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Review

Rethinking the Lake History of Taylor Valley, Antarctica During the Ross Sea I Glaciation

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Abstract: The Ross Sea I glaciation, marked by the northward advance of the Ross Ice Sheet (RIS) in the Ross Sea, east Antarctica, corresponds with the last major expansion of the West Antarctic Ice Sheet during the last glacial period. During its advance, the RIS was grounded along the southern Victoria Land coast, completely blocking the mouths of several of the McMurdo Dry Valleys (MDVs). Several authors have proposed that very large paleolakes, proglacial to the RIS, existed in many of the MDVs. Studies of these large paleolakes have been key in the interpretation of the regional landscape, climate, hydrology, and glacier and ice sheet movements. By far the most studied of these large paleolakes is Glacial Lake Washburn (GLW) in Taylor Valley. Here, we present a comprehensive review of literature related to GLW, focusing on the waters supplying the paleolake, signatures of the paleolake itself, and signatures of past glacial movements that controlled the spatial extent of GLW. We find that while a valley-wide proglacial lake likely did exist in Taylor Valley during the early stages of the Ross Sea I glaciation, during later stages two isolated lakes occupied the eastern and western sections of the valley, confined by an expansion of local alpine glaciers. Lake levels above ~140 m asl were confined to western Taylor Valley, and major lake level changes were likely driven by RIS movements, with climate variables playing a more minor role. These results may have major implications for our understanding of the MDVs and the RIS during the Ross Sea I glaciation.

Keywords: Glacial Lake Washburn; McMurdo Dry Valleys; Ross Ice Sheet; Ross Sea glaciation; Taylor Valley

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1. Introduction

The McMurdo Dry Valleys (MDVs), of southern Victoria Land, is the largest relatively ice-free area of Antarctica [1]. The modern-day MDVs are home to more than 6000 lakes and ponds [2]. Taylor Valley is an east-west trending valley within the MDVs that is blocked by Taylor Glacier, an outlet glacier of the East Antarctic Ice Sheet, on its western end, and opens to the McMurdo Sound region of the Ross Sea at its eastern margin (Figure 1). Taylor Valley can be divided into three basins. From east to west, those are: Explorers Cove Basin, a basin that opens to the McMurdo Sound, and Fryxell Basin and Bonney Basin, which both have internal drainage. The valley is also home to three major perennially ice-covered, closed-basin lakes: Lake Bonney in Bonney Basin, and Lakes Fryxell and Hoare in Fryxell Basin. The eastern margin of Fryxell Basin is defined by Coral Ridge, a 78-m above sea level (m asl) threshold.

During the last glacial stage, the Ross Ice Sheet (RIS) advanced north from near its present position to occupy much of the Ross Sea, grounding in the McMurdo Sound by

≤~26.9 ^{14}C ka BP [3]. This most recent RIS advance, known as the Ross Sea I glaciation, led to the blockage of the seaward margins of several of the MDVs by the RIS, raising the threshold elevations of those valley's mouths [4]. This included Taylor Valley, where the presence of the RIS is hypothesized to have allowed a large, proglacial lake, known as Glacial Lake Washburn (GLW), to develop and reach lake levels above the threshold elevation of Coral Ridge [4,5]. The advance of the RIS is hypothesized to coincide with a retreat of alpine glaciers within the MDVs [6], leaving valley floors wide open and providing extensive catchments for large lakes, like GLW, to fill.

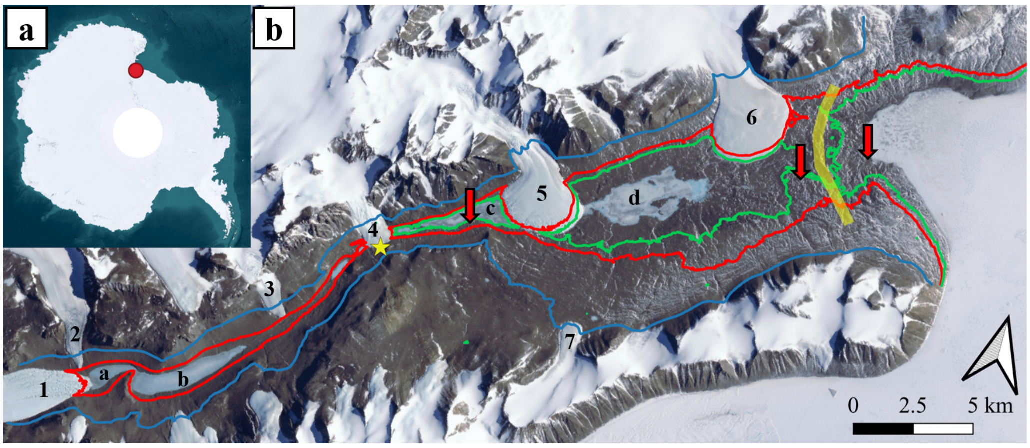

Figure 1. (**a**) Location of Taylor Valley in Antarctica (red dot). (**b**) Map of Taylor Valley. The blue line shows the extent of the maximum proposed lake level of Glacial Lake Washburn of 336 m asl [4]. The red line shows the elevation of the Suess Glacier sill (116 m asl). The Suess Glacier sill location is denoted by the yellow star. The region west of the star is Bonney Basin, and east of the star is lower Taylor Valley (Fryxell Basin and Explorers Cove Basin). The green line shows the threshold elevation of Coral Ridge (78 m asl). The yellow bar shows the location of Coral Ridge. Lakes (lettered) are (a) West Lobe Lake Bonney, (b) East Lobe Lake Bonney, (c) Lake Hoare, (d) Lake Fryxell. The glaciers (numbered) are (1) Taylor Glacier, (2) Rhone Glacier, (3) LaCroix Glacier, (4) Suess Glacier, (5) Canada Glacier, (6) Commonwealth Glacier, (7) Howard Glacier. Dry Valley Drilling Project (DVDP) core sites are marked by red arrows. From east to west those are DVDP 8–10, DVDP 11, and DVDP 12.

GLW was named by Péwé [7], who was also the first to hypothesize a high-level, valley-wide lake once occupied Taylor Valley based on the presence of "desiccated deltas and... laminated lake silt and clay" throughout the valley. Péwé [7] hypothesized that GLW existed during a glaciation that predated the most recent major glaciation in Taylor Valley. They also noted "weakly developed" paleo-shorelines in Bonney and Fryxell Basins but did not attribute them to GLW. Instead, they attribute the shorelines to Glacial Lakes Rivard and Llano, which they hypothesized formed during the most recent glaciation in Fryxell and Bonney Basins, respectively. These 2 lakes were hypothesized to have been separated from one another by a piedmont glacier that occupied the region of modern Lake Hoare [7]. Notably, all glaciations proposed by Péwé [7] were hypothesized to be expansions of local glaciers, not the RIS.

Though they were not the first to propose that an expansion of the RIS once reached the MDVs, Stuiver et al. [6] were the first to hypothesize that GLW was dammed behind a lobe of the RIS that grounded in Taylor Valley during the last glacial period. Stuiver et al. [6] expanded upon this hypothesis, adding that delicately etched shorelines near Canada and Rhone Glaciers were formed by the lake, and that GLW lake level fluctuations were driven by changing RIS grounding line positions in lower Taylor Valley. Other authors (e.g., [4,8,9]) have suggested large horizontal bench features on the walls of Bonney and Fryxell Basins are GLW strandlines and provide evidence for the paleolake. Stuiver et al. [6]

also promoted the idea that local alpine glaciers in Taylor Valley retreated during the last glacial period, pointing to spatial relationships between GLW-attributed deltas and drift deposited by the RIS (hereafter Ross Sea Drift), and local alpine glaciers.

