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# The Frontier Mountain meteorite trap (Antarctica)

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**Abstract–**The Frontier Mountain blue ice field is an important Antarctic meteorite trap which has yielded 472 meteorite specimens since its discovery in 1984. Remote sensing analyses and field campaigns from 1993 to 1999 have furnished new glaciological data on ice flow, ice thickness, bedrock topography, ice ablation and surface mass transport by wind, along with detailed descriptions of the field situation at the trap. This solid set of data combined with an updated meteorite distribution map and terrestrial ages available from literature allows us to better describe the nature of the concentration mechanism. In particular, we observe that the meteorite trap forms in a blue ice field (1) located upstream of an absolute and a shallow sub-ice barriers; (2) characterized by compressive ice flow with horizontal velocities decreasing from 100 to <10 cm/year on approaching the obstacle; (3) undergoing mean ablation rates of 6.5 cm/year; (4) nourished by a limited snow accumulation zone extending ~20 km upstream of the blue ice area. We also draw the following conclusions: (1) the origin of the meteorite trap can be explained according to the present-day glaciological situation; (2) the meteorite concentration develops according to the general principles of the "ice flow model"; (3) the accumulation model can be described as "stagnant ice or slow-moving ice against an absolute and submerged barriers", according to the descriptive schemes present in literature; (4) the Frontier Mountain ice field is an effective trap for meteorites weighing more than ~200 g; for smaller masses, the combination of wind and glacial drift may remove meteorites in less than a few tens of thousands of years; (5) although the activation age of the Frontier Mountain trap is not yet constrained, we infer that one of the most important findsites may be as old as 50 ka, predating the last glacial maximum.

## INTRODUCTION

The highest concentrations of meteorites yet discovered on Earth occur in particular blue ice fields at the edge of the Antarctic Plateau known as meteorite stranding surfaces or meteorite traps (*e.g.*, Cassidy *et al.*, 1992). As derived from field measurements in the Yamato Mountains (Dronning Moud Land) and the Allan Hills (Victoria Land) regions, these traps are areas of tens to thousands of square kilometers where the outward flow of the ice sheet is impeded by bedrock barriers and high ablation of the ice due to dry katabatic winds prevents snow accumulation. Although Huss (1990) argued that meteorite concentrations form primarily by direct infall, most authors (*e.g.*, Nagata, 1982; Whillans and Cassidy, 1983; Cassidy *et al.*, 1992) agree on the "ice flow model". According to this model, the meteorites are concentrated by englacial transport from large snow accumulation zones into the stranding surfaces where they are exhumed by ablation. The local meteorite concentration is preserved over time as a result of low weathering rates under the cold, dry Antarctic climate. Terrestrial ages for Antarctic meteorites, typically <<500 ka with a few up to 2 Ma (Nishiizumi *et al.*, 1989; Nishiizumi, 1995; Welten *et al.*, 1997; Scherer *et al.*, 1997; Jull *et al.*, 1998), indicate the time span necessary to attain the present concentrations. A clear understanding of the meteorite concentration mechanisms may thus give insight into the behavior of the Antarctic ice sheet (*e.g.*, Cassidy *et al.*, 1992) and into the flux of meteorites to Earth over the recent past (*e.g.*, Zolensky, 1998).

The Frontier Mountain blue ice field (Fig. 1) is an important Antarctic meteorite trap located in the catchment area of the upper Rennick Glacier (Höfle, 1989), northern Victoria Land

FIG. 1. The Frontier Mountain meteorite trap photo-gallery. (a) Aerial view of the Frontier Mountain blue ice field from the northeast. (b) The "wind-scoop" meteorite accumulation site as seen from the east, the "Meteorite Valley" is in the background. (c) Field situation at the "firn-ice edge" meteorite accumulation site; picture taken looking east. (d) Field situation at the "scatterfield"; picture taken from the northeast. (e) Photomosaic of the "Meteorite Valley moraine"; pictures taken from the southern valley wall.

(Figs. 2 and 3). Discovered by chance in 1984 by a Ganovex IV party (Delisle *et al.*, 1986, 1989) and then systematically searched by EUROMET and PNRA teams in 1990, 1993, 1995, 1997 and 1999, it has yielded a total of 472 meteorite fragments (Delisle *et al.*, 1993; Folco *et al.*, 1995, 1996; Folco and Mellini, 2000). The concentration mechanism operating at Frontier Mountain is discussed in several papers that followed the 1984 and 1990 campaigns (Delisle *et al.*, 1986, 1989, 1993; Cassidy *et al.*, 1992; Delisle, 1993). Briefly, the 270 fragments recovered during the 1984 and 1990 campaigns were found in a supraglacial moraine in a valley (unofficially called "Meteorite Valley") at the southeast-end of the mountain and along the northern boundary of the blue ice field (Fig. 3). The meteorites of the first site were interpreted as being transported within the ice from the polar plateau to the point of emergence (Delisle *et al.*, 1989); the light (<110 g) specimens of the second site, as the wind-blown portions of meteorites exposed in the blue ice field (Delisle *et al.*, 1993). Cassidy *et al.* (1992) and Delisle (1993) further hypothesized that the concentration in the moraine did not develop under present conditions, but under a former highstand of the East Antarctic ice sheet. Indeed, these works provided useful indications for the subsequent search campaigns and lay the foundations for understanding the accumulation process; however, the models are largely hypothetical and little constrained because based solely on preliminary field observations and measurements of ice thickness along a traverse extending for 5 km east-northeastward from the "Meteorite Valley".

In this paper we provide further descriptions of the recovery site and report new glaciological data on the Frontier Mountian blue ice field. Data has been obtained through remote sensing analyses and field surveys conducted from 1993 to 1999. In particular, glaciological data include ice flow measurements, ice thickness and bedrock topography in the Frontier Mountain drainage area, and ablation rates and surface mass transport by wind in the Frontier Mountain blue ice field. This data, combined with an updated distribution map of recovered meteorites and terrestrial ages available from literature (*i.e.*, Wieler *et al.*, 1995; Terribilini *et al.*, 2000; Welten *et al.*, 2001; Welten, 2001, pers. comm.) provide us with a solid basis for discussing the concentration mechanism at Frontier Mountain.

## DATA SOURCES AND METHODS

### Remote Sensing Analysis

A Landsat Thematic Mapper (TM) scene has been used to produce a georeferenced image map of the Frontier Mountain region. Geomorphological analysis of the Landsat image provided information on the ice flow and the prevailing wind directions. The Landsat TM has a ground resolution of 28.5 m and seven spectral bands: three in the visible spectrum (bands 1, 2 and 3), three in the near infrared (bands 4, 5 and 7) and one in the thermal infrared (band 6). To enhance the topographic features and reduce the noise inherent in any single band, we used the first principal component (PC1) of TM bands 1, 2, 3, 4, 5 and 7 and removed scan-line striping. In the principal component analysis, linear combinations of the original data bands are searched in order to maximise data variance in a minimum number of components. The PC1 contains the greatest variance and various authors (Orheim and Lucchitta, 1988; Bindschadler and Scambos, 1991) have shown that it produces the clearest image of ice sheet morphology. A satellite image map with a spatial resolution of 30 m/pixel was created using the Landsat TM image (66–112) dated 1990 January 29. Five global positioning system (GPS) ground control points were used to georeference the image which was rectified to a Lambert Conformal Conic cartographic projection (standard parallels 72°40' S and 75°20' S, central meridian 164° E, World Geodetic System 1984, WGS-84) using a linear conversion matrix with a root mean squared (RMS) error lower than two pixels. This image map was then integrated with elevation data from a Digital Elevation Model (DEM) of Antarctica (Remy *et al.*, 1999) available for the plateau side of Frontier Mountain. DEM data, based on the ERS-1 satellite radar altimeter, have accuracy better than 1 m. Additional elevation data were imported from the digitised U.S.G.S. 1:250 000 reconnaissance maps Freyberger Mountains, Mount Murchison, Sequence Hills and Welcome Mountains. This integrated map has been used as a basis for mapping and displaying the gathered data.

Through the analyses of the Landsat image we derived the wind field responsible for ablation and redistribution of meteorites in the Frontier Mountain blue ice field. The albedo of snow, firn and ice generally decreases from the visible to the near infrared wavelengths (Warren, 1982; Zibordi *et al.*, 1996). This difference in spectral response enables distinction of blue ice from snow-covered areas and identification of major snowdrifts, snowplumes and sastrugi, whose orientation is controlled by dominant wind directions (Figs. 2 and 3).

Furthermore, the analyses of the Landsat image, integrated with DEM, has provided us with the ice flow pattern in the Frontier Mountain region. According to the principle that ice masses move under the force of gravity towards topographic lows, flow directions were drawn along the prominent surface slopes observed in the Landsat scene and perpendicular to the trend of DEM surface contours (Fig. 2). From flow directions we have then defined the drainage area of the Frontier Mountain blue ice field.

### Meteorite Search Campaigns

Two of us (L. Folco and M. Mellini) took part in the 1993, 1995, 1997 and 1999 meteorite search campaigns which lasted 2 to 4 weeks, from mid-December to early January of the following year. Field teams consisted of three to five searchers operating from a tent camp pitched on the blue ice field (Fig. 3), ~5 km due east of the mountain (~72°57'12" S to 160°28'39" E,

