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Fieldwork Methods of the U.S. Antarctic Search for Meteorites Program

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2.1. INTRODUCTION

The U.S. Antarctic Search for Meteorites (ANSMET) program has recovered more than 20,000 meteorite specimens since fieldwork began in 1976. The methods employed during fieldwork have evolved considerably over that interval in response to demand, logistical support, and an improved understanding of the links between Antarctic meteorite concentrations and their geographical and glaciological setting. This chapter describes how ANSMET fieldwork has evolved over the years to produce the current meteorite recovery methods and discusses how they relate to the complex phenomena of Antarctic meteorite concentrations, both in theory and in practice.

2.2. ANSMET FIELD SEASONS YESTERDAY AND TODAY

2.2.1. ANSMET's Place Among Modern Antarctic Meteorite Recovery Efforts

Meteorites have played a role in Antarctic science since the earliest years of the twentieth century. The first meteorite recovered from Antarctica, about 10 cm across and fully fusion crusted, was found by one of Douglas Mawson's field parties in 1912, lying on hard snow on the Adelie Coast [*Mawson*, 1915]. F. L. Stillwell, a geologist in the field party, immediately recognized the rock as a meteorite and studied it in detail after the expedition returned to Australia [*Bayly and Stillwell*, 1923]. Four decades later cooperative international scientific exploration of the Antarctic continent commenced with the 1957 International Geophysical Year. The global and developmental nature of that effort led to the high level of scientific activity in Antarctica that continues today.

During those early years, 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, as described by *Ford and Tabor* [1971]. These authors also noted that the association of the specimens with morainal debris implied that the specimens had been transported from their original fall site, and that the weathering state of the specimens implied that abrasion in the cold, dry katabatic winds of the polar plateau was extremely effective as a local mechanism of erosion. Their observations proved prescient; 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].

There is little ambiguity as to the event that revealed the existence of Antarctic meteorite concentrations. On 21 December 1969, Renji Naruse of the tenth Japanese

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Antarctic Research Expedition (JARE-10) was one of several glaciologists establishing 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 a total of nine meteorite specimens [*Yoshida et al.*, 1971; *Yoshida*, 2010). Within a few years, mounting numbers of meteorite recoveries by the Japanese eventually convinced the United States Antarctic Program (USAP) to begin supporting active searches, as described in chapter 1 [*Marvin*, 2014 (this volume)].

As of this writing, ANSMET has recovered more than 20,000 meteorites, but these numbers account for only part of the program's success. Consistent initial characterization of recovered specimens, curation at the highest level, and rapid, cost-free availability have given ANSMET meteorites unique value within the planetary materials research community, as described in chapter 3 [*Righter et al*., 2014 (this volume)].

The early successes of the U.S. Antarctic meteorite program quickly led to increasing demand for new specimens and to the well-supported, institutionalized programs of recovery in place today. With a strong backbone of aerial logistics, U.S. expeditions have ranged widely across Antarctica, predominantly in East Antarctica along the Transantarctic Mountains. ANSMET has been one of the most active governmentally-supported meteorite recovery programs, with 45 independent field parties deployed to more than 75 different sites during 36 seasons of fieldwork (Figure 2.1 a through e). Continued demand for specimens recovered by ANSMET has been the primary driver for annual field parties, which are enabled by improvements in remote sensing of polar regions, an increased understanding of meteorite concentrations, and better access to remote locations. The fieldwork has evolved with these changes, resulting in a field program that is highly adapted to available logistics and the needs of the planetary materials community. This chapter documents the field practices that have helped ANSMET support research through the past four decades.

2.2.2. Preseason Planning and Site Selection

U.S. activities in the Antarctic are carried out within the U.S. Antarctic Program (USAP), funded and managed by the Office of Polar Programs (OPP) of the National Science Foundation. During its history, ANSMET has been supported through USAP, both directly (through OPP grants) and indirectly (through logistical support funded by NASA). As a result, planning for any given season may begin as many as seven years before deployment (at the time a grant is funded). Grants supporting ANSMET have been competitively selected, with durations ranging from as many as six seasons to as few as one. Grant proposals may request support for field seasons dedicated to systematic meteorite recovery from known sites (hereafter called a systematic activity), reconnaissance efforts dedicated to improving our understanding of poorly known or previously unvisited sites (hereafter called a reconnaissance or recon activity), or some combination of these. A typical proposal will therefore include a list of sites prioritized from among potential targets based on our understanding of each site's potential. The highest-priority fieldwork targets are, not surprisingly, those we think will yield the most meteorite specimens. However, this is typically based on prior experience at the site, which is always incomplete during early visits. More practical issues such as logistical availability can trump potential meteorite yield. For example, when a remote helicopter camp allows us to reach otherwise inaccessible locations, those targets become a higher priority; and when aircraft support is predicted to be limited, we may choose targets demanding fewer flight hours.

Recon and systematic targets are both mixed into the long-term plan; the former typically result in fewer meteorite recoveries but are essential to ensure a continuous supply of new specimens. On a few occasions we have also adjusted the recon/systematic activity mix to reduce stress on the curatorial system, favoring recon activities when a characterization backlog is growing. The desire for geographical separation between ANSMET field parties (to minimize the effects of individual weather systems) is also considered. Every ANSMET proposal also includes alternate targets for either style of activity, allowing the project to adjust to rapid changes in USAP logistics and programmatic issues.

Meteorite concentration sites tend to occur on exposed blue ice in a variety of specific geographical and glaciological settings; the characteristics of these icefields and meteorite concentration mechanisms are discussed in detail in *Harvey* [2003]. Identification of such sites through examination of maps and imagery has been a natural first step in ANSMET's work since the program began. USAP-produced topographic maps and aerial photography documenting much of the Transantarctic Mountains became available throughout the 1960s and 1970s, and during ANSMET's early years these served as a primary means for identification of meteorite concentration sites. These maps, however, were primarily meant to serve navigational and geological needs, and do not document blue ice. Similarly, while aerial photography coverage was excellent, many blue ice areas were visible only in low-angle oblique images that mask their full extent. The most powerful "remote sensing" tool employed by ANSMET in this era was opportunistic reconnaissance flights, during which field personnel would sit glued to the windows of an aircraft, annotating maps and photographing key

