The “Dirty Ice” of the McMurdo Ice Shelf: Analogues for biological oases during the Cryogenian

Abstract

The Cryogenian (~717–636 Ma) is characterized by widespread glaciation and dramatic fluctuations in biogeochemical cycling during the Sturtian and Marinoan glaciations. The Snowball Earth hypothesis posits that during this period, ice-covered oceans of more or less global extent shut down or greatly diminished photosynthesis in the marine realm. However, rather than suffering a catastrophic loss of biodiversity, fossil evidence suggests that major eukaryotic lineages survived and, indeed, the end of the Cryogenian marks the onset of a rapid diversification of eukaryotic life. Persistence of diverse life forms through glaciations is thought to have occurred in supraglacial refugia although the exact nature and full extent of such habitats remain uncertain. We present further evidence for the diversity and characteristics of supraglacial ecosystems on the McMurdo Ice Shelf in Antarctica and suggest that refugia analogous to “dirty ice,” that is debris-covered ice shelf ecosystems, potentially provided nutrient-rich and long-lasting biological Cryogenian oases. We also discuss how features of the McMurdo Ice Shelf indicate that mechanisms exist whereby material can be exchanged between the shallow sea floor and the surfaces of ice shelves along continental margins, providing vectors whereby ice shelf ecosystems can nourish underlying seafloor communities and vice versa.

1 | INTRODUCTION

The Cryogenian Period (~717–636 Ma) was marked by glacial deposits of global extent, extending to equatorial latitudes. Dramatic fluctuations in climate and biogeochemical cycling during this epoch are hypothesized to have set the stage for the radiation of the eukaryote kingdom including the rise of animals (Fedonkin, 1996). Recent geochronological data identify two long-lasting episodes comprising the Sturtian (~717–660 Ma) and Marinoan (~645–636 Ma) glaciations (Macdonald et al., 2010; Rooney, Strauss, Brandon, & Macdonald, 2015; Rooney et al., 2014) as summarized by Hoffman et al. (2017). Multiple lines of evidence, including the occurrence of anomalous banded iron formations (Kirschvink et al., 2000), paleomagnetic data (Evans, Beukes, & Kirschvink, 1997; Evans, Li, Kirschvink, & Wingate, 2000; Sohl, Christie-Blick, & Kent, 1999), and post-glacial cap carbonate sequences (e.g., Macdonald, Jones, & Schrag, 2009)), suggest that the glaciations extended to low latitudes in a Snowball Earth scenario and had profound effects on ocean geochemistry including extensive hypoxia (Hoffman, Kaufman, Halverson, & Schrag, 1998; Kirschvink, 1992). These glaciations are proposed to have been triggered by enhanced weathering of continental flood basalts leading to a significant reduction in atmospheric pCO₂ (Cox et al., 2016). Other hypotheses concerning the drivers for global cooling include emission of sulfur aerosols (Macdonald & Wordsworth, 2017), atmospheric pCO₂ drawdown through changes in carbonate alkalinity and increased dissolved inorganic carbon pool through anoxic remineralization of organic matter (Tziperman, Halevy, Johnston, Knoll, & Schrag, 2011), an anomalous methane flux to the atmosphere (Halverson, Hoffman, Schrag, & Kaufman, 2002), and variations in continental volcanic arc emissions (Mckenzie et al., 2016). An ensuing runaway ice-albedo feedback then enabled the expansion of sea ice toward the equator. Modeled variations in thicknesses of equatorial sea ice vary strikingly from a few meters to values in excess of 1,000 m (Pollard & Kasting, 2005; Tziperman et al., 2012; Warren, Brandt, Grenfell, & Mckay, 2002). Realistic variations in the configuration of the continents can lead to models characterized by heavy continental glaciation together with substantial areas of open water at equatorial latitudes (Liu & Peltier, 2010).

