

Results from the Greenland Search for Meteorites expedition

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Abstract—Following discoveries of blue ice areas in Greenland resembling meteorite-bearing blue ice fields in Antarctica, a surface search of several of the most promising sites was carried out in August 2003. The ice fields are located in Kong Christian X Land, in northeastern Greenland around 74°N at elevations between 2100 and 2400 m. No meteorites were found in any of the localities that were searched. Evidence of occasional significant melting (filled crevasses and melt sheets) suggest that summer temperatures are sometimes high enough that dark rocks, like meteorites, can melt through the upper layers of ice. Small terrestrial rocks and cryogenite were found down to 50 cm below the ice surface. Meter-sized terrestrial rocks were found on top of the ice downstream from nunataks. These rocks shade the ice below, and since they were apparently too massive to warm up during warm days, they remained at the surface as the surrounding ice ablated away. Our findings strongly suggest that Greenland is currently unlikely to harbor significant meteorite concentrations on blue ice fields.

INTRODUCTION

Significant concentrations of meteorites have been located in Antarctica in places where evaporation of stagnant ice exposes embedded meteorites on the surface (Cassidy et al. 1992; Harvey 2003). The meteorite concentrations are typically found on exposed areas of blue ice that can be easily detected and mapped using air- and space-based remote sensing. However, seemingly identical ice fields can have very different meteorite concentrations, and many of the ice fields that have been found in Antarctica have shown few or no meteorites at all. Some factors have been identified that may be used as proxies to evaluate the potential of a given blue ice field (Harvey et al. 2001). High-elevation areas with low precipitation, limited or preferentially no summer melting, strong katabatic winds, and stagnant ice flow seem to have the best potential for building up meteorite concentrations. Another factor, not easily quantifiable, that may be responsible for the difference in meteorite concentrations between seemingly identical ice fields is the age of the ice field. As meteorites are expected to accumulate at the surface over time, young ice fields may harbor few or no meteorites at all.

Northeastern Greenland is the coldest and driest part of

Greenland. High mountains block the ice flow toward the coast, creating areas of stagnant ice at high elevations. Blue ice is seen at elevations of up to 2600 m in Kong Christian X Land and up to 2000 m in Dronning Louise Land (Harvey et al. 2001). Although Kong Christian X Land is at 2 degrees lower latitude than Dronning Louise Land, we found the former more promising since the higher elevation suggests a mean average temperature about 3 °C lower (Reeh 1989). Climate models and sparse weather station data suggest that the annual mean temperature around the blue ice fields in Kong Christian X Land is approximately –19 °C (Box and Rinke 2003). The ice fields in Kong Christian X Land have many of the features associated with meteorite concentration sites of Antarctica, such as exposed blue ice within regions generally characterized by accumulation, high altitude, strong katabatic winds, and nearly or totally submerged nunataks that block and divert the flow of the ice toward the sea. Analysis of satellite imagery and aerial photography allowed the identification of 28 ice-field-bearing subregions of interest within the Kong Christian X Land study area. The target ice fields stretch approximately 150 km from end to end (Fig. 1); our goal was to examine as many of these ice fields as possible, performing ski traverses to get from site to site and making foot searches when on exposed ice.