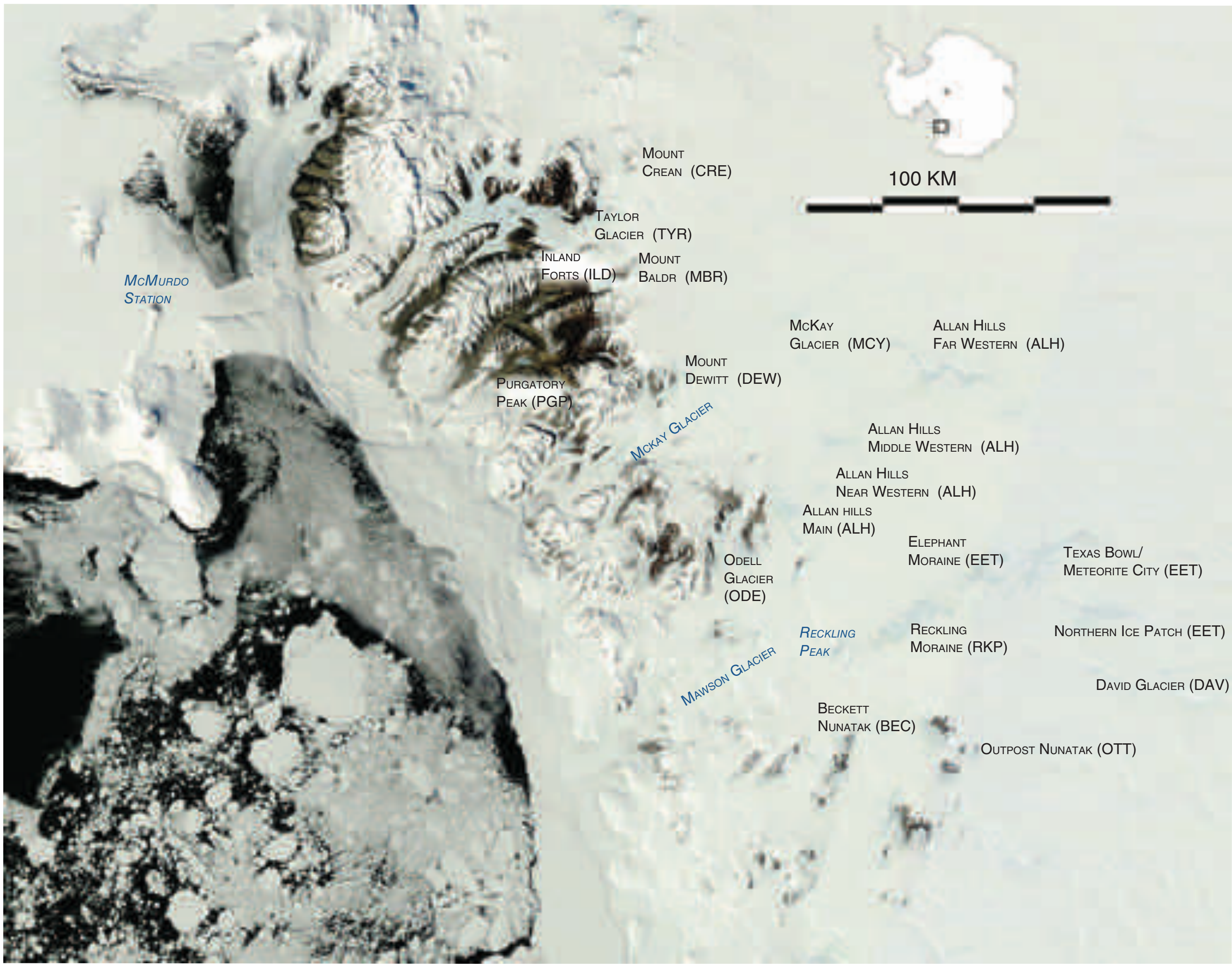

Figure 2.1(a through e). Meteorite concentration localities explored by ANSMET to date. The localities shown represent targets of ANSMET field seasons, typically icefields or groups of icefields within a target region. All location names should be considered informal, and where meteorites have been recovered the appropriate three-letter location code assigned to those specimens (e.g., ALH) is shown. In many cases a single code is used for several icefields, particularly where smaller geographical features were unnamed. The outline of Antarctica above the scale bar shows the approximate context of the figure within the Transantarctic Mountains. For additional context, a few geographical features are also shown in blue. A mosaic of MODIS Rapid Response Terra images (250-m resolution) is used as a base for all sections of the figure.
Figure 2.1a. ANSMET meteorite localities in the McMurdo Sound region, including many of the sites explored in the earliest period of ANSMET activity.

features of promising sites. Such flights were a common feature of early ANSMET seasons and remain a part of our reconnaissance tool kit, given their ability to reveal current surface features and conditions (rather than those in maps or images that can be decades old). On several occasions, "low and slow" flights led to the identification of meteorites from the air in areas where terrestrial rock was known to be absent; but in general, such discoveries have been very rare due to the small average size of meteorite specimens, the vibration of the aerial platform, and the limits of human visual acuity.

Satellite imagery became publicly accessible at about the same time ANSMET was formed, and with each technological advance it has played an increasing role in the project. ANSMET first used Landsat satellite imagery for reconnaissance purposes in the late 1970s, with significant help from the U.S. Geological Survey (USGS) [e.g., *Lucchitta et al.*, 1987]. Although initially restricted to latitudes north of 80° S and with limited surface resolution (80 m initially, 15 m later), the "bird's eye view" and geolocation afforded by this imagery dramatically improved ANSMET's identification of targets for

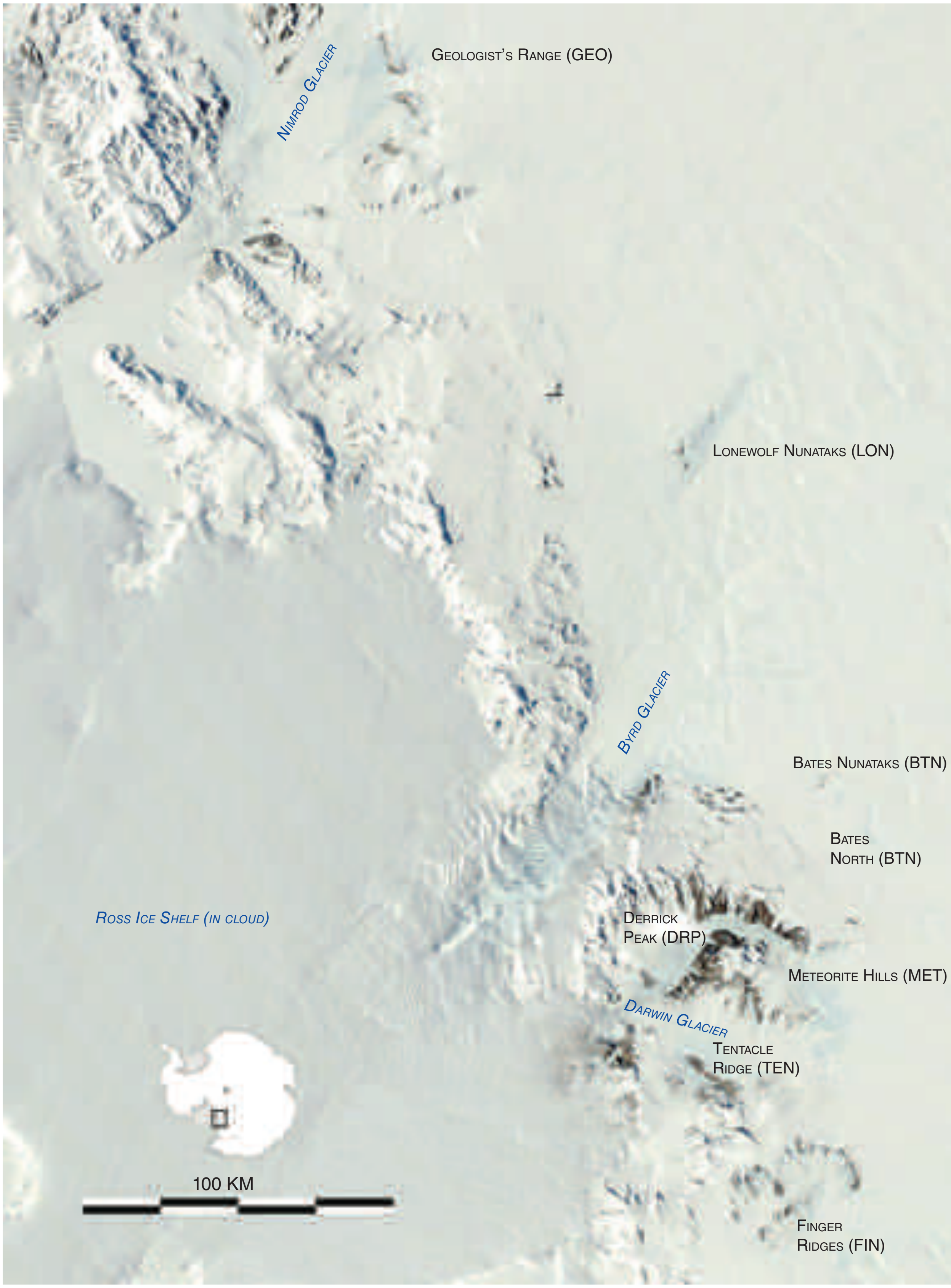

Figure 2.1b. Icefields further south and east along the Transantarctic Mountains between the Darwin Glacier region to the north and the Nimrod Glacier to the south.