The “Hard” Snowball Earth scenario posits an ice-covered ocean of global extent (Hoffman & Schrag, 2000; Hoffman et al., 1998, 2017) where photosynthesis in the marine realm was greatly diminished, or shut down completely, and the oceans were largely anoxic and ferruginous (Rooney et al., 2015). Rather than causing a catastrophic loss of biodiversity, fossil evidence suggests that all major eukaryotic lineages, including the opisthokonts, amoebozoans, plants, chromalveolates, rhizaria, and excavates not only survived but thrived (Bosak et al., 2011, 2012; Cohen & Macdonald, 2015; Dalton, Bosak, Macdonald, Lahr, & Pruss, 2013). This is astonishing given that the initial Cryogenian episode, the Sturtian glaciation, lasted in excess of 55 myr (Rooney et al., 2015). Furthermore, recent discoveries of diverse protist fossils in Sturtian and Marinoan sequences confirm that a marine biosphere must have been active during the Cryogenian Period (Cohen & Macdonald, 2015; Cohen, Macdonald, Pruss, Matys, & Bosak, 2015; Le Heron et al., 2016; Moore et al., 2017). Sedimentary biomarker hydrocarbons derived from algae and demosponges provide further evidence for the presence of a productive biosphere during the Cryogenian Epoch (Grosjean, Love, Stalvies, Fike, & Summons, 2009; Love et al., 2009). Molecular clock data suggest that animal phyla, and specifically sponges, appeared in the time window just prior to the Snowball Earth Epoch (Dohrmann & Wörheide, 2017; Erwin, 2015) and well before the Doushantuo embryos which comprise...
the earliest body fossil evidence for metazoans, dated to about 600 Ma, and which precede the earliest documented Ediacaran biota of ~571 Ma (Erwin, 2015; Pu et al., 2016). If so, there must have been refugia capable of supporting complex ecosystems during Cryogenian times. To provide robust refuges, these would likely need to be sufficiently long-lived and productive to support substantial heterotrophic communities.

It has been suggested that biological oases may have existed around marine hydrothermal vents or in small and perhaps intermittent open-water systems within the sea glacier (Costas, Flores-Moya, & López-Rodas, 2008). Recently, however, cryoconite pans (decimeter-scale bodies of meltwater formed where dust accumulation reduced surface albedo) on equatorial ablation surfaces are hypothesized to have provided relatively long-lived and stable environments supporting not only cyanobacterial photosynthesis but also acting as potential habitats where green algae, fungi, and other protists may have thrived (Hoffman, 2016; Vincent et al., 2011). For a contrary view, see Cohen and Macdonald (2015). Given the ephemeral nature of ice, fossil records of such communities are likely to be sparse, if they exist at all, leaving open the question of their role as Cryogenian cold water cradles for metazoan evolution (Fedonkin, 1996).

There are, however, additional ice-based environments that currently harbor biological oases that are potential analogues for Cryogenian refugia. One such cryosphere environment is provided by debris-covered ice shelves, of which the McMurdo Ice Shelf is the best-documented extant example (Howard-Williams et al., 1989; Hawes, Howard-Williams, & Sorrell, 2014). In this study, we describe the McMurdo Ice Shelf in the context of Cryogenian analogues. We summarize evidence of the biological diversity and extent of supraglacial ecosystems on its surface; we review the geological and glaciological requirements for formation of debris-covered ice shelves; and we argue that such ecosystems potentially constitute diverse, nutrient-bearing and long-lasting Cryogenian refugia. We also discuss how features of the McMurdo Ice Shelf suggest that mechanisms exist whereby organic and inorganic materials can be exchanged between the shallow sea floor and the surfaces of ice shelves along continental margins, creating a situation where ice shelf surface productivity could support under-ice ecosystems.

