Management Plan

for Antarctic Specially Protected Area No 172 LOWER TAYLOR GLACIER AND BLOOD FALLS, MCMURDO DRY VALLEYS, VICTORIA LAND

Introduction

Blood Falls is an iron-rich saline discharge located at the terminus of the Taylor Glacier, Taylor Valley, McMurdo Dry Valleys. The source of the discharge is believed to be a subglacial extensive brine aquifer located beneath the measureable length (~5 km) of the ablation zone of the Taylor Glacier, estimated to be located between one to six kilometres above Blood Falls. Approximate area and coordinates: sub-surface area 436km^2 (centered at 161°40.230'E, 77°50.220'S); sub-aerial area 0.11km2 (centered at the Blood Falls discharge at 162°15.809'E, 77°43.365'). The primary reasons for designation of the Area are its unique physical properties, and the unusual microbial ecology and geochemistry. The Area is an important site for exobiological studies and provides a unique opportunity to sample the subglacial environment without direct contact. The influence of Blood Falls on adjacent Lake Bonney is also of significant scientific interest. Furthermore, the ablation zone of the Taylor Glacier is an important site for paleoclimatic and glaciological research. The lower Taylor Glacier subglacial brine reservoir and Blood Falls are globally unique and a site of outstanding scientific importance. Designation of the Area allows for scientific access to ice deep within Taylor Glacier, provided measures are in place to ensure this does not compromise the Blood Falls reservoir and hydrological system. Under the Environmental Domains Analysis for Antarctica (Resolution 3 (2008)) the Area lies within Environment S – McMurdo – South Victoria Land geologic. Under the Antarctic Conservation Biogeographic Regions (v2) (Resolution 3 (2017)) the Area lies within ACBR 9 – South Victoria Land.

1. Description of values to be protected

Blood Falls is a distinctive glacial feature located at 162°16.288'E, 77°43.329'S, at the terminus of the Taylor Glacier in the Taylor Valley, McMurdo Dry Valleys, southern Victoria Land (Map 1). The feature forms where an iron-rich, saline liquid discharge of subglacial origin emerges at the surface and then rapidly oxidizes to give it a distinctive red coloration (Figure 1). Available evidence suggests the source of the discharge is a subglacial marine salt deposit and brine reservoir located beneath the Taylor Glacier (Keys 1980; Hubbard *et al*. 2004; Mikucki *et al*. 2015) (Map 1). The feature is unique in its physical configuration, microbial biology and geochemistry and has an important influence on the local ecosystem of Lake Bonney. Furthermore, the episodic discharge events at Blood Falls provide a unique opportunity to sample the properties of the subglacial reservoir and its ecosystem.

Blood Falls was first observed by Griffith Taylor, Robert F. Scott's Senior Geologist, in 1911. However, scientific research into its unusual morphological and geochemical characteristics did not commence until the late 1950s (Hamilton *et al*. 1962; Angino *et al*. 1964; Black *et al*. 1965). The feature named as Blood Falls is the primary discharge site at the terminus of the Taylor Glacier (Map 2). A secondary lateral saline discharge has been observed to emerge at the surface from under sediments ~40 m north from the Taylor Glacier at the margin of the Santa Fe Stream delta (162°16.042'E, 77°43.297'S, Map 2). The exact location and form of the subglacial reservoir source feeding Blood Falls is currently uncertain, although geological, glacio-chemical and geophysical mapping results suggest that the reservoir extends from beneath Lake Bonney and below the glacier terminus to at least 5 km up-valley (Keys 1980; Hubbard *et al*. 2004; Mikucki *et al*. 2015, Foley *et al*. 2015). It has been estimated that the brine reservoir became encased by ice approximately 3 to 5 Ma BP (Marchant *et al*. 1993) and may represent the oldest liquid feature in the Taylor Valley (Lyons *et al*. 2005).

The Blood Falls outflow contains a unique microbial community of apparently marine origin. The microbes may survive in the subglacial environment for millions of years without external carbon input. On account of its high iron and salt content, and its physical location below glacier ice, the microbial ecosystem at Blood Falls is an important site for exobiological studies and may provide an analogue for the conditions found beneath the polar ice caps on Mars or ocean worlds such as Enceladus and Europa. It is therefore important to ensure that the Blood Falls microbial community, the brine reservoir and associated subglacial hydrological system are protected.

The discharge episodically released from Blood Falls into adjacent Lake Bonney alters the geochemical composition of the lake and provides nutrients that are otherwise limited, making the site valuable for investigation of the impacts of subglacial outflow on lake ecosystems. There is growing evidence that brine from the subglacial aquifer also has a direct, subglacial connection with Lake Bonney bottom waters (Mikucki *et al*. 2015; Spigel *et al*. in press 2018).

The Taylor Glacier is an important site for Antarctic glaciological and paleoclimatic studies. It provides a unique opportunity to study Antarctic outlet glacier behaviour in relation to environmental change, using ice core paleoclimatic data from Taylor Dome, geologic evidence from the Taylor Valley and climatic data from nearby US Long Term Ecological Research (LTER) sites (Kavanaugh *et al*. 2009a; Bliss *et al*. 2011). The lower ablation zone of the Taylor Glacier has been identified as a potentially valuable site for paleoclimatic studies, as it exposes ice from the last glacial period and allows past concentrations of trace gases to be measured at a high temporal resolution (Aciego *et al*. 2007). In addition, the Taylor Glacier is of scientific value for glaciological studies, in particular glacier dynamics and the relationships between stresses and glacier flow, and for other glaciological research (Kavanaugh & Cuffey 2009).

The Blood Falls system is a valuable site for study of microbiology, water chemistry, glaciology, and paleoclimatology. The most unusual aspects of the Blood Falls system are its physical configuration, brine chemistry and microbial ecosystem. Blood Falls also exerts considerable influence over the geochemistry and microbiology of Lake Bonney.

The Area possesses outstanding aesthetic values and significant educational value, as the site has been the subject of a range of scientific and media articles in recent years. Blood Falls and the Taylor Glacier brine reservoir merit special protection due to their outstanding scientific values, unique configuration, ancient origin, importance to ecosystems in the local area, and their vulnerability to disturbance by human activities.

On the basis of presently available knowledge, the input of contaminants directly into the subglacial reservoir or into areas of the bed from which subglacial fluids could flow towards the reservoir has been identified as the most likely potential mechanism for contamination of the Taylor Glacier brine reservoir. However, the uncertainties surrounding the location of the subglacial reservoir and its connectivity with the subglacial hydrological system make it difficult to assess the likelihood of this occurring and for this reason a precautionary approach has been adopted when defining the boundaries of the sub-surface component of the Area.

2. Aims and objectives

Management at the lower Taylor Glacier and Blood Falls aims to:

- avoid degradation of, or substantial risk to, the values of the Area by preventing unnecessary human disturbance and sampling in the Area;
- allow scientific research, in particular on the microbial community, water chemistry and physical configuration of the lower Taylor Glacier and Blood Falls;
- allow other scientific research and visits for education / outreach provided they will not jeopardize the values of the Area;
- minimize the possibility of introduction of alien plants, animals and microbes into the Area; and
- allow visits for management purposes in support of the aims of the Management Plan.

3. Management activities

The following management activities shall be undertaken to protect the values of the Area:

- Markers or signs illustrating the location and boundaries, with clear statements of entry restrictions, should as appropriate be placed at locations on the boundary of the sub-aerial component of the Area to help avoid inadvertent entry;
- Markers, signs or structures erected within the Area for scientific or management purposes shall be secured and maintained in good condition, and removed when no longer necessary;
- Visits shall be made as necessary (no less than once every five years) to assess whether the Area continues to serve the purposes for which it was designated and to ensure management and maintenance measures are adequate;
- A copy of this Management Plan shall be kept available in the principal research hut facilities proximal to the Area, in particular the Lake Bonney, Lake Hoare, Lake Fryxell, F6, and New Harbor camps, and at McMurdo Station and Scott Base;
- National Antarctic programs operating in the region shall consult together for the purpose of ensuring that the above provisions are implemented.