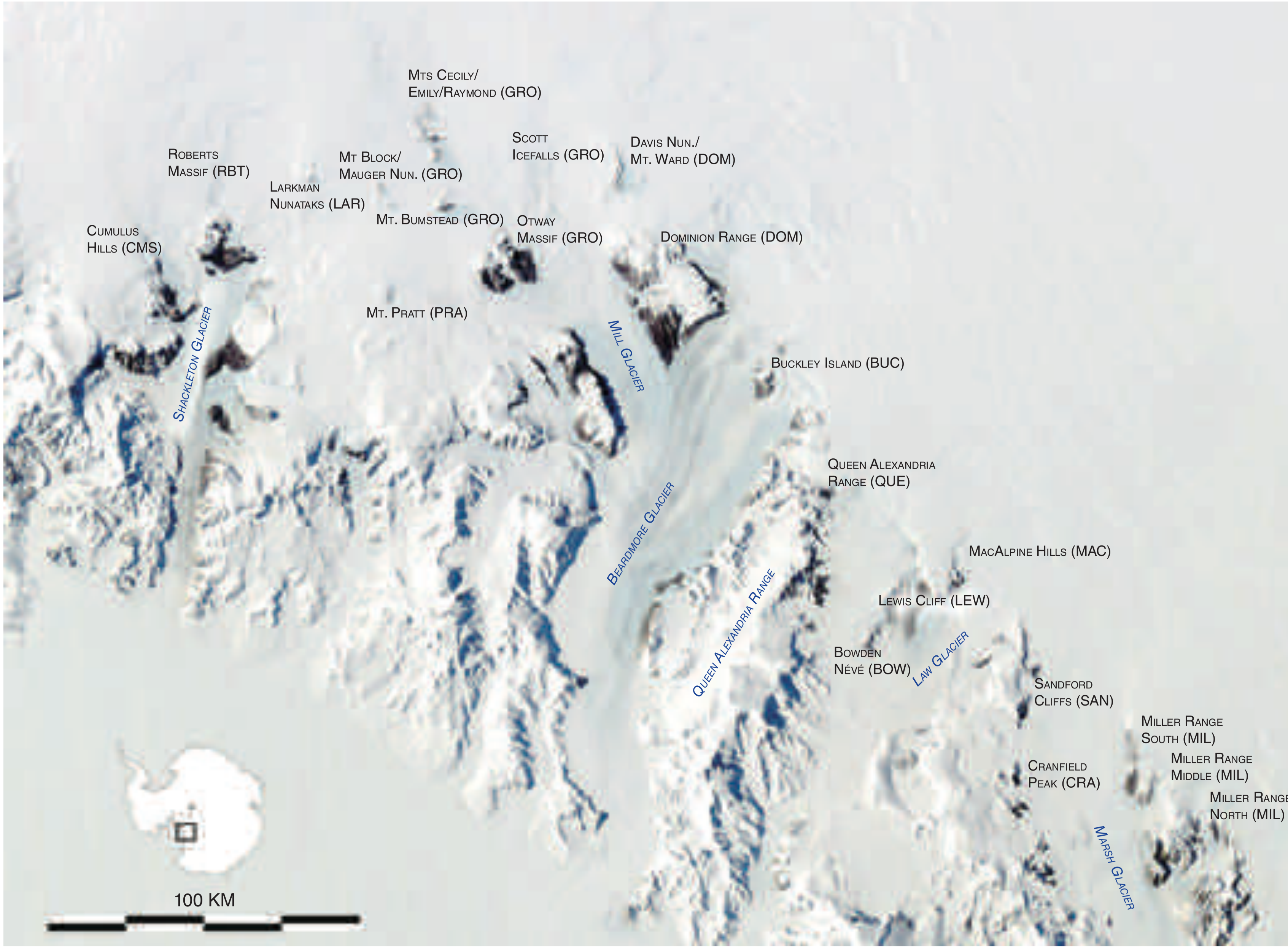

Figure 2.1c. The central Transantarctic Mountains region, from the Miller Range in the northwest to Roberts Massif in the southeast.

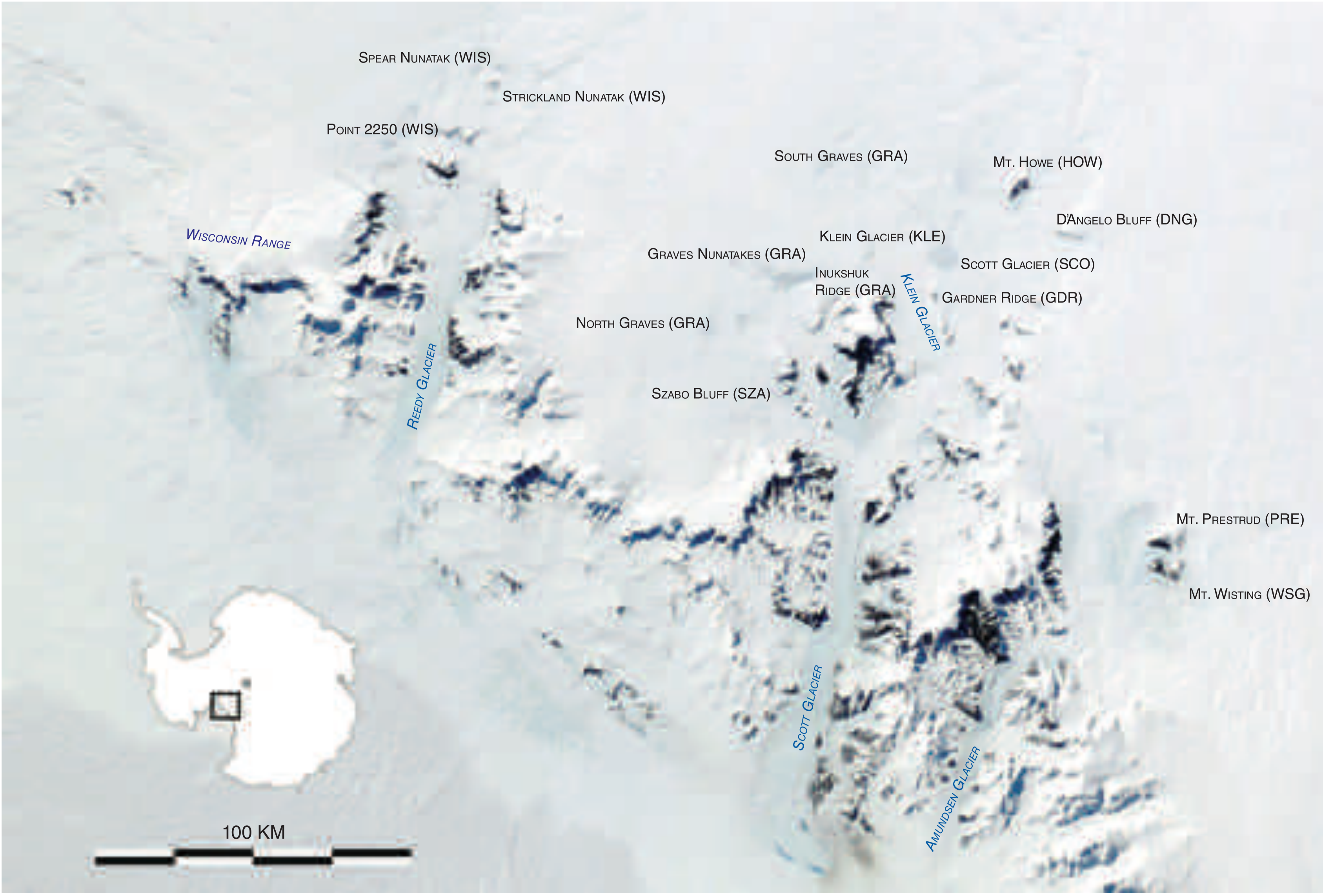

Figure 2.1d. Localities in the southernmost Transantarctic Mountains between the Amundsen glacier to the northwest and the Wisconsin Range to the east.