Several radiocarbon dating campaigns have targeted desiccated algal mat deposits found in perched deltas attributed to GLW, among other deposits attributed to the paleolake, to try and constrain the timing and history of the paleolake (e.g., [6,9–11]). Based on the results of these campaigns, GLW is hypothesized to have occupied much of Taylor Valley from ~24–~8 ^{14}C ka BP [11], though luminescence dating of perched delta deposits [12,13] and permafrost refreezing rates of a remnant talik marking the former outline of the paleolake in Fryxell Basin may indicate the final drawdown of GLW occurred more recently [14]. Radiocarbon ages of dated lacustrine features in Fryxell Basin do not demonstrate a logical pattern of becoming younger from west to east and from high to low elevations, as would be expected if lake levels were controlled by RIS fluctuations and retreat [4,6]. This has led some authors to conclude that GLW lake levels were controlled by climate-driven changes in meltwater production from the RIS and that the RIS never penetrated west of Coral Ridge in Taylor Valley (e.g., [4,15,16]). According to this hypothesis, Ross Sea Drift beyond Coral Ridge in lower Taylor Valley was deposited via lake ice rafting across the surface of GLW, not by the RIS itself [4,15,17]. The mobile lake ice cover (lake ice conveyor [17]) is also thought to be responsible for depositing the wide variety of landscape features found throughout the Ross Sea Drift in lower Taylor Valley, including features previously attributed to glacial processes [4,15,17]. Thus, these landscape features are now thought to provide evidence for the existence of GLW and its lake ice conveyor [4,15].

More recently, based on soluble salt accumulations in Taylor Valley soils, Toner et al. [5] hypothesized again that the RIS advanced westward beyond Coral Ridge, occupying much of lower Taylor Valley at its greatest extent. In their model, lake levels were controlled by fluctuations in the RIS grounding line.

In the lake ice conveyor model, GLW is hypothesized to have occupied all of Taylor Valley, between Taylor Glacier and Coral Ridge, reaching lake levels > 300 m asl [4]. Alternatively, according to Toner et al. [5], lake levels $\geq$ 300 m asl were restricted to Bonney Basin. As the RIS retreated from Fryxell Basin, lake levels dropped, and lake levels in Fryxell Basin are thought to have been limited to 120 m asl or less [5].

Despite many publications promoting the existence of GLW during the Ross Sea I glaciation (e.g., [4–7,9]), there is no consensus on how expansive the lake was, how the meltwater supplying the lake's immense volume was produced, the role the lake played in sedimentation and landscape evolution, the stability of paleolake levels, and the drivers of paleolake level changes, to name a few. Some authors even question the lake's existence altogether (e.g., [18,19]). Here, we reconsider the lacustrine history of Taylor Valley during the Ross Sea I glaciation based on an extensive review of literature concerning the valley history, landscape development, and the modern features of the Taylor Valley environment. Our goal is to form a concise, data driven, and up-to-date hypothesis for the history of the valley during the Ross Sea I glaciation, thus establishing a model upon which to test future geochronologic data. We generally aim to avoid discussions of absolute ages of various landscape features. However, we do include a discussion of radiocarbon dating of lacustrine samples in the MDVs and the radiocarbon reservoir effect due to those data being used to justify various hypotheses for the relative history of GLW and Taylor Valley during the Ross Sea I glaciation (e.g., [11,15,16]). This paper is composed of three main sections that touch on the lines of evidence affecting paleolakes that may have existed in Taylor Valley: (1) the source, path, and signatures of meltwater that would have fed paleolakes, (2) signatures of the paleolake or paleolakes themselves, and (3) evidence for past glacial movements within the valley.

2. Water Source, Path, and Signatures

To form and maintain any water body, water input must outpace, or at least match, water loss. In perennially ice-covered lakes, larger lake surface areas lead to greater ice-cover ablation (combined mass loss of ice, in this case evaporation and sublimation), and thus greater volume loss. It is estimated that if a paleolake occupied the entire length of Taylor Valley between Coral Ridge and Taylor Glacier (Figure 1), at its maximum lake level its volumetric loss rate due to ablation would have been ~12 times greater than is observed in modern Taylor Valley lakes given modern ablation rates [20]. Even a smaller paleolake occupying only the Bonney Basin (Figure 1) as Toner et al. [5] suggest would have lost ~3 times as much volume to ablation than do the modern lakes [20]. To keep up with this volume loss, the quantity of meltwater production and input into a paleolake at the scale of GLW would have to have been very large. Thus, understanding the source of the immense volume of water needed to produce GLW is an important component of the GLW hypothesis and warrants review.

Determining where the waters of any MDV paleolake came from is important for understanding the impact relict carbon may have on the apparent ages of radiocarbon samples used in deciphering the lake's history. Radiocarbon ages of desiccated algal mat deposits found in perched deltas and other lacustrine deposits in Taylor Valley have played a major role in constraining the span of GLW and the timing of paleolake level fluctuations (e.g., [6,10,11]). These data have also been used as evidence to help justify several hypotheses relevant to the relative history of GLW, including the lake ice conveyor hypothesis for the distribution of Ross Sea Drift in lower Taylor Valley [4,11,15]. As such, a discussion of the reliability of radiocarbon dating of lacustrine materials in the MDVs is relevant to deciphering relative history of lower Taylor Valley during the Ross Sea I glaciation.

2.1. Water Source

It is generally agreed that the RIS was the main contributor of meltwater to GLW (e.g., [4,6,16]). Sandy terraces, generally considered to be perched delta deposits, are attributed to GLW and are distributed along modern, alpine glacier fed stream channels throughout Taylor Valley, making it apparent that the paleolake did receive meltwater contributions from local alpine glaciers as well [6]. Local alpine glaciers are thought to have been smaller during the Last Glacial Maximum (LGM), and, as Stuiver et al. [6] points out, the lack of perched deltas at higher elevations could be due to LGM-era retreated alpine glaciers being too small to create enough meltwater to produce recognizable deltas during paleolake highstands.

Glacial meltwater production in the MDVs is largely a function of surface temperature and solar radiation, both of which likely played a role in generating enough melt from the RIS to facilitate high-level paleolakes during the LGM [20]. In the MDVs, high streamflow summers correspond to a greater amount of degree days above freezing (DDAF (DDAF refers to the cumulative number of above freezing days and is calculated by adding the above freezing portion of 15-min average temperature measurements recorded at a meteorological station for each 24-h span [21])) than low streamflow summers do [21,22]. The Taylor Dome ice core record indicates colder regional temperatures during the LGM [23,24], and some suggest that our understanding of the timing of paleolake highstands may be wrong, occurring instead during warm intervals such as during the early Holocene [12–14]. However, Obryk et al. [20] showed that an increase in the frequency of strong, warming, down-valley winds (Foehn winds) during and following the LGM could have led to increased meltwater production. Although their Foehn wind driven melt model was only able to produce enough meltwater to fill Bonney Basin to GLW highstand levels, coupled with the presence of increased low elevation glacier ice (i.e., the grounded RIS), an increase in the frequency of Foehn winds could help explain how enough meltwater was produced to create and sustain a high-level paleolake in Taylor Valley [20,21] (Increased aerosol loading and decreased ^{10}Be accumulation recorded in the Taylor Dome ice core indicate the region was windier during the LGM than present [23]. However, Foehn wind driven warming in Taylor or other MDVs cannot be directly inferred from the Taylor Dome ice core record as low accumulation rates prevent the core from capturing past seasonality and its extremes [20]).