4. Period of designation

Designated for an indefinite period.

5. Maps and photographs

Map 1: ASPA 172: Lower Taylor Glacier and Blood Falls sub-surface protected area boundary. Projection: Lambert Conformal Conic; Standard parallels: 1st 77°35'S; 2nd 77°50'S; Central Meridian: 161°30'E; Latitude of Origin: 78°00'S; Spheroid and horizontal datum: WGS84; Contour interval 200m.

Inset 1: Location of ASMA 2 McMurdo Dry Valleys in the Ross Sea region.

Inset 2: Location of the Taylor Glacier in ASMA 2 McMurdo Dry Valleys.

Map 2: ASPA 172: Blood Falls sub-surface and sub-aerial protected area boundary and designated camp site. Projection: Lambert Conformal Conic; Standard parallels: 1st 77°43'S; 2nd 77°44'S; Central Meridian: 162°16'E; Latitude of Origin: 78°00'S; Spheroid and horizontal datum: WGS84; Contour interval 20m.

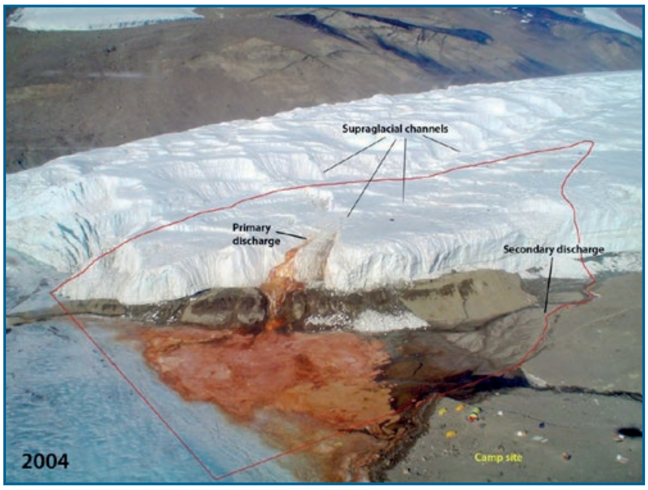

Figure 1. Aerial view of the terminus of the Taylor Glacier in 2004, with Blood Falls at center and Lake Bonney at lower left (Photographer unknown: 18 Nov 2004). Note that the camp site shown is now largely submerged by Lake Bonney (January 2018).

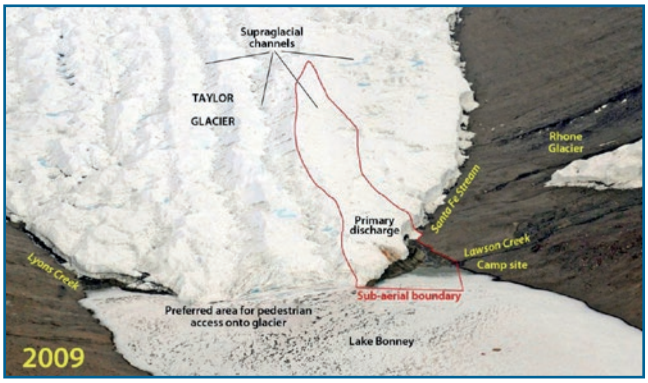

Figure 2. Aerial view of the terminus of the Taylor Glacier in 2009, showing the extent of the sub-aerial component of the Area. A comparison with Figure 1 highlights the extent to which the size of the discharge varies over time (C. Harris, ERA / USAP: 10 Dec 2009).

6. Description of the Area

6(i) Geographical co-ordinates, boundary markers and natural features

Overview

Blood Falls (located at 162°16.288'E, 77°43.329'S) is an iron-rich, hypersaline discharge that emerges from a crevasse near the terminus of Taylor Glacier, in the McMurdo Dry Valleys, southern Victoria Land. The brine initially lacks color, but freezes to a bubbly white icing as it flows off the glacier and then oxidises to produce its distinctive red- orange colour. Many traces of iron coloured material remain encapsulated in former crevasses and cracks in the glacier especially near the primary discharge point. A secondary, much smaller and less distinct, surface discharge has been observed twice (1958, 1976) ~40m north of Taylor Glacier at the margin of the Santa Fe stream delta (162°16.042'E, 77°43.297'S, Map 2). The secondary discharge has a similar physical and chemical composition to the primary outlet at Blood Falls (Keys 1980).

The volume and physical extent of the primary Blood Falls surface outflow and icing accumulation varies over time, ranging from a few hundred to several thousand cubic metres of saline icing, and the discharge events occur at intervals of one to three years or more (Keys 1980). An unknown proportion of brine sometimes drains, before it freezes (e.g. 1972, 1978) into Lake Bonney. At its minimum extent, the discharge appears as a small area of discoloration at the Taylor Glacier terminus, but can extend tens of metres across Lake Bonney at its maximum (see e.g., Figures 1 & 2).

The source of the brine discharges is subglacial, and the water in the discharge brine is melted glacial ice (Mikucki *et al.* 2009) but the original source and formation age and evolution for the subsurface brine remains unclear. Chemical and isotopic analyses indicate that a marine salt deposit or deposits are melting and / or have melted ice of Taylor Glacier (Keys 1980). Deepened subglacial topography beneath the Taylor Glacier between one to six kilometres from the terminus suggests the salt body is likely to be located there but there could be other locations further up glacier. The thickness and extent of the resulting subglacial brine, or the exact location and nature of the resulting reservoir(s) and brine drainage paths have yet to be firmly established (Keys 1980; Hubbard *et al.* 2004).

Boundaries and coordinates

The boundaries of the Area are designed to protect the values of the subglacial brine reservoir and the Blood Falls surface discharge, taking into account the size of the catchment, likely hydrological connections and practicality. Because there is evidence that hydrological connections and interactions between the surface and bed of the Taylor Glacier are likely to be minimal, restricting access on and / or over the majority of the surface of the catchment is not considered necessary. However, a small area encompassing the confirmed primary and secondary Blood Falls discharges, including a part of the Taylor Glacier surface that drains directly into the primary discharge, is included within the boundary at the surface to provide adequate protection for the confirmed outflow areas (Map 2). The 'possible discharge' location examples shown on Map 1 are not currently included within the Area because they remain unconfirmed. They may represent exposures that indicate basal processes that may at one time have involved the reservoir or related features rather than be points of contemporary discharge. Moreover these features do not feed into the reservoir or primary outflow site at Blood Falls.

Subglacial interconnections, on the other hand, could be extensive, so a relatively large sub-surface component extending ~50km up-glacier aims to protect the main part of the subglacial catchment of the lower Taylor Glacier that could be interconnected with the brine reservoir (Map 1). This extent is currently considered sufficient to protect the values of the reservoir, although it is recognized that some interconnections may extend further since technically the catchment extends far onto the polar plateau; the western boundary was therefore selected in part as a practical limit beyond which the risks to the Area are considered minimal.

In summary, the vertical and lateral extents of the Area were defined on the grounds that the boundary:

- protects the integrity of the subglacial reservoir and the confirmed primary and secondary Blood Falls discharge areas;
- allows for uncertainties in the location of the reservoir and in the connectivity within the subglacial hydrological system;
- provides a practical boundary based on catchments that is straightforward to map and identify in the field; and
- does not unnecessarily restrict activities on and / or over the surface of the Taylor Glacier. Key boundary coordinates are summarized in Table 1.