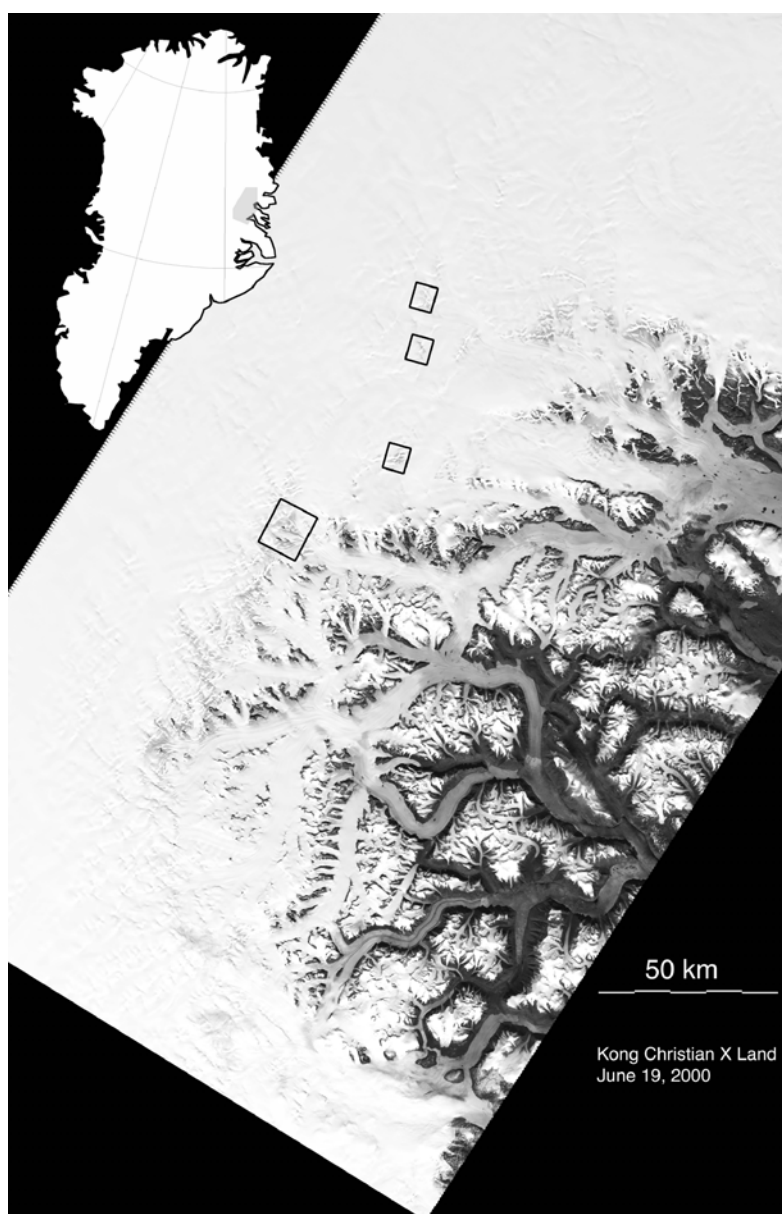


Fig. 1. Landsat image showing the four ice fields searched during the Greenland Search for Meteorites (GREENSMET) expedition. The ice fields in boxes are (from above) N7, N6, N12, and S2.

SELECTION OF ICE FIELDS FOR GROUND SEARCH

Prior to put-in, we conducted an aerial reconnaissance of the target region, using a Twin Otter aircraft to overfly the entire 150 km traverse route. This flight provided a close-up look at the target ice fields, local snow and ice conditions, and traverse routes. Based on this reconnaissance, we chose a put-in site at the northwest end of the possible traverse route, where the ice fields were less closely spaced but the settings of the individual ice fields most closely resembled those of Antarctic meteorite stranding surfaces. The N7 site was chosen for our initial put-in site based on a number of

observations made during the reconnaissance flight. The reconnaissance showed no signs of local melting at N7, and the absence of terrestrial rocks would make it easier to search this site. The large ice fields to the east of N7 were at lower elevations and showed signs of significant melting. Ice fields at the southern end of the study area were at favorably higher altitudes and more closely spaced to each other.

However, the southern ice fields were also imbedded in a more mountainous terrain, and many of the exposed blue ice areas appeared to consist of relatively fast-moving glacier ice rather than stranded ice. Traverses between ice fields in this region were relatively short, but would have required crossing relatively difficult sloping and heavily crevassed