2 GEOLOGICAL AND GLACIOLOGY CONDITIONS NEEDED TO CREATE A DEBRIS-COVERED ICE SHELF OASIS

The MIS is defined by the Antarctic Place-names Committee as the part of the Ross Ice Shelf that lies between the McMurdo Ice Shelf and Ross Island to the north, and Minna Bluff to the south (Figure 1). While the northern part of the MIS has the appearance of a “normal” ice shelf, satellite imagery of the southern half shows it contains large ablation zones (Swithinbank, 1970), particularly along the shores and

![Figure 1](https://example.com/figure1.png)

**Figure 1** (a) Geographic location of the McMurdo Ice Shelf (MIS) in Antarctica. (b) McMurdo Ice Shelf is a part of the Ross Ice Shelf and located in the south-west corner of the Ross Sea bounded to the south by Minna Bluff and the west by the coast of Southern Victoria Land. Dirty ice is highlighted in green [Colour figure can be viewed at wileyonlinelibrary.com]
to the north of Brown Peninsula (an area of >1,500 km²; Howard-Williams, Pridmore, Broady, & Vincent, 1990), where it is more or less completely covered by surface debris. Within this debris, modern marine organisms including shells, sponges, and bryozoans are abundant (Figure 2a, b). These unusual characteristics of the MIS were first recognized by members of Scott’s 1903 Expedition, when crossing from Ross Island to the Antarctic mainland, as reported by Debenham (1919).

The mechanism supporting the delivery of debris to the ice surface of the MIS is now known to be quite different to that of debris-covered glaciers and inland ice sheets, where debris is delivered to the ice surface by wind and rockfall (Kirkbride, 2011), and helps to define the circumstances under which such a phenomenon can occur. Ablation is a key element of the process, and at the MIS, ablation is enhanced by warm, dry winds descending from Mount Discovery and Minna Bluff to the south (Glasser, Goodsell, Copland, & Lawson, 2006). What ensures that the ice shelf does not ablate entirely is nourishment of the floating ice shelf by the freezing of seawater beneath (Figure 3). This ablation-basal freezing conveyor belt mechanism was first proposed by Debenham (1919) to explain the mirabilite and marine organisms that he found on the ice surface. Under this mechanism, ice removed from the surface leaves behind any debris that it carried and, as more ice accreted onto the base of the ice shelf as seawater freezes, trapped sediment and animals are continually moved to the surface (Debenham, 1919). The isotopic composition of the ice (Gow & Epstein, 1972) and biological affinities of organisms in the surficial materials (Kellogg, Kellogg, & Stuiver, 1990) supports this marine origin for the ice and the debris.

The debris-covered area of the MIS has become known as the “dirty ice” and has been divided into the undulating ice, with a low-surface debris cover and the pinnacle ice, with less debris and a dynamic regime of ice pinacles and sediment-covered hollows (Howard-Williams et al., 1989) (Figure 4a, b). The undulating ice occurs primarily between Bratina Island and Brown Peninsula, and has a rolling surface relief of approximately 10 m, with most of the surface covered by >100 mm of sediment (Glasser et al., 2006). Typically, the undulating ice terrain comprises an array of sediment-lined, meltwater ponds of 10s to 100s of m², lying between rounded mounds of ice-cored sediment (Figure 4b). These ponds, which host diverse ecosystems (Figure 5), melt out during the summer months to varying degrees, some losing all ice cover, and others retaining a substantial ice cover. The pinnacle ice (Figure 4a) is more widely distributed and comprised of small (10s of m²) thin patches of sediment with large areas of the surface ice exposed. Meltwater in the pinnacle ice occurs in small ponds and streams and flows along the irregular surface to discharge into cracks in the ice surface (Figure 6). At land–ice interfaces around Brown Peninsula, tidal lagoons occur which are flushed by water flowing up through hinge cracks with the once-daily tide (Downes, Howard-Williams, Hawes, & Schwartz, 2000).

