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Meteorites constrain the age of Antarctic ice at the Frontier Mountain blue ice field (northern Victoria Land)

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Abstract

We show that meteorites can provide chronological constraints upon the age of the ice cropping out at the Frontier Mountain meteorite trap (Antarctica) when their terrestrial age is placed in a glaciological context. Amongst the over 700 meteorites found so far, Frontier Mountain (FRO) 84001, 99028, 93005 and 93054 were most likely not wind-drifted across the ice field, since their masses (772–1665 g) are much heavier than the local ~200 g wind transport threshold. The four meteorites were found along a stretch of ice where a representative section of the Frontier Mountain blue ice crops out. Based on the bedding of englacial tephra layers, the structure of the ice along the section appears to be essentially an up-glacier dipping monocline. The ^{14}C terrestrial age of FRO 8401, 99028 and 93005 are 13±2, 21±3 and 27±2 ky, respectively; the $^{41}Ca/^{36}Cl$ age of FRO 93054 is 40±10 ky. The terrestrial ages of the four meteorites increase from the top to the bottom layers of the monocline. This geographic distribution is best explained by delivery of meteorites at the ice surface through the "ice-flow model" (i.e., englacial transport from the snow accumulation zone and exhumation in the blue ice area through ablation) rather than direct fall. Since the effect of ablation in decoupling terrestrial ages of meteorites and the age of the ice on which they sit must have been minor (most likely ≤7 ky) based on the local ice dynamics, we conclude that the age of the bulk of the ice body currently under ablation at Frontier Mountain is up to ~50 ky old. This result has implications on both the meteorite concentrations mechanism at Frontier Mountain and the regional ice dynamics.

Keywords: FRO 84001; FRO 93005; FRO 93054; FRO 99028; Antarctic meteorites; terrestrial ages; ice dynamics; Frontier mountain; Antarctica

1. Introduction

The Antarctic ice sheet is the most productive terrain for the search for meteorites on Earth. Since systematic collection programs started in the mid-1970s, over 30,000 meteorite specimens have been found on blue ice fields of the Antarctic Plateau. These areas extend for tens to thousands of square kilometers and account for about 1% of the surface of the Antarctic continent [1]. They are characterised by negative surface mass balance (with ~5 cm yr^{-1} average ablation rates) and outward flow impeded by bedrock barriers; thus, they act as stranding surfaces for meteorites englacially transported from the snow accumulation zones where they fell (i.e.,

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"the ice flow model"; [2,3]). Terrestrial ages for Antarctic meteorites (i.e., the time since their fall), typically <500 ky with a few up to 2 my [4–7], provide information on the time necessary to attain the present accumulation. A clear understanding of the meteorite concentration mechanism operating at the various blue ice fields may thus provide insight into the flux of extraterrestrial matter to Earth and into the regional behaviour of the Antarctic ice sheet over the recent geological past [8,9]. Such blue ice fields are also of potential interest for the scientific community, because they represent natural "windows" into relatively old ice of the Antarctic ice sheet, which may offer an easy access to the record of past atmospheric chemistry and fallout [1,10,11].

The Frontier Mountain blue ice field (northern Victoria Land), an important meteorite trap of the Antarctic ice sheet (Fig. 1), has yielded more than 700 meteorite specimens since its discovery in 1984 [12,13]. In 1993, we initiated a detailed study of the Frontier Mountain blue ice field in order to define the concentration mechanism. A description of the local glaciology, including ice-flow and ice ablation rates, bedrock topography and ice thickness, was recently presented by [13] together with a model for the meteorite trap. An analogue modelling study presented by [14] focused on ice flow dynamics. Terrestrial ages of 50 meteorites from Frontier Mountain were reported by [15–17] to discuss pairings and provide an estimate of the actual number of individual meteorites found in the trap.