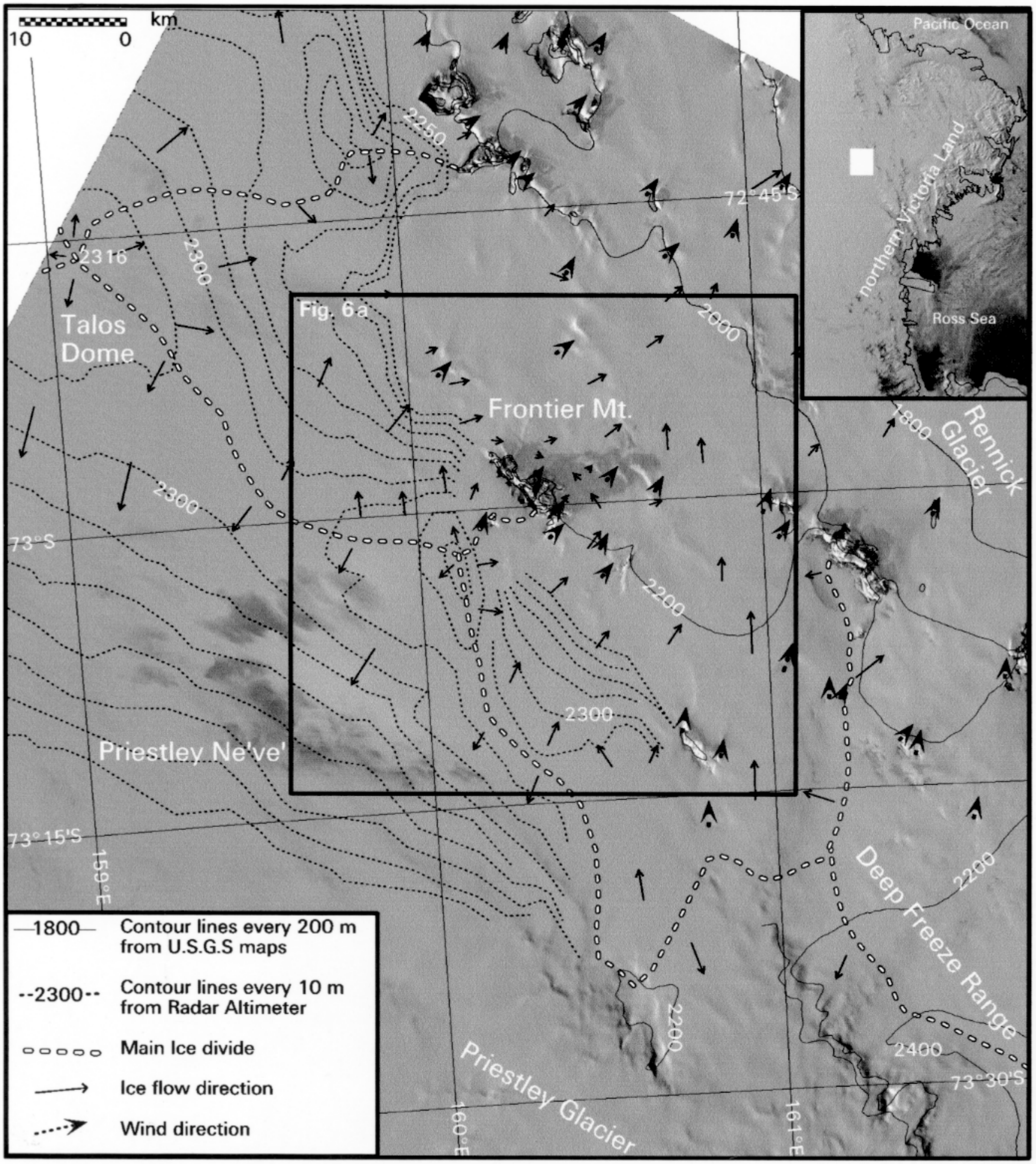

FIG. 2. Satellite image map showing the wind field and ice flow pattern in the Frontier Mountain area. Additional information on the outlined area are given in Fig. 6a.

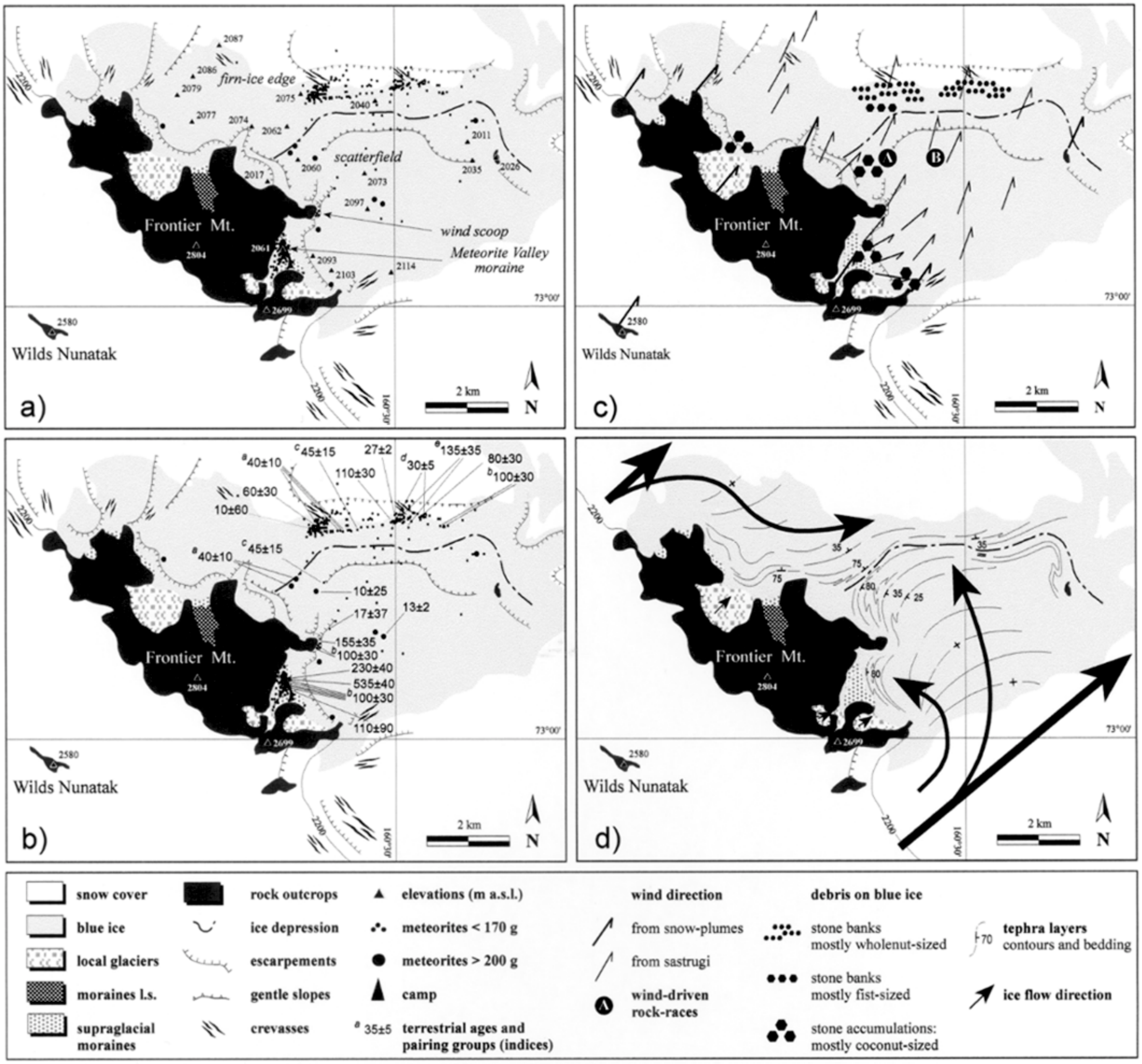

FIG. 3. Sketch maps of the Frontier Mountain blue ice field. (a) Main geomorphological data and meteorite distribution. (b) Geographic distribution of terrestrial ages of meteorites and pairing groups available from literature (*i.e.*, Wieler *et al.*, 1995; Terribilini *et al.*, 2000; Welten *et al.*, 2001; Welten, 2001, pers. comm.); indices (a) and (b) correspond to the FRO 90001 and FRO 90174 showers recognized by Welten *et al.* (2001) and Welten (2001, pers. comm.), respectively; other indices indicate possible pairs according to Welten *et al.* (2001) and Welten (2001, pers. comm.). (c) Wind field, geographic distribution of local stones and location of the wind-driven rock-races. (d) Generalized contours and bedding of tephra layers and ice flow pattern.

~2040 m above sea level). The entire extension of the blue ice area and moraines were systematically searched on foot or through snowmobile traverses to verify the existence of other meteorite accumulations, besides the two previously discovered in the "Meteorite Valley" and at the northern boundary of the blue ice area (Delisle *et al.*, 1989, 1993). With the exception of strong blizzards with gusts up to 70 knots (~130 km/h) which stopped the search for several days in 1993, and a transient snow-cover which blanketed 30–50% of the blue ice area in the 1993 and 1999 campaigns, operating conditions were generally good: the average air temperature was –18 °C and the strength of the dominant south-southwesterly winds did not exceed 35 knots (~65 km/h), with no or minor snow drift. From 1993 to 1999, 205 meteorite fragments were recovered.

Specimens were found not only in the "old sites", but also scattered in the blue ice area in between. Their find locations were acquired by hand-held GPS receivers (accuracy ±100 m) and recorded together with a description of the recovery site. Once returned to the laboratory, the meteorite specimens were dried, weighed, sectioned and classified (see meteorites named Frontier Mountain (FRO) 93###, FRO 95###, FRO 97### and FRO 99### in The Meteoritical Bulletin No. 81, 82, and 84 (Grossman, 1997, 1998, 2000). All these data have been included in a data base, along with data relative to the meteorites found in the previous 1984 and 1990 expeditions (see meteorites named FRO 84### and FRO 90### in The Meteoritical Bulletin No. 72, 73, 74, 75, and 77 (Wlotzka, 1992a,b, 1993a,b, 1994) and in Delisle *et al.*, 1989). A Geographic Information System (GIS) which allows the display of specimens and their attributes (*e.g.*, name, position, class, weight, *etc*.) on a georeferenced Landsat scene was developed to obtain precise distribution maps (Palladino *et al.*, 1996). The geographic coordinates of the 1984 finds necessary for the GIS were derived from the description of the recovery sites given by Delisle *et al.* (1989); those relative to the 1990 finds were provided by one member of the 1990 expedition (I. A. Franchi, pers. comm., 1994).

A number of local geomorphological features were mapped during the course of the four search campaigns including overall morphology of the blue ice area, local glaciers, moraines and major crevasses fields. Data is shown in Fig. 3.

Furthermore, the numerous tephra layers cropping out at the blue ice surface (Perchiazzi *et al.*, 1999) were mapped to gain qualitative information on ice flow; the horizontal bedding at the time of deposition of tephra layers is in fact deformed by movement of ice against bedrock relief (*e.g.*, Koeberl *et al.*, 1988; Koeberl, 1989). Data is shown in Fig. 3.

## Wind-Driven Rock Races

Delisle *et al.* (1993) suspected that small (up to 110 g) meteorite fragments are wind-blown across the Frontier Mountain ice field. In fact, Schutt *et al.* (1986) demonstrate that wind action plays an important role in redistributing stones on the Allan Hills bare ice and measured a mass-threshold for wind-driven stones of ~70 g (see also Harvey and Cassidy, 1989; Harvey, 1995). In order to better constrain the mass transport by wind at Frontier Mountain, in the 1993 campaign we installed two "rock races" in a flattish area of the blue ice field (Fig. 3), in a manner similar to the experiment conducted by Schutt *et al.* (1986). The "racers", two suites of rounded local stones weighing from 1 to 780 g, were painted red and placed in rows perpendicular to prevailing winds (Fig. 4). During the 1995 and 1997 campaigns, the movement of "racers" was surveyed. Results are reported in Table 1.