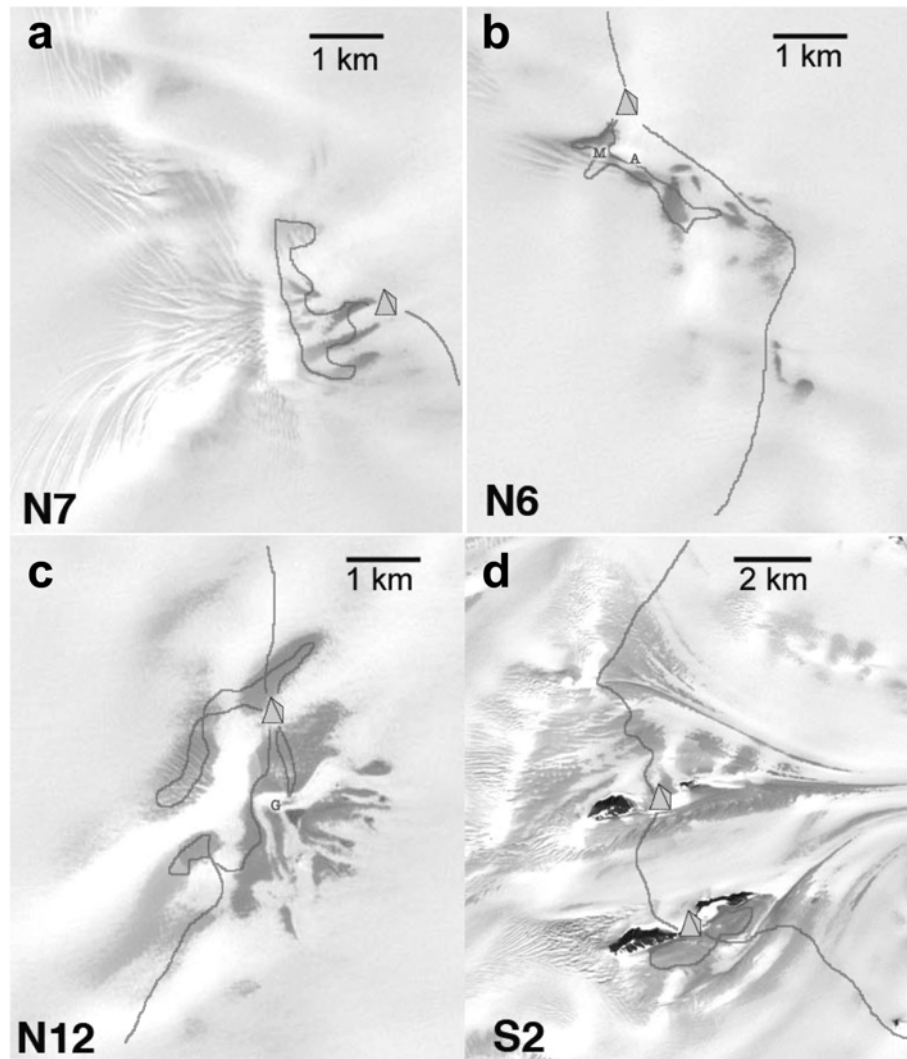


Fig. 2. Landsat images showing the four main ice fields that we searched. The tents mark campsites, lines show track lines of one of our GPS navigators. The letters mark the muskox (M) and the nunataks discovered by the expedition: the Ackaruna nunatak (A), and the GREENSMET nunataks (G). The triangular area to the southeast of G is a frozen meltwater pond.

terrain. In contrast, ice fields in the northern half of the study area were at somewhat lower altitudes, but were generally larger and more widely spaced, in settings more analogous to Antarctic meteorite stranding surfaces. Although starting at this northern end of the study region would require longer traverses between ice fields initially, the traverses themselves would be through safer, less demanding terrain. Based on these observations, and using N7 as our starting place, we planned to traverse as far south as possible in the time allotted.

N7 Site

The N7 ice field is at an elevation of 2250–2300 m. It is a few kilometers to the north of an eastgoing ice stream passing between sites N7 and N6 (Fig. 1). The three “fingers” of dark blue ice seen in Fig. 2a are located below a 50 m high

snow-covered slope to the west. The three fingers, which were our primary search area, are a few hundred meters wide and up to 1 km long. There is also blue ice in the area above the slope, but it is heavily crevassed and more snow-covered. We infer that a subsurface obstruction underneath the heavily crevassed area blocks the ice flow, creating stagnant ice on the down- and upstream side where the blue ice is observed.