One important unknown of the Frontier Mountain blue ice field is the age of the ice currently under ablation. Radiometric dating of polar ice is problematic [18]. Tephra layers frequently found embedded in Antarctic polar ice are thought to be isochronous time planes of the ice sheet, and their radiometric dating is a potential alternative [11]; however, $^{40}Ar/^{39}Ar$ dating of the Frontier Mountain tephra is difficult mainly due to their limited K-content, particularly if younger than ~50–100 ky [19]. A further alternative to gain insights into the age of polar ice in ablation areas is by modelling ice flow [20], but the restricted temporal and spatial coverage of the necessary input field data can be a severe limitation.

In this paper we adopt an original approach to constrain the age of the ice under ablation in the Frontier Mountain meteorite trap. This approach involves placing terrestrial ages of meteorites within the glaciological context defined in our previous works [13,21]. Implications on the stability of the meteorite trapping mechanism at Frontier Mountain are also discussed.

2. Glaciological setting

Fig. 1a shows the Frontier Mountain blue ice field with information on the meteorite concentration mechanism described in detail by [13] and summarised here below.

Frontier Mountain (~72°59′S, 160°20′E) is a nunatak within the Transantarctic Mountains, in the inland catchment area of the upper Rennick Glacier. On its regional northeastward flow from the Polar Plateau towards the outlet Rennick Glacier, ice flows past both ends of Frontier Mountain at velocities in excess of 1 m yr^{-1}. On the downstream side of Frontier Mountain, turbulent south-southwesterly katabatic winds form a ~40 km^2 blue ice area which undergoes relatively high ablation (average 6.5±2 cm yr^{-1}). The ice removed by ablation is replenished by ice from the Polar Plateau which flows around 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. Horizontal velocities of the ice are reduced to <10 cm yr^{-1} on approaching the obstacle; similarly, sub-horizontal, continuous tephra layers embedded in ice acquire progressively steeper dips until they become almost vertical, discontinuous and severely folded at the ice depression. The load of meteorites present in the snow accumulation area along the two ice flows is exhumed from 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 (72°47′14″S, 159°04′2″E; 2318 m WGS84 elevation; ~60 km due north-west of Frontier Mountain; [22]) defines the limited drainage area of the Frontier Mountain ice field.

If lighter than ~200 g, the meteorites released by the ice flow that enters the blue ice area from the south are windblown north-northeastward at velocities of over 1 m yr^{-1} across the "scatterfield." They eventually accumulate at the "firn-ice edge" findsite where winddrift is impeded by snowfields and the ice is nearly stagnant. This stretch of ice extends for ~5 km in an east–west direction and moves eastward at velocities <10 cm yr^{-1}, thus providing the conditions necessary for long-term storage of meteorites (up to many tens of thousands of years) before being flushed towards the outlet Rennick Glacier. Following the scheme proposed by [8], the mechanism at work at the "firn ice edge" can be described as "slowly moving ice against a submerged bedrock barrier" [13]. This mechanism appears to be very sensitive to variations in the ice sheet thickness, since the bedrock would not act as an effective barrier to ice flow if the ice sheet thickened by a few hundreds of