Table 1: Summary list of key protected area boundary coordinates (see Maps 1 & 2)

Location	Label	Longitude (E)	Latitude (S)
Sub-surface boundary			
Blood Falls primary discharge	A	162° 16.305′	77° 43.325′
Taylor / Ferrar glaciers ice divide, southern margin of Kukri Hills	B	161° 57.300′	77° 49.100′
Knobhead, foot of NE ridge	C	161° 44.383′	77° 52.257′
Kennar Valley, center at Taylor Glacier margin	D	160° 25.998′	77° 44.547′
Beehive Mountain, foot of SW ridge	E	160° 33.328′	77° 39.670′
Mudrey Cirque SW extent	F	160° 42.988′	77° 39.205′
Mudrey Cirque SE extent	G	160° 48.710′	77° 39.525′
Sub-aerial boundary			
Taylor Glacier terminus, ice / moraine outcrop	a	162° 16.639′	77° 43.356′
Supraglacial catchment feeding Blood Falls, western extent	b	162° 14.508′	77° 43.482′
Taylor Glacier, northern margin	c	162° 15.758′	77° 43.320′
Santa Fe Stream delta, western margin	d	162° 15.792′	77° 43.315′
Lawson Creek, boulder on west bank	e	162° 16.178′	77° 43.268′
Lake Bonney, ~180m east from shore at Santa Fe Stream delta	f	162° 16.639′	77° 43.268′

Sub-surface

The sub-surface boundary encompasses the entire ablation zone of the Taylor Glacier, from a depth of 100m below the surface to the glacier bed. In order to aid identification of the boundary at the surface, and because of practical constraints over the availability of data on the configuration of the 100m depth within the glacier, the surface margin of the Taylor Glacier is used as a surrogate for the 100m depth line and thus is used to define the lateral extent of the sub-surface component of the Area. The following description first defines the lateral extent of the sub-surface component of the Area and subsequently defines the vertical extent.

The sub-surface component of the protected area boundary extends from the primary Blood Falls discharge site (162°16.288′E 77°43.329′S) (labelled ‘A’ in Table 1 and on Maps 1 & 2) and follows the Taylor Glacier terminus southward 0.8km to the southern margin of the glacier at Lyons Creek. The boundary of the Area thence extends 19.3km SW (Map 1), following the southern margin of the Taylor Glacier to the western extremity of the Kukri Hills. The boundary thence extends 7.8km east to an approximate position where the ice divides between the Taylor and Ferrar glaciers along the southern margin of the Kukri Hills, located at 161°57.30′E, 77°49.10′S (‘B’, Table 1, Map 1). The boundary thence extends 7.9km SW, following the approximate divide between the Taylor and Ferrar glaciers to the eastern extremity of Knobhead at 161°44.383′E, 77°52.257′S (‘C’, Table 1, Map 1). The boundary thence follows the southern margin of the Taylor Glacier westward 11.8km to Windy Gully, crosses Windy Gully and thence extends 45.2km NW, following the margins of the Taylor, Beacon and Turnabout glaciers to the Kennar Valley, located at 160°25.998′E, 77°44.547′S (‘D’, Table 1, Map 1). The boundary thence extends NE across the Taylor Glacier 9.5km to the foot of Beehive Mountain at 160°33.328′E, 77°39.670′S (‘E’, Table 1, Map 1). As a visual reference, the protected area boundary runs parallel to a distinct ridge evident in the surface of the Taylor Glacier immediately downstream from an area of heavy crevassing.

From Beehive Mountain, the boundary extends 5km east to the boundary between Mudrey Cirque and the Taylor Glacier at 160°42.988′E, 77°39.205′S (‘F’, Table 1, Map 1). The boundary thence follows the margin of Mudrey Cirque for 9.6km to rejoin the Taylor Glacier at 160°48.710′E, 77°39.525′S (‘G’, Table 1, Map 1) and thence extends 59.6km SE to the foot of the Cavendish Icefalls, following the northern margin of the Taylor Glacier.

The boundary thence extends north and east along the Taylor Glacier margin for 16.9km, excluding Simmons Lake and Lake Joyce, and extends a further 15.4km east to the primary Blood Falls discharge site (‘A’, Table 1, Map 2).

The vertical extent of the sub-surface component of the Area is defined in terms of depth below the surface of the Taylor Glacier (Figure 3). The sub-surface boundary extends from a depth of 100m below the Taylor Glacier surface to the glacier bed, which is defined as the underlying bedrock surface below the glacier. The subglacial hydrological system, the Blood Falls brine reservoir, and any layers of mixed ice / sediment and / or unconsolidated sediments are included within the boundary. The sub-surface component of the Area does not impose additional constraints on activities conducted at the surface or within the upper 100m depth within the body of the Taylor Glacier.

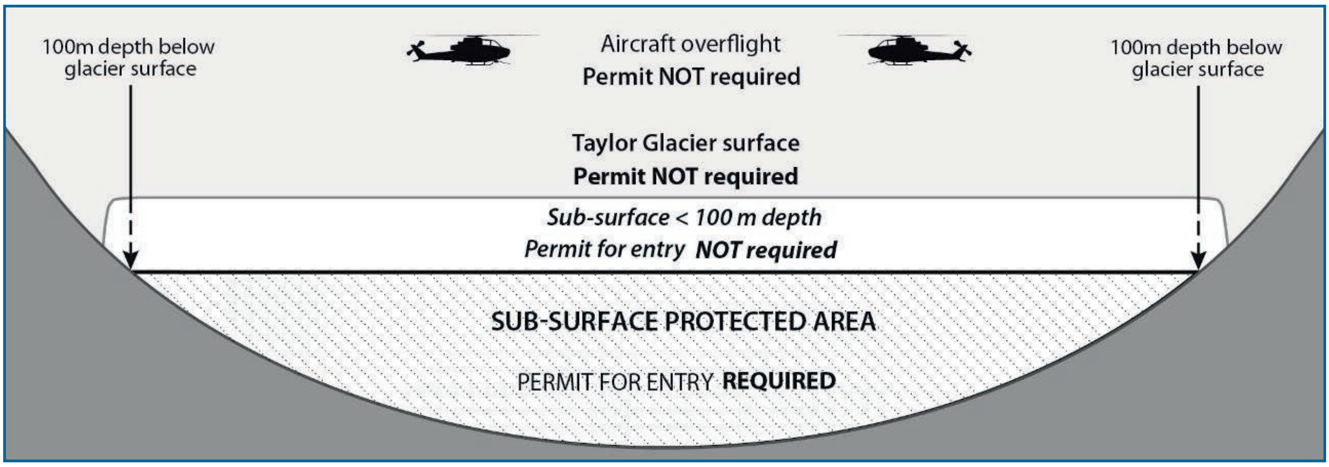

Figure 3: Depth-based definition of the vertical extent of the sub-surface component of the lower Taylor Glacier and Blood Falls protected area

Sub-aerial

This sub-aerial component of the Area comprises the delta of Santa Fe Stream, part of the western extremity of Lake Bonney, and a small supraglacial catchment surrounding Blood Falls that is defined by a system of ice ridges that persist in the local glacier morphology over at least decadal time-scales. The SE boundary of the sub- aerial component of the Area is indicated by a prominent ice and moraine outcrop extending from the Taylor Glacier terminus at 162°16.639'E, 77°43.356'S (labelled 'a' in Table 1 and on Map 2). The boundary thence extends SW and up-glacier for 900.8m, following the southern margin of the supraglacial catchment surrounding Blood Falls to the most westerly extent of the supraglacial catchment, located at 162°14.508'E, 77°43.482'S ('b', Table 1, Map 2). The boundary thence extends NE by 594.5m to the Taylor Glacier margin at 162°15.758'E, 77°43.320'S ('c', Table 1, Map 2), following the northern margin of the supraglacial catchment. The boundary of the Area thence extends 16.8m NE in a straight line, to the top of the river bank above the Santa Fe Stream delta at 162°15.792'E, 77°43.315'S ('d', Table 1, Map 2). The boundary thence extends NE for 198.7m, following the top of the bank to the point at which it meets Lawson Creek, at 162°16.178'E, 77°43.268'S ('e', Table 1, Map 2). The boundary thence extends due east in a straight line for 180.5m to a point on Lake Bonney at 162°16.639'E e.g., 77°43.268'S ('f', Table 1, Map 2) and thence due south in a straight line for 166.5m to the prominent ice and moraine outcrop.