## Strain-Net Measurements

In the 1993 field season, a network of 23 aluminium stakes was planted in the ice of the Frontier Mountain area (Fig. 5) to

TABLE 1. Results of wind-drifted rock-races after 4 years from installation in 1993.

| Team A (72°58'09" S to 160°25'36" E) | | | Team B (72°58'05" S to 160°28'30" E) | | |
|---|---|---|---|---|---|
| Racer weight (g) | Distance travelled (m) | Direction of movement (°N) | Racer weight (g) | Distance travelled (m) | Direction of movement (°N) |
| 1 | nf | – | 2 | nf | – |
| 4 | 4 | 30 | 6 | 0.8 | 20 |
| 7 | nf | – | 14 | nf | – |
| 15 | nf | – | 24 | 0 | – |
| 17 | 0 | – | 41 | 2.5 | 15 |
| 23 | nf | – | 55 | 0 | – |
| 35 | 0.5 | 40 | 75 | 0 | – |
| 47 | 0 | – | 86 | 0 | – |
| 69 | 40 | 70 | 98 | 0 | – |
| 75 | 4.5 | 30 | 109 | 0 | – |
| 82 | 50 | 60 | 121 | 0 | – |
| 91 | 1 | 40 | 129 | 2.5 | 20 |
| 103 | 0 | – | 171 | 7 | 20 |
| 118 | 3 | 40 | 205 | 0 | – |
| 128 | 0 | – | 223 | 0 | – |
| 159 | 0 | – | 265 | 0 | – |
| 201 | 0 | – | 377 | 0 | – |
| 444 | 0 | – | 666 | 0 | – |
| 780 | 0 | – | | | |

nf = not found.

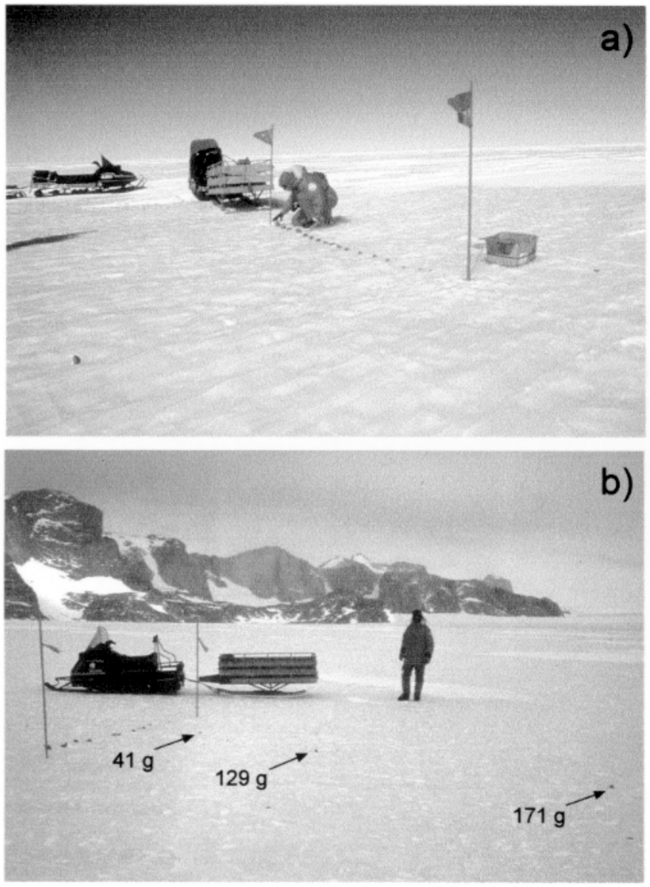

FIG. 4. Wind-driven rock race "team B". (a) Picture taken from the north at the time of installation in 1993. (b) Picture taken 2 years later (1995) from the east recording the northeastward drift of three "racers" up to 171 g in weight.

gain information on annual ice movement and ablation rates. Twenty-one stakes were set in the blue ice area where meteorites accumulate, including four in the moraine of the "Meteorite Valley" and two outside the blue ice area, upstream and downstream of Frontier Mountain, respectively.

The planimetric variation in the position of stakes was monitored over a 4 year period through GPS measurements in order to obtain the annual horizontal component of the ice flow at the surface. Positions were determined by means of the fast-static GPS method relative to a base station installed on the rock outcrop 5 km due east of Frontier Mountain, <12 km away from the farthest stake of the network. Signal acquisition typically lasted 15 to 25 min. The absolute positions of the stakes in WGS-84 coordinates were then derived from the coordinates of the baseline station, measured by means of the static GPS method relative to a master GPS station at Terra

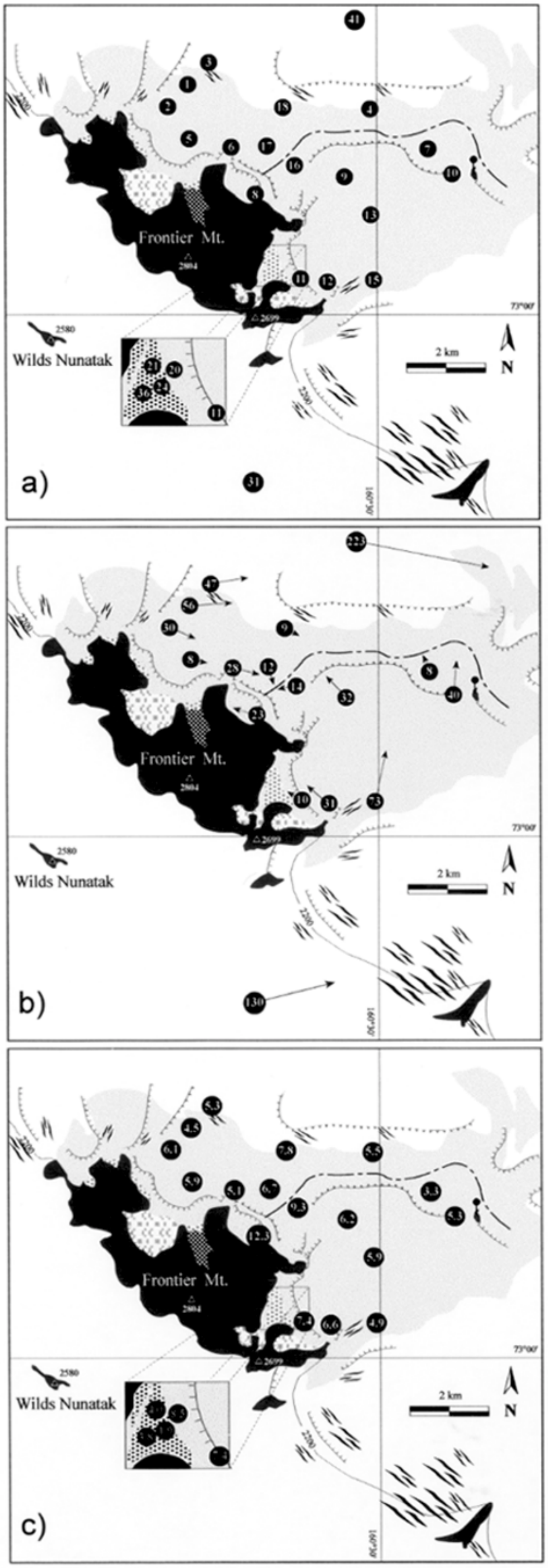

FIG. 5. (*Right*) Sketch maps showing data from the strain-net network installed in the Frontier Mountain ice field. (a) Station numbers. (b) Horizontal component of ice movement given in centimeters per year. (c) Ice ablation rates given in centimeters per year.

Nova Bay Station. The master station is ~221 km due south-southeast of the base station at Frontier Mountain, thus signal acquisition lasted up to 9 h. The instrumental accuracy for the planimetric positioning is ±1 cm; operator precision in measuring the pinpoint position of the stake is estimated to be lower than ±1 cm; the total error is thus conservatively estimated to be ±2 cm. The GPS measurements also provided WGS-84 elevations at each station, providing additional information on the morphology of the area. Results are reported in Table 2. Due to either unfavorable satellite configuration at the time of signal acquisition or bad weather conditions, repetition of the GPS measurements at stations #4, #5, #13, #20, #21, #24 and #36 was not possible; however, available data provide us with good coverage of the ice movement in the area (Fig. 5).

The height above ice surface of the 21 stakes in the blue ice field and in the moraine of the "Meteorite Valley" were repeatedly measured in the 1993, 1995, 1997 and 1999 field seasons to determine the annual rate of ice ablation or snow accumulation. As the blue ice surface is irregular because sun cupped, maximal and minimal heights were estimated during each survey and then averaged. Results are reported in Table 2 and Fig. 5. Values are averages from the three surveys carried out every 2 years after installation in 1993.

## Radar Echo Sounding Survey

Measurements of ice thickness and bedrock topography were obtained by digital airborne radar surveys carried out in the 1995 and 1997 field seasons. As shown by the flight paths drawn in Fig. 6, the investigated area is a 20 by 45 km southwest-northeast trending stretch extending from the Polar Plateau, through the Frontier Mountain blue ice field, to the inland sector of the upper Rennick Graben.

The radar equipment was a 60 MHz apparatus that transmits a pulse of controlled duration of ~1 kW peak power with a pulse lenght of 1 $\mu$s. The radar equipment was deployed by a Twin Otter aircraft with folded, dipole radar antennas under each wing: one for transmittal, the other for reception. In 1997, improvements were made to the system's hardware and software (Tabacco *et al.*, 1999). The sampling rate of the analog signal was doubled to 1024 samples every 50 ns to increase the

TABLE 2. Strain-net data.*

| Station number | Description of site | Location | | | Ice ablation Annual rate (cm/year) | Ice movement† | |
|---|---|---|---|---|---|---|---|
| | | S Latitude | E Longitude | WGS84 Elevation (m) | | Annual velocity (cm/year) | Bearing (°N) |
| 1 | blue ice | 72 56 57 | 160 21 55 | 2086 | 4.5 | 56 | 86 |
| 2 | blue ice | 72 57 14 | 160 20 54 | 2079 | 6.1 | 30 | 114 |
| 3 | blue ice | 72 56 41 | 160 22 49 | 2087 | 5.3 | 47 | 81 |
| 4 | blue ice | 72 57 14 | 160 29 07 | 2042 | 5.5 | nd | nd |
| 5 | blue ice | 72 57 34 | 160 21 18 | 2077 | 5.9 | 8 | 93 |
| 6 | blue ice | 72 57 45 | 160 22 59 | 2074 | 5.1 | 28 | 104 |
| 7 | blue ice | 72 57 40 | 160 32 54 | 2011 | 3.3 | 8 | 325 |
| 8 | blue ice | 72 58 19 | 160 24 18 | 2017 | 12.3 | 23 | 288 |
| 9 | blue ice | 72 58 01 | 160 28 21 | 2073 | 6.2 | 32 | 315 |
| 10 | blue ice | 72 58 03 | 160 33 28 | 2035 | 5.3 | 40 | 5 |
| 11 | blue ice | 72 59 26 | 160 25 48 | 2093 | 7.4 | 10 | 308 |
| 12 | blue ice | 72 59 32 | 160 26 23 | 2103 | 6.6 | 31 | 318 |
| 13 | blue ice | 72 58 31 | 160 29 29 | 2097 | 5.9 | nd | nd |
| 15 | blue ice | 72 59 21 | 160 29 59 | 2114 | 4.9 | 73 | 12 |
| 16 | blue ice | 72 58 01 | 160 26 03 | 2060 | 9.3 | 14 | 257 |
| 17 | blue ice | 72 57 51 | 160 25 17 | 2062 | 6.7 | 12 | 164 |
| 18 | blue ice | 72 57 15 | 160 26 11 | 2075 | 7.8 | 9 | 122 |
| 20 | blue ice | 72 59 22 | 160 24 47 | 2061 | 8.5 | nd | nd |
| 21 | moraine | 72 59 19 | 160 24 35 | 2085 | 4.0 | nd | nd |
| 24 | moraine | 72 59 27 | 160 24 29 | 2068 | 1.9 | nd | nd |
| 31 | firn | 73 02 48 | 160 23 49 | 2277 | nd | 130 | 76 |
| 36 | moraine | 72 59 27 | 160 24 13 | 2061 | 3.8 | nd | nd |
| 41 | firn | 72 56 00 | 160 28 27 | 2067 | nd | 223 | 111 |
| Baseline stn. | rock outcrop | 72 58 09 | 160 34 50 | 2026 | – | – | – |

*Ablation rates are relative to the 1993–1999 period; surface ice velocities (horizontal component) are relative to the 1993–1997 period.
†Horizontal component of the ice movement.
nd = not determined.