Wind can also have a negative impact on meltwater production by increasing sublimation on glaciers, reducing the amount of ice readily available for meltwater production [16,25–27]. In addition, while temperature driven processes certainly play a role in meltwater production, the colder atmospheric and deep ice temperatures of MDV glaciers (relative to more temperate glaciers) tend to draw heat away from the glacier's surface, hampering ablation [28]. Ice at a glacier's surface also does not melt readily due to heat loss via sublimation, and even after melting has occurred, surface melt is subject to evaporation and refreezing [27,29]. Instead, other factors such as surface roughness and albedo changes have much greater impacts on ablation rates and meltwater production [28].

Melt and ablation inducing decreases in albedo may be driven by wind-blown sediment being deposited on the surface of a glacier [28]. Likewise, the presence or absence of fresh snow on a glacier's surface may be significant in inhibiting or facilitating melt, respectively [16,22,29]. Fresh snow increases the albedo of a glacier's surface and insulates the underlying ice, decreasing its sensitivity to changes in surface temperature [30,31]. Snow also shields the underlying glacial ice from solar radiation, reducing meltwater production in the shallow subsurface [31]. The Taylor Dome ice core record indicates that the region received less precipitation during and following the LGM than it does today [23,24]. Thus, Hall et al. [16] hypothesize that a lack of snowfall and subsequent reduction of albedo on the RIS could have led to an extraordinary amount of meltwater production; enough to facilitate GLW highstand levels. In contrast, Doran et al. [21] found no conclusive evidence supporting the role of snow fall and cloud cover in driving increased meltwater production during the high stream flow flood year versus a low stream flow year.

Solar radiation has been shown to facilitate meltwater production in MDV glaciers even when temperatures are below freezing [29,32]. Most solar-radiation-driven glacial melt occurs in the ice of the shallow subsurface where it is not impacted by evaporation [27,29,31]. Thus, so long as it discharges from the glacier rather than refreezing, shallow-subsurface melt can account for a substantial amount of glacial mass loss [31].

The means by which meltwater may have been discharged from the RIS into GLW is a subject of debate. Authors in favor of subglacial discharge cite geomorphic evidence as support; including features interpreted in some cases to be eskers (Though these authors hypothesize these features are eskers in their earlier works (e.g., [6,33]), in later works they argue against subglacial discharge (e.g., [9]). However, no evidence is presented to falsify the interpretation of these features as eskers, and thus we cannot rule out the possibility that these features are eskers) on the floor of the Fryxell and Explorers Cove Basins (hereafter lower Taylor Valley) [33], wedges of stratified sediment along the RIS grounding line near Commonwealth Glacier (suspected by Stuiver et al. [6] to be sheet flow deposits from subglacial discharge), and a lack of evidence for ice marginal channels near the mouth of Taylor Valley along the hypothesized edge of the former expanded RIS [18]. Assuming most meltwater formed at the surface of the RIS, subglacial discharge requires the melt to move downward through crevasses and other channels into an internal drainage system that emerges along the glacier's edge. This internal drainage system can be formed, over time, by the exchange of heat between the surface meltwater and the ice beneath the glacier's surface. However, if the heat carried by the meltwater does not exceed the heat conducted into the ice, as is thought to be the case in the modern MDVs, the meltwater will freeze, and an internal drainage system will not develop [27].

Physical evidence for surface or near surface discharge from the RIS into Taylor Valley is lacking. Headland moraines in the region suggest the RIS and its margins sloped toward the MDVs, which should have funneled meltwater from the ice sheet toward Taylor Valley [34]. However, sedimentary flow structures indicating flow in direction of the MDVs and evidence for high-volume ice marginal streams fringing the RIS have not been identified in the reviewed literature despite GLW requiring an inflow > 12 times the mean annual flow of the Onyx River to keep up with ablation [18]. Longitudinal ridges found on the valley floor, which may have been deposited by 'supra-lake-ice streams' discharging from the RIS and flowing on top of GLW [4], may also provide evidence. However, the origin of these features is a subject of debate and is discussed in Section 4.5.

Although the sheer size of the RIS during the Ross Sea I glaciation likely provided ample area for large amounts of melt to be produced, the face of the RIS may have been a significant source of meltwater as well. Conovitz et al. [22] found that in the MDVs, most meltwater comes from a glacier's face rather than from its surface. For example, the face of Canada Glacier is estimated to contribute 5–13 times as much meltwater to Anderson Creek than the remaining drainage area of the glacier does, despite making up only ~3% of the total drainage area [27].

Direct glacial melt by the lake waters of a paleolake in Taylor Valley may also have played a role in sustaining the lake. Hendy et al. [17] propose an 'inverted convection cycle' as a mechanism for meltwater formation in locations where lake waters are in direct contact with glacial ice (Figure 2). Near-freezing lake waters at the top of the water column are heated by solar radiation penetrating the lake ice cover, causing the density of this lake water to increase (since maximum density of water is at 4 °C). This relatively warm, denser water sinks toward the bottom of the lake. Meanwhile, along the glacial front, cold (below 4 °C), less dense waters rise, pulling the warmer, sinking waters toward the glacier face. This warmer water causes melting along the glacial front, causing the water to cool down, become less dense, and rise. This allows the cycle to repeat and, causing lake waters to undercut the glacier front beneath the surface.

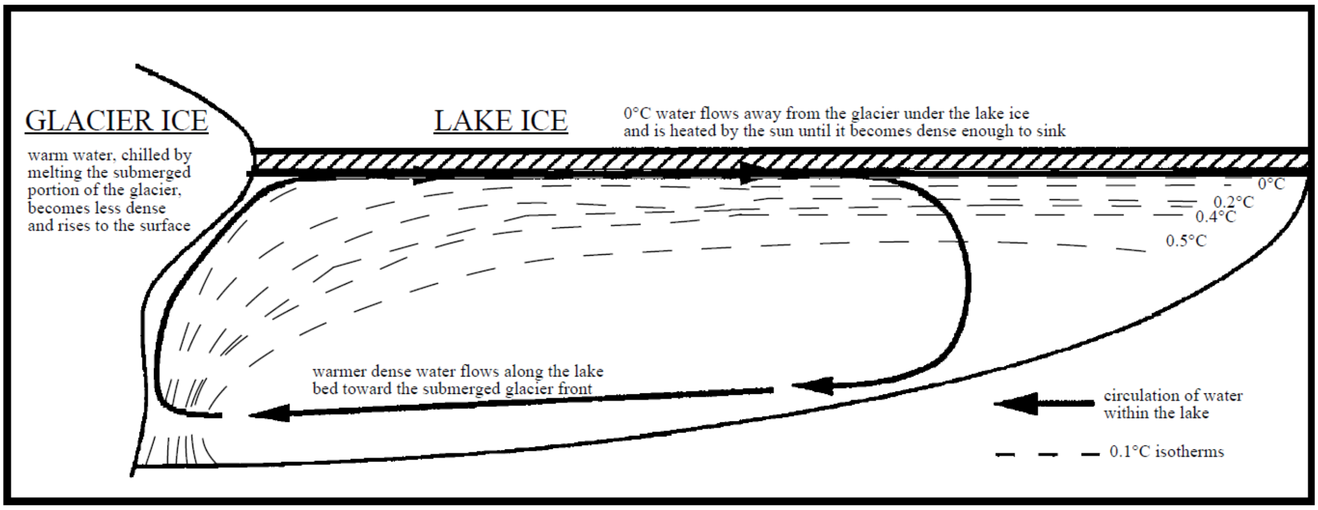

Figure 2. The 'inverted convection cycle' formed in MDV proglacial lakes hypothesized by Hendy et al. source [17]. Near-freezing surface waters are heated toward 4 °C and descend due to increased density. Meanwhile, along the glacier front, the relatively warm dense bottom waters melt and are cooled by the glacial ice, becoming less dense and ascending toward the surface. As a result, the lake waters undercut the glacier (from source [17]).