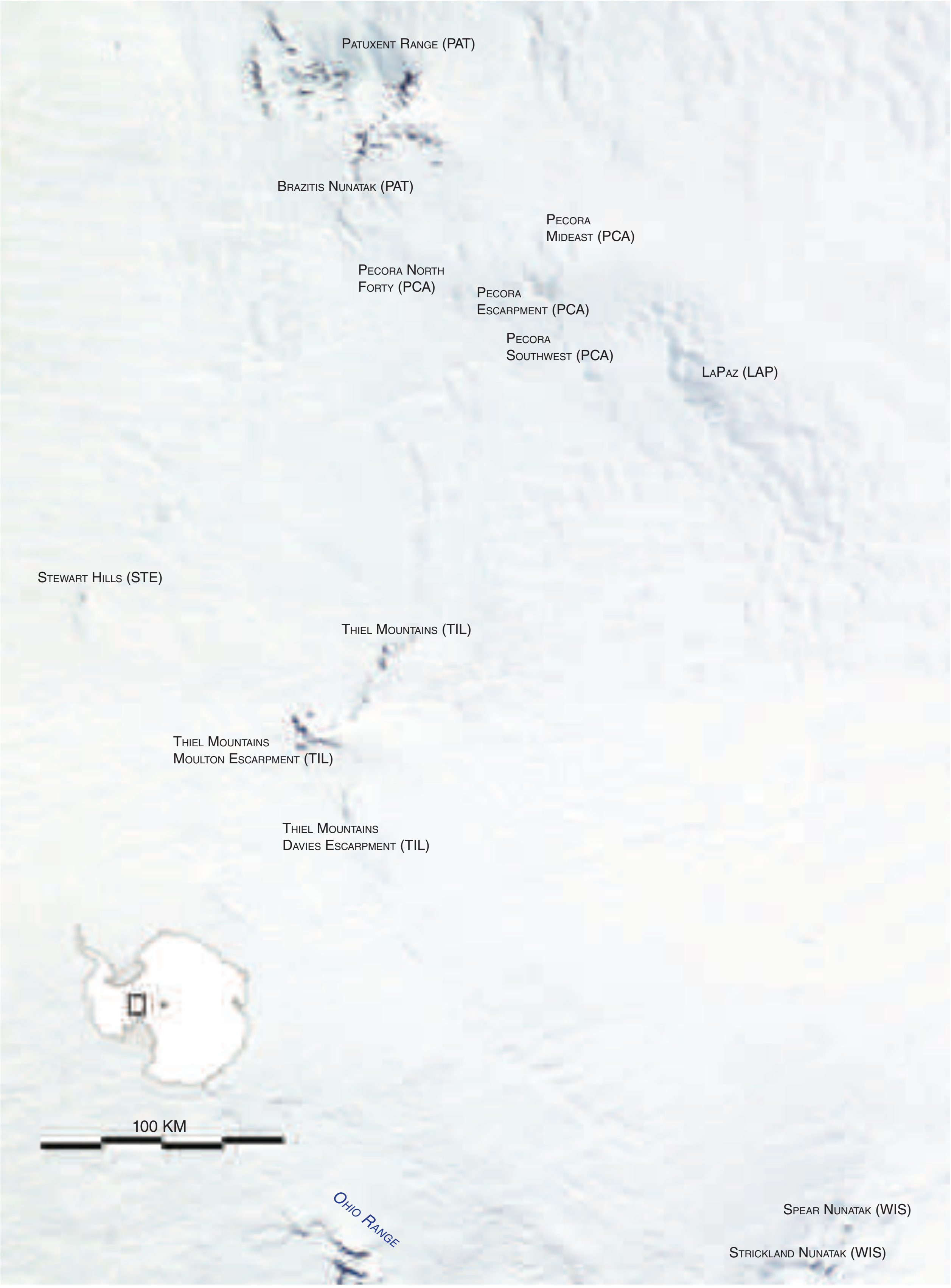

Figure 2.1e. Localities in the easternmost part of the Transantarctic Mountains, in the Weddell Seas sector of Antarctica, ranging from the Wisconsin Range to the west (bottom of figure) to the Patuxent Range in the east (top of figure).

exploration. A continent-wide mosaic of Advanced Very High Resolution Radiometer (AVHRR) satellite imagery prepared by the USGS in 1991 and revised in 1996 afforded a similar leap forward [*Ferrigno et al.*, 1996]. Although significantly poorer in resolution than Landsat (about 1 km per pixel), the AVHRR satellite map removed the latitude restriction and documented the East Antarctic ice sheet in its entirety. This in turn led to the discovery of several key icefields distant from the Transantarctic Mountains, notably the informally named LaPaz icefields. In the same time frame, Radarsat imagery also proved useful to ANSMET. It too was relatively limited in resolution (around 125 m per pixel) but had no latitude restrictions and when properly processed distinguished dense, bubble-free blue ice from surface snow. Comparisons of Radarsat and AVHRR datasets proved valuable in the identification of many of the icefields studied by ANSMET, particularly those in the most southerly Transantarctic Mountains.

Today ANSMET relies on two current-generation products for its remote sensing needs, both provided through the USAP-supported Polar Geospatial Center (PGC) at the University of Minnesota. First is imagery from the MODIS (Moderate Resolution Imaging Spectroradiometer) Rapid Response System [*Justice et al.*, 1998]. MODIS instruments aboard both the *Terra* and *Aqua* satellites image the entire Earth's surface every one to two days at ~250 m/pixel, acquiring data in 36 different spectral bands. The Rapid Response System provides daily images of Antarctica in true color. These images have proven exceptionally useful for direct confirmation of the presence of blue ice, and their daily recurrence allows selection for cloud-free views with limited snow cover and maximum Sun angles, helping us identify many smaller icefields throughout the Transantarctics and reducing our dependence on reconnaissance overflights.

When localized detail is needed, such as to serve as a base map for meteorite searches, the PGC also provides ANSMET with high-resolution satellite imagery. This imagery, licensed by the PGC from GeoEye, Digital Globe, Ikonos, and other sources, can have resolutions as high as 1 m/pixel. The main value of such images is in the tremendous geographical control they provide when used in concert with GPS-derived meteorite and base station locations.

Planning for individual seasons typically begins about eight months before any given austral summer, with the preparation and submission of a detailed support request to USAP. Called the Support Information Package (SIP), this document summarizes and formalizes ANSMET's needs across a broad spectrum of categories, including the specific targets for field work; a schedule of support events; participant lists; permitting needs (to comply with Antarctic treaties and federal regulations); shipping and cargo handling; potential environmental impacts; staging and storage needs; field equipment requests; laboratory, computing, and communication needs; food and fuel requirements; and myriad other details. This document, often 70+ pages for each field party, becomes the basis for negotiations between the project and USAP contractors, eventually leading to concurrence before the start of fieldwork in November.

Field party selection typically takes place in the same time frame as the support request SIP preparation. ANSMET field teams typically consist of a science leader (ANSMET project personnel), a mountain guide who also serves as camp manager, and a mixture of ANSMET veterans and first-time volunteers, with a targeted ratio of experienced to first-time field party members around 50:50. ANSMET is relatively unique among Antarctic field projects in that we welcome the involvement of volunteers from the research community, including international participants. Preference is given to those whose research involves Antarctic meteorites, but individuals with related research and/or significant related experience are also considered. After selection by the ANSMET principal investigator, all applicants must pass a set of qualifying medical and dental screening exams required by USAP due to the limited emergency treatment available in Antarctica. Inclusion of volunteers from the planetary research community does pose challenges, given that some have limited field experience in isolated or cold weather environments. However, the payback has been significant, since inclusion of volunteers reinforces the altruistic nature of the Antarctic meteorite program as a whole, encourages continuous and conservative field safety training, promotes highly efficient and robust field practices, lowers costs, and perhaps most importantly, injects new energy into the fieldwork each season. As of this writing, more than 170 scientists have participated in ANSMET fieldwork, and our record of safe field operations and continuous recoveries validates the inclusion of newcomers to the program.

2.2.3. Field Season Structure and Logistics

The basic unit of ANSMET activity is the field season: the annual period when one or more teams are deployed to target icefields for as long as six weeks. Fieldwork typically begins in early December, when the Sun is at its highest and the lack of diurnal atmospheric cooling helps to minimize katabatic winds on the East Antarctic Plateau. The season often continues until late January, when logistical support in the McMurdo region shifts away from science and toward preparations for the coming Antarctic winter.

McMurdo Station, the largest U.S. base in Antarctica, serves as USAP's hub for operations in the Transantarctic

Mountains and as the starting point for ANSMET expeditions. During a typical season, a few experienced ANSMET personnel will arrive in McMurdo in mid-November to begin assembling and preparing expedition gear. The remainder of the team typically arrives in McMurdo in late November and immediately engages in an intense 7–10 day preparation period. In addition to assembling and testing the remaining field gear and entering it into the cargo stream, the team spends several days training both to meet the challenges of the Antarctic environment and to introduce ANSMET procedures and protocols.

The remote nature of ANSMET field sites requires that the material needs of the field team be minimized, allowing the team and all its gear to be efficiently moved by aircraft in as few loads as possible. Aircraft use varies considerably between field seasons, but most seasons require the team to first move from McMurdo to an intermediate site suitable for landings by large, ski-equipped aircraft (usually the iconic LC-130 Hercules). From there the team will move to the target site, either by smaller aircraft (Twin Otter or helicopter) or by overland traverse using snowmobiles and sleds to move our gear. Travel to and from target sites can consume a significant proportion of a field season and logistical resources. Systematic field parties are typically larger and less mobile than reconnaissance parties, with six to eight people and one or two main targets for a given season. In contrast, reconnaissance teams are smaller (two to four people) and may move many times during a season, with stays at target icefields as short as a few hours or as long as a few weeks. Living in tents and conducting most searches from aboard snowmobiles, the field team will typically deploy with enough fuel, food, and other expendables to cover a significant portion of an entire six-week season; one or two resupply visits by light aircraft make up the difference and provide the opportunity for swapping out waste and damaged gear. When distances between target icefields are low and aircraft are available, ANSMET sometimes conducts a "flying traverse," with bulk cargo moving from one site to the other via airplane while the field team transports itself and survival gear overland by snowmobile.

ANSMET fieldwork is supported with rugged and functional equipment that serves both survival and scientific needs. USAP provides each participant with a basic wardrobe of extreme cold weather (ECW) clothing, including the infamous big red parka. Many ANSMET participants supplement this clothing with more personal or specialized gear for improved function and mobility (notably eyewear, gloves, and underwear). USAP also provides the four-sided, double-walled pyramidal Scott tents that serve as shelter, each occupied by two field party members and containing a propane stove for warmth and cooking. Plywood and thick insulating pads on the floors help keep the tents warm, while thick sleeping bags provide overnight comfort. In recent years, each tent has also been equipped with a 65W solar panel/field power station that makes modest electrical power available for electronic devices such as computers, GPS, cameras, and satellite phones. Expendables for the field camp primarily include food and fuel (propane, gasoline, and aviation fuel), with all solid waste recovered for recycling and/or removal from the continent.

