sample of Harvey and Cassidy (1989) as a representative of what has fallen to Earth over historical times, in concert with camera network and satellite data determinations of the total flux. We will also make comparisons to a hot desert meteorite collection, selecting the Dar al Ghani meteorites from the Libyan Sahara as the sample exhibiting the most evidence for systematic, unbiased collection.

Antarctic meteorites and the extraterrestrial flux

Establishing the flux of extraterrestrial material to the Earth (the frequency with which the Earth encounters extraterrestrial material of a given size) has been a major goal of planetary science for decades. The extraterrestrial material we call meteorites make up a limited size range within the total flux, generally larger than a few mm in diameter and larger than a few tens of milligrams in mass. In spite of this limitation, the meteorites are of key importance in influx studies- they represent ground truth in ways remotely sensed data and micrometeorites cannot. Several sources can provide information concerning the current meteorite flux. Spacecraft studies and military "early warning" networks provide information regarding the size distribution and time frequency of arrival of meteoritic debris, while dedicated camera networks provide data on the frequency with which arrival events produce recoverable meteorites (e.g. Halliday 2001; Brown et al., 2002). These have allowed the development of a reasonably accurate understanding of the size distribution and relative frequency of different types of meteorites arriving at our planet's surface. The shortcomings of the Antarctic finds (specifically the pairing problem) make it difficult to examine the longer-term flux through a comparison of numbers of events. However, comparisons of relative proportions of mass remain valid, and the examination and comparison of size distributions allows an indirect look at how the flux may have changed over time.

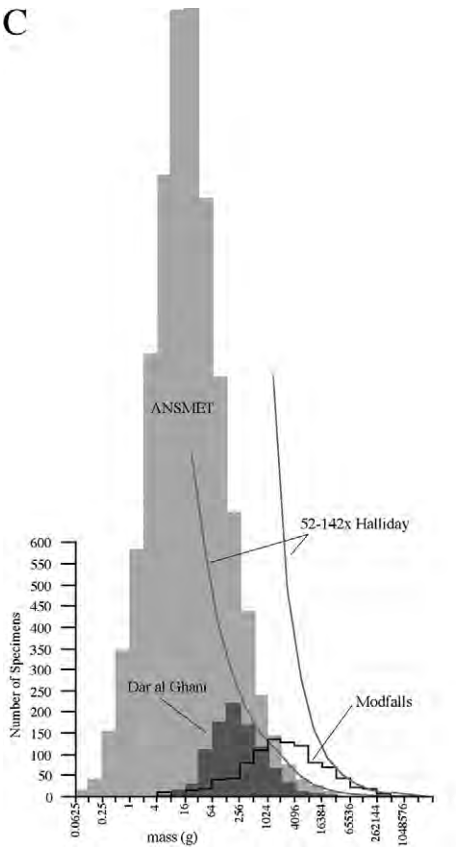
- Size distributions

Size distributions convey the frequency with which certain size or mass ranges appear within a sample, and are a convenient way to compare various meteorite collections. Two forms of size distributions are commonly used; simple histograms such as seen in Figs. 7 and 10, and cumulate distributions showing the total number of specimens above or below a given size. Typically the mass or size scale is displayed along the abscissa (x-



axis) and is logarithmic, following convention; the ordinate (y-axis) can be either linear or logarithmic. The flux of extraterrestrial material to the Earth is traditionally portrayed as a cumulate size distribution of negative slope, on a logarithmic scale. These log-log distributions have been termed "power laws" and mimic the fragmentation of target material during explosive events such as impact on asteroids and other solar system bodies.

Fig. 11 shows size distributions for the meteorite samples discussed in this paper. As mentioned previously, the all-ANSMET sample (as of December, 2002) has been chosen to represent Antarctic meteorites given that recovery standards have been stable and characterization is 97% complete. The form of the all-ANSMET distribution is beautifully symmetric, with a near-normal (Gaussian) shape, but this is almost certainly coincidence. Normal distributions are a product of natural variation around a mean value, while the ANSMET meteorite distribution is better explained as the product of power law delivery of meteoritic material with loss mechanisms that dramatically reduce the number of smaller specimens recovered (Harvey, 1995). There is a slight skew to the ANSMET distribution, a tail extending toward higher mass values. This suggests that the loss mechanisms increase in power dramatically as smaller and smaller meteorite masses are considered, as might be expected from previous sections of this paper. The overall shape



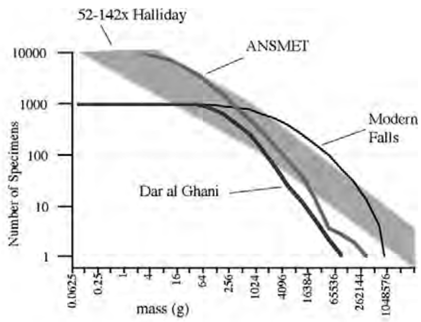


Fig. 11. Size distributions of various meteorite samples. A) the all-ANSMET meteorite sample (n = 11418) compared to the meteorite production flux of Halliday (2001). The curves shown are fits of the Halliday flux to either the full size distribution right of the mode (8-16 g) or all specimens larger than 1030 g. B) The stranded LCIT sample (n= 1291) with Halliday flux fits as in A). C) Size distributions of the all-ANSMET, Dar al Ghani (n=962) and updated witnessed Modern Falls samples (Modfalls; n=964) drawn to scale. Halliday flux fits are those to specimens larger than 1030g in the ANSMET and Modfalls distributions.

of the Antarctic size distributions, as well as many desert samples, can also be well modeled by a Weibull-Rosin distribution characteristic of fragmentation in crushers and ball mills (Harvey, 1990).

