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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 wind-drift 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