Snowmobiles are a key part of the ANSMET tool kit. Not only do they serve as an individual mode of transportation, they also dramatically increase the range over which an ANSMET field party can conduct searches. They also allow independent mobility and constant team restructuring, serve as mobile storage and measurement stations, and dramatically reduce the fatigue associated with human-powered transport in the Antarctic. Unquestionably, the logistical costs associated with snowmobile use are high, due to the need for aerial transport not only of the vehicles but also of up to 700 kg of fuel and spare parts for each in a typical season, as well as off-season maintenance and storage. However, the gains in terms of mobility and search efficiency are equally large. Snowmobiles are to ANSMET field party members what horses are to cowboys, serving a multitude of needs and dramatically increasing the effectiveness of each individual. ANSMET personnel have tested the human-powered model, and while such efforts are good for soul and body, they can dramatically reduce the effectiveness of meteorite searches [*Haack et al.*, 2008].

2.3. SEARCHING FOR METEORITES IN ANTARCTICA

The goal of ANSMET fieldwork is to recover a complete and representative sample of the extraterrestrial materials falling to Earth so that it can be made available for research. While to some ANSMET's main task may seem simple (only slightly elevated above an Easter egg hunt), meeting these goals efficiently and with high standards requires planning and a particularly methodological approach. ANSMET has developed procedures and protocols to systematically recover meteorite specimens, ensuring few missed specimens, avoiding preferential sorting by type or by size, and maximizing scientific returns through contamination control and detailed record keeping. These procedures and protocols are a critical component of ANSMET success, helping ensure that the U.S. collection is both representative of the materials coming to Earth from space and contains the maximum number of samples of the rarest types of lithologies.

2.3.1. Reconnaissance Procedures

The goal of ANSMET reconnaissance work is to determine whether a blue ice area harbors a meteorite concentration, and if so, to understand its full extent. While individual rocks can be seen from the air (even satellite-based imagery can now pick out rocks in the 10's of cm range), determining the nature of these rocks (extraterrestrial or otherwise) still requires a personal visit. Reconnaissance visits typically take a variety of forms in a hierarchy of effort levels, from first visits to full-scale expeditions (Figure 2.2 a and b).

2.3.1.1. Early visits. Even a single meteorite find can prove the value of the site to ANSMET and serve as the impetus for future larger-scale recoveries. As a result (and given time constraints) the goal for most early visits is to examine as much high-priority blue ice as time and equipment allow. Often the first visit to a site will occur as part of a long day trip, where icefields within reach of an existing ANSMET camp are visited by snowmobile and examined for a few hours. Day trips are fairly common during the early sessions of systematic searching at a given icefield, since they are easily supported by the larger field team and fuel supply associated with such a camp. These efforts can also be very effective; day trips taken during the early years of systematic searching at the Lewis Cliff Ice Tongue led to the discovery of several additional meteorite concentrations in the Walcott Névé region, including the Foggy Bottom/Goodwin Nunatak and MacAlpine Hills icefields, home of the QUE and MAC meteorites, respectively. Thus a few reconnaissance day trips more than tripled the number of specimens recovered in the Walcott Névé region. Aerial support has also been effective in spite of obvious limits on the number of people and amount of equipment that can be transported. The first meteorite concentrations discovered by ANSMET in the Allan Hills region were all found during helicopter-supported day trips, as at the Lewis Cliff Ice Tongue and the Miller Range icefields about a decade later. Similar day trips, supported by helicopter or Twin Otter, take place whenever aerial support and potential targets coincide.

When a target icefield is simply too distant to be visited without an overnight stay, the need for increased survival gear scales up the complexity of a reconnaissance visit. For such visits ANSMET will typically send a team of two equipped with snowmobiles and survival gear sufficient for several days. Many major meteorite concentrations were first explored through two-person visits; notable examples include the LaPaz icefields, first visited in 1991, and more recently the Buckley Island icefields. The additional time and mobility available during such visits dramatically increases the area of ice that can be examined and allows the visit to do more than establish the presence or absence of meteorites; the full scope of the concentration can often be gauged. These extended first visits therefore often lead to some important decision making for ANSMET. Sometimes a two-person field party will find too few meteorites to support full-scale systematic recovery, and under those conditions the team may try to complete systematic recovery themselves. Examples of this kind of action from recent ANSMET history include the icefields near Bates Nunatak, Lonewolf Nunatak, and in the Geologist's Range. Similarly, an icefield may be considered "uneconomical" for other reasons, such as a very low concentration of meteorites, or an overwhelming abundance of terrestrial rock that compares poorly with other known icefields where recoveries are easier. The best situation is when the team quickly encounters large numbers of meteorites, immediately proving the need for large-scale systematic recovery. Having met the primary goal of reconnaissance, that team will typically move on to new targets as soon as possible. Nature, of course, has provided us with icefields exhibiting every level of concentration between these end members, and as the availability of logistical support and the demand for meteorites change, some icefields thought uneconomical by earlier explorers may be targets of systematic work in the future.

2.3.1.2. Large-scale reconnaissance. ANSMET has periodically dedicated whole field teams and seasons to reconnaissance efforts, usually when we have identified a broad region that contains numerous potential target icefields. Such a season is designed to send a lightly-equipped four-person team to a number of icefields, either on a long overland traverse or with extensive aerial support. Such a season may include opportunistic first visits to icefields, as well as visits to sites where meteorites have been previously recovered but the extent of the concentration (if any) remains unknown.

The amount of time planned for each icefield is estimated from previous visits or its geographical extent, with visits lasting from a few days to a week or more. With the many unknowns including rapidly changing weather conditions and challenging logistical schedules, preseason reconnaissance plans rarely survive first contact with the target icefield. We have learned that a dedicated reconnaissance season requires a very flexible timeline that allows for dramatic shifts in priorities as the season progresses. As noted previously, even a single meteorite find can lead to many days of searching a new icefield; and on many occasions long days of searching can lead to few or no finds at all. High numbers of meteorite recoveries are not typically expected during large-scale reconnaissance: the increased number of days dedicated to travel between icefields alone limits searching time.