One way to measure the relative importance of the ANSMET meteorite sample is to compare it to the known meteorite production flux. For purposes of comparison we use the empirical flux of Halliday (2001), which is based on observed falls detected by camera networks over several decades and estimates the size and frequency of meteorite falls per year in 10^6 km^2. This power law has a pronounced change of slope (a “kink”) at 1030 g mass that corresponds to an observed decrease in the number of smaller meteorite producing events; the mechanism responsible for this decrease is not specified, but could be anything from search losses on the ground to an unreported maximum potential for mass loss during atmospheric entry (Halliday, 2001; Bland 2001). Fig. 11a shows a comparison between the Halliday power law and the ANSMET sample. When fit to the entire right side of the ANSMET sample (masses above 16 g), a multiplier of 111.68 is required to explain the ANSMET sample based solely on the Halliday flux; when fit to only those specimens larger than the “kink” at 1030 g, the multiplier is 51.72. In either case, we can see that the ANSMET meteorite represents the equivalent of a year’s flux over $0.50–1.0 \times 10^8$ km^2, between a quarter and a half of the area of the East Antarctic Ice sheet. More realistically, the ANSMET sample is integrated over time; and given that the included samples were recovered during searches of an area estimated to be between 1.5×10^3 and 2.0×10^3 km^2, this sample represents an “average” collection age of somewhere between 25,000 and 65,000 years. This is in good agreement both with the typical distribution of terrestrial ages of Antarctic meteorites (which show a mode in the same range) and the previously discussed origins of most icefields by deflation of older ice over the past 20,000 years (Jull 2001).

The same kind of comparison offers additional insight when compared to individual icefields where geographical area and collection characteristics are more constrained. Fig. 11b compares the Halliday flux to the meteorites recovered from the stranded section of the Lewis Cliff Ice Tongue; here multipliers of 1.3 and 4.6 are required to fit the ranges above the mode and above the 1030 g “kink” respectively. The LCIT size distribution is much less symmetrical, with a stronger tail toward larger sizes and a much more prominent peaked than is seen in the all ANSMET sample. Both the all-ANSMET and LCIT distribution typically cross the Halliday flux, with fewer large specimens and many more smaller specimens than the flux would normally produce. This is particularly pronounced for the LCIT, where there are 313 more specimens in the 4 to 64 g size range than a Halliday flux fit to all meteorites above 8 g would predict. In concert with this, roughly 150 meteorites larger than 64 g are “missing” from the LCIT. The most probable explanation for this conundrum is that weathering has converted larger meteorites into smaller specimens over time, with a commensurate mass of specimens lost to the wind and other processes.

The area of the stranded region of the LCIT (as shown in Fig. 6) is approximately 4.53 km^2. Using the Halliday fits to this sample, the meteorite collection found on the stranded section of the LCIT is what might be expected to fall over between 2.67×10^5 and 1.84×10^6 years. Considering the “whole” LCIT sample (which is only about 50 meteorites larger, but 2× the area), these numbers become 1.36×10^5 and 9.37×10^5 years, respectively. These are quite considerable apparent ages, but not outside of reason; the distribution of terrestrial ages for the LCIT extends to great values (Fig. 12). One meteorite from the nearby Meteorite Moraine locality has a terrestrial age that is over 2.3×10^6 years old (Welten et al., 1997) Clearly the LCIT is among the most highly concentrated meteorite recovery sites known, compressing a long history of meteorite influx into a very small geographical area.

A final comparison of value is between the ANSMET sample and two non-Antarctic samples; an updated version of the witnessed modern falls sample (from Harvey and Cassidy, 1991), and the Dar al Ghani sample, both culled from recent editions of the Meteoritical Bulletin (e.g. Russell et al., 2002) and the Catalogue of Meteorites (Grady, 2000). The Modern Falls sample as used here is a tabulation of witnessed falls where the majority of the mass seen to fall was collected; the mass of each clearly identified piece of the fall is included in the tabulation. Showerfalls are purposely excluded; several historically recorded falls have produced tens of thousands of individual pieces, and would essentially overwhelm any comparison with the Halliday flux, which estimates "events" that produce single specimens. The Dar al Ghani sample was chosen as a representative of systematic hot desert meteorite collections, based on its comparable numbers to the retabulated Modern Falls sample and apparently consistent and complete reporting of data.

Fig. 11c shows size distributions for the ANSMET, Modern Falls and Dar al Ghani samples, with Halliday flux distributions superimposed. One feature of note is almost certainly an artifact of collection conditions; the mode of each distribution is offset, occurring at about 1 kg for the Modern Falls, 100 g for Dar al Ghani, and about 10 g for the ANSMET collection. These figures are consistent with relative abundance of confusing background materials for each collection, which is lowest for Antarctica and highest for the populated continents. Like the ANSMET collection, the Dar al Ghani size distribution is skewed toward smaller sizes, presumably due to the collection of fragments and a strong size dependence on sample loss. In contrast, the Modern Falls much more closely approximate a normal or Gaussian distribution than do the other samples.