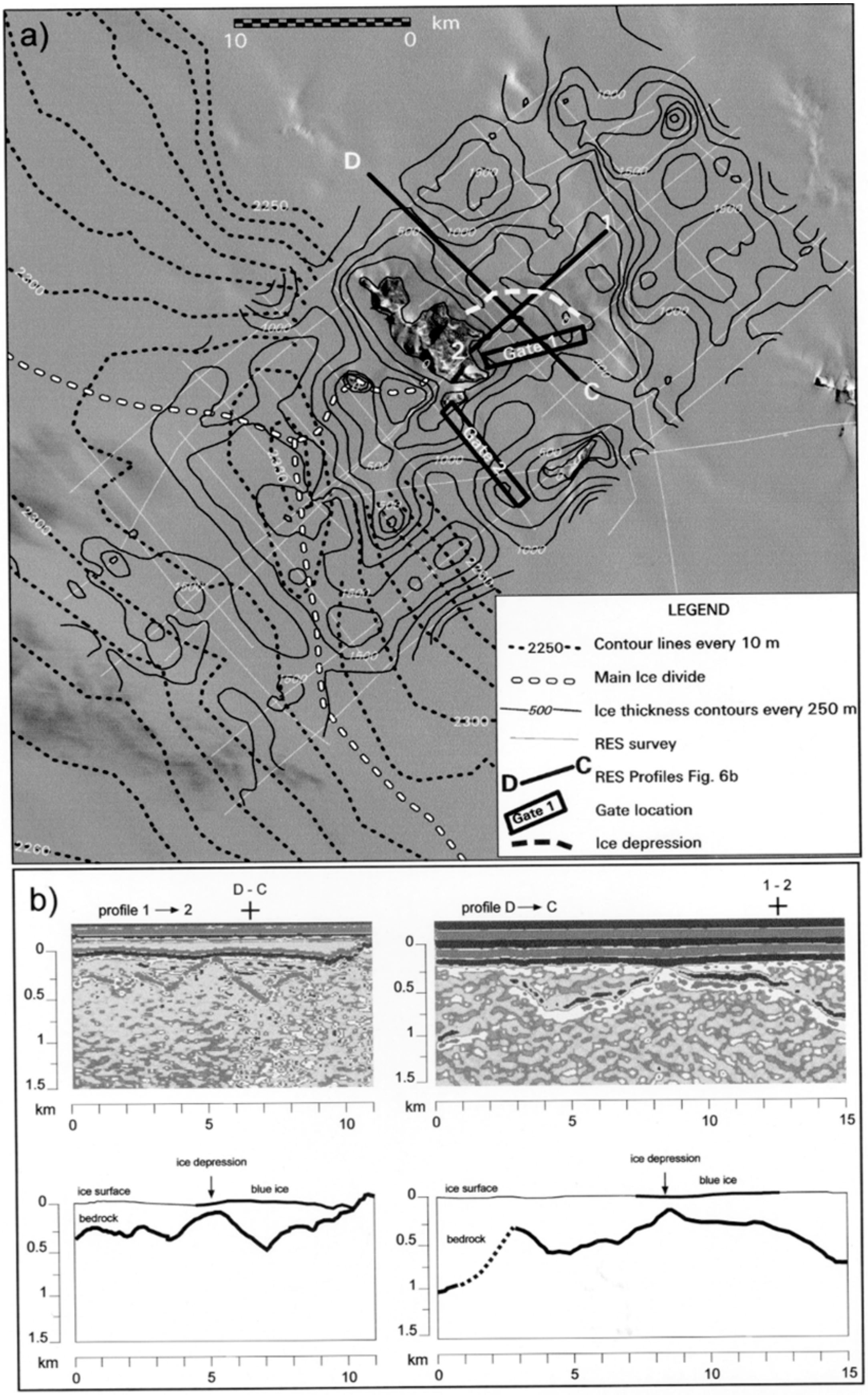

FIG. 6. (a) Satellite image map of the Frontier Mountain area showing the flight paths of the airborne RES, the locations of GATES, generalized bedrock and ice surface contours; for ice flow pattern in the area see Fig. 2. (b) Echograms 1–2 and C–D in the blue ice area.

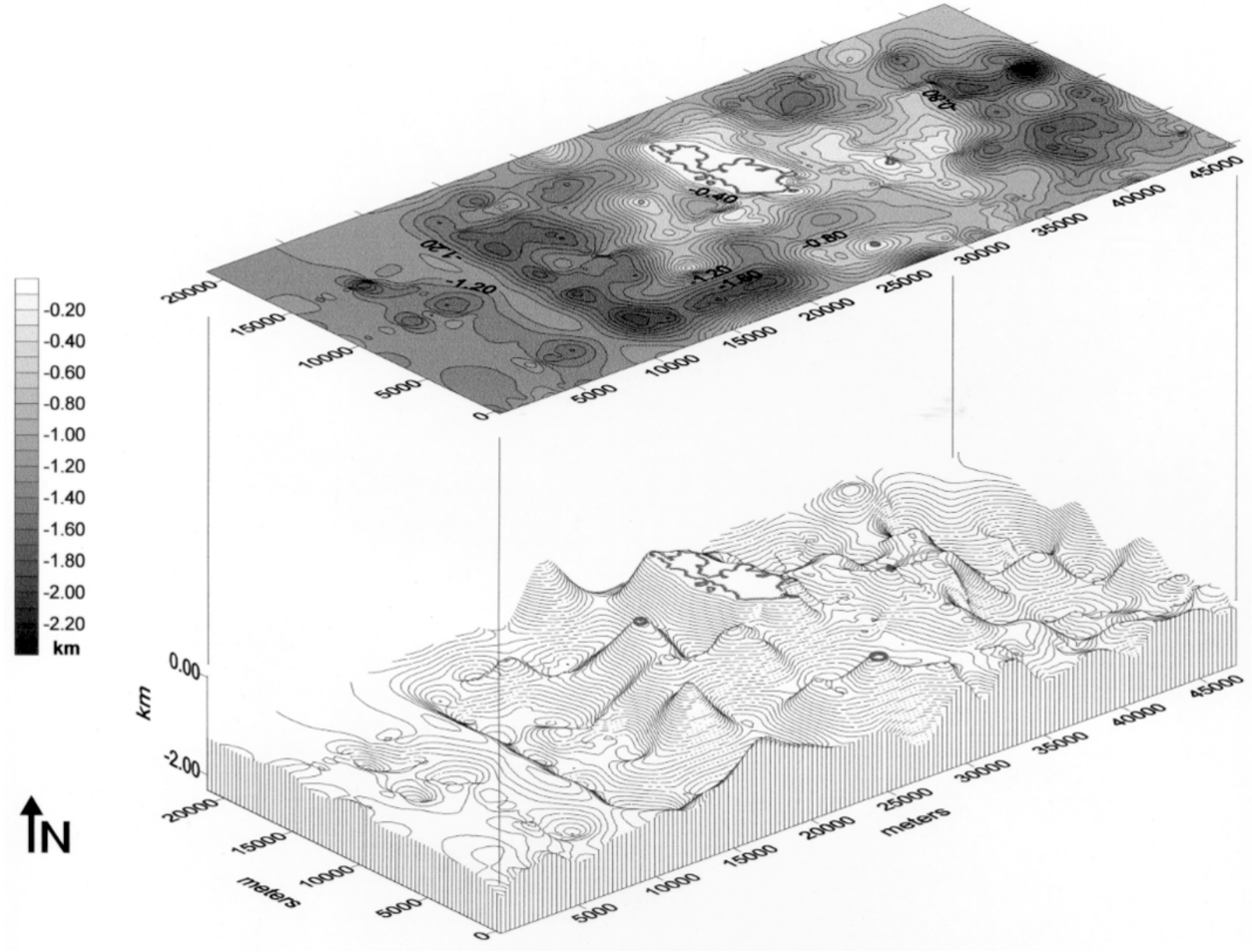

FIG. 7. Bi- and tridimensional view of bedrock topography in the Frontier Mountain area.

precision of ice-depth determination (±4 m). Antenna gain is estimated to be 4 dB. A GPS Trimble 4000 SSE system (L1 and L2 frequency) with the antenna mounted on the fuselage was installed and linked to the radar. A master GPS station, synchronized with the rover, was installed at Terra Nova Bay Station. to enable differential correction of data. The survey was completed in two flights with cruise speed ranging from 100 to 120 knots (~185 to 222 km/h) and an average altitude from surface of 1000 feet (~328 m) controlled by radar altimeter. A synchronized GPS system with ±20 m precision in $X$, $Y$ coordinates (only pseudo-range differential corrections were done) was used to georeference the radar data. A constant electromagnetic wave propagation velocity of 168 m $\mu s^{-1}$ was assumed. Thickness was determined to the nearest digital sample on the record with a digitizing error of ±100 ns (1995) and ±50 ns (1997) for both surface and bed reflections. This corresponds to an RMS uncertainty in thickness of about ±16 m for the 1995 data set or ±8 m for the 1997 data set. Ice thickness data at each intersection of longitudinal and transverse profiles were compared; measurements differed by <10 m (*i.e.*, lower than the estimated accuracy in thickness determination). Ice thickness data have been used to model the tridimensional view of the bedrock topography shown in Fig. 7. The lack of an accurate elevation model for the whole investigated area has been circumvented referring the bedrock depths to a model surface of the ice sheet which approximates the actual ice surface (*i.e.*, an inclined plane with a 250 m relative elevation difference from southwest to northeast). This approximation is acceptable given that variations of ice thickness are generally 1 order of magnitude greater than elevation of the ice surface. Nevertheless, one must bear in mind that Fig. 7 provides us with the bulk of the bedrock topography in the Frontier Mountain area, and that more precise ice thickness values can only be obtained from analyses of the radar echograms, such as those given in Fig. 6.