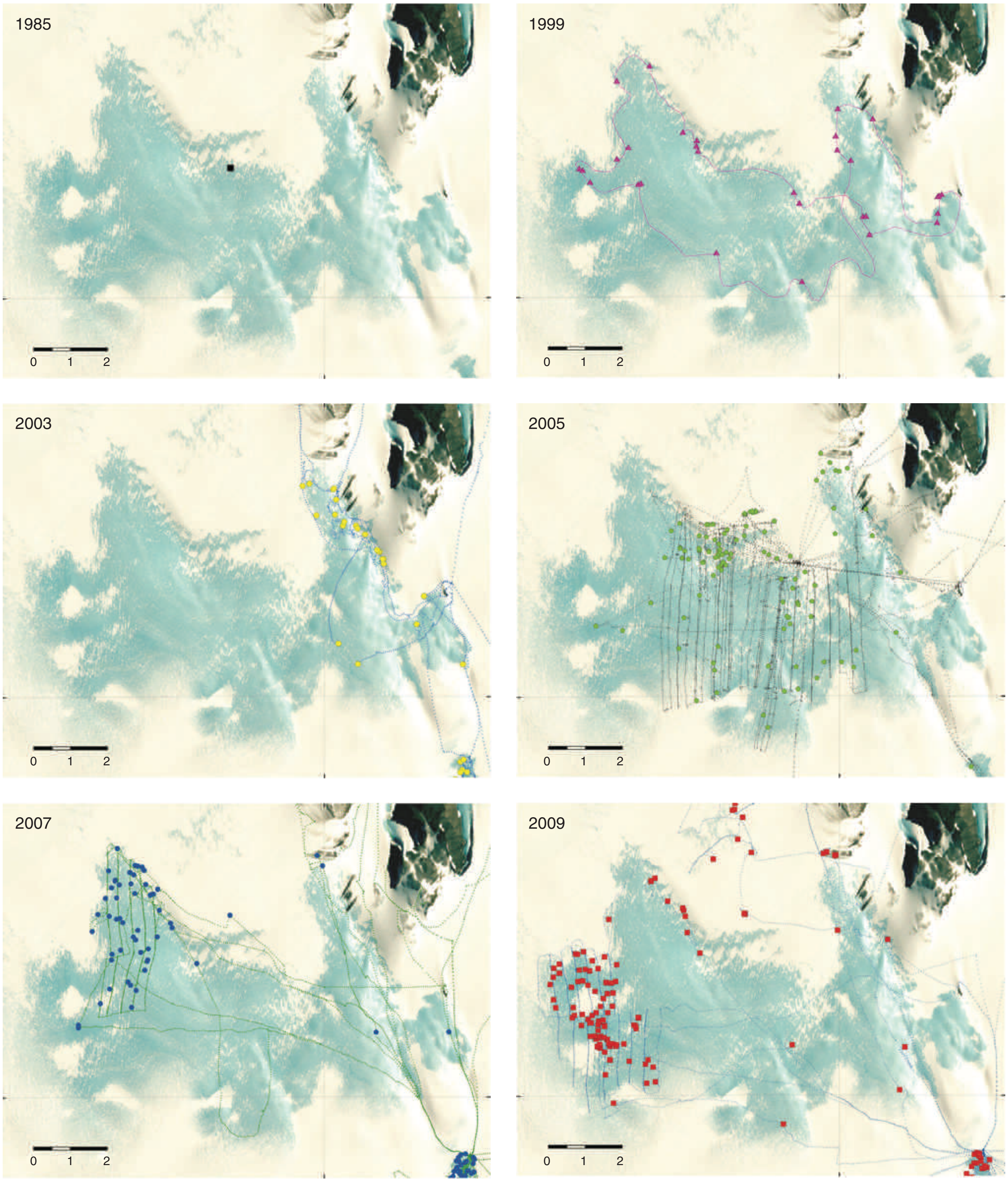

Figure 2.2a. Six seasons of ANSMET activities at a single icefield demonstrating reconnaissance and systematic styles of searching. An Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite image of the Miller Range northern icefield is shown with finds and snowmobile traces for each season as labeled. Boxes, dots, and so on show individual finds in various colors. In all seasons, the path of a single GPS-equipped snowmobile is shown to demonstrate search activity; one or more additional snowmobiles would have also been active. The first visit, in 1985 (upper left), was a single overflight by helicopter; one meteorite was recovered. A two-person reconnaissance visit in 1999 (upper right) led to the recovery of 30 specimens, with searching suspended after two days given clear signs of a major concentration. A four-person team conducted extensive reconnaissance throughout the Miller Range in 2003 (middle left), recovering meteorites and documenting the need for systematic meteorite recoveries. The weather-plagued first season of systematic recoveries in 2005 (middle right) concentrated primarily on the northern icefield, with most systematic searches on the eastern side and including a few reconnaissance trips to nearby ice patches. Systematic meteorite recoveries from the northern icefield continued during the 2007 field season (lower left) and were completed in 2009 (lower right) with the middle icefield (extreme lower right) as a main target of activity.

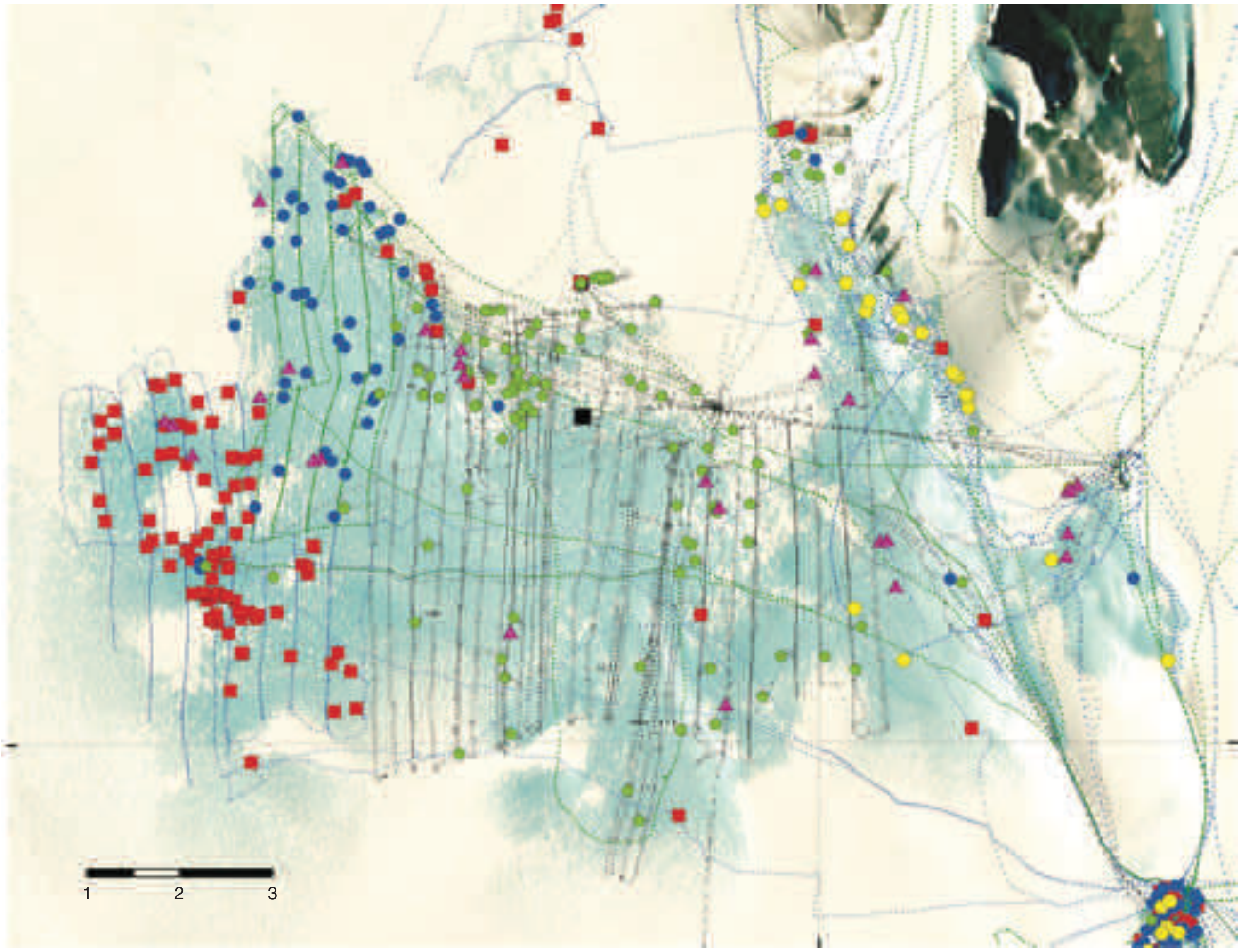

Figure 2.2b. (*Continued*) The 365 meteorite locations and snowmobile paths for all six seasons of ANSMET meteorite recoveries at the Miller Range northern icefield. Base map and symbols are as described in Figure 2.2a. Systematic recovery from the region continues to this day, primarily focused on other local icefields further to the south and smaller icefields in surrounding areas (not shown).

The payback comes in the form of future systematic meteorite recoveries that in many cases involve multiple seasons and thousands of new specimens.

2.3.1.3. Reconnaissance searching techniques. The imposed time limits and distinct goals of reconnaissance searching have led to search techniques that differ from those employed during more systematic meteorite recovery efforts. Reconnaissance searching is designed to cover large areas of blue ice quickly rather than to completely examine the surface in a systematic fashion. Reconnaissance searching typically takes the form of a loosely organized series of transects, with experienced personnel forming two semiparallel paths separated by several hundred meters and the other members of the team widely spaced between them. Overlap between searchers is neither encouraged nor controlled, and spacing between field party members may vary considerably as the team tries to accommodate local topography, hazards such as crevasses and moraines, and maintain continuous visual contact. The latter is important both for safety reasons (these are usually sites not previously visited) and to ensure that any meteorite discoveries are quickly noted. When a suspected meteorite is spotted, all members of the team converge on the find. Not only can the group as a whole establish whether or not it is a meteorite (and participate in subsequent collection activities), but the act of converging itself creates a locally dense search grid that often leads to further nearby discoveries.

Priorities can change dramatically during such a search. When a meteorite is found, the field team leaders may choose to redirect the transect in a new direction rather than continue on the previous bearings. If the find is in an area certain to be revisited and time is short, the specimen may be flagged and left for later recovery. When few or no meteorites are encountered, reconnaissance transects will explore as much of the icefield as possible, to eliminate (as far as possible) the possibility that a concentration was missed. When more meteorites are encountered, spacing within the transects may be narrowed to better define the scope of the concentration; and when abundant meteorites are encountered, the reconnaissance team may choose to conduct fully systematic recoveries using overlapping, highly controlled transects (as described in the next section). Typically, this happens when the scale of the concentration appears too small to warrant a future visit by a larger team, and enough time remains in the season to complete the work. Alternatively, the reconnaissance team may choose to move on to a new site as soon as possible and leave the rest of the recoveries to a larger, better-equipped team. Reconnaissance at any scale is considered complete when the value of possible future visits to the site by ANSMET is known.

2.3.1.4. Systematic searching procedures. Systematic searching is among the most basic of ANSMET field activities. It involves the methodical recovery of meteorites from a stranding surface where a meteorite concentration is known to exist and the potential for large numbers of recoveries is high. Typically, systematic searching field teams consist of eight individuals, but there can be more or fewer depending on factors such as logistical availability and the area of ice to be searched. Systematic search teams are normally only sent to sites that have been explored in some detail by prior reconnaissance teams, allowing priorities for a given season to be set in advance and logistical demands to be well constrained.