Observations from the MIS allow inference of the geological and glaciological conditions that need to be in place to allow for the formation of a debris-covered ice shelf. Of critical importance for the

**FIGURE 2** Marine macrofauna on the McMurdo Ice Shelf include (a) fish, (b) glass sponges, and (c) bryozoan [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 3** Diagram of cross section of the McMurdo Ice Shelf along the coast of Bratina Island, Antarctica, modified version from https://www.niwa.co.nz/publications/wa/vol11-no3-september-2003/pond-life-on-the-mcmurdo-ice-shelf-one-of-the-worlds-strangest-ecosystems [Colour figure can be viewed at wileyonlinelibrary.com]
accumulation of debris by the “nourished-from-below” process includes the need for a net wasting of surface ice and basal freezing. In addition, shallow depth is required for sediments to be incorporated into ice and slow movement of the ice shelf to allow thick debris to accumulate and persistent pond features to develop.

Surface wasting is dependent on ablation exceeding precipitation and, as discussed above, at the MIS is partly due to warm, dry, katabatic winds draining from the polar plateau (Glasser et al., 2006). In a cold, dry Cryogenian environment, it seems likely that continental drainage winds delivered relatively warm, dry air to the ice shelf surface in multiple coastal locations and similar coastal high ablation zones could have existed.

Basal freezing at the MIS may reflect the relatively thin ice cover. In places, it is only 10 m thick (Swithinbank, 1970). Similar thicknesses of equatorial ice cover have been suggested for the Cryogenian, based on heat flux calculations (Tziperman et al., 2012). As shallow depths occur whenever permanent ice abuts land, it therefore seems likely that, in places, marginal ice shelves will have been accreting ice and debris at their bases, and transferring it to the surface, during Cryogenian glaciations. Revised global paleographic maps for the Sturtian cryochron at 680 MA (Li, Evans, & Halverson, 2013) identify the extent of low-latitude continental margins and, potentially, regions where conditions would favor thin, shallow-water ice shelves; potential katabatic wind flows would promote ablation and thus were favorable for formation of debris-covered ice shelves through basal freezing. However, under what conditions can a basally nourished ice shelf be expected to persist?
For the case of the MIS, simple calculations can examine whether observed air temperatures and ablation rates are consistent with hypothesized basal accrual mechanism. In its simplest case, during winter when there is no radiative heating of the ice surface, a floating Antarctic ice shelf can be considered as a one-dimensional heat conduction problem. If the basal temperature is taken as −1.8°C, the freezing temperature of modern seawater, and the ice assumed to be uniform, then the heat flux upwards through the ice shelf (Q, W/m²) is given as:

\[ Q = k \cdot \frac{dT}{dz} \]

Where \( k \) is the thermal conductivity of ice (2.3 W m⁻¹ K⁻¹), and \( \frac{dT}{dz} \) is given by the air–water temperature differential (K) over the ice thickness (m). If we assume that the maximum potential for ice to form on the underside (G, m/s) is given by:

\[ G = \frac{Q}{(\rho_i \cdot L_m)} \]

where \( \rho_i \) is the density of ice (taken to be 916 kg/m³) and \( L_m \) the latent heat of fusion (taken as 3.34 × 10⁵ J/kg), the potential rate of basal accrual can be estimated.

Summer ablation rates have been measured for the MIS (Glasser et al., 2006) at 143 mm/year (N = 8, interquartile range 79–233 mm/year). Winter ablation rates are not available, but those of the analogous debris-covered perennial ice cover of the nearby McMurdo Dry Valley lakes have been shown to be a minor component (Dugan, Obryk, & Doran, 2013). Using an ablation rate of 80–230 mm/year for the MIS, and an observed average winter temperature of −25°C, for 200 days (Hawes, Howard-Williams, & Fountain, 2008), we can estimate the ice thickness that could potentially allow basal freezing to compensate for ablation loss. At an average winter air temperature of −25°C, net ice accretion is feasible at 18 m thickness at median ablation rate, with a range from 12 to 40 m using the interquartile range of ablation rate (Figure 7). These estimates are consistent with surface ablation/basal freezing maintaining the MIS.