Climate

Two meteorological stations operated by the McMurdo Dry Valleys Long Term Ecological Research (LTER) program are located close to Blood Falls (http://www.mcmlter.org/): 'Lake Bonney' (Point 'a', 162°27.881'E, 77°42.881'S) located ~4.5 km to the east, and 'Taylor Glacier' (162°07.881'E, 77°44.401'S), located ~4 km up-glacier. The mean annual air temperature at both stations was approximately –17°C during the period 1993 – 2015. The lowest temperature at these stations during this period was –48.26°C, recorded at Lake Bonney in August 2008, whilst the maximum of 10.64°C was recorded at Lake Bonney in December 2001. August was the coolest month at both stations, with January and December the warmest at Lake Bonney and Taylor Glacier respectively.

Mean annual wind speeds over the same period (1995 – 2009) ranged from 3.89 m/s at Lake Bonney to 5.16 m/s at the Taylor Glacier. A maximum wind speed of 44.12 m/s was recorded at Taylor Glacier on 11 May 2014. Taylor Valley topography, in particular Nussbaum Riegel, encourages formation of isolated weather systems within the Lake Bonney basin and limits the flow of coastal winds into the area (Fountain *et al*. 1999).

Average mean annual precipitation at Lake Bonney between 1995 and 2009 was 340mm water equivalent. Ablation rates on the Taylor Glacier are highest in the area surrounding the Cavendish Ice Falls, reaching a maximum at the base of Windy Gully (~ 0.4m a-1), and are lowest up-glacier of Beacon Valley (~0 to 0.125m a-1). Ablation rates on the lower Taylor Glacier generally range from 0.15 to 0.3m a-1 (Bliss *et al*. 2011).

Geology and geomorphology

The Taylor Valley is comprised of a mosaic of tills of varying ages and rock types, including: Precambrian metamorphic basement rocks (Ross Supergroup), early Paleozoic intrusives (Granite Harbor formation), a series of sedimentary rocks of Devonian to Jurassic age (Beacon Supergroup) and the Jurassic age Ferrar Dolerite sills (Pugh *et al*. 2003).

The Blood Falls subglacial reservoir is thought to be a marine brine originating from a marine incursion into the McMurdo Dry Valleys during the Pliocene (3 to 5 Ma BP) and may represent the oldest liquid water feature in the Dry Valleys (Lyons *et al*. 2005). It has been proposed that during the subsequent retreat of seawater from the Taylor Valley, the brine was trapped close to the modern-day terminus of the Taylor Glacier and was then 'sealed' beneath the glacier as ice advanced during the late Pliocene or Pleistocene (Marchant *et al*. 1993). The brine deposit is now thought to form a subglacial reservoir, which episodically emerges at the surface at the primary outflow and the secondary lateral discharge site. It has been suggested the brine has been modified since entrapment, partly due to inputs from chemical weathering (Keys 1980; Lyons *et al*. 2005; Mikucki *et al*. 2009).

Soils and sediment

Taylor Valley soils are generally poorly developed and largely composed of sand (95- 99% by weight) (Burkins *et al. 2000; Barrett et al. 2004). Taylor Valley soils have some of the lowest organic matter concentrations on Earth (Campbell & Claridge 1987; Burkins et al. 2000) and soils within the Lake Bonney basin are particularly low in organic carbon content (Barrett et al. 2004). In the Taylor Valley, soils generally extend to a depth of 10 to 30cm, below which is permafrost (Campbell & Claridge 1987). In addition to glacial till, the Taylor Valley floor is covered by lacustrine sediments, deposited by the formerly extensive glacial Lake Washburn, which extend to a depth of approximately 300m (Hendy et al. 1979; Stuiver et al. 1981; Hall & Denton 2000).*

Moraines at the snout of the Taylor Glacier are composed of reworked lacustrine sediment, which dates from approximately 300 ka BP (Higgins *et al*. 2000). Sediments at the Taylor Glacier margin are also composed of silty and sandy tills, formed by melt-out from debris-rich basal glacier ice and from erosion by ice marginal streams (Higgins *et al*. 2000). A thick basal ice sequence characterised by fine-grained sediments and thought to contain salts originating from the Blood Falls subglacial reservoir was documented in a tunnel excavated on the northern margin of the Taylor Glacier (Samyn *et al*. 2005, 2008; Mager 2006; Mager *et al*. 2007). These observations suggest that the base of the Taylor Glacier is interacting with the underlying sediment and that localised melting and refreezing may be occurring (Souchez *et al*. 2004; Samyn *et al*. 2005; Mager *et al*. 2007).

Glaciology and glacial hydrology

The Taylor Glacier is an outlet glacier of the East Antarctic Ice Sheet and terminates in the western lobe of Lake Bonney. A comprehensive study has recently been undertaken to investigate the dynamics of the Taylor Glacier ablation zone, including its geometry and surface velocity field (Kavanaugh *et al*. 2009a), its force balance (Kavanaugh & Cuffey 2009) and its contemporary mass balance (Fountain *et al*. 2006; Kavanaugh *et al*. 2009b). Results suggest that the glacier primarily flows through deformation of cold ice and that the Taylor Glacier is approximately in mass balance. Ice samples from the lower Taylor Glacier ablation zone have been used in paleoclimatic studies and the ice has been dated to the last glacial period (Aciego *et al*. 2007). Recent investigations on the lower Taylor Glacier identified a complete sequence of ice well-preserved in age and structure spanning from 8 to 55 ka BP (Baggenstos *et al*. 2017), with some ice aged at least 150 ka BP (Severinghaus pers. comm. 2018). Ice cores extracted from this area have been used to analyse changes in atmospheric gas constituents (Bauska *et al*. 2016; Petrenko *et al*. 2017). Other recent glaciological studies conducted on the Taylor Glacier have investigated the evolution of the dry ice cliffs at the terminus (Pettit *et al*. 2006; Carmichael *et al*. 2007), carried out textural and gas measurements on basal ice within a subglacial tunnel proximal to the primary Blood Falls outlet (Samyn *et al*. 2005, 2008; Mager *et al*. 2007) and assessed the surface energy budget of the glacier (Bliss *et al*. 2011). Studies of the supraglacial hydrology of the Taylor Glacier suggest that meltwater channels cover approximately 40% of the lower ablation zone of the Taylor Glacier and melting within the channels contributes significantly to total runoff into Lake Bonney (Johnston *et al*. 2005). Two large channels drain across the primary Blood Falls outlet, but it is considered highly unlikely that direct connections exist between surface meltwater channels and the Blood Falls subglacial reservoir due to the cold temperatures of the near- surface ice and the lack of crevasse penetration beyond 100m depth (Cuffey, Fountain, Pettit and Severinghaus, pers. comms. 2010).