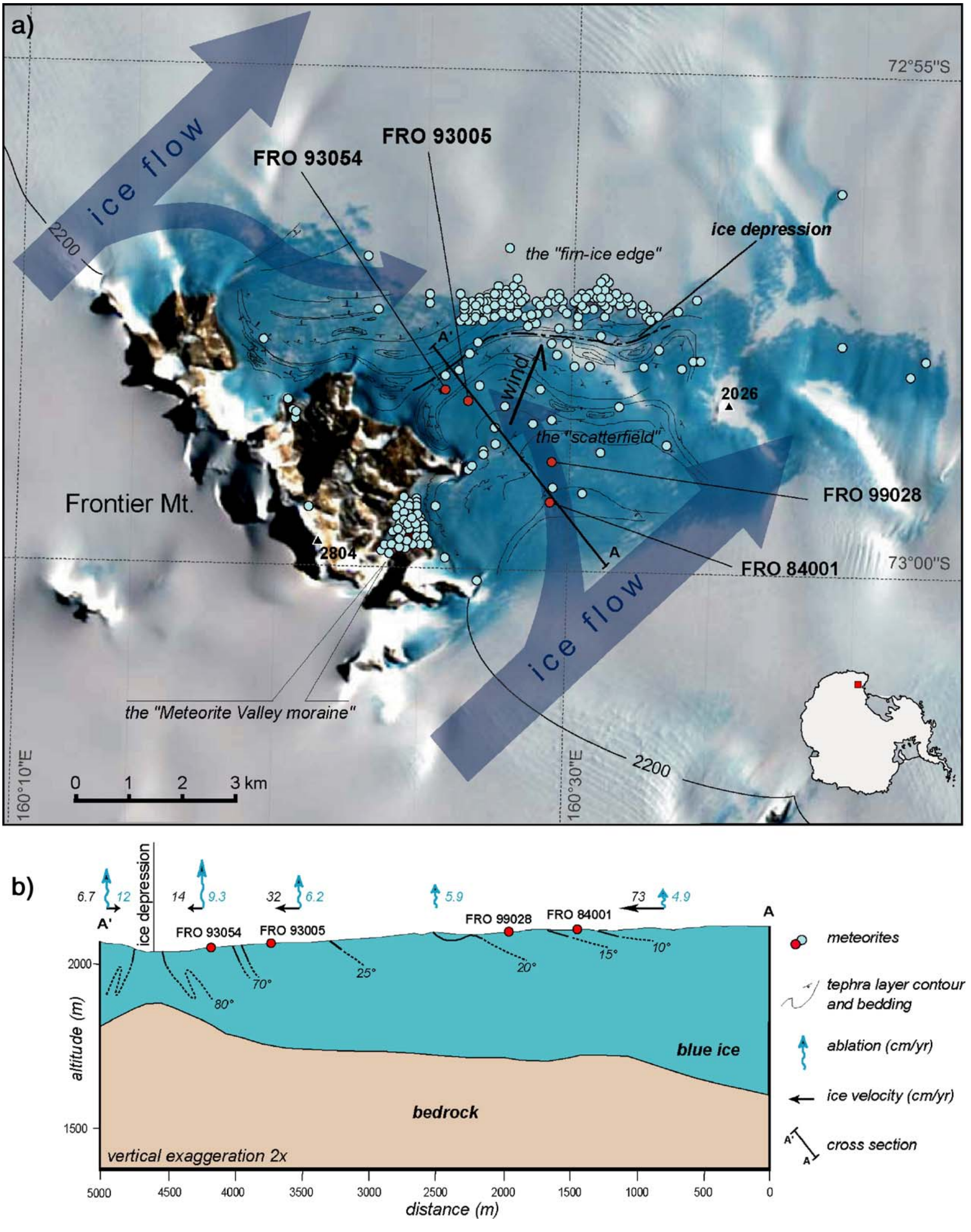

Fig. 1. (a) Sketch map of the Frontier Mountain meteorite trap (base map: satellite image LANDSAT 006-112, 1990, January 1, false colour composite 432) showing an up-to-date meteorite distribution. (b) Cross-section (AA′) through the blue ice field. Glaciological data are from [13,21].

metres. The meteorites found in the "Meteorite Valley moraine" are stranded in a sort of cul-de-sac against the bedrock, as horizontal displacement by wind or glacial drift is impossible at this site. The mechanism at work at the "Meteorite Valley moraine" can be described as "stagnant ice against an absolute bedrock barrier" [13], following the scheme proposed by [8]. Compared to the mechanism at the "firn-ice edge", this one appears to be less sensitive to variations in the ice sheet thickness, since the bedrock barrier to ice flow protrudes through the ice sheet for ~500 m.