2.2. Radiocarbon Reservoir Effect

Radiocarbon dating of organic materials relies on the assumption that the carbon consumed by an organism reflects the isotopic composition of atmospheric carbon during its lifetime. In cases where this assumption is known not to be accurate, such as can be the case in glacial- [35] or groundwater-fed systems [36], the apparent age of the carbon source used by the organism must be removed from the final age calculation of the dated material. Carbon sources that contain isotopic ratios not reflective of current atmospheric conditions are known as radiocarbon reservoirs, and reservoir corrections refer to the amount of time an organic radiocarbon date must be adjusted by to correct for the influence of radiocarbon reservoirs.

A reservoir correction of 1.3 kyr has been demonstrated to be effective for marine shells from the Ross Sea, such as those used to date raised beaches at the mouth of Taylor Valley [37]. However, no such standard correction exists for lacustrine deposits in the region. In the lakes of the MDVs, three primary drivers of the radiocarbon reservoir effect have been identified: (1) glacial meltwater input into the lakes, (2) the density stratification and stability of the lake water columns, and (3) the lack of wind driven mixing due to the presence of perennial lake ice covers [38]. Understanding the role that each of these primary drivers played in a lake's history is key to deciphering the amount of radiocarbon reservoir continuation that needs to be accounted for when calibrating radiocarbon sample ages. Glacial ice contains old carbon, and thus can increase the apparent radiocarbon ages of organisms that consume its melt. For example, Doran et al. [35] found that the dissolved inorganic carbon (DIC) of glacial ice sampled for radiocarbon dating from Howard Glacier produced an apparent age of 7.43 $\pm$ 0.06 ^{14}C ka BP. Therefore, the direct, subsurface melting of a glacier by an abutting proglacial lake has the potential to introduce a large amount of old carbon into the water body, skewing the apparent ages of the organisms living within its waters.

Hendy & Hall [39] found that waters sampled near the ice front of glaciers submerged in Dry Valley lakes contained significant radiocarbon reservoirs in the DIC, yielding apparent ages of thousands to more than ten thousand radiocarbon years old. Likewise, a radiocarbon date of modern discharge DIC collected from Blood Falls at the toe of Taylor Glacier yielded an apparent age of 41.3 $\pm$ 0.054 ^{14}C ka BP [40]. The radiocarbon reservoir effect has also been hypothesized to explain extreme old radiocarbon ages of proglacial paleolake samples collected near LGM grounding lines of the RIS. A comparison of U/Th and radiocarbon ages of carbonate bearing materials of suspected paleo-lacustrine origin in Miers Valley, thought to have formed as the result of calcite precipitation resulting from planktic algal blooms in the upper water column, indicated a radiocarbon reservoir offset of ~18 kyr for one grounding line sample [38]. While grounding line reservoir effects are significant, it is hypothesized that the effects diminish rapidly as you move further from the grounding line [38,39].

Surface flows discharging from glaciers have been demonstrated to equilibrate quickly to the modern atmosphere. Water sampled from a waterfall discharging from Wright Lower Glacier in Wright Valley produced an apparent DIC age of just 0.614 $\pm$ 0.056 ^{14}C ka BP [39]. However, the young apparent ages of the DIC in the glacier-proximal meltwater are not necessarily reflected by organisms living in their melt: a modern microbial mat sample collected from a meltwater pool near calved glacier ice in Taylor Valley produced an apparent age of 1.7 $\pm$ 0.06 ^{14}C ka BP despite DIC in the waters from the same pool dating to 0.57 $\pm$ 0.06 ^{14}C ka BP [35]. The reason for such discrepancies are unknown but may be due to strong modern carbon gradients within these meltwater pools, or input from shallow soil water [35].

Streamflow away from glacial ice further allows meltwater to equilibrate with the atmosphere, and modern algae samples collected from streams often yield modern to near-modern apparent ages [35,38–40]. Stream gradient may impact the rate of meltwater-atmosphere equilibration: radiocarbon dates from algal mat, DIC, and particulate organic carbon (POC) samples from Taylor Valley streams all suggest steeper gradient streams equilibrate more rapidly than gentle gradient streams, possibly due to increased turbulence in the steeper streams [40]. Regardless, the radiocarbon reservoir effect in DIC, POC, and algal mat samples from waters near a stream's terminus is largely absent [35,40], which led to the assumption that radiocarbon samples from delta and lake edge deposits do not require any reservoir correction, regardless of stream length [35].

The reservoir effect in lake edge deposits is more complex than originally thought. Modern algal mat and DIC samples from moat waters in Lake Bonney and Lake Hoare produced apparent ages of several thousand years, while those from Lake Fryxell's moat produced modern ages [40]. This has been attributed to the number of atmospherically equilibrated streams entering Lake Fryxell verses Lakes Hoare and Bonney, and to the generally larger size of the ice-free (open) moat that forms around Lake Fryxell each year relative to the other two lakes, allowing for greater exchange between the moat waters and the atmosphere [40]. However, Hendy & Hall [39] found that, in a single lake, the apparent age of DIC in moat waters ranged from thousands of years to near modern in a frozen (closed) versus open moat, respectively. They speculate the old apparent age of closed moat waters is due to the infiltration of the moat by deeper (older) lake waters during the winter. During the summer, the moat ice often recedes from the lake shore, allowing moat waters to equilibrate with the atmosphere. Modern algae sampled from the same moat as the water samples had an apparent age of only a few hundred years [39]. Hendy & Hall [39] hypothesize that the apparent age of algae collected from lake edge deposits will be near modern as algal growth occurs in summer, when moat waters should be near equilibrium with the atmosphere. However, moat ice melts from the lake floor up, and solar radiation penetrating through the moat ice can be absorbed by moat algae even when the ice cover still exists [41]. Thus, the apparent age of algae grown in a closed moat may reflect the large radiocarbon reservoir found in the waters of that closed moat.

DIC in MDV stream waters entering a lake at a delta is likely equilibrated with the atmosphere [35,40]. Therefore, when streams are flowing, it is likely algae growing on the delta at the streams outlet just below lake level are uptaking equilibrated DIC and therefore will produce a modern radiocarbon age. However, streams in the MDVs are ephemeral. Therefore, prior to the start of a stream's annual flow, it can be hypothesized that the algae living on a delta submerged within a lake would uptake DIC from moat waters, which have been shown to have a variable reservoir effect [39]. Therefore, the radiocarbon age of algae found in delta deposits may or may not require reservoir correction depending on when the algae grew relative to the timing of streamflow events during the delta's formation. An added complexity with delta deposits is the possibility of redeposition of radiocarbon reservoir bearing algal mats from further upstream, and the inability to distinguish such mats from those that formed in situ on the delta [42]. Radiocarbon ages of algal mats collected from deltas and lake edge deposits may not, therefore, provide accurate ages reflecting the absolute timing of past lake levels, but they may provide an upper bound for the timing of such events [42].