Boundary conditions during the Cryogenian would have differed from those currently prevailing at the McMurdo Ice shelf. While simulations using global climate models for snowball scenarios suggest that air temperature in tropical regions could have been similar to the current Antarctic (Abbot et al., 2013), other boundary conditions would not. In particular, advection of Ross Sea water underneath the MIS and contiguous Ross Ice Shelf provide a source of heat not present in models of snowball Earth with a complete ice cover. Models where the only source of heat to the under-ice ocean under snowball conditions is geothermal heat flux yield predictions of ice thickness of many hundreds of meters (Abbot et al., 2013; Pollard & Kasting, 2005). However, more complete models of snowball Earth ocean–climate coupling reveal that a wide range of potential solutions are possible, particularly at low latitudes. Pollard and Kasting (2005) developed a coupled energy balance climate/sea glacier model that accounted for ice flow from polar to tropical regions which, equator-wards of 12° of latitude, predicts ice of a few tens of meters thickness. They also note the significance of enhanced net ablation in tropical regions on maintaining thinner ice, and the potential for this to be reinforced locally by debris on the ice surface. Abbot et al. (2013) used an ensemble global climate model approach to predict ice conditions under snowball scenarios and also report the possibility of thin ice solutions for tropical (and subtropical) regions where ice is optically clear, and ablation exceeds accumulation. Tziperman et al. (2012) and Abbot et al. (2013) conclude that under snowball conditions, thin ice oases may also have been favored in coastal regions with topographical restrictions to sea glacier flow and high ablation rates. Conditions for generation of nearshore, debris-covered ice shelves maintained by basal freezing and surface ablation are thus not precluded by existing models of snowball Earth climate and ice dynamics, and the elements of high ablation, surface debris, and flow constriction that contribute to the persistence of the MIS emerge in modelling studies as important contributing factors to snowball Earth simulations.

There are no known geological records demonstrating the presence of such environments during the Cryogenian, and their ephemeral nature suggests such records may not exist. However, geochemical signals and microfossil remnants of the ecosystems they supported may exist within or below glacial diamictite strata that are the dominant component of the Cryogenian sedimentary record. The Wilsonbreen Formation, Svalbard, is proposed to record orbitally forced ice-sheet advance and retreat (Benn et al., 2015). Within the Wilsonbreen Formation, for example, Benn et al. (2015) documented fluvial channel, floodplain, lake-margin, and carbonate lacustrine facies with evidence that these supported microbial communities and which they liken to environments now evident in the present-day McMurdo Dry Valleys in Antarctica.

### 3 | MCMURDO ICE SHELF’S DIRTY ICE CREATES OASES FOR RICH BIOLOGICAL DIVERSITY AND ACTIVITY

The first descriptions of the cyanobacteria from the McMurdo Ice Shelf were made during the National Antarctic Expedition 1901–1904, Discovery Expedition, led by Captain R.F. Scott. During their
exploitations that crossed the MIS region, members of Scott’s team noted that the debris-covered ice supported large meltwater ponds that contained high biomass comprised of cyanobacteria-based microbial mats (Figure 5a, b) that coat the bottom of the ponds (Fritsch, 1912). In these ponds, cyanobacteria are key primary producers and contribute most of the total ecosystem biomass and productivity, as they are able to withstand persistent low temperatures, repeated freeze–thaw cycles, and highly variable light, nutrient, and osmotic regimes (Jungblut & Neilan, 2010). Biomass of the cyanobacterial mats can be very high, with chlorophyll a concentrations of over 400 mg/m² (Hawes, 1993; Howard-Williams et al., 1990) and are best developed in the ponds and streams of the "undulating Ice." Recent re-analysis of the mats collected from the MIS by the early explorers has shown that community composition has changed little over 100 years, suggesting that it is a stable environment for life to persist over long timescales (Jungblut & Hawes, 2017).