## THE SITE

Figures 2 and 3 show the location of the Frontier Mountain meteorite stranding surface and its main morphological features, obtained from field surveys and remote sensing analyses.

Frontier Mountain is an ~9 km northwest-southeast trending ridge within the Transantarctic Mountains in northern Victoria Land (72°59' S, 160°20' E). The mountain, culminating at 2804 m a.s.l., projects for as much as ~800 m above the ice sheet descending northeastward from the Polar Plateau toward the upper sector of the outlet Rennick Glacier. The ice surface swells above ~2300 m above sea level on the plateau side of Frontier Mountain, slopes around both its ends through a series of crevassed ramps, then levels to about 2000–2100 m above sea level on its northeastern side.

The Frontier Mountain area is beaten by southwesterly katabatic winds, as indicated by the orientation of large snow-plumes, snow-drifts and sastrugi. On the down-wind side of Frontier Mountain, turbulent windfalls prevent snow accumulation and expose a ~42 km$^2$ blue ice field to active ablation. A major feature of the blue ice area is a shallow (down to ~30 m deep), east-west trending depression which crosscuts the blue ice field. At the foot of the mountain, the blue ice surface drops down ~70 m along steep ramps and windscoops.

The mountain is mainly ice-free and consists of felsic granitoids belonging to the Granite Harbour Intrusive Complex (Gunn and Warren, 1962) and minor dark thermometamorphosed schists (GANOVEX III, 1987). Three local glaciers extending for less than a few square kilometers descend the northeastern flank of Frontier Mountain. A number of glacial valleys running on the northeastern side of Frontier Mountain admit blue ice tongues fringed by supraglacial moraines of local drift. Wilds Nunatak (~2580 m above sea level), a granitic crest 3 km due west of Frontier Mountain, and an unnamed outcrop of bedrock schists (2026 m above sea level) which marks the eastern end of the ice depression in the blue ice field, are two very minor nunataks in the close proximity of Frontier Mountain.

With the six search campaigns the entire extension of the blue ice field and the glacial valleys were thoroughly searched. 472 meteorite totaling 11.744 kg have been recovered (Folco and Mellini, 2000). The Frontier Mountain meteorite collection (1) is characterized by a high frequency of ordinary chondrites (96%), with a high H-/L-class ratio of 3.4 that can in part be explained by the presence of a few showerfalls in the H-class population (Welten *et al.*, 2001); (2) lacks iron meteorites, stony-iron meteorites and enstatite chondrites, in keeping with the low-frequency trend common to other Antarctic populations; (3) includes some remarkable specimens such as eight ureilites, three lodranites, one acapulcoite, two eucrites, two CO3 and two CV3 (Folco and Mellini, 2000). Figure 3 shows the meteorite distribution map, derived from a GIS (Palladino *et al.*, 1996). The distribution is very localized. The majority (88%) of meteorites comes from the stretch of ice on the northern slope of the ice depression at the firn-ice boundary (the "firn-ice edge") and from the moraine of the "Meteorite Valley" (the "Meteorite Valley moraine"). The remaining specimens were found either scattered across the ice patch in between the firn-ice edge and Frontier Mountain (the "scatterfield") or accumulated in a wind scoop at the mouth of the "Meteorite Valley" (the "wind-scoop"). Specimens are small ranging from 0.15 to 1667.8 g, with 90% of the fragments weighing less than the average mass of 25 g. The largest meteorites were found in the "scatterfield". Pictures of the four recovery sites are given in Fig. 1. Since the Frontier Mountain ice field has been thoroughly searched for six times, we believe that the map in Fig. 3 is representative of the actual meteorite distribution, (*i.e.*, that no other localized accumulation sites are expected to be found). However, due to the unfavorable conditions such as the snow cover that hampered search in the 1993 and the 1999 campaigns, more meteorites are expected to be found in some areas. In particular, we suppose that the meteorite trap has so far yielded >50% of its potential (both in terms of number of specimens and of total mass to be found).

### The "Meteorite Valley Moraine"

The southeastern end of Frontier Mountain is crosscut by a glacial valley (Figs. 1 and 3). As described by Höfle (1989) and Delisle (1989), the valley walls bear roches moutonnées, striations and friction cracks indicating that during a former, undated highstand the ice sheet streamed northeastward through the valley. Today blue ice enters the valley from the east and meets an ice flow descending from a local glacier. A depression occurs where the blue ice tongue enters the valley. Rows of local, coconut-sized stones cover the bottom of the depression. A few boulders, likely fallen from the valley walls, are scattered on the ice ramp on the upwind side of the depression. Meter-sized wind scoops at the base of these boulders are filled with wind-drifted, pebble-sized stones. Further on towards the center of the valley, a 0.3 km$^2$ supraglacial moraine of local rocks lies on the terminal front of the blue ice tongue. The moraine is characterized by a number of lunate crests indicating recession of the moraine front. The topographic profile gently slopes from the crests towards the center of the valley. Here a frozen lake gathers occasional melt-water run-off (not observed in the 1993, 1997 and 1999 campaigns). The moraine deposit consists of a centimeter thick veneer of stones and meter-sized boulders scattered throughout. Meteorites were found scattered across the whole extension of the moraine, with a higher concentration on the moraine crests. They were usually mixed within the rock debris, with some resting on the moraine-ice interface (see also Delisle *et al.*, 1986, 1989, 1993). The moraine has yielded a total of 170 specimens. With the exception of five specimens in the 23–106 g mass range, the meteorites from the moraine typically weigh <20 g (Fig. 8), with average mass of 7 g. Meteorites from the "Meteorite Valley moraine" may be more weathered than those from elsewhere.

## The "Wind Scoop"

The ice ramp at the entrance of the "Meteorite Valley" ends in a wind scoop at the foot of the northern valley wall (Figs. 1 and 3). The "wind scoop" consists of a series of ice terraces, which are closed upwind by ice cliffs. Here a total of nine meteorite fragments lighter than 10 g (Fig. 8) were found in the 1990 and 1993 visits. Samples were found mixed together with a wind-blown debris of pebble-sized stones resting on bare ice. Subsequent visits proved unproductive.

## The "Firn-Ice Edge"

The northern flank of the ice depression is the most productive site and has yielded 244 meteorite specimens (Figs. 1 and 3). Meteorites are small: the average weight is ~11 g, and no sample exceeds 166 g (Fig. 8). Most specimens rest on bare ice within an aeolian accumulation of local stones on the downwind side of the ice-firn boundary. The local stones have subangular shapes (indicating the importance of abrasion) and are arranged in banks which lie perpendicular to the wind direction and parallel to the firn edge.

## The "Scatterfield"

Forty-nine meteorite samples were found strewn across the blue ice area stretching from the mountain to the "firn-ice edge" accumulation (Figs. 1 and 3). This area is characterized by the presence of millions of scattered local stones with angular to subangular shapes. The size of the stones ranges from ~15 cm down to <1 cm in diameter. Large stone accumulations are observed close to the foot of the mountain. Likewise, meteorites weigh from 1670 g down to <1 g (Fig. 8). Eight of nine large specimens (>200 g) were found due south of the ice depression, with the majority near the foot of the mountain or close to the bottom of the ice depression (Fig. 3). Meteorites from the "scatterfield" are typically less weathered than those from elsewhere.

The overall distribution of stones in the Frontier Mountain blue ice area indicates that wind plays an important role in redistributing meteorites on bare ice. Stones are size-sorted with masses decreasing from the foot of the mountain to the northern boundary of the ice field (Fig. 3). The strength of the southwesterly katabatic winds recorded during the 1993, 1995, 1997 and 1999 expeditions typically ranged between 20 and 35 knots (~40 and 65 km/h); occasional storms with wind strengths exceeding 70 knots (~130 km/h) were recorded in 1993. The orientation of the sastrugi encarved in snow-dunes in the blue ice area indicate only some deflection of the katabatic winds at the foot of the downwind side of the mountain (Fig. 3).

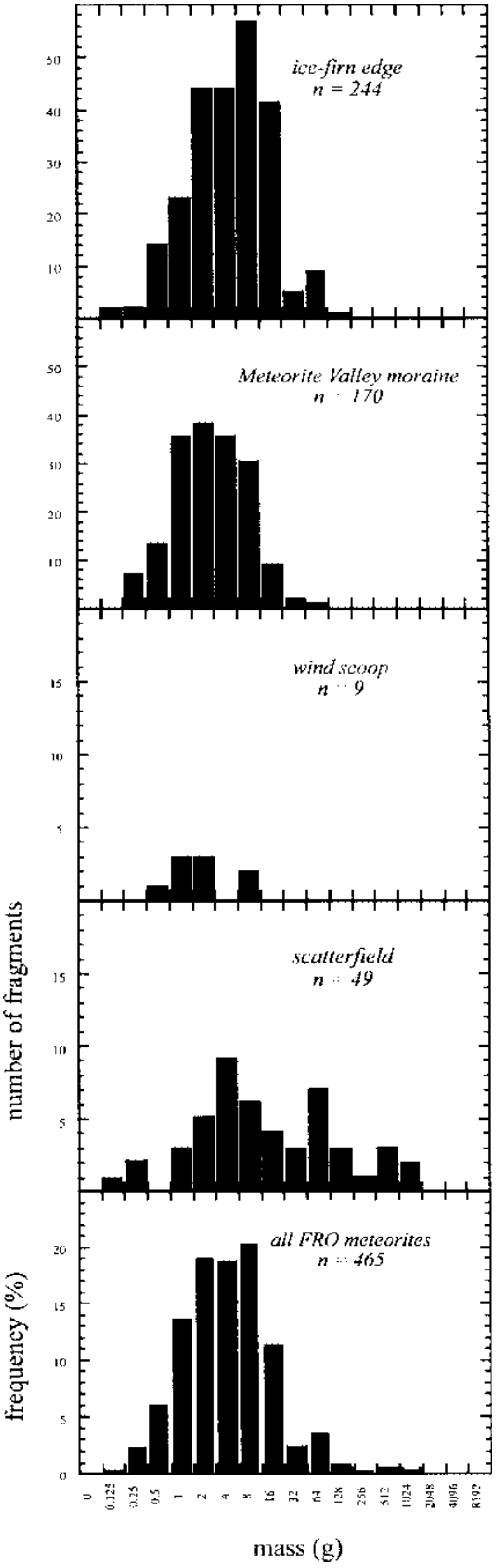

FIG. 8. (*Left*) Mass distribution of the 472 meteorite specimens so far found at Frontier Mountain. The total recovered mass is 11.744 g; masses range from 0.15 to 1667.8 g; the mean mass is 25.3 g; the median mass is 5.6 g; the mode mass is 1.9 g.