The permanent ice covers of Dry Valley lakes prevent wind driving mixing and atmospheric exchange, and facilitate the development of stratified water columns, all of which can have significant impacts on radiocarbon reservoirs within a lake's water column [38]. Reservoir effects found in DIC sampled from near the top of the water column may be influenced by annual moat development and/or the amount of surface flow versus direct glacial melt input into the lake. The effects can range from non-existent, as is the case for DIC sampled from the waters of Lake Fryxell, to a thousand or more years, as is the case for DIC sampled from the waters of Lakes Hoare and Bonney [35,40].

Density stratification of lake water columns inhibits the mixing of the younger, near-surface waters with the older waters at greater depths (e.g., [43]). This can lead to very old apparent ages of DIC sampled from lake bottom waters, which may reflect when those waters were last exposed to the atmosphere [35]. Carbonate material sampled from deep lake deposits, however, does not necessarily reflect the apparent age of the deep water they were deposited in. In modern Lake Fryxell, for example, calcite precipitates from planktic organisms in the lower eutrophic zone (8–9 m depth) as the result of biogenic processes, and the precipitates settle to the lake floor as pelagic rain [44]. Thus, the radiocarbon age of carbonate samples from deep lake deposits likely reflects the apparent age of the upper water column at the time the carbonates were precipitated.

Benthic organisms form algal mat communities, which depend heavily on light availability and thus are limited to the depth of maximum light penetration within a lake's water column [17,45]. Radiocarbon dates from algal mats collected from paleolake deposits therefore reflect the timing of a lake level that was either at or several meters above the elevation of the sampled deposit [17], assuming the water the mats formed in was equilibrated with the atmosphere. If the water an algal mat formed in was not at equilibrium with the atmosphere, the mat's age will reflect the timing of the given lake level plus any radiocarbon reservoir the lake waters possessed at the time of the mat's formation.

Lift-off mats are algal mats that detach from the lake floor and float to the top of the water column, often passing through the lake ice cover [46]. Most lift-off mats occur in shallow waters [46], though they can occur at greater depths in response to environmental disturbances, such as the deposition of sediment that has passed through the lake ice cover [47]. While lift-off mats that reach the top of the lake ice cover often ablate away, they do provide another possible confounding factor for dating paleolake deposits as they have the potential to pull radiocarbon reservoir bearing mats from deeper depths to depths where those effects are not present or are less severe. For example, Hendy & Hall [39] dated two lift-off mats found atop the lake ice at Trough Lake, south of Taylor Valley, and found that both samples produced apparent radiocarbon ages > 3 ^{14}C ka BP despite all of the other samples from that lake's moat dating to <2 ^{14}C ka BP.

2.3. Sills and Overflow Signatures

The RIS fed meltwaters responsible for GLW would have had to overcome two prominent sills in Taylor Valley to form a valley-wide lake: one at Coral Ridge (78 m asl minimum elevation) separating the Fryxell and Explorers Cove Basins, and one at Suess Glacier separating the Bonney and Fryxell Basins (Figure 1; 116 m asl minimum elevation). A prominent east-west trending scour cut through Coral Ridge provides evidence for the exchange of waters between the Fryxell and Explorers Cove Basins. The presence of lacustrine algae bearing sandy terraces on either side of the scour below its threshold elevation suggest that lake waters have flowed in both directions through the scour and indicate that a paleolake existed in the Explorers Cove Basin [6,9,33].

RIS meltwater entering Taylor Valley would have first filled the Fryxell Basin, then spilled over the Suess Glacier sill into Bonney Basin. Even in scenarios where the RIS is hypothesized to have advanced westward into the Fryxell Basin, the drift distribution indicates that it did not penetrate so far west as to discharge directly into Bonney Basin (e.g., [6]), and thus this spillover is necessary if we assume the RIS proglacial lake extended into Bonney Basin. Several radiocarbon chronologies attributed to GLW show lake levels dropping below and climbing above the Suess Glacier sill elevation multiple times throughout the lake's history (e.g., [6,11,16]). No documented geomorphological evidence preserves these spillover events. It is possible that there were erosional features that have since been buried beneath Suess Glacier. Downstream (west) of the sill, moraines from earlier Taylor Glacier advances remain preserved on the valley bottom, and a geomorphological survey covering the spillway leading to modern Lake Bonney does not note the presence of any significant erosional features suggesting east to west flow (e.g., [48]).

2.4. Lake Water Columns

Limited evidence for a high-level, valley-wide paleolake is preserved within the water columns of Taylor Valley lakes. Lake Hoare contains fresh water throughout its water column [49–51], and is the youngest of Taylor Valley's main lakes, having formed ~1.2–~1.0 ka [50,52,53], well after the hypothesized span of GLW had ended (e.g., [11]). Lake Fryxell contains brackish bottom waters attributed to marine inputs [52–54]. The salts they contain may be the product of an ancient marine incursion [53] or may have come from the Ross Sea Drift (The term Ross Sea I Drift refers to drift deposited by the RIS during the Ross Sea I glaciation, characterized topographically and by weathering characteristics as described by Stuiver et al. [6]. Ross Sea Drift refers to drift hypothesized to have been deposited by the RIS during the Ross Sea I glaciation, including the Ross Sea I Drift and possibly including parts of surrounding drift sheets. When specified, Ross Sea Drift also refers to older drift sheets deposited during pre-Ross Sea I glaciation RIS advances. In general, our usage of Ross Sea I Drift and Ross Sea Drift aligns with the term used by the author of the text being referenced) [54]. A groundwater system connecting Lake Fryxell and Lake Hoare may also contribute to the salinity of Lake Fryxell's bottom waters [55,56].

Lake Bonney also contains saline bottom waters attributed to marine inputs [52–54]. Although the deep waters of both Lake Bonney and Lake Fryxell have been greatly influenced by marine sources, differing δD trends in the bottom waters of both lakes suggest the two lakes generally have different histories [50]. The salts in Lake Bonney are thought to come from the same ancient marine incursion responsible for Blood Falls [53,54,57] and are not ascribed to GLW. Lake Bonney receives much of its melt from Taylor Glacier, which discharges directly into the west lobe of Lake Bonney (WLB) [40,57]. WLB waters then move across a submerged sill north of Bonney Riegel to enter the east lobe of Lake Bonney (ELB) [40,58,59]. Evidence from the water columns of WLB and ELB indicate a lifetime of west to east flow [40,57–59], with no known publications providing evidence for east to west flow at any point during the lake's history.

3. Paleolake Signatures

If a valley-wide proglacial lake did exist during the Ross Sea I glaciation, physical signature of the water body should exist amongst the valley landscape and in the sediment beneath the valley's modern lakes. Here, we discuss physical evidence from Taylor Valley pertaining to the existence of a large paleolake.