According to this scenario, the great majority of meteorites found at Frontier Mountain only come from the ice flow that enters the blue ice area from the south. The gross of the northern ice flow (i.e., the ice due north of the ice depression and due west of the "firn-ice edge") does not produce meteorite accumulations due to its destructive behaviour in its general eastward flow out of the blue ice field at velocities ranging from 30 to 60 cm yr^{-1}. A possible addition to the meteorite population that travelled within the ice are direct falls onto the blue ice field. Once landed, these meteorites are redistributed on the ice field by wind or glacial drift according to size.

Four relatively large meteorites (Table 1), Frontier Mountain (FRO) 84001 (942 g), 93005 (1665 g), 93054 (1423 g) and 99028 (772 g) were found along a stretch where a representative section ("AA′"; Fig. 1) of the ice feeding the Frontier Mountain meteorite accumulations crops out. The section extends for ~5 km across "the scatterfield" in a roughly southeast–northwest direction, from the southern edge of the blue ice field to the ice depression (Fig. 1a). As indicated by the geometry of tephra layers embedded in the ice (which are isochronous time planes), the ice layers show SE-dipping bedding (i.e., ice layers dip up-glacier) with increasing dips moving northwards (Fig. 1b). Some undulation of the ice layers was observed halfway along the section, whereas severe folding was observed at its northern end, in the ice depression. On the whole, however, the structure of the ice along the section appears to be essentially an up-glacier, SE-dipping monocline with increasingly older layers moving northwards. All other meteorites found on this ice flow (Fig. 1a) are smaller than ~200 g.

Based on their cosmogenic nuclide and noble gas concentrations [17], FRO 84001, 93005, 93054 and 99028 (Table 1) are ordinary chondrites belonging to four distinct meteorite falls. The ^{14}C terrestrial age of FRO 8401, 99028 and 93005 are 13±2, 21±3 and 27±2 ky, respectively [17]. FRO 93054 is the largest piece of a group of paired fragments (namely, the FRO 90001 pairing group) with a $^{41}Ca/^{36}Cl$ age of 40±10 ky [17].

3. Discussion: the age of the Frontier Mountain blue ice

Terrestrial ages of meteorites found on the surface of a given blue ice field can provide chronological constraints on the age of the ice upon which they sit. This is possible if they arrived at the surface of the blue ice field through the "ice flow model" and, once exhumed, did not move significantly relative to the ice layer that originally contained them. Meteorites found stranded in traps may have wind-drifted across the ice field and/or have been released onto the blue ice surface some time ago, thus yielding information on the age of the ice ablated in the past only. Terrestrial ages of meteorites must therefore be placed in a well-constrained glaciological context in order to provide information on the age of the ice currently under ablation.

FRO 84001, 93005, 93054 and 99028 meteorites (Table 1) have masses significantly heavier than the ~200 g wind transport threshold defined by [13]. Therefore, contrary to all other meteorites found in the area which have masses ≤200 g, they were most likely not wind-drifted across the ice field once they reached the blue ice surface.

The geographic distribution of the terrestrial age of the four meteorites (Fig. 1) is best explained by meteorite delivery to the ice surface via the "ice-flow model". Terrestrial ages increase moving from "A" to "A′", i.e., towards lower stratigraphic layers of the ice

Table 1
Frontier Mountain meteorites used in this work and their terrestrial ages (T_{age})

Meteorite	Latitude S	Longitude E	Mass (g)	Class	T_{age} * (ky)	Method
FRO 84001	~72°59′18″	~160°29′51″	942.3	L6	13±2	^{14}C
FRO 99028	72°58′47″	160°29′11″	771.8	L6	21±3	^{14}C
FRO 93005	72°58′11″	160°26′16″	1665.4	L5	27±2	^{14}C
FRO 93054	72°58′05″	160°25′23″	1423.4	H6	40±10	$^{41}Ca/^{36}Cl$

Meteorites are ordered according to their relative position along the "AA′" section in Fig. 1.
* [17].