The two wind-driven rock races installed in 1993 in two flattish areas of the "scatterfield" (Figs. 3 and 4) indicated that stones heavier than 201 g did not move, whereas the 171 g stone and several of the lightest ones moved northeastward in the direction of prevailing winds. All of the stones weighing <23 g were lost, except for the "team A" racer weighing 17 g that did not move. Several stones ranging from 24 to 171 g moved from 0.5 to 50 m in 2 years. The field test thus indicates that stones lighter than ~200 g can be displaced by wind action along flattish areas of the Frontier Mountain ice field; the annual velocity for stones weighing from ~100 to ~170 g is in the order of 1 m/year, that for lighter stones decreases to ~25 g is 10 m/year, whereas much faster velocities are inferred for stones lighter than ~25 g. The lack of a clear negative correlation between weight and distance traveled is due to the dissimilar shapes of "racers" and to the roughness of the sun cupped blue ice surface. In addition to the rock race experiment, the local stones arranged in banks at the "firn-ice edge" were weighed using a field scale (see also Folco *et al.*, 1995). Measurements were carried out at several banks along a traverse parallel to the prevailing wind direction. Stones are sorted by weight with masses decreasing along wind direction on the upwind flank of the ice depression; the trend is not linear because sorting is complicated by the presence of transient snow dunes. Importantly, however, the stones of the first bank weigh <250 g and have an average weight of 175 g. This data, coupled with the 166 g of the heaviest meteorite fragment found in the "firn-ice edge", is in substantial agreement with the 200 g transport threshold obtained from the rock races experiment. The threshold is almost twice as high as that reported for the Allan Hills ice fields (Shutt *et al.*, 1986) and suggests different maximal wind speeds.

## ICE FLOW

### Ice Flow Pattern and Drainage Area

Figure 2 shows the ice flow pattern in the Frontier Mountain area determined from DEM data available only for the plateau side of the Frontier Mountain region, and the geomorphological analysis of a Landsat image. Additional information on ice flow in the blue ice field were inferred from the bedding of tephra layers (Fig. 3).

A northwest-southeast trending, curvilinear ridge of the ice sheet runs on the plateau side of Frontier Mountain (Fig. 2) at an elevation of ~2310 m above sea level. It marks the main ice divide separating two drainage systems of the southeastern flank of the Talos Dome, a ~2316 m above sea level peripheral dome of the East Antarctic ice sheet, ~65 km due northwest of Frontier Mountain. On the southern side of the divide, the ice descends southwards through the Priestley Glacier towards the Ross Sea. On the northern side, the ice sheet moves in a northeastward direction, flows around Frontier Mountain and descends onto the inland sector of the Rennick Graben. The ice ultimately feeds the upper Rennick Glacier which streams northward into the South Pacific Ocean. About 10 km due west of the southeast end of Frontier Mountain, the divide separating the Priestly Névé from the Rennick Névé runs over a modest bulge (~2300 m above sea level). A secondary ice divide connecting this bulge, Wilds Nunatak and the western flank of Frontier Mountain separates the two accumulation areas feeding two ice flows passing both ends of Frontier Mountain. A large part of these two ice flows proceed northeastward; however, portions curl back towards the downstream side of Frontier Mountain to form two lobes which meet along the depression in the blue ice field (Fig. 3). Tephra layers cropping out at the surface of the blue ice field indicate that the otherwise undisturbed, horizontal bedding of the ice is deformed and upthrust at the northeastern foot of Frontier Mountain and on both sides of the ice depression, indicating compressive flow against a shallow bedrock.

Although these results confirm the regional ice flow pattern illustrated by Höfle (1989), we observe that the Frontier Mountain blue ice field is supplied by smaller drainage basins. In fact, we locate the ice divide separating the Priestly Névé and the Rennick Névé 10–30 km further northeast. In particular, we infer that the ice flowing around the southern and the northern ends of Frontier Mountain have modest catchment basins extending for only ~15 and ~20 km upstream of the mountain.

### Ice Velocity

Figure 5 and Table 2 report annual horizontal components of the surface ice movement, obtained from the network of 17 GPS stations monitored in the Frontier Mountain area.

In general, these quantitative results confirm the qualitative flow pattern previously defined through interpretation of ice surface features and bedding of tephra layers. Furthermore, we observe that the blue ice field is a stagnant area where the horizontal velocity of the ice sheet is significantly decelerated; ice from the polar plateau approaches Frontier Mountain at a speed in excess of 100 cm/year (station #31), slows down to tens of centimeters per year (or less) in the blue ice field (stations #1 to #18), and then leaves as fast as 200 cm/year on its descent towards the Rennick Glacier (station #41). This feature is characteristic of the blue ice fields where meteorites are found concentrated (*e.g.*, Cassidy *et al.*, 1992).

Strain-net data also indicates that the ice depression is the actual boundary between the two ice flows invading the blue ice field from the polar plateau. The southern ice flow turns back in an overall north-northwest direction and its forward flow appears impeded between the mountain and the northern ice flow. Annual horizontal velocities decrease considerably from ~73 cm/year down to <10 cm/year on approaching the mountain and the ice depression. Most of the northern ice flow proceeds eastward parallel to the ice depression, away from the blue ice field; horizontal velocities range from ~60 to 10 cm/year and, in general, decrease towards the mountain and the ice depression. The southermost ice patch at the foot of the mountain slowly moves towards the ice depression.

## Ice Thickness and Bedrock Topography

Ice thickness and bedrock topography in the Frontier Mountain area were measured by digital airborne radar surveys. As shown by the flight paths drawn in Fig. 6, the investigated area is 20 km wide and extends northeastward for over 45 km from the snow accumulation zone on the Polar Plateau, through the Frontier Mountain blue ice field, to the inland sector of the upper Rennick Graben.

As shown in Fig. 7, the bedrock topography consists of three northwest-southeast trending zones sub-parallel to the axis of the Rennick Glacier. There is a deep basin on the polar plateau side of Frontier Mountain, where the thickness of the ice sheet ranges from 1000 to 2000 m. The basement rises in the central zone around Frontier Mountain and beneath its blue ice field, and then descends to depths lower than 2000 m below ice surface further downstream toward the Rennick region. A pass as deep as 1000 m below ice surface cuts across the northern foot of Frontier Mountain and connects the two low bedrock zones. Due southwest of Frontier Mountain there are two sharp subsurface peaks, culminating at depths lower than –50 m. These peaks, Wilds Nunatak and Frontier Mountain, are interconnected by shallow (350 m below ice surface) saddles and represent the upstream extension of the Frontier Mountain massif. On the whole these heights give rise to a wedge-shaped structure pointing in the southwest direction. Underneath the eastern end of the blue ice field, there is a major shallow ridge parallel to Frontier Mountain but offset due southeast by a few kilometers. The crest of this ridge extends for ~5 km at depths lower than 300 m below ice surface, and culminates with the rock outcrop at the eastern end of the depression in the blue ice. A saddle running underneath the ice depression in the blue ice field connects the sub-ice ridge with Frontier Mountain. Thus, the eastern flank of Frontier Mountain and its eastern sub-ice extensions give rise to a southwest facing amphitheater-like structure where the bulk of the Frontier Mountain blue ice field develops. The radar profiles which provides us with ice thickness with an uncertainty of less than ±16 m (Fig. 6) indicate that the head-wall of the amphitheater-like structure underneath the ice depression is <200 m below ice surface and that the bottom of the amphitheater is sitting at 470 m below ice surface at most. This sub-ice structure is consistent with ice thickness data from a 5 km east-northeastward radar traverse from the "Meteorite Valley" by Delisle *et al.* (1989). A 700 m deep pass runs across the southermost end of the sub-ice ridge and connects the two bedrock lows due southwest of Frontier Mountain and due east of its blue ice area.

Figure 6 also shows that the ice divide separating the Rennick Névé and Priestley Névé is located over the bottom of the bedrock low upstream of Frontier Mountain. Thus the location of the ice divide is not controlled by bedrock topography, but most likely by climatic conditions, such as wind regimes, snow accumulation rates and the surface morphology of the Transantarctic Mountains.

There is a good consistency between bedrock topography and the ice flow pattern outlined in Figs. 2, 3 and 5. The wedge-shaped upstream roots of Frontier Mountain pointing against the direction of the northeast regional ice flow deflect the ice coming from the snow accumulation zone into two streams flowing around it. The northern ice flow encounters essentially no bedrock barrier during its flow toward the Rennick Glacier: the northeastern end of the sub-ice ridge downstream of Frontier Mountain affects the northern ice flow only marginally, decelerating its northeastward flow within the blue ice area. In contrast, part of the southern stream is blocked by the southwest facing amphitheater-like structure, given by the eastern flank of Frontier Mountain and its eastern sub-ice extensions running underneath the depression in the blue ice field.

## Ice Ablation

Figure 5 shows annual rates of ice ablation in the Frontier Mountain ice field, relative to the 1993–1999 time period, for 18 sites located in the blue ice area and three in the "Meteorite Valley moraine".

As observed during each survey, all measuring stations recorded surface ablation. No significant variations of surface ice loss were observed at each site during the various surveys, although important variations were recorded according to location and surface conditions, indicating an erosion process variable in space but constant in time.

Annual ablation rates in the blue ice area range from 3.3 to 12.3 cm/year, with a mean value of 6.5 cm/year. The minimal value of 3.3 cm/year was measured at station #7, located in the blue ice area close to the eastern end of the ice depression, where a transient 10 and 30 cm thick snow cover was observed in 1995 and 1999, respectively. The maximal value of 12.3 cm/year was measured at station #8, located in an ice fall at the foot of the mountain.

The mean annual ablation rate in the "Meteorite Valley moraine" is 3.2 cm/year, with values ranging from 1.9 to 4.0 cm/ year. The ice loss in the moraine is thus significantly lower than observed in the blue ice area with maximal value that barely overlaps the minimal value recorded in the blue ice field.