The blue ice fields were almost snow-free with a corrugated, wind-sculptured surface similar to that seen in Antarctic blue ice fields. Patches of coarse-grained snow with occasional layers of frozen meltwater (Fig. 3a) and crevasses filled with clear ice (Fig. 3b) did, however, show that significant melting episodes had taken place, which were much more severe than any observed associated with Antarctic meteorite concentration sites. The three fingers are sloping gently toward the east and there is therefore no place where meltwater can accumulate.

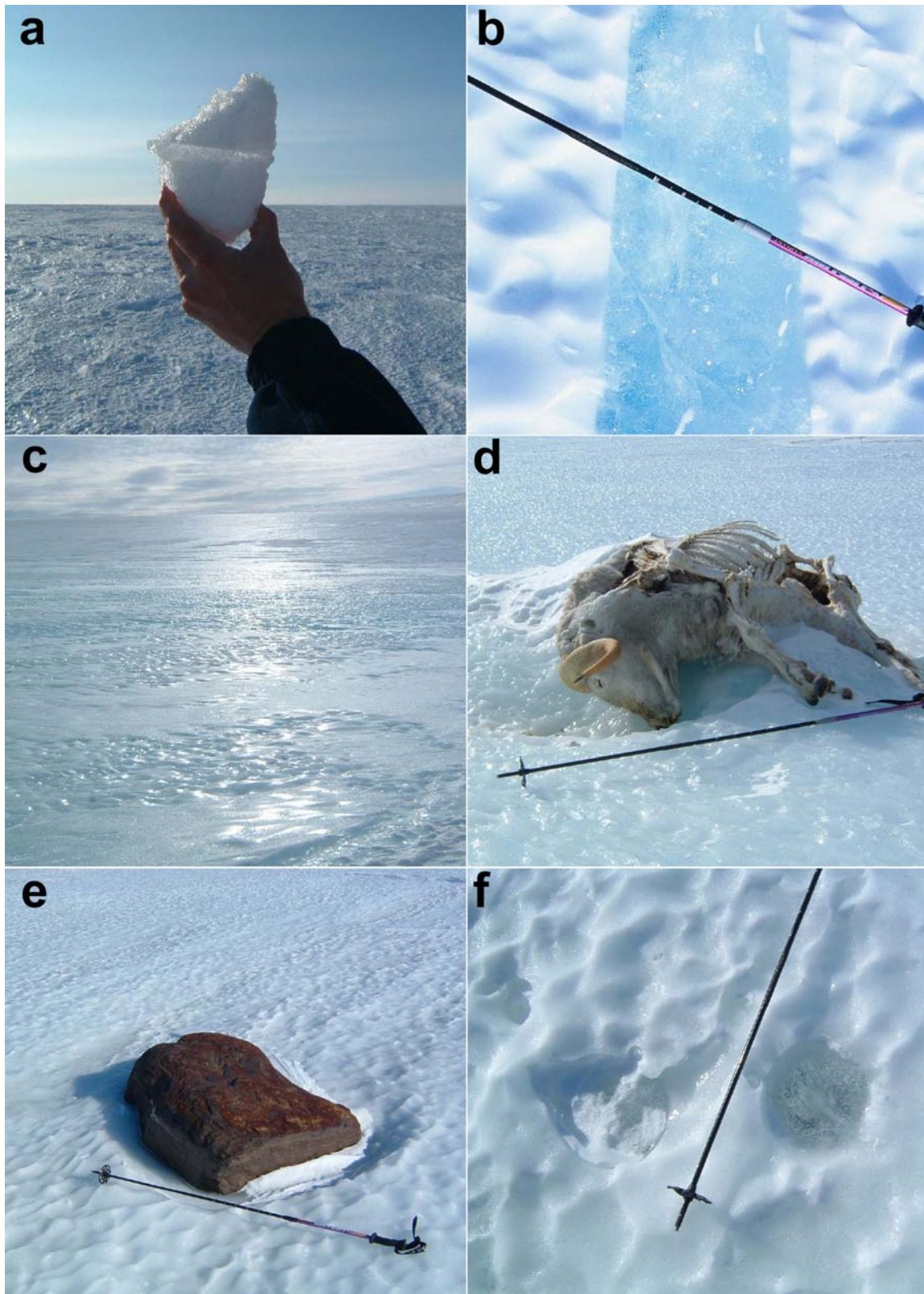


Fig. 3. a) Sample of coarse surface snow showing a frozen melt layer. b) Crevasse filled with bubble-free frozen meltwater. c) Smooth areas on the normally sun-cupped ice field surface are areas where melt has pooled or infiltrated overlying snow and refrozen. d) Muskox found on blue ice at N6 ice field. e) Large terrestrial rock floating on ice surface. f) Cryoconite holes left behind when smaller terrestrial rocks thermally tunnel downward into the ice.