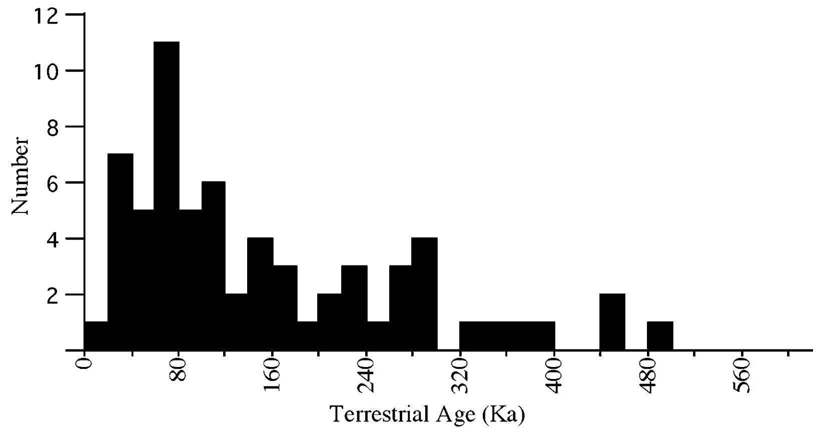


Fig. 12. Terrestrial age of LEW meteorites from all the Lewis Cliff Icefields. After Jull (2001).

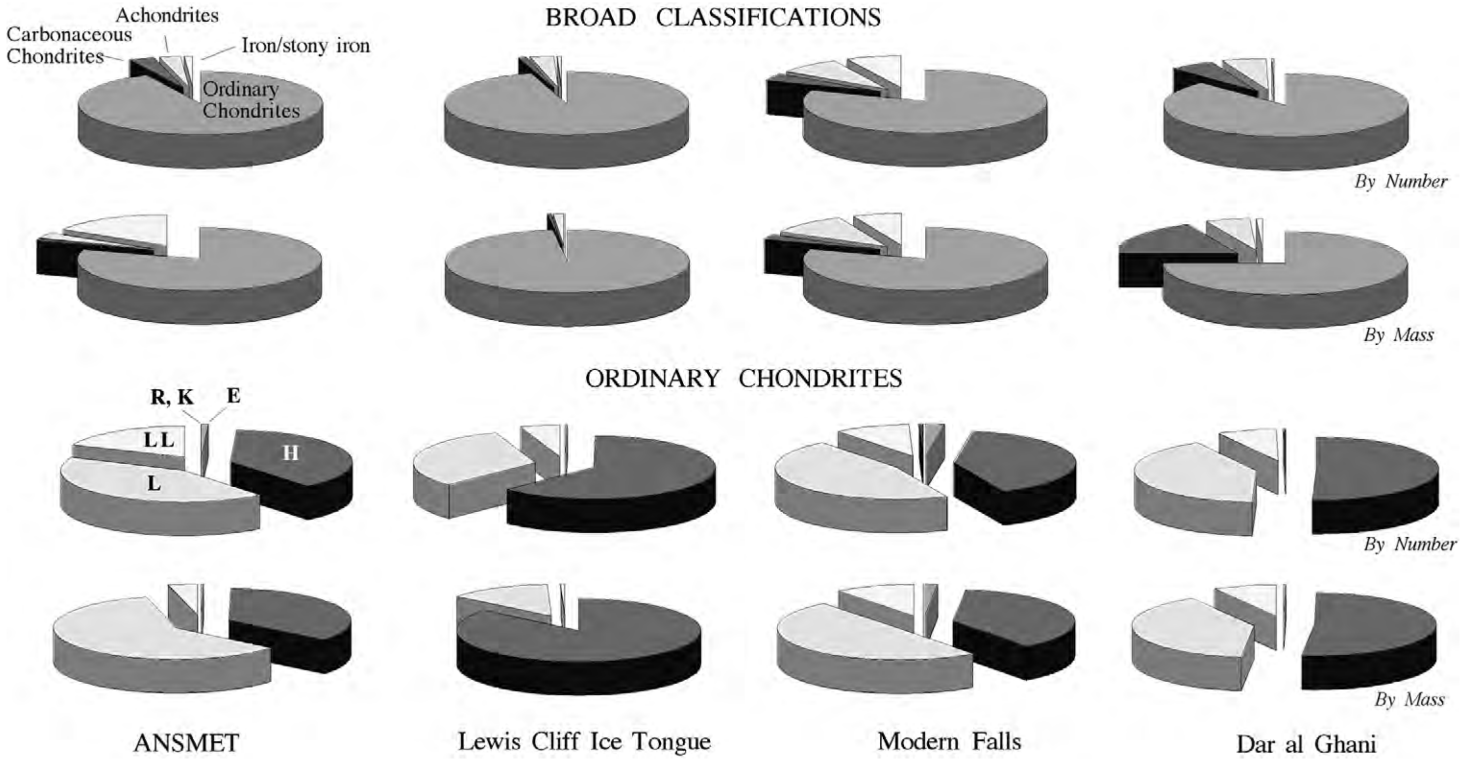


Fig. 13. Relative proportions of meteorite types, by number and mass, for the all-ANSMET, LCIT, Modern Falls and Dar al Ghani specimens.

• Petrological distinctions between Antarctic and non-Antarctic meteorites

Under ideal circumstances, the relative proportion of different types of meteorites found within a given collection will be a mirror of the abundance of these materials among the parent bodies of meteorites. More realistically, there are many processes that intervene to change these proportions during their release from their parent bodies, transit to earth, passage through the atmosphere, residence on Earth, and subsequent recovery. Because the recovered meteorites themselves are the "ground truth" of these processes, we can only hope to work backward from the collection we have in hand, and explore how well it represents the meteoritical complex of our solar system both now and in the past.