Table 3 compares annual ablation rates measured at Frontier Mountain with those existing in literature from other meteorite stranding surfaces, including Allan Hills, Elephant Moraine, Reckling Moraine (Victoria Land) and Yamato Mountains (Dronning Maud Land). The values measured at Frontier Mountain are consistent with those from other meteorite stranding surfaces. In particular, our survey confirms that lower ice ablation rates occur in moraines; Faure and Buchanan (1991) suggest that the lower rates measured in the moraines of the Allan Hills, Elephant Moraine, Reckling Moraine ice fields are due the fact that the debris cover provides some kind of protection to erosion. Nonetheless, the Frontier Mountain blue ice field records the higher mean ablation rate (6.5 cm/year *vs.*

TABLE 3. Comparison of annual ablation rates (cm/year) from various blue ice fields.

| | Blue ice | | | Moraine | | | Survey | Reference* |
|---|---|---|---|---|---|---|---|---|
| | Mean | Min. | Max. | Mean | Min. | Max. | | |
| Frontier Mountain<br>(72°57' S; 2100–2000 m a.s.l.) | 6.5 | 3.3 | 12.3 | 3.2 | 1.9 | 4.0 | 1994–1999 | This work |
| Allan Hills main ice field | 5 | 3.1 | 5.9 | – | – | – | 1979–1981 | (a) |
| (76°47' S; 2050–1900 m a.s.l.) | 4.6 | 2.7 | 5.7 | – | – | – | 1985–1987 | (b) |
| Elephant Moraine<br>(76°17' S; ~2150 m a.s.l.) | 4.1 | 2.9 | 5.3 | 2.5 | 0.2 | 4.5 | 1985–1987 | (b) |
| Reckling Moraine<br>(76°15' S; ~2100 m a.s.l.) | 4.1 | 1.5 | 6.7 | 1.6 | 0.6 | 3.5 | 1985–1987 | (b) |
| Yamato Mountains<br>(71°50' S; 2400–2250 m a.s.l.) | 5.4 | 2 | 7 | – | – | – | 1969–1973 | (c) |

abbreviations: a.s.l. = above sea level.
*References: (a) = Annexstad and Schultz (1983), Schultz and Annexstad (1984); (b) = Faure and Buchanan (1991); (c) = Nagata (1982).

4.1 to 5.4 cm/year in the other blue ice fields) and the highest minimal and maximal values (3.3 and 12.3 cm/year, respectively, against the 1.5 to 3.1 and 5.3 to 7 cm/year in other blue ice fields). This data parallels the outcome of the rock race experiments, which documents that the wind drift at Frontier Mountain is stronger than at Allan Hills. We infer that the higher ablation rates recorded at Frontier Mountain are due to stronger wind regimes. In addition, we observe that at Frontier Mountain we have the widest range of values. This is true even if we discard the minimal value at station #7 where erosion might have been periodically hampered by transient snow covers, and the maximal value at station #8 where it might have been fostered by the solar radiation reflected by the mountain. The wide range of rates recorded at Frontier Mountain is likely due to the turbulent wind regime which develops on the downwind side of the mountain. Such a high wind barrier does not occur at Allan Hills, Reckling Moraine, Elephant Moraine and Yamato Mountains.

As the variables related to the complex process of ice ablation surely include ice temperature, we wish to report a measurement carried out at the campsite during a clear evening, at ~08.00 P.M., 1999 December 18: the ice temperature measured in a 30 cm deep bore-hole was –14 °C, whereas the air temperature was –18 °C.

## THE METEORITE CONCENTRATION MECHANISM

### The Model

On the basis of our field measurements and laboratory data, we propose the following meteorite concentration model for the Frontier Mountain ice field. The model is a development of previous hypotheses by Delisle *et al.* (1993).

The model assumes that the meteorite concentration developed (1) under glaciological circumstances similar to those acting today; (2) according to the general principles of "ice flow model" proposed by Nagata (1982), Whillans and Cassidy (1983) and Cassidy *et al.* (1992) for the meteorite traps in the Allan Hills and Yamato Mountains regions (*i.e.*, that meteorites are concentrated by englacial transport from large snow accumulation zones into the stranding surfaces where they are exhumed by ablation) and that the meteorite concentration is possibly augmented by direct infall.

Ice flows around both ends past Frontier Mountain at speeds in excess of 1 m/year on its regional flow from the Polar Plateau towards the outlet Rennick Glacier. On the downstream side of Frontier Mountain, turbulent wind falls of southwesterly katabatic winds form a ~42 km$^2$ blue ice area which undergoes very high ablation (average 6.5 cm/year). The ice removed by ablation recalls ice from the Rennick Névé, and two ice flows continuously invade the blue ice area from both ends of the mountain. The two ice flows meet along a curvilinear ice depression which runs over a shallow (100–200 m below ice surface) sub-ice bedrock crest, and their load of meteorites, once fallen in the snow accumulation area, is exhumed in the blue ice field by ablation. An ice divide located only 15–20 km due west of Frontier Mountain on the southeastern flank of Talos Dome defines the limited drainage area of the Frontier Mountain ice field.

The meteorites released by the ice flow that enters the blue ice area from the south are glacial-drifted if heavier than ~200 g; they accumulate by compressive flow at the foot of the mountain or in the ice depression where the forward flow of the ice is blocked by the mountain and its eastern sub-ice extensions. In turn, meteorites weighing less than ~200 g are wind blown north-northeastward across the "scatterfield" and eventually accumulate at the "firn-ice edge" findsite where wind-drift is impeded by snowfields and the ice is nearly stagnant (the ice flows eastward at velocities <10 cm/year). The meteorites found in the "Meteorite Valley moraine" are stranded as horizontal displacement by wind or glacial drift is impossible. The "wind-scoop" appears to act as a minor catchment area for wind-blown meteorites exhumed on the northermost part of the ice tongue entering the "Meteorite Valley". According to this scenario, the meteorites found at Frontier Mountain only derive from the ice flow that enters the blue ice area from the south. Exceptions are the two isolated finds from the northwestern part of the Frontier Mountain ice field. The northern ice flow produces much fewer meteorites because it is destructive in its overall eastward flow out of the blue ice field at velocities ranging from 30 to 60 cm/year. Direct falls onto the Frontier Mountain ice field are possible additions to the meteorite population that traveled within the ice. Once landed they are redistributed on the ice field by wind or glacial drift according to size.

Contrary to what appears from surface morphology, the Frontier Mountain meteorite stranding surface develops in a blue ice area located upstream of a bedrock barrier, given by the eastern flank of the Frontier Mountain and its eastern sub-ice extensions which form a southwest facing amphitheater-like structure. The blue ice area is characterized by mean ablation rates of 6.5 cm/year and horizontal velocities that decrease from >1 m/year to <10 cm/year on approaching the obstacle. The general glaciological features of the Frontier Mountain ice field are thus consistent with the general model proposed by Nagata (1982), Whillans and Cassidy (1983), Delisle and Sievers (1991) and Cassidy *et al.* (1992) for the Allan Hills and Yamato Mountains ice fields. In particular, the meteorite accumulation model can be described as "stagnant ice or slow-moving ice against an absolute and submerged barriers", according to the descriptive scheme proposed by Cassidy *et al.* (1992).

## Testing the Model

Our model indicates that the forward flow of the ice that enters the blue ice area from the south—the one that carries the great majority of the meteorites found at Frontier Mountain—is totally blocked along the ice depression (Figs. 3 and 5). This point is an important one because it implies that meteorite transport by glacial drift is impossible across the ice depression, and therefore that (1) the ice depression acts as an accumulation zone for large meteorites and (2) the "firn-ice edge" findsite is not flushed northeastward. As shown by bedrock topography, ice thickness and strain net data, this is due to presence of a shallow bedrock barrier running underneath the ice depression, which determines an important decrease of the horizontal velocities of the incoming ice from ~1 m/year to <10 cm/year. The model thus predicts that there is equilibrium mass balance between the incoming ice and the ice lost by ablation. With available data on ice dynamics we can attempt a rough estimate of the annual volume of ice flowing through GATE1 located at the southern edge of the blue ice area (Fig. 6). The GATE1 section extends for 3.45 km$^2$. As the driving stress which makes the ice flowing in the direction of decreasing surface elevation is strongly opposed by basal drag in cold-based polar ice sheets, the surface velocity is 1.2 to 1.5× faster than the mean velocity through the ice thickness (Whillans and Cassidy, 1983; van der Veen, 1999); therefore, the mean annual velocity of the ice flow through GATE1 has been calculated as the 75% of the average value of the three surface velocities measured close to the center and sides of GATE1 (stations #10, #12 and #15; Table 2) (*i.e.*, 0.4 m/year). As such, the calculated annual volume of ice passing through GATE1 is close to 0.00138 km$^3$/year. The blue ice area between the ice depression and GATE1 stretches for ~22 km$^2$ and undergoes mean annual ablation of 6.7 cm/year (average from stations #7, #8, #9, #10, #11, #12, #13, #15, #16, #20 and the moraine mean value; Table 2); the annual ice loss thus amounts to 0.00147 km$^3$/year as predicted by our model. The mass balance model test is consistent with the fact that there is no meteorite transport across the ice depression through glacial drift. In addition, the substantial equilibrium mass balance inferred for the Frontier Mountain blue ice field agrees with observations by Yokoyama (1975) and Nagata (1978) at the Yamato Mountains ice field obtained through measurements of the vertical component of the ice flow and ablation rates.

Figure 3 shows the geographic distribution of the terrestrial ages of 33 Frontier Mountain meteorites and pairings obtained from the study of noble gases and cosmogenic nuclides concentrations by Wieler *et al.* (1995), Terribilini *et al.* (2000), Welten *et al.* (2001) and Welten (2001, pers. comm.). Eight meteorites from the "Meteorite Valley moraine" have terrestrial ages ranging from 100 ± 30 to 535 ± 30 ka; 16 from the "firn-ice edge" have terrestrial ages ranging from 27 ± 2 to 135 ± 35 ka; seven from the "scatterfield" have terrestrial age ranging from 10 ± 2 to 45 ± 15 ka and two from the "wind scoop" have terrestrial ages of 100 ± 30 and 155 ± 35 ka. This data from literature, combined with our glaciological data, allows us to further test our model for the meteorite concentration mechanism at the Frontier Mountain ice field.

The fact that the terrestrial ages of the meteorites from the "Meteorite Valley moraine" can be older than those from the "firn-ice edge" (Fig. 3) is consistent with our data which indicates that the first findsite acts as a "cul-de-sac", whereas the second findsite is a "conveyor-belt" which slowly drains the accumulation. As the ice at the "firn-ice edge" accumulation lies on a stretch of ice that moves eastward at a velocity of ~10 cm/year and extends for ~5 km in the same direction, any meteorite stranded there would be removed from the Frontier Mountain blue ice field in less than ~50 ka. The eastward increase of terrestrial ages is also consistent with the drainage model for this findsite. In addition, the fact that terrestrial ages are progressively younger from the "scatterfield" to the "firn-ice edge" to the "Meteorite Valley moraine" (Fig. 3) is consistent with the "ice flow model" proposed for the Frontier Mountain trap. Interestingly, this pattern parallels the geographic distribution of the degree of weathering experienced by Frontier Mountain meteorites which is typically high in the "Meteorite Valley moraine" and low in the "scatterfield".