Cyanobacterial oxygenic photosynthesis is widely accepted as the driver of the Great Oxidation Event ~2.3 Ga (Soo, Hemp, Parks, Fischer, & Hugenholtz, 2017) and evidently underpinned much of Earth’s primary productivity until the rise of algae during the Cryogenian (Brocks et al., 2017). Thus cyanobacteria would have formed an integral part of any Cryogenian ice-based aquatic ecosystems as evidenced by the presence of microbialites in a putative ice shelf environment preserved in a Cryogenian sequence in the Yukon of Canada (Macdonald et al., 2017). Cyanobacteria-dominated microbial mats on the MIS are mm-cm thick, with physical and chemical stratifications creating niches that provide habitats for diverse communities of heterotrophic bacteria and eukaryotes. Some cyanobacteria such as the heterocyst-forming genera Nostoc, Anabaena, and Nodularia are able to contribute to the nitrogen budget, and therefore, cyanobacteria-dominated microbial mats rely less on allochthonous nitrogen input (Fernandez-Valiente et al., 2007; Jungblut & Neilan, 2010). Metagenomic analysis also identified diverse genomic capabilities for nutrient scavenging and recycling systems (Varin, Lovejoy, Jungblut, Vincent, & Corbeil, 2010).

The MIS aquatic ecosystems not only support a rich biology of prokaryotic assemblages but also microbial eukaryotes and microfauna as part of the benthos and plankton (Figure 5c). Although they usually have lower abundance and biomass volume, a considerable diversity has been discovered across all major groups of the tree of life. For eukaryotic algae, 18S rRNA gene, metagenomic sequences, and microscopy have been reported such as Chlorophyceae, Bacillariophyceae, Ulvophyceae, Glaucoystophyceae, Prasinophyceae, Dinophyceae, and Euglenozoa (Jungblut, Vincent, & Lovejoy, 2012; Varin et al., 2010). There is less known about heterotrophic eukaryotes in the MIS microbial mats, but first 18S rRNA clone sequencing and metagenomic screening found sequences related to ameba, ciliates, fungi, and Mycetozoa as well as Cercozoa (Jungblut et al., 2012; Varin et al., 2010). A study of the lipid content of some mats of the MIS revealed hydrocarbons and fatty acids with abundant bacterial unsaturated, branched, and cyclic forms as well hopanoids. The sterol fraction contains subequal contents (~22%–36%) of C27, C28, and C29 sterols together with notable contents of dinosteroids (~3.5%–6%) (Jungblut, Allen, Burns, & Neilan, 2009). The microfauna community comprises tardigrades, rotifers, and nematodes species (Suren 1990; Jungblut et al., 2012). However, no other invertebrate groups can be found in MIS meltwater pond ecosystems.

In summary, supraglacial meltwater pond networks are recognized as oases of microbial biodiversity in a landscape that is otherwise largely lacking liquid water and poorly supportive of life (Hawes et al., 2008; Hoffman, 2016; Vincent et al., 2000). The "dirty ice" MIS ecosystems offer an additional and distinct scenario that was potentially present during the Cryogenian and which could support high biomass accumulations, diverse prokaryotic communities, and refugia for microbial eukaryotes to thrive under apparently adverse conditions.