3.1. Lake Core Evidence

Sediment cores extracted from the bottoms of Lakes Fryxell, Hoare, and Bonney preserve signatures of the lakes' histories. Thus, these cores should contain evidence for GLW and other major lake related events recorded in other archives of the valley's history.

3.1.1. Lake Fryxell

Several short (~2 m or less) [60,61] and one 9.14 m long core (Figure 3) [62] have been extracted from the lakebed of Lake Fryxell to decipher the history of the Fryxell Basin. Older studies have hypothesized the entire span of GLW is recorded within the top ~2 m of sediment beneath the lakebed and have suggested a gravel-bearing unit recovered from near the base of some short cores may be a glacial diamict deposited by the RIS during the Ross Sea I or some previous Ross Sea glaciation [60,63,64]. However, radiocarbon dates from organic materials that were recovered from below this gravel-bearing unit via the long core provide a maximum age estimate of ~22 cal. kyr BP, confirming the unit was deposited during or following the Ross Sea I glaciation [62]. Sedimentological, chemical, and biostratigraphic data from deeper parts of the long core may indicate much or all of the core below the gravel-bearing unit was deposited during the Ross Sea I glaciation as well [45,62].

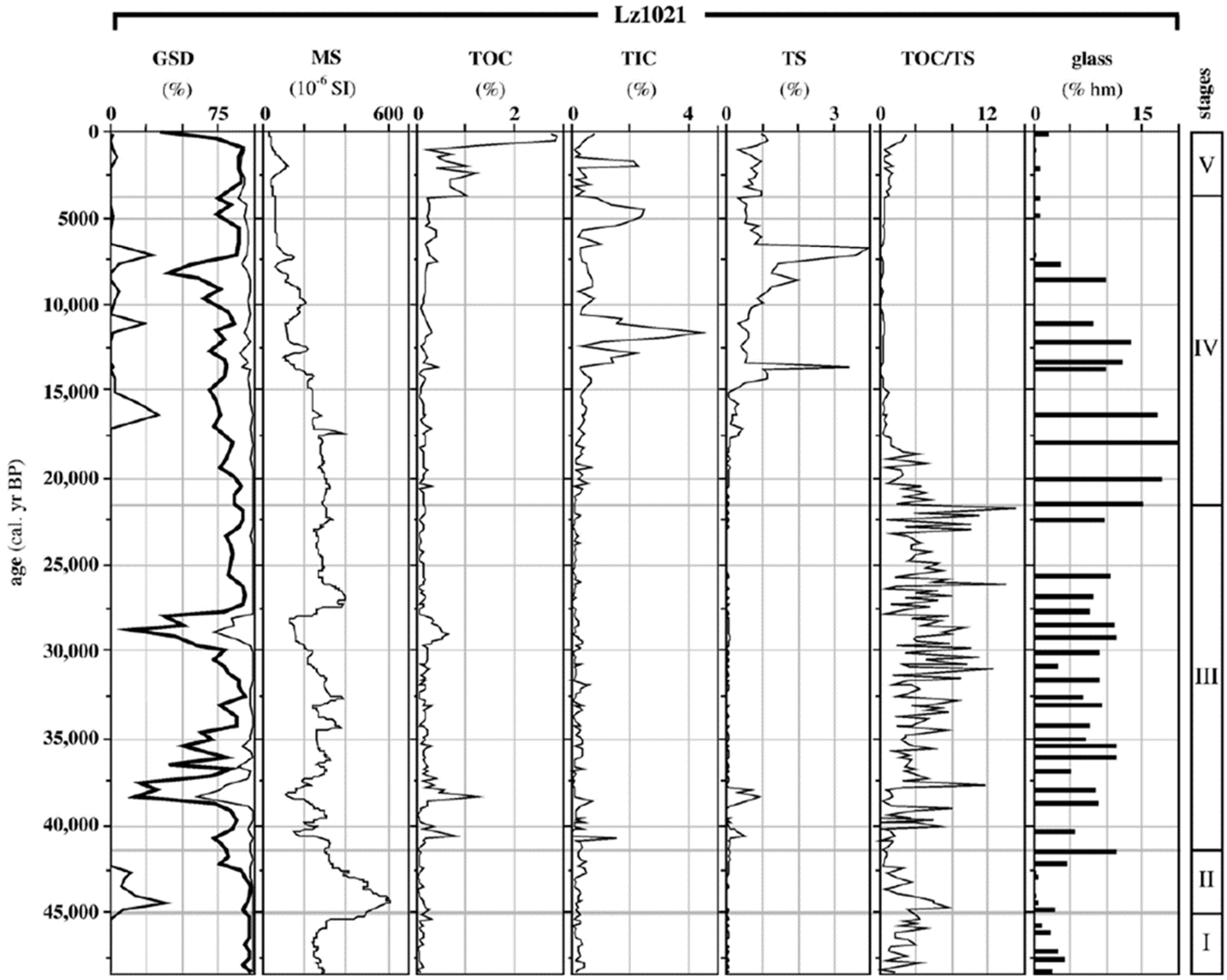

Figure 3. Lake Fryxell sediment core log. GSD = Grain Size Distribution (the gravel, sand, silt, and clay fractions are shown from left to right), MS = Magnetic susceptibility, TOC = Total Organic Carbon, TIC = Total Inorganic Carbon, TS = Total Sulphur, and glass refers to volcanic glass associated with the Ross Sea Drift. All ages are estimated based on radiocarbon dates from core materials (modified from source [62]).

The deepest sediments sampled from beneath Lake Fryxell are well sorted sands that contain volcanic glass (Figure 3, stage I). The glass is attributed to McMurdo Volcanic Group materials thought to have been transported from Ross Island via the RIS [62]. The presence of volcanic glass suggests these sediments were deposited at or following a time when the RIS was present in Taylor Valley [62]. Diatom assemblages [45] and an up-core increase in the total organic carbon to total sulfur (TOC:TS) ratio (Figure 3) indicate increasingly freshwater conditions at the site during the deposition of these sediments [62].

Wagner et al. [62] hypothesized that these sediments were deposited in a fluvial or lacustrine environment between ~48–45 cal. kyr BP, during a time of warm regional temperatures [23,24] and increased melt.

Above the deepest sediments, the grain size increases and coarsens upward, poorly rounded gravels appear, volcanic glass becomes less abundant, and the TOC:TS ratio decreases (Figure 3, stage II) [62]. This is followed by a zone of variation in grain size, organic matter content, the TOC:TS ratio, and magnetic susceptibility, which contains increased amounts of volcanic glass (Figure 3, stage III) [62]. The sedimentary sequence preserved in these zones is hypothesized to represent a lake drawdown stage, during which the lake ice cover thinned and potentially disappeared due to increasing salinity, followed by the emergence or re-emergence of the RIS into the mouth of Taylor Valley, indicated by the increased presence of volcanic glass, and the refilling of the lake basin by low salinity waters, potentially by the early stages of GLW [62]. The variability in the upper zone may indicate that lake levels fluctuated during its deposition [62]. Freshwater lacustrine diatom assemblages throughout the upper zone further support the presence of a lake during this interval [45]. Konfirst et al. [45] note that the high number of diatoms in this part of the core is surprising given that diatoms are normally produced in the shallower regions of Dry Valley lakes. Assuming higher than present lake levels, shallow regions would have been far from the core site when this zone was deposited, meaning diatoms would have to have been transported downslope to the core site. The relatively good preservation of the diatoms, however, implies that downslope transport of the diatoms did not take place [45]. Konfirst et al. [45] provide a few hypotheses for how the diatom assemblages and higher lake levels could have coexisted, including deposition in a shallower-than-hypothesized lake, formation of the assemblages in meltwater pools atop the lake ice and deposition through the lake ice cover above the core site, or diatom deposition during intermittent low-stands.