N6 Site

The N6 site is also far inland from the nunataks at a high elevation (2250 m), and has more exposed blue ice than the first site. Another reason to go was a black object spotted from the air during the reconnaissance flight. This object turned out to be a previously unknown moraine.

The dark area between our campsite and the muskox (Fig. 2) appeared to be a frozen meltwater pond. There was no liquid water at this site, and the sun-cupped surface of the ice suggests that the pond had remained largely frozen throughout the summer of 2003. Despite evidence of occasional melting, coherent linear dust bands across the ice fields south of the suspected meltwater pond suggest that the original layering in the snow had been preserved and that most of the exposed ice is pristine with a possible contribution from percolated meltwater. Snow drifts also frequently contained ice layers (Fig. 3a), which shows that brief melting episodes are common.

A well-preserved carcass of a muskox was found at the N6 site (Fig. 3d). The muskox was draped over a 50 cm high knob in the ice, possibly because the ice underneath the ox was shielded from the sun. In order to test if the ox had flowed with the ice and had become exposed in the blue ice fields much like meteorites in Antarctica, a piece of rib bone was removed for C^{14} analysis. The abnormal high C^{14} of the rib bone shows that the muskox died in the mid-1960s during the atmospheric nuclear tests (Table 1). The relatively young age of the muskox suggests that it died on the ice field; it may therefore never have been deeply buried by snow.

N12 Site

The N12 site was chosen because it is the most extensive of the blue ice fields inland from the nunataks at a fairly high elevation (2100 m), and because we saw no signs of melting from the air. The ice flow is generally toward the southeast in the area around the N12 site. The top of a subsurface obstruction to the ice flow is exposed in the form of several narrow bands of moraine that form an arch upstream from a meltwater pond (Fig. 2). There is a 50 m high slope running southwest-northeast between the nunataks and the campsite. All of the ice fields on top of the slope to the west and north of the campsite were systematically searched for meteorites. Due to the signs of melting at lower elevations, the southeastern ice fields were not searched. The setting is a near-perfect analog to many Antarctic meteorite traps, with stagnant clean ice upstream from an exposed obstruction. The big difference between this locality and Antarctica is the omnipresent signs of melting. At N12 we saw the first liquid water around the edge of the moraine. One of the days at N12 was also one of the warmest days we had and we did see

Table 1. Results from the ^{14}C dating of the muskox rib bone.

^{14}C age (BP)	-4099 ± 46^a
Percent modern carbon	166.57 ± 0.95^b
Calibrated age	1963 A.D. or 1967 A.D.

^a ^{14}C ages are reported in conventional radiocarbon years BP (before present = 1950) in accordance with international convention.

^bPercent modern carbon indicates the ^{14}C concentration as a fraction of modern (1950) carbon corrected for fractionation.

minor melting on top of the ice. Signs of previous melting episodes were similar to those described at N6 and N7.

S2 Site

The S2 site was chosen because it is extensive, complex, and quite different from the other ice fields that we searched. It is at an elevation of about 2200 m. Two sets of nunataks divide an eastgoing ice flow into three separate flows (Fig. 2d). Areas of exposed stagnant ice are seen around and between the nunataks on either side of the central ice flow. Melting of ice and snow on the dark rocks had created frozen pools on the south side of the nunataks where the ice was at a lower elevation than on the cooler north side. Along the north side of all nunataks, we found wind-carved valleys that were 15–20 m deep with vertical walls. A dry meltwater drainage channel 1 m in diameter at the base of one of these cliffs showed that occasional melting takes place. Frozen streams and ponds were also found in the wind-carved channels. We had one calm, warm, and sunny day at the southernmost set of nunataks where we observed small amounts of water at the surface in the northern valley and small amounts of running water on the sunny south side of the nunataks.