Fig. 13 shows the relative proportions (by number and mass) of various classifications of meteorites for the ANSMET, LCIT, Dar al Ghani and Modern Falls samples described in previous sections. The Modern Falls sample is an obvious representative of the frequency with which different types of meteorites fall today and over the past several hundred years, and because large shower falls have been excluded, both numbers and mass show fairly consistent percentages; roughly 80% ordinary chondrites, 10% achondrites, 6% metal-bearing (irons and stony irons) and 3% carbonaceous chondrites. The mass proportions shown by the other samples differ only modestly; however, they show much higher numbers of ordinary chondrite specimens; roughly 90% for the Dar al Ghani specimens, and nearly 95% of the Antarctic samples. Weathering is a likely culprit; oxidation of the metal in ordinary chondrites is a major factor mechanism behind physical fragmentation of desert specimens, increasing numbers at the expense of mass and often (but not consistently) making numerical percentages for a given type higher than the corresponding mass percentage. The cold and hot desert samples also typically show number and mass proportions that vary considerably; for example, while irons make up only 1% of the ANSMET numbers, they make up 16% of the mass. In this case, the dichotomy is clearly the result of inclusion of showerfalls in the samples- the Derrick Peak irons alone account for the observed difference. Because we cannot reliably account for either showerfall or weathering effects in Antarctic samples, it becomes difficult to argue that the differences in proportions seen between the various samples are a result of changes in the proportions of types delivered over time.

The relative proportions of the various ordinary chondrite groups reveal a similar problem in unraveling whether or not Antarctic meteorites represent changes in delivery over time. Again, the modern falls can be considered representative of what is falling today in terms of frequency of events, with H and L chondrites making up nearly 90% of the ordinary chondrites delivered to Earth, with L chondrites arriving slightly more frequently and carrying slightly more mass. LL chondrites arrive at about 1/4th this rate, and other classes (E, R, K chondrites) are rare. The large ANSMET sample is fairly consistent with these proportions, but as was the case for iron meteorites shows the influence of a few massive showerfalls (notably a showerfall of small LL5 chondrites among the QUE specimens). The individual desert collections, however, show a lot more variation; in the LCIT collection H chondrites outnumber L chondrites nearly two to one, and out-mass the L chondrites nearly five to one. This has been observed for several other collections as well, and described as either a showerfall effect, or a weathering effect (Harvey and Cassidy, 1991; Ashley and Velbel, 2000). In favor of the weathering explanation is the observation that the excess is usually H chondrites over other types, and H chondrites, which contain more metal, should produce more fragments than L or LL chon-

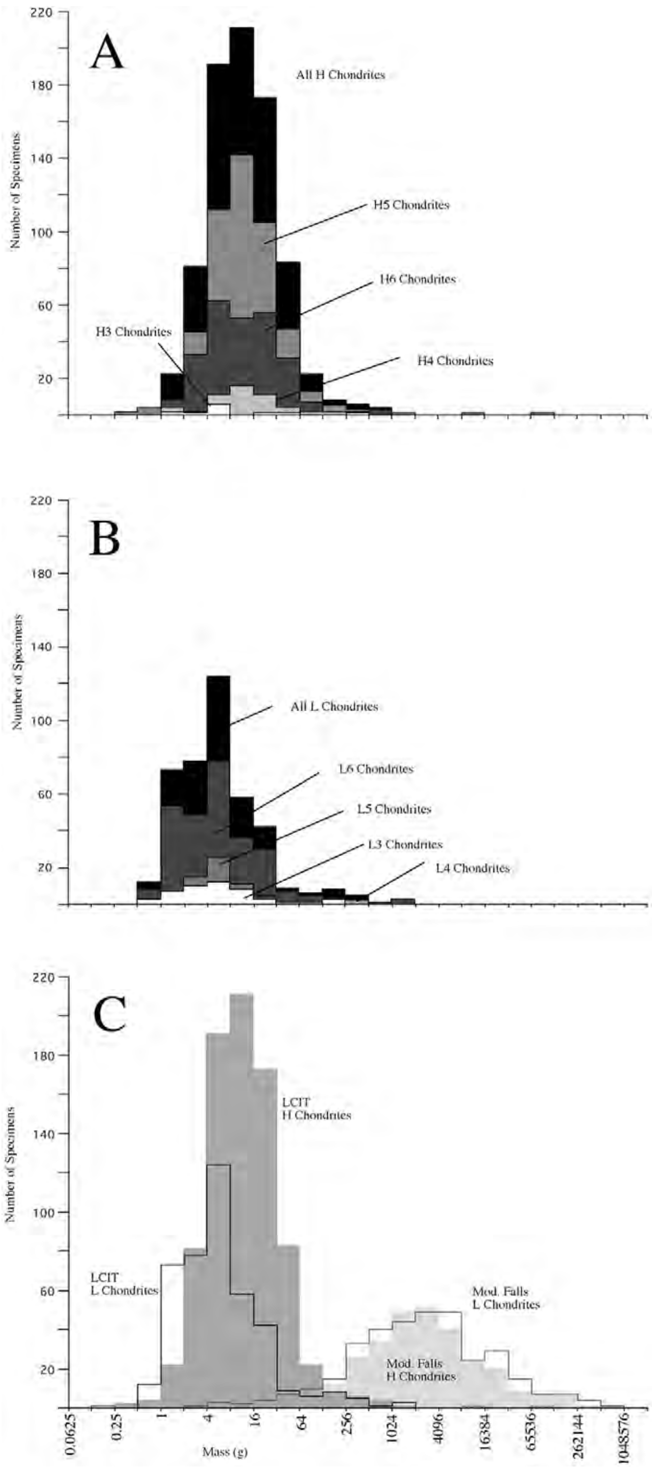


Fig. 14. Size distribution of H and L chondrites for the LCIT and Modern Falls samples. A) Distribution of H chondrites for the LCIT. All 4 petrographic grades show nearly identical modes and variance, suggesting no significant relative differences in weathering rates or delivery processes. B) Distribution of L chondrites for the LCIT, showing a similar relative distribution of petrographic grades. C) H's and L's for both the LCIT and the Modern Falls. There is a strong distinction between H's and L's at the LCIT, with L's being fewer in number and smaller. The same cannot be said for the Modern Falls, where H's and L's show nearly identical distributions.