The extent of subglacial meltwater beneath the Taylor Glacier and its connectivity with the Blood Falls system is currently uncertain. Inferred basal temperatures suggest that the majority of the Taylor Glacier base is substantially below the pressure melting point (Samyn *et al*. 2005, 2008) and a radar survey conducted by Holt *et al*. (2006) found no evidence of widespread liquid water beneath the Taylor Glacier. Measurements made by Samyn *et al*. (2005) recorded a basal temperature of -17°C at the side of the glacier near Blood Falls. However, ice thickness and plausible gradients of englacial temperature are consistent with temperatures around -5 to -7°C at the base of the glacier within 1–3km of Blood Falls, similar to the measured temperatures of brine discharging at the primary and secondary sites (Keys 1980). Ice-penetrating radar surveys suggest that water, probably hypersaline, may exist within an 80 m bedrock depression, located between 4 and 6km from the Taylor Glacier terminus (Hubbard *et al*. 2004).

Saline water is released episodically from the subglacial reservoir of Blood Falls, usually via the primary outlet and on occasions via the secondary lateral discharge site. However, detailed underwater surveys of the Taylor Glacier terminus conducted by the ENDURANCE (Environmentally Non-Disturbing Under-Ice Robotic Antarctic Explorer) AUV (autonomous underwater vehicle) suggest that the subglacial brine may enter Lake Bonney across the majority of the Taylor Glacier terminus (Stone *et al*. 2010; Priscu, pers. comm. 2011). In addition, a number of sites have been identified on both the northern and southern margins of the Taylor Glacier where salts and orange discolouration exist in layers (examples of which are identified on Map 1 as 'Possible discharge'), but the nature of these features has yet to be confirmed (Keys 1980; Nylen, pers. comm. 2010). The trigger for subglacial release events is uncertain, although it has been suggested that after accumulating under pressure beneath the glacier, the brine must travel through a discrete subglacial conduit which controls the location of the primary discharge: this behavior is similar to some aperiodic glacier bursts (jökulhlaups) where basal melting processes and changing stress patterns (such as physical shifts of the Taylor Glacier) may create a passage for the brine through impounding basal ice or force the subglacial liquid out from its bedrock depression (Keys 1980; Higgins *et al*. 2000; Mikucki 2005). Badgeley *et al*. (2017) suggest Blood Falls acts as a 'pressure-release valve' for the hydrologic system, where pressurized subglacial brine pools upstream from Blood Falls are injected englacially by basal crevassing where it can remain liquid due to cryoconcentration and latent heat release. Ultimately brine is released as an episodic artesian well through connection with surface crevassing events at Blood Falls after it has been advected towards the terminus by ice flow.

The primary Blood Falls discharge is cold (– 6°C), high in dissolved organic carbon, iron and sodium chloride, and has a conductivity approximately 2.5 times seawater (Mikucki *et al*. 2004; Mickuki 2005). A number of lines of geochemical evidence support a marine origin for the Blood Falls outflow, which generally shows very similar characteristics to seawater. Studies have demonstrated that the volume, spatial extent and geochemistry of the Blood Falls discharge varies over time (Black *et al*. 1965; Keys 1979; Lyons *et al*. 2005) and differs between normal flow and rapid discharge events (Mikucki 2005).

Ecology and microbiology

The Blood Falls outflow contains a microbial community, apparently of marine origin (Mikucki & Priscu 2007; Mikucki *et al*. 2009). The bacteria may be capable of metabolising iron and sulphur compounds, allowing the population to survive in the subglacial environment for extended periods of time, possibly millions of years (Mikucki *et al*. 2009). The microbes are also thought to play an important role in carbon cycling, allowing the ecosystem to survive without external carbon input (Mikucki & Priscu 2007). The primary controls on the characteristics of the microbial ecosystem at Blood Falls may provide an analogue for the conditions found beneath the polar ice caps on Mars (Mikucki *et al*. 2004). A living bacterial assemblage has been identified within the basal ice and sediments sampled within the tunnel excavated on the northern margin of Taylor Glacier (Christner *et al*. 2010).

Microbial studies have provided further support for a marine origin of the brine reservoir, as the microbial assemblages recorded at Blood Falls are similar to those found in other marine systems (Mikucki *et al*. 2004; Mikucki & Priscu 2007). The ecosystem has been highlighted as an important site for exobiological studies, particularly as an analogue for Martian ice masses (Mikucki *et al*. 2004; Mikucki 2005). The primary controls on the Blood Falls microbial assemblage are thought to be the pre-glacial history of the ecosystem and the surrounding terrain, the bed lithology and the glacier hydrology, although the extent of contact between the microbial ecosystem and the glacial hydrological system is currently uncertain (Mikucki 2005; Mikucki & Priscu 2007).

The saline subglacial waters of Blood Falls meet the comparatively fresh surface water of western Lake Bonney in the lake perimeter area (often referred to as a 'moat', as this zone is prone to melt in summer). The moat area acts as a transition zone and its geochemical composition becomes less similar to Blood Falls with distance from the primary discharge site (Mikucki 2005). The Blood Falls discharge is also diluted in the moat area by input from Santa Fe Stream, which is primarily fed by surface melt from the Taylor Glacier and flows along its northern margin (Mikucki 2005). Lawson Creek also flows into the Area and drains into Lake Bonney approximately 100m north of the primary Blood Falls outflow.

Saline discharge, organic carbon and viable microbes from Blood Falls are episodically released into the western lobe of Lake Bonney, altering the geochemistry and biology of the lake and providing nutrients that are otherwise limited (Lyons *et al*. 1998, 2002, 2005; Mikucki *et al*. 2004). Discharges into Lake Bonney have been observed at a depth of 20 to 25m, and below this depth Lake Bonney exhibits a very similar geochemistry to Blood Falls, including high iron levels and a similar ion chemistry to seawater (Black & Bowser 1967; Lyons *et al*. 1998, 2005; Mikucki *et al*. 2004). Studies have shown that bacteria in the deep areas of western Lake Bonney are similar in size to those from Blood Falls, but much smaller than other those found in the deep waters of other lakes in the Dry Valleys (Takacs 1999).

Terrestrial ecology

Invertebrate communities in the Blood Falls area have not been extensively studied. However, soil samples from the shore of western Lake Bonney identified Scottnema lindsayae as the most abundant nematode in the Lake Bonney basin and also recorded Eudorylaimus antarcticus and Plectus antarcticus (Barrett *et al*. 2004).

Human activities and impact

Local field camps historically have been located in two main areas on the north-western shore of Lake Bonney, close to the moat area and the primary Blood Falls outflow (Map 2). The camp site contains a number of tent sites marked by stone circles. This has resulted in localized soil disturbance, although activities at the camp site are considered unlikely to have had an impact on Blood Falls (Keys, Skidmore, pers. comms. 2010). Until recently, a helicopter landing site was located approximately 160 m north of the primary Blood Falls outflow, although usage is also unlikely to have adverse effects on Blood Falls (Hawes, Skidmore, pers. comms. 2010). A pedestrian trail has formed to the west of Lawson Creek, which extends parallel to and above Santa Fe Stream around 50 – 100 m from the northern margin of the Taylor Glacier. The trail has become prominent due to foot traffic and shows signs of minor erosion.

Stream monitoring equipment, including a weir, was installed by the LTER in the Santa Fe Stream delta area (Map 2), which was largely removed in January 2010. Parts of the weir embedded into stream sediments proved difficult to extract and have been left *in situ* because the impact of removal was considered greater than leaving the material in place. A number of items of disused glaciological equipment have been collected from the northern margin of the Taylor Glacier in the Santa Fe Stream delta area, and it is possible some of these items remain either on inaccessible locations on the glacier surface and / or embedded in sediments at the foot of the ice cliffs. Two tunnels cut into the basal ice remain from previous scientific studies, on the northern margin of Taylor Glacier ~ 600m and 1000m from Blood Falls respectively, although in time these will collapse and melt out.