flow, as expected for a normal monocline under ablation (Fig. 1b). The alternative hypothesis that some of these meteorites fell directly onto the blue ice surface, can be ruled out since their terrestrial ages are significantly older than the travel time of a glacially drifted mass across the ice field. Based on present horizontal ice velocities obtained by [13] and reported in Fig. 1b, the on-ice travel time along the "AA′" section from the southern edge of blue ice to the findspot for FRO 84001, 99028, 93005 and 93054 are ∼1, ∼2.5, ∼6, ∼10 ky, respectively (see also Table 2). Note that the travel times were calculated using present-day ice velocities. This is a reasonable assumption since such glacial drift would have occurred within the Holocene epoch, and no significant variation of the ice dynamics is expected within the same glacial period.

Once meteorites are released on the ice surface through the "ice flow model," ongoing ice ablation introduces a decoupling between meteorites and the ice layers that once contained them. In particular, as ablation proceeds, meteorites will sit on ice layers which are older than the one in which they were originally contained. In order to evaluate the importance of this ablation effect, we must establish a relationship between the terrestrial age of the meteorite (T_{age}) and the age of the layer of ice on which they sit (T_{ice}). This relationship is illustrated in Fig. 2, where we have a succession of ice layers with a annual-layer thickness (i.e., the thickness of an ice layer produced by one year of snow accumulation), λ, and inclination, α. Let t_s be the duration in years of the ablation after exhumation. During t_s, a meteorite will move vertically within the body of ice from A to B:

$$\overline{AB} = at_s \quad (1)$$

where a is the annual ablation rate. The vertical path from A to B corresponds to a deepening in the stratigraphic succession from C to B:

$$\overline{CB} = \overline{AB}\cos\alpha = at_s\cos\alpha \quad (2)$$

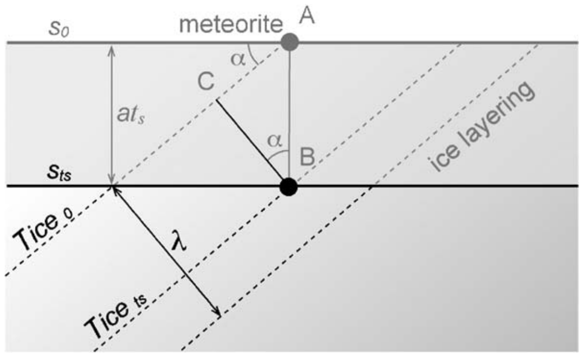

Fig. 2. Schematic path (from A to B) of a meteorite through an ice succession (and, therefore, through stratigraphic time) due to continued ablation after exhumation. See text for explanation. Abbreviations: s_0 = ice surface at exhumation; t_s = period of ablation; s_{ts} = ice surface after t_s; α = inclination of the ice layers; a = annual ablation rate; λ = annual-layer thickness of the ice (corresponding to the thickness of an ice layer produced by a 1-yr accumulation of snow); T_{ice0} = age of the ice layer that originally contained the meteorite; T_{icets} = age of the ice on which the meteorite is found sitting after t_s.

where $\overline{CB}$ is due to an "aging" ΔT (with $\Delta T = T_{icets} - T_{ice\,0}$ in Fig. 2) within the stratigraphic succession

$$\Delta T = \frac{\overline{CB}}{\lambda} = \frac{a}{\lambda} t_s\cos\alpha \quad (3)$$

Therefore, the age of the ice on which a meteorite sits is the sum of its terrestrial age and the stratigraphic age difference with respect to the ice layers that released the meteorite

$$T_{ice} = T_{age} + \Delta T \quad (4)$$

A rough estimate of ΔT values for the four meteorites found at Frontier Mountain can be obtained by solving Eq. (3) with input parameters derived from the available literature data. Although t_s cannot be quantified by any analytical means at present, it is certainly shorter than the travel time of an object glacially drifted from the

Table 2
Maximum age difference (ΔT_{max}) between the age of the ice layers on which meteorites were found and their terrestrial age