drites during desert weathering. However, the collections in question usually show an excess in both numbers AND mass, and excessive weathering should produce a number excess accompanied by a mass deficit. In the essentially unweathered Modern Falls sample, H and L chondrites have nearly identical number and mass distributions (Fig. 14). The excess of H chondrites among Antarctic and hot desert finds is thus better explained as the presence of a few extra H showerfalls influencing specific collection sites. This is within reason given that a count of historical showerfalls (of 10 or more stones) in Grady (2000) shows that H chondrite showerfalls are roughly 50% more common than L showerfalls, supporting this mechanism as the source of the overabundance of H chondrites.

One final set of observations, although anecdotal, may offer key insight into the significance of the Antarctic meteorite collections with regards to the relative proportions of types within the various collections. Although it is obvious that Antarctic finds contain a large number of paired specimens, both fragments from weathering or individual stones from showerfalls, it has also been observed that there are an exceptional number of very rare specimens that exist only as single fragments or individuals. For example, the LCIT sample contains a shergottite, an acapulcoite, two distinct angrites, a lodranite, a brachinite, a CR chondrite, and a CV chondrite, all small and unpaired. This remarkable presence of small and unique specimens has a simple explanation. The power law delivery of meteorites demands that smaller specimens outnumber larger ones, and that they be delivered more frequently. The power law can also be considered a description of the relative probability that meteorites of a given size will fall within a given time period and geographical area. With all the meteorite samples under consideration of limited timescale and area, the much greater relative probability that any type of meteorite will fall as a small sample (as opposed to a large sample) becomes significant, particularly for the rare classifications. For example, angrites make up about 0.1% of all falls; using the Halliday (2001) flux as a guide, the probability that an 8–16 g angrite (the modal recovery size for the Lewis Cliff Ice Tongue) will fall in a given 10^6 km^2 area per year is the product of its numerical frequency and type frequency, or about 0.004%. In the same interval and area, the probability that a 128–256 g angrite will fall (the modal size range for Dar al Ghani recoveries) is nearly an order of magnitude smaller, 0.0007%. When scaled up by larger search areas or longer time intervals, it becomes clear that small meteorites of rare classes will be orders of magnitude more common than their larger siblings. Even if two collections are equivalent in terms of number of recoveries, the collection that consistently recovers smaller meteorites is therefore more likely to contain rare specimens. Furthermore, the fragmentation suggested as a factor in antarctic and other desert collections adds to this boon, leading to the dispersal and recovery of small portions of a larger mass when a fully intact specimen might never have been located. Finally, the low terrestrial background of Antarctica and the ability to recognize specimens that must have fallen from the sky clearly will aid in the recognition of meteorites even if they are nearly terrestrial in observable characteristics.

This "enhanced frequency/more rarities effect" (hereafter called the "effemmer rule") is probably responsible for many of reported petrographic distinctions between Antarctic and non-Antarctic meteorites. For example, several authors have puzzled over the remarkable abundance of ungrouped iron meteorites in the Antarctic collection, noting that these specimens are also quite small (Clarke, 1986; Wasson, 1990, 2000). The "effemmer rule" is a simple explanation for this excess. Furthermore, it suggests that the Antarctic samples are simply more representative of the full range of iron meteorite parent bodies contributing to the meteorite flux, including a diverse group of small parent bodies that simply are not falling frequently enough to be found as larger specimens over short timescales and/or small geographical areas. Proposed temporal changes in the relative abundance or size-related orbital resonance distinctions are not required, even if these play some role (Koeberl and Cassidy, 1991; Wasson, 2000).

There are numerous examples of Antarctic specimens that were considered unique or difficult to classify when originally encountered, but later became prominent members of the freshman class of new groups or grouplets. Sometimes these Antarctic specimens were the first of a new group to be identified, sometimes not; but their availability helped in each groups common characteristics; in many cases (such as the angrites and CK chondrites) the majority of known specimens are Antarctic. Among the rare achondrites, examples include the rare planetary samples- the Martian specimens (ALH77005, EETA79001, LEW88516, ALH84001, Yamato 793605, GRV 99027, Yamato 1075, QUE94201 and Yamato 000593), and the lunar specimens (ALH81005, MAC 88104/88105, Yamato 82192/82195/86032, QUE93069/94269, QUE94281, Yamato 791197, Yamato 983885, Yamato 793274/981031, EET87521/96008, Yamato 793169, and Asuka 881757). Other rare achondrites include the brachinite ALH84025, the acapulcoite/lodranites (ALH 77081, 78230, 81187, 81261, 81315, 84190, FRO 95029, LEW 86220,Yamato 74063, Yamato 8307, EET84302, FRO90011, FRO93001, GRA 95209, LEW 88280, MAC 88177, QUE93148, Yamato 74357, Yamato 75274, Yamato 791491, Yamato 791493 and Yamato 8002) and the angrites (LEW 86010, LEW 87051 and Asuka 881371) (McKay et al., 1995; Mittlefehldt et al., 1998). Some achondrites remain unique: LEW86220 is related to the acapulcoite/lodranite group but isotopically distinct (McCoy et al., 1997). In these cases, the Antarctic meteorites have aided in our identification of the number of meteorite parent bodies, a fundamental (and rapidly increasing) measure of our understanding of our solar system (Burbine et al., 2002)