6(ii) Access to the Area

- Access to, movement on, and / or over the surface of the Taylor Glacier within the region covered by the sub-surface component of the Area is not subject to any special restrictions (Figure 3).
- Access to the sub-aerial component of the Area is normally made first by helicopter to the designated landing site on the north-western shore of Lake Bonney (162°16.47'E, 77°43.17'S, Map 2), and from there on foot. Access may also be made on foot from the direction of Lake Bonney or from higher up the Taylor Glacier.
- The preferred route for pedestrian access to the sub-aerial component of the Area from the designated helicopter landing site and camp site is from Lake Bonney, avoiding the coloured saline icing of the discharge and Santa Fe Stream delta when possible, ascending the terminus of the Taylor Glacier from slopes to the south of the sub-aerial component boundary (Map 2). Steep ice cliffs impede foot access to the sub-aerial component of the Area along the northern margins of the Taylor Glacier. Moats and pools forming around the margin of Lake Bonney may impede access later in the season.
- A pedestrian walking route has formed parallel to and ~50 – 100 m from the northern margin of the Taylor Glacier, providing access several kilometres up-valley from the designated helicopter landing site and camp site. Steep ice cliffs on the northern margin of the Taylor Glacier impede access onto the surface of the glacier from this route.

6(iii) Location of structures within and adjacent to the Area

No permanent structures exist within the Area. Two permanent survey markers are set in a boulder located approximately 175m north of the Area: NZAP Benchmark TP01 is a tube with female thread (162°16.466›E, 77°43.175›S, elevation 72.7m); UNAVCO benchmark TP02 is a 5/8» threaded bolt (162°16.465›E, 77°43.175›S, elevation 72.8m). The boulder is located on an area of sloping ground on the northern shore of Lake Bonney situated ~15 m S of the helicopter landing site. A stream weir and a stream gauge are located ~80 m NW of the Area at Lawson Creek. Lake Bonney Camp is located ~4.3 km east of the Area.

6(iv) Location of other protected areas in the vicinity

The Area lies within ASMA No.2 McMurdo Dry Valleys. The closest Antarctica Specially Protected Areas (ASPAs) are: Canada Glacier (ASPA No.131) which is located 22 km NE of Blood Falls in the Taylor Valley; Linneaus Terrace (ASPA No.138), which lies 31 km NW of Blood Falls in the Wright Valley; and Barwick Valley (ASPA No.123) situated approximately 43 km NW of Blood Falls.

6(v) Special zones within the Area

There are no special zones within the Area.

7. Terms and conditions for entry permits

7(i) General permit conditions

Entry into the sub-aerial or sub-surface component of the Area is prohibited except in accordance with a Permit issued by an appropriate national authority. Conditions for issuing a Permit to enter the Area are that:

- it is issued for compelling scientific, educational or outreach reasons that cannot be served elsewhere, or for reasons essential to the management of the Area;
- the actions permitted are in accordance with this Management Plan;
- the activities permitted will give due consideration via the environmental impact assessment process to continued protection of the environmental, ecological, scientific, or educational values of the Area;
- the Permit shall be issued for a finite period;
- the Permit, or a copy, shall be carried within the Area.

7(ii) Access to, and movement within or over, the Area

a) **Sub-surface component (lower Taylor Glacier)**

- Access to, and movement over, the sub-surface component of the Area by aircraft, vehicle or on foot are not subject to any special restrictions (Figure 3).

b) **Sub-aerial component (near Blood Falls)**

Aircraft access and overflight

- Overflight below 100 m (328 ft) AGL of, or landings within, the sub-aerial component of the Area by aircraft, including Remotely Piloted Aircraft Systems (RPAS), are prohibited unless authorized by Permit;
- Helicopters facilitating access to Blood Falls should normally avoid landings within the sub-aerial component of the Area, and instead land at the designated landing site on the NW shore of Lake Bonney (162°16.47'E, 77°43.17'S, Map 2);
- Helicopters or other aircraft may be used for the acquisition of data within, or delivery of essential equipment into, the sub-aerial component of the Area when necessary for scientific or management purposes for which a Permit has been granted, taking care that to the maximum extent practicable any surface access avoids supraglacial channels.

Vehicle access and use

- Vehicles are prohibited within the sub-aerial component of the Area.

Pedestrian access and movement within the Area

- Access to and movement within the sub-aerial component of the Area shall normally be on foot;
- Visitors accessing the sub-aerial component of the Area should avoid the primary and secondary Blood Falls discharge areas unless permitted activities specifically require access to these sites;
- The preferred route for pedestrian access to the sub-aerial component of the Area from the designated helicopter landing site and camp site is from Lake Bonney, ascending the terminus of the Taylor Glacier from slopes to the south of the sub-aerial component boundary (Map 2).
- Movement within the sub-aerial component of the Area should be limited to that which is necessary for the performance of permitted activities.

7(iii) Activities that may be conducted in the Area

- Scientific research that will not jeopardize the ecosystem or scientific values of the Area or compromise the integrity of the Blood Falls system;
- Essential management activities, including monitoring and inspection;
- Activities with educational aims (such as documentary reporting (photographic, audio or written) or the production of educational resources or services) that cannot be served elsewhere;
- Specific conditions apply to activities that are or may be conducted in the sub-surface and sub-aerial components of the Area, which are as follows:

a) Sub-surface component

- All projects proposing to access the sub-surface component of the Area shall consider in advance the uncertainties that exist in the properties of the sub-surface hydrological system, and the risk that such activities could have more than a minor or transitory impact on the values of the Area. As such, prior environmental impact assessment of such activities should include a detailed and robust scientific review with the opportunity for input by relevant experts.
- Such proposals shall take into account the SCAR Code of Conduct for Subglacial Aquatic Environments, and as appropriate other best-practice protocols and procedures which have been developed for safe and environmentally sound access to the subglacial environment (see e.g., Committee on Principles of Environmental Stewardship for the Exploration and Study of Subglacial Environments 2007; Arctic and Antarctic Research Institute 2010; Lake Ellsworth Consortium 2011).
- Any activities involving entry into the sub-surface component of the Area shall monitor the effectiveness of control measures to minimize / prevent releases to the environment.

b) Sub-aerial component

- Meltwater sampling from supraglacial channels draining into the primary Blood Falls outflow is permitted, provided the appropriate measures specified in Section 7(vi) are taken to minimize potential contamination.

7(iv) Installation, modification or removal of structures / equipment

- No structures are to be erected within the Area except as specified in a permit and, with the exception of permanent survey markers and signs, permanent structures or installations are prohibited;
- All structures, scientific equipment or markers installed in the Area shall be authorized by permit and clearly identified by country, name of the principal investigator and year of installation. All such items should be made of materials that pose minimal risk of contamination of the Area;
- Installation (including site selection), maintenance, modification or removal of structures or equipment shall be undertaken in a manner that minimizes disturbance to the environment and to flora and fauna;
- Removal of specific structures / equipment for which the permit has expired shall be the responsibility of the authority which granted the original Permit, and shall be a condition of the Permit;
- If equipment is left *in situ* in the sub-surface component of the Area for extended periods, provisions shall be made to minimize the risk of contamination and / or loss of the equipment;
- Certain equipment and materials may need to be installed into subglacial aquatic environments for scientific and / or monitoring purposes (e.g., to measure geophysical or biogeochemical processes, or to monitor impacts of human activities on the subglacial environment). Any such installations shall be specifically covered in the environmental impact assessment for the activity, and include consideration of procedures for removal and the risks and benefits should removal not be practical.