ANSMET search strategies typically follow the transect sampling model in use by natural scientists for hundreds of years [e.g., *Anderson et al.*, 2002; *Barabesi et al.*, 2002; *Chen et al.*, 2002; *Hammond et al.*, 2002]. During these transects the field team forms a line, each member a few tens of meters to several tens of meters apart. The team then proceeds to cross the meteorite stranding surface in a direction perpendicular to this line. After each pass is completed, the team changes direction and a new transect is started, covering new ground and exploring new areas of exposed ice (Figure 2.2). The orientation and pattern of the traverses are adapted to local geographical features, hazards, and weather conditions (wind, Sun angle, and snow cover) to maximize the coverage and efficiency of the search. The spacing, amount of overlap, and method of travel (foot or snowmobile) may also vary depending on frequency of meteorite encounter and density of terrestrial rock.

During early recovery efforts, single transects may be used as sampling tools to prioritize among several search areas. Because each field party member is capable of independent mobility (everyone has their own snowmobile), it is not unusual for an ANSMET party to split into temporary subparties to cover immediate needs (such as distinct GPS surveying and sample recovery groups when a large number of specimens has been found in a confined area). The location and path of at least one team member's snowmobile is continuously recorded to establish the geographical location of the transects and provide a record of the field team's progress (Figure 2.2). This record of traverses, available with the advent of high-resolution satellite imagery and GPS, has dramatically improved ANSMET's ability to track our own progress both during and between field seasons.

2.4. METEORITE RECOVERY TECHNIQUES

2.4.1. Minimizing Biases

The recovery of scientific samples always involves sampling biases related to the techniques used to acquire the samples and the choices made by the scientists during sampling. Throughout its history, ANSMET has chosen to use a simple and inexpensive but very effective meteorite detection system: the human vision system. For areas where the background of terrestrial rock is very low or absent, the innate human ability to rapidly differentiate a scene into key elements and recognize those that are unique or out of place 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, centimeter-sized meteorite to be resolved at distances of up to 100 meters on the light-colored ice [*Harvey*, 2003]. Given that ANSMET searches typically involve much shorter distances, we routinely recover meteorite specimens much smaller than this; catalogs of Antarctic specimens contain many rare types recovered in the subcentimeter size range.

Meteorite recovery tasks become more difficult and the risk of biases rises when terrestrial rocks become abundant, such as on icefields adjacent to nunataks and moraines, or in the moraines themselves. In the earliest years of ANSMET fieldwork, moraine searches were avoided because many regions free of terrestrial rock were available for searching and the difficulty of distinguishing terrestrial rocks from meteorite could be easily avoided. ANSMET has tried several different meteorite detection strategies and techniques in such environments, and we have found none more effective than simply trusting the human eye-brain combo to identify the rocks that "don't belong" after a period of familiarization with local lithologies. Recovering all the rocks from such areas has been suggested and even tested, but as the number density of terrestrial rock increases, the scale of such an effort becomes impractical, even absurd. For example, in 1997 and 1998 ANSMET marked off a 100 × 100 m region of the informally named Mare Meteoriticus icefield in the Foggy Bottom region of the Walcott Névé (the major source of QUE specimens), an area subjectively considered representative of the average numerical surface density of rocks. One hundred twenty-five rocks were recovered during this exercise, but no meteorites. This same exercise, if scaled up to the entire Mare Meteoriticus icefield, would require the collection of more than 500 million rocks in the <4-g range alone, of which roughly one in 250,000 would probably be a meteorite. Sorting meteorites from terrestrial rocks in some fashion must inevitably be considered more effective.

A number of technologically sophisticated sorting tools have been suggested and tested by ANSMET, including everything from simple metal detectors to a meteorite-hunting robot (NOMAD) equipped with multiple sensors and intelligent processing algorithms [e.g., *Apostolopoulos et al.*, 2001]. In our experience, such technological sensors have inevitably proven both slow and prone to unintentional sorting. For example, while well-calibrated metal detectors can efficiently sort iron, stony iron, and ordinary chondrite meteorites from terrestrial rock due to the presence of metal in the former, many of the most scientifically valuable Antarctic meteorites contain little or no metal and are effectively indistinguishable from common Antarctic igneous rocks. Equally important is that operation of such detectors divides the operator's attention between their eyes and the signals from the detection device; all too often, the latter takes precedence because it seems less subjective and involves conscious recognition of a signal. In fact, it *is* simpler, but primarily because it is a less data-rich detection technique, focused on the ferromagnetic properties of a rock and ignoring other key variables such as size, shape, texture, patina, and color. Second, while the speed of modern computer processors and robotic systems is growing exponentially, it has not yet come close to the human mind's ability to integrate a scene and pick out key elements. Our experiments with NOMAD suggest that a trained individual with innate positioning, path-choosing, and visual synthesis skills may be several hundred times more efficient than a robot (at least from that era) [*Harvey*, 2003]. Finally, there is ample indication that the human visual system is effective even in confusing environments. Of the 5,900 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, five lunar specimens, and several rare igneous specimens such as angrites and brachinites. Certainly some proportion of meteorites were not recovered, particularly those lacking diagnostic fusion crust; but the overall success of meteorite recovery in such confusing environments suggests losses are not high enough to warrant dramatic changes to our current operational procedures.

Another proposed sorting strategy is "high-grading": purposefully targeting recoveries on achondrites or large specimens that are of the most interest to science and ignoring more mundane discoveries such as small ordinary chondrites [*Harvey*, 2003]. Some amount of this does in fact take place during reconnaissance searches, when unique specimens are encountered by sheer chance, time is limited, and any recoveries that do take place must be prioritized, given the risk that a site might not be revisited. Unfortunately, the potential loss of interesting specimens during high-grading is very high. As noted earlier, 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, and fusion crust typically hides their interior. Many unique specimens in the existing Antarctic collections were not recognized as such while in the field (Figure 2.3). 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. Getting to the meteorite concentration site for even the most cursory examination is the major logistical cost faced by ANSMET, and with actual collection times that are short, the value of high-grading decreases. ANSMET field searches take the opposite approach, choosing to recover everything that is clearly a meteorite or has the potential to be a meteorite. By doing so, we accept some level of false positives but increase the likelihood that unusual specimens will not be overlooked.

2.4.2. Recognizing Meteorites

Many of the meteorite stranding surfaces explored by ANSMET are far enough inland of the Transantarctic Mountains that they are devoid of terrestrial rocks; any rock found at such sites almost certainly fell from the sky, essentially making recognition of them as meteorites a trivial pursuit. At the remaining sites, however, meteorites are often mixed with terrestrial rocks, either blown out onto the ice by the katabatic winds or carried in by glacial movement to form moraines. Recognizing meteorites in such settings is thus a crucial task for ANSMET field parties. The capability of the human visual system as an innate and not-entirely-conscious tool for meteorite

Figure 2.3. Field portraits of meteorites illustrating some diagnostic characteristics. The counter shows the field number used to identify each specimen while in the field (and is not the formal sample number later assigned by the Antarctic meteorite curator at NASA's Johnson Space Center). (a) LAR 06266, A typical (albeit large) find in a moraine showing the distinctive fusion crust and rust staining associated with an H5 ordinary chondrite. (b) A large rounded CV3 carbonaceous chondrite (LAR 12002) showing prominent chondrules and evaporite growth on its downwind and sunnier northern side. (c) GRO 06059, an achondrite displaying the glossy fusion crust commonly associated with feldspar-rich eucrites. (d) LAR 12320, a diogenite with multicolored fusion crust ranging from black to yellow-green. (e) Reasons not to high-grade during searches, example one: this mundane-looking specimen is MIL 11207, an amphibole-bearing R6 chondrite. (f) Reasons not to high-grade during searches, example two: MIL 07259, an acapulcoite / lodranite of nondescript appearance.

detection can be improved through training designed to let the conscious mind play a supervisory role. Over the years we've made efforts to deconstruct the meteorite recognition process, and we now recognize two "trainable" factors: the visual clues provided by the meteorite itself, and development of an internal catalog of local terrestrial lithologies.