Among the more common types of achondrites, Antarctic specimens have provided an understanding of the range of materials associated with specific parent bodies rather than simply identifying their existence. For example, while Antarctic specimens are relatively rare and unassuming among the known aubrites, a few offer significant insights into a very puzzling parent body enigma. There is broad scale agreement that the aubrites are a residual of the partial melting of a precursor material similar (if not identical) to the enstatite chondrites; but such an event also predicts the existence of a corresponding basaltic lithology, which seems to be missing from the world's meteorite collections. However, small clasts of indigenous basalt-like material have been identified within the LEW 87007 and Khor Temiki aubrite breccias, providing evidence (if nothing else) that this basaltic lithology could exist; and QUE99387, a recently recovered plagioclase-bearing lithology, is the first meteorite whose basic lithology is consistent with an origin as an "aubritic" partial melt (Fogel, 1997; Satterwhite and Allan, 2002). If a basalt meteorite from the aubrite parent body does exist, Antarctica is a likely place for it to be found. There have even been speculations regarding meteorite types that might someday be found, such as samples from Mercury (e.g. Love and Keil, 1995). Such speculations are greatly assisted by the potential of Antarctic systematic searches to bear them fruit.

Another group of achondrites that has been greatly expanded by Antarctic recoveries is the ureilites. Roughly 2/3rds of the known ureilites are Antarctic specimens. These have helped illuminate the groups fascinating and contradictory features, such as their unequilibrated oxygen isotope signature (exhibiting a mixing relationship among its members and suggesting little or no igneous fractionation), variable but inevitably high levels of mineralogical and textural equilibration among silicates (perversely suggesting a high degree of igneous processing) and a wide variety of complex and sometimes incongruous lithologies (including unique all-pyroxene specimens, unique chromite assemblages, intimate mixtures of refractory silicates and volatile C-bearing phases, low- and high-shock features, and polymict, monomict, bimodal and poikilitic textures). The Antarctic specimens have shown clearly that there IS no single process responsible for the ureilites; instead, they produce a view of the ureilite parent body as a very alien place with many processes far removed from the terrestrial experience and no guarantees of consistency from place to place. This is a good thing-greatly increasing our understanding of how different the geology of asteroids can potentially be from terrestrial paradigms.

Another example of what Antarctic meteorites have sometimes revealed can be found by examining one of the most widely known, but still relatively unstudied groups, the pallasites. Here the Antarctic specimens reveal that some pallasites are not representatives of a single family tree. The pallasites consist almost entirely of olivine and metal, and generally show amazing consistency in terms of mineral modes, mineral and bulk compositions, sharing an oxygen isotope trend with the HED achondrites and IIIAB irons. This consistency has suggested to some that the pallasites represent, in some broad sense, the core-mantle boundary of a partially disrupted parent body to all of these groups. But there are exceptions to this consistency, one of which is Yamato 8451, which with Vermillion makes up the pyroxene-pallasite grouplet described by Boesenberg (2000). These pallasites bear macroscopic pyroxene grains, and along with another pallasite subgroup (the Eagle Station grouplet) show oxygen isotope trends and elemental compositions very distinct from main group pallasites. These rare achondrites almost certainly correspond to a distinct, 2nd pallasite parent body, given that it is difficult to envision such highly differentiated meteorites originating from a heterogeneous, unequilibrated parent.

The most common achondrites are those of the Howardite-Eucrite-Diogenite (HED) group; Antarctic meteorites make up the majority of this group by number, and have played an important role in our developing understanding of the group and its parent body. Sharing many mineralogical consistencies and a common, highly-collimated oxygen isotope trend, the group has long been recognized to have potentially been the product of a fractionated igneous system on a single parent body (e.g. Mason, 1962). While the advent of Antarctic recoveries has clearly provided key new specimens, it has also vastly extended the range of lithologies, igneous textures and bulk compositions observed in these rocks, significantly muddying waters that were much clearer when fewer specimens were involved. For example, early models considered eucrites (the basaltic members of the HED's) either primary partial melts of the HED parent body, or the last remaining liquids of a prolonged fractional crystallization sequence on a body melted to a significant degree. Antarctic samples have proven consistent with both of these scenarios and everything in between, providing unbrecciated cumulate eucrites such as EET87548 (with the highest bulk Cr content measured so far); Asuka 881394 with the most calcic plagioclase yet observed; nearly vitrophyric ALH81001 and PCA91007 (flow-tops or impact melts?); Yamato 791195, the most ferroan (and thus fractionated) of these coarse-grained samples; and a variety of partial cumulates (cumulates with substantial intercumulate melt) such as Yamato 791186 and RKPA80224 (Takeda et al., 1988, 1995; Warren et al., 1996a, b; Mittlefehldt et al., 2000). The diogenites, usually considered either residues after extraction of a eucrite melt or cumulates from a thick magmatic ocean, show surprising compositional and textural range, include GRO 95555 and LEW88679 (unusually coarse-grained diogenites with an almost adcumulate texture); EET79002, the most magnesian and olivine-rich diogenite; and the Yamato 75032 pairing group, most ferroan and cpx-rich diogenites (Takeda and Mori, 1981; Sack, 1991; Mittlefehldt et al., 1998;Papike et al, 2000). The Antarctic HED's offer us a welcome reality check; while bodies like the HED parent and the Moon may show relative mineralogical simplicity compared to the Earth, a rich and complex level of igneous activity may simply be hidden behind the scarcity of samples.