7(v) Location of field camps

- Camping on the surface of the Taylor Glacier within the region covered by the sub-surface component of the Area is not restricted.
- Camping within the sub-aerial component of the Area is prohibited.
- A designated field camp is located on the northwestern shore of Lake Bonney approximately 150 m north of the primary Blood Falls outlet. It covers an area of gently sloping rocky terrain in the vicinity of 162°16.34’E, 77°43.20’S, extending ~100 m from the shore of Lake Bonney and ~200 m northeast from Lawson Creek to a permanent survey benchmark (TP02), which is located ~20 m from the lake shore. Individual tent sites are marked by stone circles. Where practicable, use tent sites located furthest from the shore of Lake Bonney.

7(vi) Restrictions on materials and organisms that may be brought into the Area

- No living animals, plant material, microorganisms or soils shall be deliberately introduced into the Area, and the precautions listed below shall be taken against accidental introductions;
- To help maintain the ecological and scientific values at Blood Falls and to minimize the risk of microbial introductions to the Blood Falls system visitors shall take special precautions against introductions. Of concern are pathogenic, microbial, invertebrate or plant introductions sourced from other Antarctic sites, including stations, or from regions outside Antarctica. Precautions shall be taken within the sub-surface and sub-aerial components of the Area as follows:

a) Sub-surface component

All equipment that is proposed to enter the sub-surface component of the Area shall be sterilized prior to deployment into the sub-surface component of the Area to prevent microbial introductions to the maximum extent practicable. Sterilization shall be by acceptable methods and specified in the environmental impact assessment for the activity;

b) Sub-aerial component

Visitors shall ensure that sampling equipment or markers are clean. To the maximum extent practicable, footwear and other equipment (including crampons, stabilizers, backpacks and carry- bags) shall be thoroughly cleaned prior to entry. Changing into clean footwear (including crampons, etc.) to be worn only inside the Area is also an appropriate option. To reduce the risk of microbial contamination, the exposed surfaces of footwear, sampling equipment and markers should be sterilized before use within the Area. Sterilization should be by an acceptable method, such as by washing in 70% ethanol solution in water or in a commercially available solution such as 'Virkon'. Sterile protective overclothing shall be worn when undertaking sampling within the sub-aerial component of the Area. The overclothing shall be suitable for working at temperatures of -20°C or below and comprise at a minimum sterile overalls to cover arms, legs and body and sterile gloves suitable for placing over the top of cold-weather gloves. Disposable sterile / protective foot coverings are not suitable for glacier travel and should not be used;

- No herbicides or pesticides shall be brought into the Area;
- Any other chemicals, including radio-nuclides or stable isotopes, which may be introduced for scientific or management purposes specified in the permit, shall be removed from the Area at or before the conclusion of the activity for which the permit was granted;
- Chemical tracers shall not be introduced into the sub-surface component of the Area, and use of tracers in the sub-aerial component of the Area shall follow the guidelines for 'Streams' in the Environmental Guidelines for Scientific Research contained in Appendix B of the Management Plan for ASMA No.2 McMurdo Dry Valleys;
- Fuel, food, and other materials shall not be stored in the Area, unless required for essential purposes connected with the activity for which the permit has been granted;
- In general, all materials introduced shall be for a stated period only and shall be removed at or before the conclusion of that stated period, unless installed into subglacial aquatic environments for scientific and / or monitoring purposes on a permanent basis in which case the conditions for their deployment shall be justified and specified in the environmental impact assessment for the activity;
- All materials shall be stored and handled so that risk of their introduction into the environment is minimized;
- If release occurs which is likely to compromise the values of the Area, removal should be undertaken only where the impact of removal is not likely to be greater than that of leaving the material *in situ*.

7(vii) Taking of, or harmful interference with native flora and fauna

Taking or harmful interference with native flora and fauna is prohibited, except in accordance with a separate permit issued under Article 3 of Annex II of the Protocol on Environmental Protection to the Antarctic Treaty by the appropriate national authority specifically for that purpose.

7(viii) Collection or removal of materials not brought into the Area by the Permit holder

- Material may be collected or removed from the Area only in accordance with a permit and should be limited to the minimum necessary to meet scientific or management needs.
- Material of human origin likely to compromise the values of the Area, and which was not brought into the Area by the permit holder or otherwise authorized, may be removed from the Area, unless the impact of removal is likely to be greater than leaving the material *in situ:* if this is the case the appropriate authority should be notified.

7(ix) Disposal of waste

All wastes, including human wastes, shall be removed from the Area.

7(x) Measures that may be necessary to continue to meet the aims of the Management Plan

Permits may be granted to enter the Area to:

- carry out monitoring and Area inspection activities, which may involve the collection of a small number of samples or data for analysis or review;
- install or maintain signposts, markers, structures or scientific equipment; and
- carry out protective measures.

7(xi) Requirements for reports

- Parties should ensure that the principal holder for each Permit issued submits to the appropriate authority a report describing the activities undertaken. Such reports should include, as appropriate, the information identified in the visit report form contained in the Guide to the Preparation of Management Plans for Antarctic Specially Protected Areas. If appropriate, the national authority should also forward a copy of the visit report to the Party that proposed the Management Plan, to assist in managing the Area and reviewing the Management Plan.
- Parties should maintain a record of such activities and, in the Annual Exchange of Information, should provide summary descriptions of activities conducted by persons subject to their jurisdiction, in sufficient detail to allow evaluation of the effectiveness of the Management Plan. Parties should, wherever possible, deposit originals or copies of such original reports in a publicly accessible archive to maintain a record of usage, for the purpose of any review of the Management Plan and in organising the scientific use of the Area.
- Where access to the sub-surface component of the Area is undertaken, reports shall additionally document the location of drilling sites to an accuracy of ±1m, details of the drilling method and type of drilling fluid used. Any contamination of the sub-surface environment shall be reported. Reports shall include the results of monitoring carried out to assess the effectiveness of contamination control measures, particularly those relating to microbial control.
- The appropriate authority should be notified of any activities / measures undertaken, and / or of any materials released and not removed, that were not included in the authorized permit.