## 4 | Exchange of Supraglacial Ecosystems and Ice Processes between MIS and Ocean

Exchange between the sea floor and the surfaces Cryogenian ice pans along continental margins has been proposed for cryoconite pans during Snowball Earth through moulins and provide a mechanism to transport organic matter that was generated by photosynthetic activity in supraglacial ecosystems into the ocean to support benthic fauna (Hoffman, 2016). As proposed with cryoconite systems, this exchange has been documented for the MIS dirty ice systems in the form of moulins (Figure 6a) and tide cracks (Figure 6b) that can deliver organic matter and O₂ to the ocean beneath the MIS. Evidence of the presence of macrofauna below the MIS includes remains of marine macrofauna including Hexactinellida (glass sponges, Figure 3b), Pycnogonida (sea spiders), Cirripedia (barnacles), mollusc shells and bryozoans (Kellogg, Kellogg, & Stuiver, 1988), and fish (personal observations, Figure 3b, c) on the ice shelf. These benthic organisms were likely bound to the bottom of the ice shelf through adfreezing in shallow areas where the ice shelf grounds periodically or the formation of anchor ice. The fauna was subsequently transported through the ice and deposited on top of the ice by the ice shelf ablation processes over several thousands of years (Kellogg et al., 1988). It also shows that diverse marine macrofauna thrive on shallow sea bottom beneath the ice shelf. This is further evidence of the connection and dynamic relationship between the marine and supraglacial ecosystems of the MIS and highlights its suitability for further study of carbon fluxes from supraglacial to marine ecosystems as proposed for Snowball Earth theory.

## 5 | Evidence for Net Autotrophy

Sustained export of carbon over long time periods requires that the shallow ponds of the MIS are net autotrophic. Large deposits of dry microbial mat are found on the undulating ice where pond water
levels have declined, and these, together with waterborne and airborne particulate and aerosols, are likely mechanisms for the removal of fixed carbon from the ice surface. During summer, the persistent high pH of the pond waters is interpreted as evidence of net carbon accrual (Sorrell, Hawes, & Safi, 2013) driven by persistent net photosynthesis. At ambient pH of up to 10.5, free CO₂ will be virtually absent from pond water and there will inevitably be a net drawdown of atmospheric CO₂. Calculations of free CO₂ concentration from data presented by Sorrell et al. (2013), using methods described in Stumm and Morgan (2012), suggest CO₂ concentrations between 0.2 and 23 ppm—well below atmospheric saturation and indicative of net carbon sequestration. CO₂ does accumulate in ponds during winter darkness, although the duration of winter metabolism in these systems is curtailed by rapid winter freezing of most of the pond (Hawes, Safi, Sorrell, Webster-Brown, & Arscott, 2011). While the ability to maintain year-round net photosynthesis, and thus be a net autotrophic ecosystem capable of sustainably exporting carbon has not yet been demonstrated for the MIS, analogous systems at equatorial latitudes would not be constrained by winter darkness in supporting net autotrophy.

6 | SUMMARY
Persistence of complex life through the widespread and intense glaciations of the Cryogenian Period requires the existence of illuminated, aquatic habitats with sufficient longevity and productivity to allow a diversity of microbial and multicellular groups to survive. Here, we describe how an unusual, debris-covered ice shelf in Antarctica provides such habitat, despite mean annual air temperatures of −20°C, and summer air temperatures that rarely go above freezing. The ice shelf acquires its surface debris by vertical advection of material frozen onto its base, and solar warming of this material results in the presence of a network of surficial meltwater habitats that are stable over at least century timescales. Surface ponds are shown to support a diverse array of microbes and simple multicellular taxa, comparable to the Cryogenian biota. We argue that the existence of such refugia on the surface of ice shelves in the Cryogenian is a further potential refuge where life could have persisted.

ACKNOWLEDGMENTS
Prof Bob Spigel kindly provided guidance on heat flux calculations, and Dr Clive Howard-Williams provided helpful comments on the manuscript. We also thank Gordon Love and two anonymous referees for suggestions that helped us to improve the manuscript. Support for field research on the McMurdo Ice shelf has come from New Zealand’s Ministry of Business, Innovation and Enterprise, and logistic support from Antarctica New Zealand.

AUTHOR DISCLOSURE STATEMENT
No competing financial interests exist.

FUNDING INFORMATION
This work was funded by a grant from the MIT International Science and Technology Initiatives (MISTI-NZ). EDM and RES are otherwise supported by the NASA Astrobiology Institute (Award NNA13AA90A). Additional support came from Antarctica NZ and the NZ Antarctic Research Institute.

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