Meter-sized rocks from the nunataks were found on top of the ice, whereas centimeter-sized rocks and pockets filled with gravel were found approximately 50 cm below the surface of the ice.

WEATHER

While we did plan to carry a meteorological data logger into the field, it was damaged before it could be deployed. As a result, our observations were limited to a crude thermometer and anecdotal observations. The general weather observed during the first three weeks of August spent on the plateau was dominated by northwest winds 5–10 m/s, was partly cloudy, and had temperatures around $-5^{\circ}C$. Temperatures at or even slightly above $0^{\circ}C$ were encountered a few times on calm, sunny days, leading to localized surface melting. At the other extreme, we had a night with northwest winds up to about 15 m/s and temperatures down to $-20^{\circ}C$. Light snow fell on several occasions, and in one instance notably included freezing rain.

DISCUSSION

Based on our remote sensing data analysis of blue ice fields in Kong Christian X Land and Dronning Louise Land, we concluded that the high elevation sites in Kong Christian X Land had the biggest potential of harboring meteorites. As described above, we carefully searched the most promising of these areas with a negative result.

From the very beginning, our ice field traverses revealed a number of signs that the ice surface had periodically warmed and experienced melting. In some areas, regions of water-saturated snow had refrozen on the ice surface to form smooth capping surfaces; in other regions, refrozen meltwater drainages could be traced across the ice surface for significant distances (Fig. 3c). At a number of sites, crevasses associated with ice flow over and around sub-ice barriers were found to be filled with bubble-free recrystallized meltwater (Fig. 3b). In some cases, one could see where meltwater runoff from the nunataks in S2 had flowed underneath the ice and created “springs,” producing refrozen outflows downslope from the nunataks.

Our first encounter with liquid water was at the N12 ice field, where minor ponds existed next to moraines. At the S2 locality, where relatively tall cliffs were shedding rocks onto the blue ice, we saw that large (meter-sized) rocks remained on the ice surface (Fig. 3e), while any smaller rocks tunnelled thermally down into the ice, forming cryoconite holes (Fig. 3f). In essence, all the rocks on the ice surface warm in the sun, and will tend to sink into the ice; but larger rocks, shading the ice below them, can float on the ice surface. This phenomena (self-shading) probably also played a role in keeping the muskox at site N6 afloat.

We did an experiment with a small (6–8 cm across) rock at the N6 ice field. The rock was left for two days on the ice while its vertical positions relative to the ice was monitored. The first day was a warm and sunny day. During the day, the rock melted down into the ice by approximately 5 mm. On the second day, which was a cold and windy day, the rock re-emerged by 1–2 mm in response to ablation of the ice around it and freezing of the meltwater below it. Both processes, melting and ablation, are therefore acting, but the absence of small rocks on top of the ice suggest that the melting process is the most important.

There is one example of a meteorite found on the ice sheet in Greenland. The 5 kg Ryder Gletcher meteorite was found in the late 1980s in northern Greenland on the ice at an elevation of approximately 1000 m (Russell et al. 2004). Based on our findings in Kong Christian X Land, this discovery is difficult to interpret. Although Ryder Gletcher is approximately 800 km north of Kong Christian X Land, the much lower elevation at this site suggests that summer melting should occur frequently. We suggest that the Ryder Gletcher meteorite may have been found early enough in the year so that ablation remained strong while solar heating

could not melt it back into the ice; that its size may have allowed it to shade enough ice below it to slow submergence; or that the summer when it was found was colder and drier than the summer of 2003. Unfortunately, the lack of quantified data does not allow us to choose from among these hypotheses.