Improving the latter for ANSMET field party members is fairly simple and follows the old maxim "The best geologist is the one who has seen the most rocks" (attributed originally to H.H. Read; see *Young* [2003]). The first few days of ANSMET fieldwork are routinely dedicated to looking at lots of rocks during searches at sites rich in local lithologies. Typically, the search site will be a moraine where previous work has suggested not only a thorough representation of local lithologies but also the likely presence of a few "example" meteorites (Figure 2.3). During such searches field party members are strongly encouraged to consciously examine every rock that catches their eye and bring any rock they are curious about to the attention of the team as a whole and the veterans in particular for identification. False positives are par for the course early on and accepted as a crucial part of the training. Anecdotal evidence suggests that this early exposure to a very complex lithological environment quickly trains the brain; it is not unusual for an individual's meteorite finds to increase at a nearly exponential rate during this training period. It sometimes leads to a phenomenon we affectionately call a feeding frenzy, where the team's rapidly increasing power to recognize meteorites overwhelms leadership's attempts at managing systematic progress during the search. There are worse problems to have given our goals.

When meteorites are encountered during these early searches, focus shifts to the other trainable factor (recognition of the features of Antarctic meteorite finds). Most field party members have some prior experience with meteorites in hand sample. During training in McMurdo, they are asked to familiarize themselves with hundreds of images of previous finds. Meteorites in the wild can look very different than those images, due to lighting and background conditions, and even experienced veterans benefit from a refresher course on the features that distinguish Antarctic meteorites.

The most distinctive feature of meteorites and the one that most often distinguishes them from terrestrial rocks is fusion crust. On their way to the ground, meteorites develop a thin shell of melt as 10–20 km/s of velocity is converted into thermal energy within the Earth's atmosphere. The resulting layer of melt, once chilled to a glass, is called fusion crust. With notable exceptions, fusion crust is distinct from a meteorite's interior and much darker than the weathering rind common on native Antarctic rocks. It often shows flow lines and fluid features characteristic of a semi-liquid state and is rarely more than a few mm in thickness. Fusion crusts can range from a matte black, polygonally fractured surface reminiscent of a charcoal briquette to a smooth glassy black resembling furnace slag. Fusion crust is almost always black but can vary in color depending on the minerals being melted; gray, green, and even yellowish fusion crust has been noted on some unusual specimens (Figure 2.3). Only a very small percentage of Antarctic meteorites show no fusion crust whatsoever, usually due to physical weathering.

In the absence of visible fusion crust, other clues can help one recognize meteorites. Meteorites are often well rounded and equant in comparison to their terrestrial neighbors; their fiery plunge through the atmosphere tends to take off any sharp corners, and structural controls on their shape (such as bedding, jointing, etc.) are virtually absent in meteorites and common in terrestrial rock. Meteorites often are different in size than the local rocks, particularly in settings where aeolian sorting has occurred; they can be either larger than the wind-sorted rocks around them simply because they were delivered there by different means, or smaller because their higher density and rounded shape sorts them differently. The density of meteorites, and their ability to absorb solar energy when fusion crusted, can also lead to them sitting differently at the ice surface (often slightly sunken in). Because most meteorites contain native metal that oxidizes very easily, they can show significant spots of rust when weathered; this highly localized distribution of rust is quite distinct from the broader coloring associated with terrestrial oxidation of FeO in oxides and silicates (Figure 2.3). The presence of native metal is also readily detected by examination with a hand magnet, a test used by ANSMET field party members when other clues suggesting a meteoritic origin are not convincing enough. Chondrules can also be very diagnostic when exposed. Finally, most meteorite lithologies are distinct from most terrestrial lithologies, so any rock that just "looks different" has potential, whether or not you're a trained geologist. During ANSMET fieldwork we strive to recover any rock suspected of having fusion crust or that just seems exceptionally out of place, accepting some level of false positives and trusting the curatorial process that follows to weed these out.

In summary, ANSMET meteorite searches are an economic compromise. Maximizing recoveries for any given season means balancing currently available logistical access to a site with our understanding of local meteorite density, a site's propensity for foul weather, recent snow cover, the density of local terrestrial rock coverage, and even the expertise of a given year's field team. Our visual searches are prey to all the failings of the flesh, as well as the quirks of wind, snow cover, terrestrial rock camouflaging, and so on. For now, with no shortage of places where meteorite recovery can be effective, human visual searches continue to be extremely successful and economical. As technological advances occur, we will explore the ways these might improve the efficiency of our searches, but we will do so in ways that do not interfere with our current procedures for fast and efficient meteorite recovery.

2.4.3. Maximizing Scientific Return during Recovery

From the earliest days of fieldwork, Antarctic meteorite specimens were recognized as much more pristine chemically than most finds from the civilized continents, and the U.S. and Japanese programs worked quickly to establish collection and curation protocols. These protocols, while originally not strict or enforced in any legislative sense, have been recognized to be of immense value and 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 ensure early, unbiased access to the samples by members of the planetary materials research community. The U.S. governmental agency responsible for activity in the Antarctic has produced enforceable regulations regarding meteorite protection that guide current Antarctic meteorite recovery by U.S. citizens [*Federal Register*, 2004].

The ANSMET program files a meteorite sample recovery plan for each field season that describes how we intend to meet or exceed NSF Regulation 45 CFR Part 674 concerning the collection and curation of Antarctic meteorites, and fieldwork does not proceed without prior USAP approval of that sample plan. As described in our sample plan, the typical procedure for recovery of a find is as follows. Upon discovering a meteorite, the finder signals the remainder of the team, who mark their current positions within the transect and converge on the find site. A single GPS-equipped snowmobile is brought near the find, down- or side-wind to minimize contamination, while all other vehicles remain several meters away (Figure 2.4). While the location of the find is being accurately determined, several field party members begin the collection procedure. The first step is the assignment of a field number that is used as a unique identifier for the sample throughout all subsequent recovery procedures. The specimen is photographed using a digital camera while detailed notes are entered into the field notebook to record the measured size of the find (along three ordinal directions), the percentage of the specimen covered by fusion crust, the presumed type (chondrite, iron, etc.), and any distinguishing characteristics of the find, such as fractures, nearby fragments, contact with snow or terrestrial rocks, or accidental human contact. During this process the field number is continuously cross-checked among all records.

Figure 2.4. A typical ANSMET collection scene. Two field party members (C. Corrigan and J. Pierce) assist each other in placing a meteorite in its protective bag while J. Schutt (above right) notes distinguishing characteristics of the find such as fusion crust coverage, size, and presumed type. The GPS-equipped snowmobile shown approached from downwind and carefully parked to the right (side-wind) of the specimen, placing the GPS antenna closest to the find and the exhaust on the other side of the vehicle.

The sample itself is placed into a clean Teflon or nylon bag, and all contact with skin, clothing, or "dirty" implements is avoided (Figure 2.4). A clean aluminum tag punched or anodized with the field number is then inserted into a fold of this bag, arranged to prevent contact with the meteorite. The bag is then securely sealed with Teflon freezer tape. The samples are then collectively put into a larger bag or dedicated sample container where they remain during the workday. Upon return to camp, the samples are sorted by sample number into further labeled bags to aid daily and weekly inventories and put into a dedicated storage and shipping container, which is left outdoors to keep the meteorites frozen. These containers are locked before shipping from the field, and (still frozen) accompany the field team back to McMurdo at the end of the field season. While in McMurdo the storage containers are kept closed whenever possible, and stored in a clean -20° C freezer. In late February the specimens are transported by ship (still frozen) to Port Hueneme, California, and upon arrival are forwarded by freezer truck to the Johnson Space Center in Houston, Texas, where they can be thawed under controlled dry conditions to minimize interaction with liquid water. Curatorial and characterization activities associated with ANSMET-collected meteorites are described in Chapter 3 (Righter et al., this volume).

Note that our sample protocols are designed to fully document possible anthropogenic contamination of samples rather than totally eliminate such contact. Prior studies conducted during ANSMET fieldwork have shown that imposing dramatic "cleanroom-style" constraints on meteorite recovery does little to reduce such contamination [*Fries et al.*, 2012]. In fact, the specimens have typically been immersed in the Antarctic environment for thousands of years; terrestrial contamination is completely unavoidable, and some part of that baseline is already anthropogenic.

2.5. CONCLUSIONS: THE FUTURE OF ANSMET METEORITE RECOVERIES

To date, ANSMET has conducted meteorite searches on nearly 200 icefields at 75 different sites in the Transantarctic Mountains and nearby regions (Figure 2.1). These icefields have ranged in size from parts of a square kilometer to several hundred square kilometers, and the number of meteorites recovered from these icefields has ranged from zero (in many cases) to several thousand (in just a few). In spite of ANSMET's long history, many icefields remain targets for both reconnaissance and systematic searching, both within and outside the Transantarctics. Given the large numbers of scientific mysteries that remain in planetary materials research, many of which can only be solved by new specimens, this is a good thing for both science and the future of the U.S. Antarctic meteorite program. ANSMET's field methods will continue to evolve with technological and logistical advances and as our understanding of meteorite concentrations improve; but we expect the baseline procedures described here, having served us so well for decades, will remain fundamental to those future operations.

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