The top ~3 m below the sediment water interface in the long core shows a decrease in the TOC:TS ratio (Figure 3, stage IV) [62]. This, along with the appearance of certain diatom assemblages throughout this section, and the appearance of poorly rounded gravels at ~2 m below the surface (also stage IV), suggests an increasing salinity and may indicate this portion of the core records a lake drawdown [45,62]. Volcanic glass is prevalent in the lower part of this section in the long core but decreases markedly in the top ~1 m, which may indicate the retreat of the RIS from the mouth of the valley at the time of deposition [62]. Thus, this section likely marks the termination of the existence of lake levels above the Coral Ridge threshold elevation in lower Taylor Valley.

Above the gravel-bearing unit near the top of the long core, the sediment transitions alternating layers of sand and laminated algal mats, thought to indicate similar to modern depositional conditions in Lake Fryxell (Figure 3, stage V) [62]. This transition towards modern conditions is also recorded in the short cores [60,61]. As these near-surface sediments are generally thought to have been deposited following the retreat of the RIS from Taylor Valley and the termination of a high-level paleolake in lower Taylor Valley [45,61,62], further discussion of them is not pertinent to this manuscript.

3.1.2. Lake Hoare

Several cores have been collected from the bottom of Lake Hoare (e.g., [35,65–67]), reaching a maximum depth of 2.33 m below the lakebed (Figure 4) [67]. Sedimentological evidence from these cores indicates changing depositional environments through time, with the deepest sampled depths containing a matrix of sand and silt interspersed with poorly rounded gravels, some of which are >1 cm in thickness, meaning they likely could not have passed through a permanent lake ice cover [67,68]. Wagner et al. [67] hypothesize that this deepest zone was deposited in GLW, with the larger pebbles being delivered via lake ice conveying from the RIS. However, minimal amounts of RIS associated volcanic glass was found in sediments extracted from the entire Lake Hoare core (Figure 4), suggesting a local source for the deposited materials or only minor drift contributions from the RIS [67].

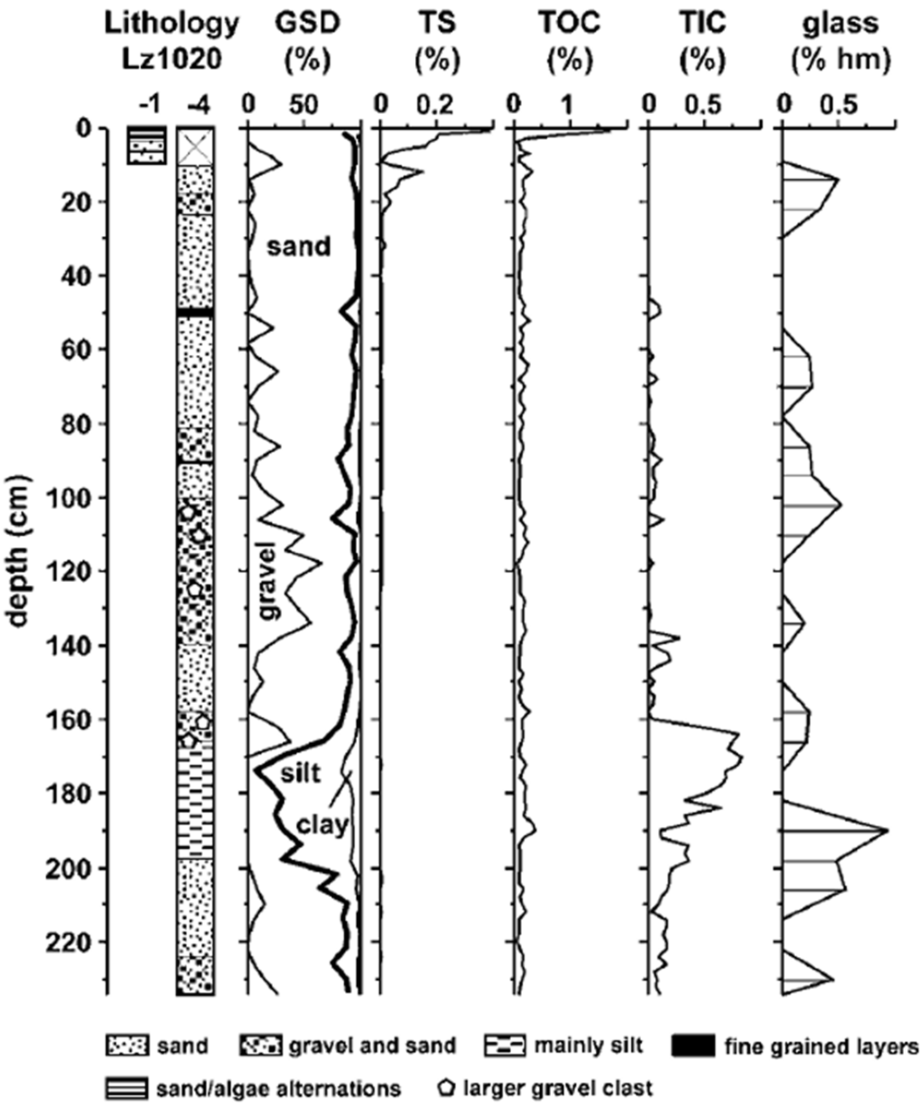

Figure 4. Lake Hoare sediment core log. GSD = Grain Size Distribution, TS = Total Sulfur, TOC = Total Organic Carbon, TIC = Total Inorganic Carbon, and glass refers to volcanic glass associated with the Ross Sea Drift (modified from source [67]).

Further up core, the sediment is dominated by clay and sand bearing silt, containing poorly rounded gravels in the upper part of this section, with total sulfur generally increasing throughout the section (Figure 4). This is capped by a unit with limited amounts of silt and clay that consists of sand near the bottom of the unit and large gravel-bearing sandy gravel near the top of the unit [67]. This sequence is interpreted to have deposited during GLW's final drawdown, with the increase in total inorganic carbon being due to the concentration of solutes within the lake's water column, leading to the eventual complete desiccation of the lake. The sand and sandy gravel unit represents subaerial conditions and desert pavement formation [67].

The upper section of sediment beneath modern Lake Hoare was likely deposited by similar-to-modern lake processes, with sediment consisting of layers of sand, clayey silt, and fine gravels [67].

3.1.3. Lake Bonney

A single, 2.70 m long piston core extracted from Lake Bonney in its eastern lobe has been used to decipher this history of ELB based on the proportion and composition of salts, clastic sediments, and water throughout the core [69]. The lower part of the core is generally dominated by salts, often forming large crystals, which decrease dramatically in the uppermost section of the core. This is thought to indicate a past interval of decreased meltwater input, leading to a drop in ELB lake levels and the concentration and precipitation of its salts, and possibly the loss of the lake's ice cover. This was followed by the refilling of ELB, leading the lobe to its present configuration. Although Wagner et al. [69] were able to obtain radiocarbon ages of 10.83 ± 0.06 and 10.94 ± 0.10 ^{14}C kyr BP from carbonates collected from bulk sediment samples from 170–174 m depth in the core, they advise that an unconstrained radiocarbon reservoir effect makes the accuracy of these dates uncertain. Despite this, they attribute the salt-dominant interval to the evaporation of GLW between ~11 and 8 ^{14}C kyr BP [11,62,64], and suggest that evidence for later drawdown events were not recorded in the core [69]. It is important to note that, in the absence of reliable age constraints, the salt-dominant interval could be attributed to any of the drawdown events proposed for ELB's history (e.g., [58,70]).