At most Antarctic meteorite sites, meteorites are found lying directly on the ice. However, anecdotal evidence suggests there is a continuum between higher altitude sites, where meteorites are often found sitting on short pedestals, and lower altitude sites, where meteorites typically sit in a cavity (Harvey 2003). At none of the currently known sites, however, are conditions warm enough for the meteorites to tunnel down more than about half their diameter. Liquid water is almost never seen because whatever liquid is produced by melting immediately evaporates into the cold dry air. Thus, in Antarctica, the prevalent conditions tend to keep a meteorite at the surface and significant numbers of stranding surfaces can be found on the ice sheet. For completeness, it should be noted that the number of blue ice sites where meteorites are consistently lost through cryogenic sinking is, for obvious reasons, difficult to estimate.

The annual average temperature on the Greenland ice sheet is warmer by about 5–10 °C compared to Antarctica at similar altitude and latitude (Box 2002; Stefan et al. 1996). This is clearly significant for meteorite concentrations; but because annual average temperatures were still significantly below freezing, we thought the “normal” Antarctic meteorite concentration mechanisms would function. But more important than this average temperature is the maximum temperature, typically reached in mid- to late summer. Whereas the maximum observed air and ice temperatures observed at Antarctic meteorite stranding surfaces rarely exceeds –5 °C for more than a few minutes, during our three weeks of fieldwork in Greenland we experienced excursions above 0 °C measured in terms of hours, if not days. Considering these experiences as typical, it seems apparent that meteorites falling onto (or being transported to) blue ice surfaces in Greenland can, within the timespan of a few warm days, tunnel a significant distance downward into the soft, near-melting ice. At the same time, simultaneous production of meltwater fills in the holes and overcaps the ice surface.

Under these conditions, meteorites being carried suspended in the ice probably never rise to the surface, because absorption of solar radiation produces warming as they rise, allowing them to stay submerged at some equilibrium depth. Even if they are exposed during a cold climatic period, only a few years under current conditions would cause a total loss of specimens due to weathering. As a result, despite the fact that the Greenland ice sheet harbors many sites that are excellent physiographic analogs to Antarctic meteorite stranding surfaces, the slightly warmer climate appears to have a strongly negative influence on meteorite concentration mechanisms. The warmer air and ice

of Greenland mean meteorites can sink faster than the ice surface can sublime or ablate, resulting in a net downward motion for the meteorite. At some depth, dependent on meteorite size and ice temperature, the meteorite will reach a steady state situation where solar heating is insufficient to allow further sinking. In Antarctica, this depth is only a part of the maximum dimension of the meteorite, if it exists at all; in Greenland, by contrast, this depth is some multiple of the meteorite's size. If this were the only difference between Greenland and Antarctica, then there might still be some possibility of meteorite recovery by searching for holes in the ice sheet surface at appropriate sites where terrestrial rocks are absent. Unfortunately, the periodic presence of meltwater actively resurfaces Greenland blue ice areas, filling holes and depressions and creating a new, featureless ice surface. Under these conditions, where traces of the meteorite's presence are actively destroyed, the advantages of any active concentration mechanism are fully negated by the difficulty in locating and recovering the specimens. Thus, while meteorites certainly are present in the Greenland ice, as they are within any natural deposit, the climatic difference between there and Antarctica make systematic meteorite recovery virtually impossible.

POSSIBILITY FOR FUTURE STUDY

Our observations strongly suggest that Greenland is currently unlikely to harbor significant meteorite concentrations on blue ice fields analogous to those found in Antarctica. Certainly there are areas of the ice sheet further north in Greenland where mean annual temperatures are a few degrees lower than those in Kong Christian X Land. For example, Dronning Louise Land, about 200 km further north, was examined in detail as a possible site for the GREENSMET field expedition. However, the exposed blue ice is at lower altitudes than in Kong Christian X Land, and meltwater is recognizable in aerial and satellite imagery around the entire periphery of the ice sheet. In the extreme north of Greenland, where the coldest conditions should be prevalent, sites with settings (ice flow, altitude, and latitude)

analogous to Antarctic meteorite stranding surface are not clearly present, and the ice sheet meets surface and subsurface obstructions at much lower altitudes (~1000 m). In general, we feel that any future meteorite recoveries in Greenland will likely be of isolated specimens found shortly after they fell, or on rocky surfaces, and that significant meteorite concentrations are unlikely to exist.

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