Meteorite	ΔT_{max} (ky)	$t_{s\ max}$ (ky)	d (m)	v (cm yr^{-1})	α (°)	a (cm yr^{-1})	λ (cm)
FRO 84001	2	1.1	800	70	10	5	2.5
FRO 99028	4.8	2.5	1600	65	15	5	2.5
FRO 93005	11.5	6.4	3400	55	25	5	2.5
FRO 93054	13.8	9.5	4000	40	45	5.5	2.5

Representative ice dynamics values used for the calculation are also reported. Meteorites are ordered according to their relative position along the "AA′" section in Fig. 1.

$t_{s\ max}$ = maximum on-ice travel time; d = distance from the beginning of the studied ice section (point "A" in Fig. 1); v = surface ice velocity; α = inclination of ice layers; a = annual ablation rate; λ = annual-layer thickness (corresponding to the thickness of an ice layer produced by 1 yr of accumulation of snow). See text for explanation.

beginning of the blue ice field to the findspot. At first approximation, then, we conservatively adopted maximum t_s values, i.e., we assumed that meteorites were released by ablation at the beginning of the blue ice field. The maximum duration of the ablation t_s corresponds to the maximum on-ice travel time calculated above using present-day horizontal ice velocities (see also Table 2). An average annual-layer thickness, λ, of 2.5 cm for the ice under ablation at Frontier Mountain (Table 2) was calculated for the ice succession comprised between FRO 84001 and 93054. We assumed a ~30 ky stratigraphic time interval corresponding to the difference between the T_{age} of FRO 93054 and that of FRO 84001 (Table 1). A total stratigraphic thickness of 750 m is obtained assuming a representative layer inclination of 15° (the assumed layer inclination for the entire ice body under study is smaller than the average inclination measured at its surface, since inclination is expected to significantly decrease with increasing depth within the first few tens of metres) and a 2900 m distance between the find positions of the two meteorites. A λ of 2.5 cm appears to be consistent with the accumulation rates in the Frontier Mountain accumulation area during the Holocene/Last Glacial Transition and Last Glacial period, i.e., the time during which the four meteorites fell ~10–40 ky ago. Such values should respectively be about a half and a third of the present accumulation rate of 80.5 kg m^{-2} yr^{-1} (corresponding to ~9 cm ice eq. yr^{-1}) reported by [22] for Talos Dome. The fact that the calculated λ is actually ~30% lower than the average value predicted on the basis of accumulation rates could account for possible thinning of the ice layers due to burial and ice-flow in the snow accumulation area. However, thinning due to burial and ice-flow should be a minor process experienced by the Frontier Mountain blue ice, considering the relatively low accumulation rates during the Last Glacial period and the limited up-glacier extension of the snow accumulation area. The values of the other input parameters to solve Eq. (3), i.e., ablation rates, a, and inclination of the ice layers at surface, α, are averages derived from present-day field data measured by [13,21] from "A" to the place of each find (Table 2). Again, present-day values should apply for the considered time interval (i.e., ~10 ky ago to present), since no significant variation of the ice dynamics is expected within the same glacial period. ΔT values for FRO 84001, 99028, 93005 and 93054 are calculated 2, 5, 12 and 14 ky, respectively (Table 2). Note, again, that these are maximum estimates because we have conservatively used the longest possible t_s values. Our conjecture is that meteorites spent less than half of the maximum on-ice travel time from "A" to the place of find, which would reduce ΔT values by a factor ≥2. For instance, meteorites with a T_{age} of ~30 or ~40 ky like FRO 93005 and 93054 would have entered the ablation area not at the surface, but at a depth of several hundreds metres in the stratigraphic sequence, assuming the normal in-ice trajectories predicted by general ice-flow models [3]. We therefore argue that ablation probably had a minor effect in decoupling the terrestrial age of meteorites from the age of the ice at the Frontier Mountain blue ice field. Furthermore, FRO 84001, 93005 and 99028 are very fresh meteorites with nearly intact fusion crusts and virtually no oxidized metal, indicating a very short t_s. Considering that the terrestrial ages of these meteorites correspond to the ages of the ice layers on which they were found, we conclude that the age of the ice body under ablation due south of the ice depression is up to 40±10 ky old. A slightly older age of ~50±10 ky is obtained if we take into account the possible difference in age between the meteorite and the underlying ice due to ablation. This argument agrees with the fact that all available terrestrial ages of small meteorites found in the "scatterfield" (6 out of 30 recovered specimens were dated) are <50 ky [17]. Furthermore, our estimate also agrees with the ~35 ky maximum travel time for meteorites conveyed to the Frontier Mountain blue ice field from its snow accumulation zone, as calculated by [13] based on present-day surface horizontal ice velocities. We cannot rule out that niches of slightly older ice may locally crop out, particularly at the very bottom of the ice depression or in the "Meteorite Valley moraine" (Fig. 1a). However, our work indicates that the bulk of the ice body under ablation at Frontier Mountain is less than ~50 ky old. Oxygen isotopes ($\delta^{18}O$) on selected ice samples may possibly be used to test our conclusion.