The geographic distribution of the meteorite fragments of the FRO 90001 shower is consistent with our model of redistribution of meteorites on bare ice by wind or glacial drift. The small (<200 g) fragments of this shower accumulate at the "firn-ice edge" after being wind-blown from the site of emergence located where the large bits accumulate (*i.e.*, due south of the ice depression, close to the mountain).

According to our scenario, the oldest terrestrial age of the meteorites found at the "firn-ice edge" findsite should be as old as the time necessary to accomplish the journey from the snow accumulation zone where they fell to the site of recovery. As already mentioned, the meteorites found at the "firn-ice edge" findsite were released by the ice flow entering the blue ice area from the south. As shown in Fig. 2, the maximum length of the "in-ice" journey (*i.e.*, from the ice divide to the ice depression in the blue ice field) is ~30 km. Based on the available ice flow vectors (Fig. 5, Table 2), we calculate that the "in-ice" journey may take 33 ka assuming that meteorites traveled at ice surface velocities. The "on-ice" journey on the "firn-ice edge" conveyor-belt may last up to 50 ka, as previously explained. The entire journey would last 83 ka. This estimate roughly agrees with available terrestrial ages of the site: the oldest terrestrial age of 16 dated fragments, most likely representing 12 individual meteorites, is 135 ± 35 ka; all others are no older than 110 ± 30 ka (Fig. 3). A closer match is obtained if we consider that in cold-based polar ice sheets horizontal ice velocities decrease with depth and towards ice divides (van der Veen, 1999). For instance, the entire journey would require ~100 ka, assuming that the "in-ice" journey occurred at a depth of 300 m in the blue ice field (*i.e.*, 80% of the 350 m average depth of the ice sheet in the area). Assuming that differences between the calculated travel time and terrestrial ages in the "firn-ice edge" findsite are realistic, in the past the ice divide could have been located only few tens of kilometers further inland. In any case, the information provided by the present study is that Frontier Mountain meteorites derive from a limited meteorite catchment area. Our ice dynamics data allow us to make a rough estimate of the extent of this area. Let us call B2 and B1 the drainage basin of GATE2 (extending from the ice divide to Frontier Mountain to the unnamed nunatak due southeast of Frontier Mountain; Fig. 6) and the drainage basin that effectively feeds the portion of the blue ice area due south of the ice depression, respectively. B2 is ~140 $km^2$. B1 will be a fraction of B2, B1*, plus a portion of the area between GATE2 and GATE1, B1°. The B1*/B2 ratio will reasonably be close to the ratio of the annual volumes of ice flowing through GATE1 and GATE2 VG1/VG2. VG1 is 0.00138 $km^3$/year, as derived above. VG2 is 0.0068 $km^3$/year assuming that a mean ice flow of ~1 m/year (*i.e.*, the 75% of the surface ice velocity measured at station #31) (Table 2). VG1/VG2 is therefore 0.2, then B1* ~28 $km^2$. Ice flow data from Landsat image interpretation allows us to infer that B1° extends for ~15 $km^2$. B1 thus sums up to ~43 $km^2$. If we now add the ~22 $km^2$ of blue ice where meteorites were found stranded, the meteorite catchment area for the Frontier Mountain meteorite trap extends for ~65 $km^2$.

Our model assumes that the meteorite concentration at Frontier Mountain formed through the general principles of the "ice flow model" by Nagata (1982), Whillans and Cassidy (1983) and Cassidy *et al.* (1992). The "ice flow model" conflicts with Huss's model (Huss, 1990) which predicts that meteorite concentrations in Antartic blue ice fields are formed primarily by direct infall, as recently pointed out by Zolensky (1998). Although the Frontier Mountain meteorite concentration may have been further fed by direct infall, we believe that Huss's model does not apply to Frontier Mountain, since it would be difficult to account for the high number of findings (170 specimens) in the small area (~0.3 $km^2$) of the "Meteorite Valley moraine" by direct infall alone. For instance, assuming that the "Meteorite Valley moraine" acted as a catchment area for infalling meteorites since the time of the oldest fall (~500 ka), canonical infall rate from fireball data (Halliday *et al.*, 1989) predicts nine falls in the mass range 10–100 g for a total of ~250 g, or four falls in the mass range 10–300 g for a total of ~500 g, or one fall in the mass range 10–1000 g for a total of ~1100 g. Even if we take into account that infall rate by Halliday *et al.* (1989) may be in error by as much as 50%, these estimates suggest that it is highly improbable that direct infall alone produced the accumulation in the "Meteorite Valley moraine" and that some transport to the area of recovery is required. In fact, the statistics for the 170 meteorite fragments found in the "Meteorite Valley moraine" is as follows: meteorites belong to 10 different meteorite classes (H3 to 6, L3 to 6, LL3 and eucritic meteorites) and thus represent at least 10 distinct falls; they weight a total of 1079 g; their average mass is 7 g; the largest mass is 106 g, with 97% of the specimens weighing <20 g. In addition, the fall-to-specimen ratios in the "Meteorite Valley moraine" would be lower than 1:19, thus very much lower than the most conservative estimate of 1:2 to 1:6 for Antarctic meteorite populations (Graham and Annexstad, 1989; Ikeda and Kimura, 1992; Lindstrom and Score, 1995; Jull *et al.*, 1998; Benoit and Sears, 2000).

Our model also assumes that the Frontier Mountain meteorite concentration formed under glaciological conditions similar to those acting today. The time since the Frontier Mountain ice field began accumulating meteorites is not yet constrained; however, as assumed for other meteorite traps, it should be in the order of magnitude of the terrestrial ages found therein (*e.g.*, Cassidy *et al.*, 1992) (*i.e.*, hundreds of thousand of years). The nine fragments of the H5/6 chondrite FRO 90174 shower recognised by Welten *et al.* (2001) are distributed between the "Meteorite Valley moraine", the "wind scoop" and the "firn-ice edge" findsites (Fig. 3). Cassidy *et al.* (1992) and Delisle (1993) suggested that the accumulation in the "Meteorite Valley moraine" started under a highstand of the ice sheet—a hypothesis largely based on interpretation of the observed field situation. Evidence for a past, yet undated, highstand of the ice sheet in the region are given by erosion features (polished surfaces, grooves, striae, friction cracks, roches moutonneés) observed on the surfaces of Frontier Mountain and nearby nunataks up to an altitude of 2800 m (Höfle, 1989; Orombelli *et al.*, 1990). With the highstand of the ice sheet proposed by Cassidy *et al.* (1992) and Delisle (1993) the "firn-ice edge" accumulation would have been flushed away, because the bedrock crest today at <200 m below ice surface, would have not act as a barrier to the ice flow. The distribution of the fragments of the FRO 90174 shower thus suggests that the meteorite accumulation in the "Meteorite Valley moraine" developed under a glaciological situation similar to the present one, at least since the inferred age of the "firn-ice edge" accumulation (*i.e.*, since ~50 ka ago). This inference, if confirmed by further data, would have important implications for the history of the Antarctic ice sheet (*i.e.*, it would indicate that ice flow and thickness did not change significantly in the inland catchment of the upper Rennick Glacier during the entire course of the last glacial cycle).

## CONCLUSIONS

The glaciological data and the meteorite distribution map presented in this paper, combined with terrestrial ages and pairings available from literature, allow us to define the nature of the Frontier Mountain meteorite trap as follows.

(1) The origin of the Frontier Mountain meteorite trap can be explained according to the present-day glaciological situation; it is therefore not necessary to call upon paleo-scenarios as previously hypothesized (Cassidy *et al.*, 1992; Delisle *et al.*, 1993).

(2) The meteorite trap develops in a blue ice area located upstream of an absolute and submerged barriers, contrary to what appears from surface morphology. The barrier is given by a shallow southwest facing amphitheater-like structure formed by the eastern flank of Frontier Mountain and its eastern sub-ice extensions which impedes the northeastward regional ice flow towards the Rennick Glacier.

(3) The blue ice field is characterized by mean ablation rate of 6.5 cm/year and compressive ice flow as testified by deformed tephra layers and horizontal velocities that decrease from 1 m/year to <10 cm/year on approaching the obstacle. The ice field appears to be a stable surface (*i.e.*, the ice lost by ablation is compensated by incoming ice) as derived from the calculated equilibrium mass balance.

(4) A portion of the meteorites found at Frontier Mountain have necessarily traveled within the ice from snow accumulation zones according to the general "ice flow model" proposed by Nagata (1982), Whillans and Cassidy (1983) and Cassidy *et al.* (1992) and therefore the Huss's model (Huss, 1990) can be ruled out. Nevertheless, the meteorite catchment area of the Frontier Mountain trap is rather small and likely extends for ~65 km$^2$, ~20 km upstream of the blue ice area.

(5) The meteorite accumulation model can be described as "stagnant ice or slow-moving ice against an absolute and submerged barriers", according to the descriptive scheme proposed by Cassidy *et al.* (1992).

(6) Wind action can move stones up to 200 g on the flattish surface of the Frontier Mountain blue ice field at speeds of 1 to 10 m/year; wind-drift thus plays an important role in redistributing the small Frontier Mountain meteorite fragments (mass range = 0.2–1667.8 g; mean mass = 25.3 g; median mass = 5.6 g; mode mass = 1.9 g).

(7) The Frontier Mountain ice field is an effective trap for meteorites weighing more than ~200 g. For smaller masses, the combination of wind and glacial drift may remove meteorites in less than a few tens of thousands of years. In particular, if the Frontier Mountain ice field is effective in the "cul-de-sac" of the "Meteorite Valley moraine", it is not so for those that reach the "scatterfield"; from here, small meteorites are wind-driven to the "firn-ice edge" where the ice slowly moves away from the blue ice area and acts as a conveyor-belt which removes the meteorites stranded there in <50 ka.

(8) The activation age of the Frontier Mountain trap is not yet constrained, however we infer that one of the most important findsites (the "firn-ice edge") may be as old as 50 ka (*i.e.*, older than the last glacial maximum) (peak at 18 ka ago; *e.g.*, Oerlemans and van der Veen, 1984). If confirmed by further evidence, particularly the bedrock exposure age, this would imply that the glaciological situation in the inland catchment of the Rennick Glacier has not changed significantly during the last glacial cycle.

(9) Grady *et al.* (1998) have emphasized that the large population of Antarctic meteorites, with terrestrial ages up to few million years, is a potential resource for estimating the flux of meteorites to Earth in the recent past. However, Zolensky (1998) has pointed out that our limited knowledge on variables related to ice flow, meteorite catchment areas and removal and decay rates prevents firm conclusions concerning the past meteorite flux from the Antarctic record. Our work provides a valuable basis for addressing the issue for the Frontier Mountain meteorite population.

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