Antarctic finds have made significant contributions to the known spectrum of chondritic lithologies in the same abundant fashion they contributed new classifications to the achondrites (e.g. Brearley and Jones, 1998). The process has been one of extending the range of known chondritic parent body processes, discovering new parent bodies, and filling in gaps between known groups. ALH85085 was the first recognized member of the CH carbonaceous chondrites, highly reduced, rich in metal and with uniquely small and infrequent chondrules (Scott, 1988; Weisberg and Prinz, 1989). The discovery of several consistent Antarctic specimens such as the EET87711 pairing group aided the recognition that Renazzo and others were members of the distinct CR classification (Weisberg et al., 1995). Similarly, the early recognition that some Antarctic carbonaceous chondrites such as Yamato 6903 were thermally metamorphosed beyond the standard petrographic grade 3 led to the eventual recognition of the CK group (Yanai and Kojima, 1987; Geiger and Bischoff, 1991; Noguchi, 1993). Yamato 75302, Asuka-881988, Yamato-791827 and ALH85151 were harbingers of the most highly oxidized group of ordinary chondrites (the R chondrite group), where unoxided metal is essentially absent (Yanai et al., 1985; Ozaki et al., 1998). QUE94411 is one of three specimens making up the proposed CB (Bencubbinite) carbonaceous chondrite grouplet, while LEW 87232 is one of only three known ordinary chondrites that together form the K grouplet (Weisberg et al., 1996, 1999). Yamato 86720, Yamato 82162, and Belgica 7904 are highly aqueously altered carbonaceous chondrites from a proposed "CY" grouplet intermediate to the CI and CM groups (Ikeda, 1992). Finally, several Antarctic chondrites are members of the exclusive "unique" or "ungrouped" club, among them LEW85332, a highly unequilibrated carbonaceous chondrite that most closely resembles the CR group (Prinz et al., 1992; Wasson et al., 2000); and GRO95551, with unique isotopics but other geochemical ties to the CB, CH and CR groups (Weisberg et al., 1999; Kallemeyn, 2000).

Chondrites by definition have experienced metamorphism but not full melting, and many groups (particularly the carbonaceous chondrites) are as recognized by their alteration state as by their primary mineralogy and texture (e.g. Brearley and Jones 1998). Contrarily, Antarctic finds have bent that boundary in a number of cases. The previously mentioned CK group meteorites show that carbonaceous chondrite parent bodies, several of which are strongly characterized by significant low temperature aqueous alteration, have on occasion experienced significant thermal metamorphism. The Antarctic collections also contain a number of meteorites whose bulk chemistry remains nearly chondritic but have textures that are nearly indistinguishable from igneous, such as Yamato 74160, PAT91501, LEW88763, and LEW88663 (Takeda et al., 1984; Harvey, 1993; Swindle et al., 1998; Mittlefehldt and Lindstrom, 2001). These rocks mark the chondritic side of the boundary between chondritic and achondritic materials, and have helped solidify the use of petrographic grade "7" as a legitimate descriptor for chondritic materials. The previously mentioned acapulcoite/lodranite group marks the other side of the border between achondrites and chondrites, also with igneous textures but with clear mineralogical and geochemical signatures of fractionation (McCoy et al., 1997). Finally, Antarctic meteorites have also helped reveal what happens to chondritic material exposed to the high end of the shock scale; Yamato 790964 and 793539 are composed almost entirely of glass (Azevedo et al., 1995; Yamaguchi et al., 1998). Representing quenched melts generated by impacts on their parent bodies, these specimens illustrate that the distinction between the indigenous processes of planetary bodies and those imposed on it from the outside is not an absolute one.

• Geochemical distinctions between Antarctic and non-Antarctic meteorites

Some of the most illustrative (and at times contentious) comparisons between Antarctic and non-Antarctic meteorites concerns their bulk properties- whole-rock elemental abundances, thermoluminescence, cosmogenic nuclide abundances, and others. There are in fact many differences between Antarctic and non-Antarctic meteorites; the difficulty comes in determining which of these result from terrestrial processes and which may be pre-terrestrial. A great many of the reported differences between Antarctic and non-Antarctic meteorites have been attributed to weathering. Carbon and oxygen isotopes in Antarctic meteorites are now known to show a significant terrestrial signature, predominantly in loosely-bound carbon-bearing material released at low temperatures in stepped-heating events (e. g. Grady et al., 1991; Ash and Pillinger, 1995; Jull et al., 1997). The origin of these elements is the terrestrial atmosphere and ice sheet, interacting with meteoritic components during the weathering-induced oxidation and the production of evaporates and other species. Fe and S deficiencies in Antarctic H chondrites have also been noted, in concert with the expected increased mobility of these species during weathering reactions (Jarosewich, 1990). The signature of many other elements can be recognized; U, Hg, halogens, noble gases and other species are often enriched in Antarctic meteorites as compared to witnessed falls, introduced to the meteorite from a variety of local sources such as the atmosphere, the Southern Ocean and local rock exposures (Dreibus et al., 1986; Jovanovich and Reed, 1987; Delisle et al, 1989; Krähenbühl et al., 1998; Scherer et al., 1992). Recognized contributions to Antarctic specimens even include marine diatoms (Burckle, 1999). Differences in the abundance of various cosmogenic isotopes are almost entirely a product of the great range of terrestrial ages of Antarctic samples as well as their enhanced exposure to solar radiation in Antarctica (e.g. Nishiizumi et al., 2000), but weathering effects can be seen as well (Pätzer and Schultz, 2000). Weathering effects are also implicated in consistent LREE depletions and irregular (for lack of a better word) Ce anomalies seen in Antarctic HED meteorites and other groups. The LREE depletions are almost certainly due to the slight relative enhancement of mobility for these elements in and out of pyroxene during oxidation. Ce anomalies are more dramatic and can be either enrichments or depletions- Ce^{+3} oxidized to Ce^{+4} becomes mobile, generally resulting in depletions in silicates and enrichments in forming phosphates or oxide products (Mittlefehldt and Lindstrom, 1991).