The two major accumulation sites at Frontier Mountain, the "Meteorite Valley moraine" and the "firn-ice edge", are fed by the ice flow under study [13] (see also Section 2). Here meteorites can have terrestrial ages much older than the oldest ice under ablation at Frontier Mountain, i.e., 500±25 ky in the "Meteorite Valley moraine" and 135±35 ky in the "firn-ice edge" [17]. This suggests that exhumation of meteorites with terrestrial ages between ~50 and ~500 ky in the Frontier Mountain meteorite trap occurred sometime in the past. This also suggests that the meteorite exhumation and storing mechanisms in the "Meteorite Valley moraine" and the "firn-ice edge" have been operative for the past ~500 and ~135 ky, respectively. Contrary to the "Meteorite Valley moraine", the concentration mechanism producing meteorite accumulation at the "firn-ice edge" is very sensitive to modest thickness variations in the ice sheet, as mentioned in Section 2. We therefore infer that, on the whole, the glaciological conditions (i.e., ice thickness and ice flow direction) in the Frontier Mountain area have been stable since at least the beginning of the former interglacial period, ~120–140 ky ago.

Another implication of our result is that the tens of tephra layers embedded in the Frontier Mountain blue ice, described by [21,23], represent a ~50 ky continuous record of explosive volcanic activity in northern Victoria Land. This age supports the argument by [23], which localized the source for the Frontier Mountain tephra within the recent activity of the Mount Melbourne Volcanic Province in northern Victoria Land, with the Pleiades and/or Mount Rittmann as possible emission centres. Our result also appears to be important in light of the forthcoming ice core drilling project at Talos Dome [22] where the same tephra layers are expected to be found: it may help define regional-scale chronostratigraphic correlations from snow accumulation zones to ablation areas in the Talos Dome–Rennick Glacier area.

4. Conclusions

We have provided an example of how Antarctic meteorites can trace the history of the Antarctic ice sheet by showing that they can be used to date polar ice in blue ice fields when their terrestrial age is placed in a glaciological context. In particular, we have shown that four meteorites constrain the age of the bulk of the blue ice under ablation at the Frontier Mountain meteorite trap to be up to ~50 ky. This result represents an additional step towards understanding both regional ice dynamics during the recent geological past and the meteorite concentration mechanism operative at Frontier Mountain [13,14]. In terms of the forthcoming ice core drilling project at Talos Dome [22], our result may also help define regional-scale chronostratigraphic correlations from the snow accumulation zones to ablation areas.

Finally, considering the enormous amount of Antarctic meteorite finds, and the difficulty in determining absolute ages of polar ice in ablation areas, the adopted method may become important for constraining the age of ice in several other blue ice fields of the Antarctic Polar Plateau.

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