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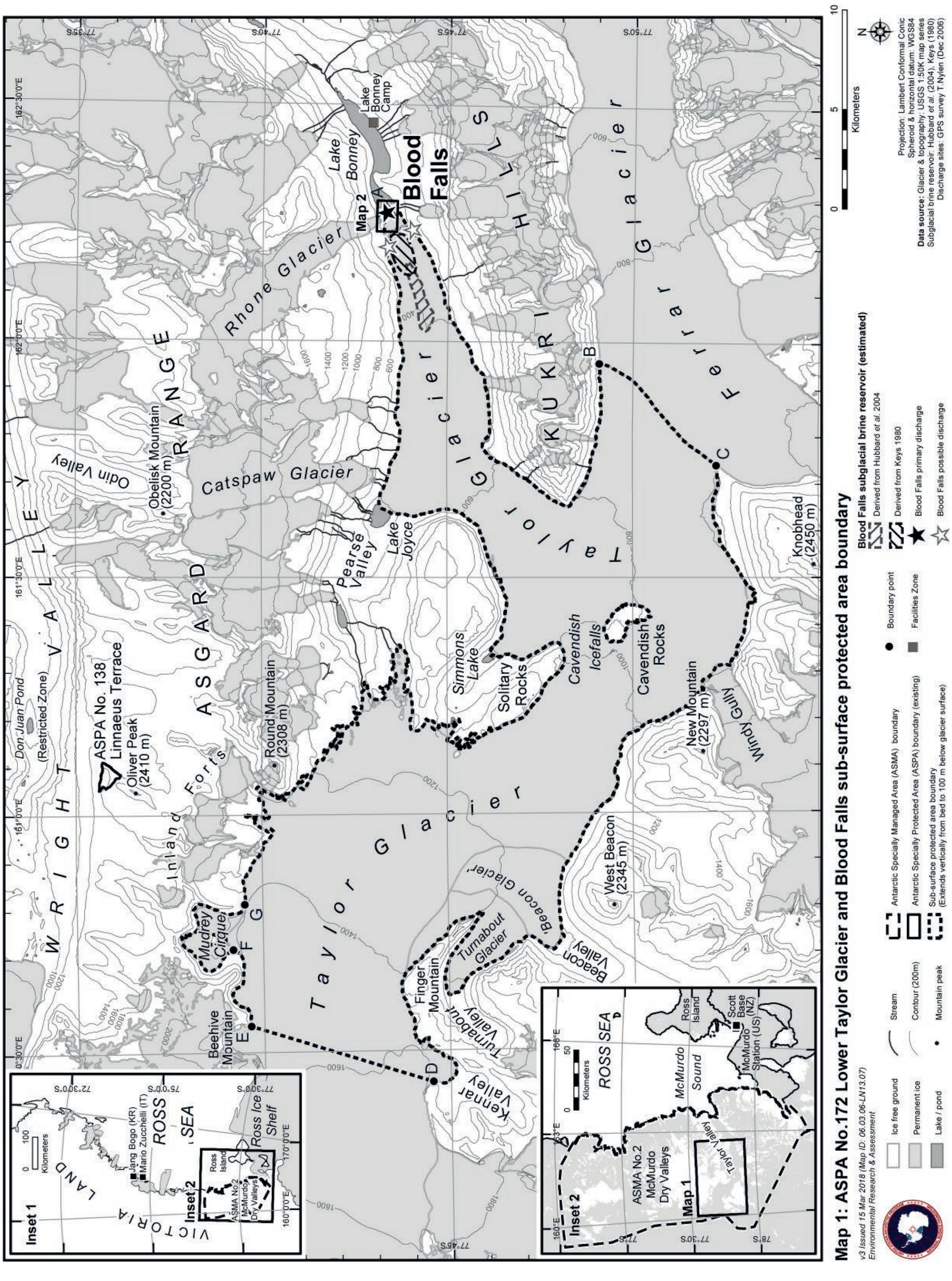
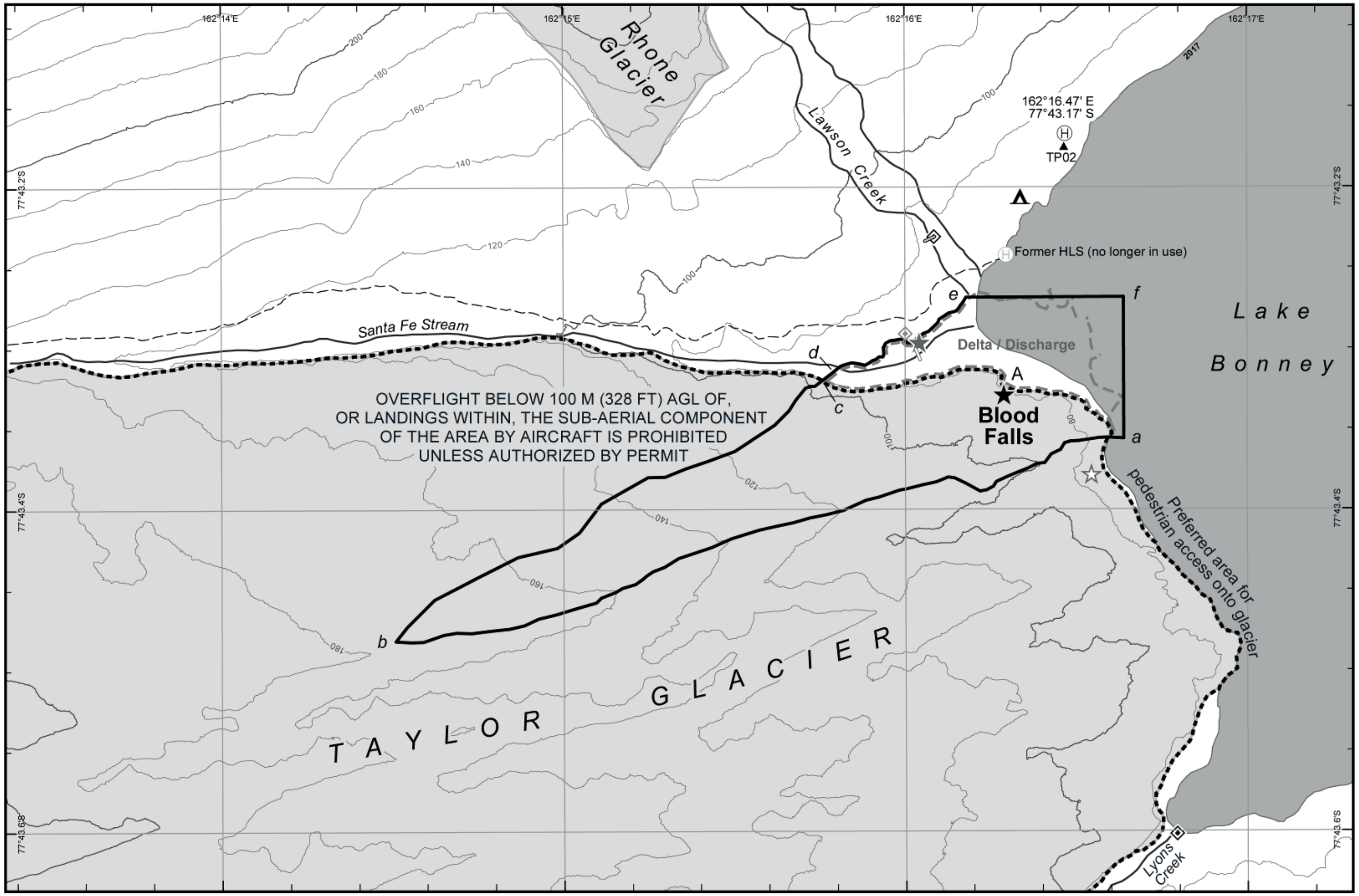


Map 1: ASPA No.172 Lower Taylor Glacier and Blood Falls sub-surface protected area boundary



Map 2: ASPA No.172 Blood Falls sub-surface and sub-aerial protected area boundary

v4 Issued 15 Mar 2018 (Map ID: 06.03.06-LN14.10)
Environmental Research & Assessment

Ice free ground
Glacier
2017 Lake (shoreline year)
Index contour (100 m)
Contour (20 m)
Stream
Stream delta / discharge area
Sub-surface protected area boundary
Sub-aerial protected area boundary
Boundary point
Blood Falls primary discharge
Blood Falls secondary discharge
Blood Falls possible discharge
Survey mark
Designated campsite
Helicopter landing site
Existing walking track
Stream gauge
Stream gauge (removed Jan 10)
Stream weir
Stream weir (removed Jan 10)

N
0 100 200
Meters

Projection: Lambert Conformal Conic
Spheroid & horizontal datum: WGS84
Data source: Contours: derived from USGS 2m LiDAR DEM
Glacier & stream digitised from aerial imagery (1993)
Lake: digitsed from orthorectified WorldView 2 imagery (Nov 2017)
Campsite, stream gauges & weirs: ERA field survey (Dec 2009)
HLS: ASC field survey (Jan 2018)
Discharge sites: GPS survey T.Nylen (Dec 2006)