In general it seems that many geochemical distinctions between Antarctic and non-Antarctic meteorites can be attributed to geological processes acting on the meteorite during its residence in Antarctica. However, some researchers feel there are geochemical differences that require a pre-terrestrial explanation. A series of works over the past 17 years have noted that the concentration of a variable suite of moderately labile to fully volatile elements are different in Antarctic and non-Antarctic meteorites (particularly H chondrites); the researchers come to the conclusion that they contain groups with distinct orbital histories (e.g. Dennison and Lipschutz, 1986; Lipschutz and Samuels, 1991; Wolf and Lipschutz, 1995a). These authors have typically discounted weathering as a source for these distinctions, citing sample selection characteristics and a lack of correlation between Fe^{3+} content, terrestrial age and their data (Wolf and Lipschutz, 1995b). Over time, increasingly sophisticated statistical techniques were employed, including bootstrapping, linear discriminant analysis, cluster analysis, logistic regression and randomization simulations, with distinctions between the Antarctic and non-Antarctic samples becoming more ardently proposed (e.g. Samuels, 1990; Wolf and Lipschutz, 1995c). Unfortunately, the dismissal of weathering for these admittedly mobile elements must be considered weak, given the known inadequacies of the A/B/C weathering classifications commonly used, clear evidence that weathering affects even much less mobile elements, and modern Mössbauer studies that clearly demonstrate a positive correlation between Fe^{3+} abundance and terrestrial age (Koeberl and Cassidy, 1991; Mittlefehldt and Lindstrom, 1991; Bland 2001). One can also question the value of the statistical techniques used as well. Although the sophistication of the applied techniques and the number of elements within the dataset increased over time, the independent behavior of these variables, a critical component of any statistical comparison, was never demonstrated (e.g. Cashore et al., 1988).

Other suggested differences between Antarctic and non-Antarctic meteorites have been put forth, some in concert with the geochemical claims. Thermoluminescence (TL) has been used as a tool for the study of Antarctic meteorites for decades; TL should broadly record radiation exposure and thermal history and results have at times suggested a distinction between Antarctic and non-Antarctic meteorites. For example, TL sensitivity is very distinct in Antarctic finds, showing about 0.1 of the range seen in observed falls. Unfortunately, this distinction goes away during acid washing, which presumably removes weathering products (Benoit and Sears, 2000). TL sensitivity is also irregularly correlated with weathering and terrestrial age- different icefields show different ranges of TL sensitivity, and natural TL levels show a rough correspondence to terrestrial ages calculated from cosmogenic nuclide abundances (Benoit and Sears, 1995). But this in fact is better explained by weathering differences correlated with time of exposure than by pre-terrestrial distinctions. Most intriguing is an observed correlation between TL, cosmic ray exposure ages, and fast metallographic cooling rates in a group of Antarctic H chondrites (Benoit and Sears, 1995). This correlation does suggest preterrestrial differences, and it has been suggested that between 50,000 and 100,000 years ago a group of "fast cooled" H chondrites dominated the H chondrite flux, then rapidly dwindled in abundance and was eventually superceded by modern "normal" H chondrites. To their credit, these authors acknowledge that this claim deserves significant further corroboration before acceptance (Benoit and Sears, 1995).

In summary, the basic concept of changes in meteorite delivery between the time periods recorded by Antarctic and non-Antarctic collections is not in itself flawed; indeed, we should accept that the meteoritic complex must change over time, producing potential meteorite streams associated with specific events on parent bodies (e.g. Drummond, 1991; Dodd, 1992; Swindle et al., 1996; Halliday, 2001). But much remains unknown; how long meteorite streams might persist, how sharply they may change the flux with time, and whether such changes can be observed in the very short period (on solar system timescales) that distinguishes the Antarctic and non-Antarctic collections (e.g. Wetherill, 1985).

Conclusions

Antarctic meteorites come to us at the end of a long series of low-probability events. Orbital resonances between a forming Jupiter and our Sun disallowed the accretion of a single larger body in the asteroid belt, and forever after perturbed the resident small bodies into orbits that produce collisions and occasionally eject the resulting material down toward the lower reaches of the system. The Earth-Moon system, a significant gravity well, careens along through these streams and clouds of asteroidal debris, gathering some small proportion of it onto the Earth's very own glassy windshield, the East Antarctic Icesheet. But the journey of the meteorites is not over yet; gravity is not yet done with them. As the icesheet sags and flows downhill under its own weight, it carries its cargo of meteorites toward the ocean. Some small percentage of this ice never makes it that far; cruelly trapped by mountains or sub-ice barriers, it slowly evaporates and erodes away in the frigid climate, leaving only its bones, the detritus of space, on its surface. And on a few occasions, a few of the life forms of our planet have demonstrated their lack of intelligence by exploring this forbidding landscape. Coming across the members of this debris layer, they have sometimes recognized the bits and pieces for what they are; the loose bricks and mortar of our solar system, delivered to us while we wait. It is an amazing journey, rife with opportunities for loss and ruin. But in the end we have nothing short of a miracle: the very stuff of space delivered to our door, free of charge. We are indeed a very lucky species at times.

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