3.2. Soil Evidence

The source of organic matter in Taylor Valley soils may provide some evidence of an LGM-era valley-wide proglacial lake. Soil organic matter source was determined based on the δ^{15}N ratio of extracted organic materials, which was found to be a better organic matter origin tracker than δ^{13}C in the region [71]. Lacustrine-derived organic matter (LDOM) is found at <150 m asl throughout the valley, except in the region of WLB where it is completely absent; marine-derived organic matter (MDOM) is common in and east of Fryxell Basin (excluding the area west of Canada Glacier) and west of Suess Glacier, but is absent in the rest of the valley; and endolith-derived organic matter (EDOM) is the most common source above 150 m asl throughout the valley (Figure 5). The prevalence of EDOM above 150 m asl may be due to the downslope movement of endolithic materials from higher elevations along the steep valley walls, while the MDOM in lower Taylor Valley and west of Suess Glacier may be derived from the Ross Sea Drift and the ancient marine waters trapped beneath Taylor Glacier, respectively [71].

The soluble salt content in the soils of Taylor Valley vary with distance from the coast and with elevation. Lower Taylor Valley soils have much lower salt contents than Bonney Basin soils, averaging 50 eq m^{-2} and 900 eq m^{-2}, respectively [5]. The climate and soils of lower Taylor Valley and Bonney Basin are different, being largely controlled by their underlying drift [19,72]. Although different leaching rates can be expected in the two parts of the valley, leaching is not a uniform process and thus does not account for the differences in soluble salt content in different parts of the valley [5].

In Bonney Basin, the soluble salt concentration of soils between 116 m asl (Suess Glacier sill elevation) and 300 m asl tends to be lower than that of soils below 116 m asl or above 300 m asl (Figure 6), which has been hypothesized to be due to a RIS-fed paleolake above 116 m asl fluctuating rapidly in level in response to grounding line fluctuations, limiting evapoconcentration in this upper range [5]. Soils above 300 m asl tend to have the highest soluble salt concentrations in Bonney Basin (Figure 6) [5]. Soils below 116 m asl also have relatively high soluble salt concentrations, with the salts having similar Na^+:Cl^- ratios to the WLB hypolimnia. This suggests that Taylor Glacier and the brine trapped beneath it may have been the major source for the most recent paleolake in Bonney Basin up to the sill height, and that the lake drawdown was due to evaporation/sublimation, leading to the evapoconcentration of its salts into the soils the lake had inundated [5].

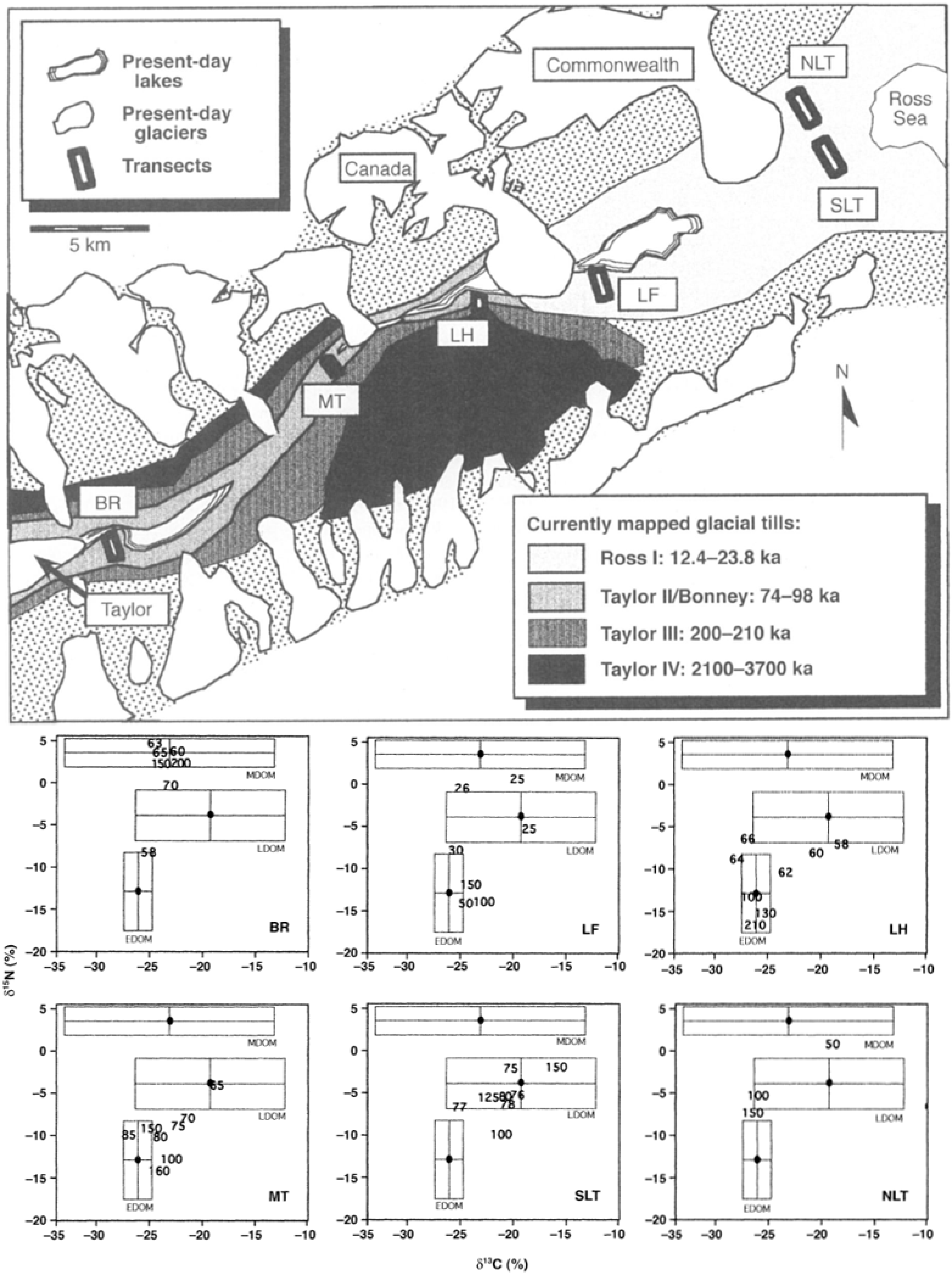

Figure 5. Soil organic matter sources in Taylor Valley. The map shows the transects the soil samples were collected from. Plots show how the isotopic signatures of soil samples from each transect compare with that of marine-derived organic matter (MDOM), lacustrine-derived organic matter (LDOM), and endolith-derived organic matter (EDOM). The numbers associated with points on the plots indicate the elevation in meters that a sample was collected from. BR = Bonney Riegel, MT = Middle Taylor, LH = Lake Hoare, LF = Lake Fryxell, NLT = North Lower Taylor, SLT = South Lower Taylor (modified from source [71]).

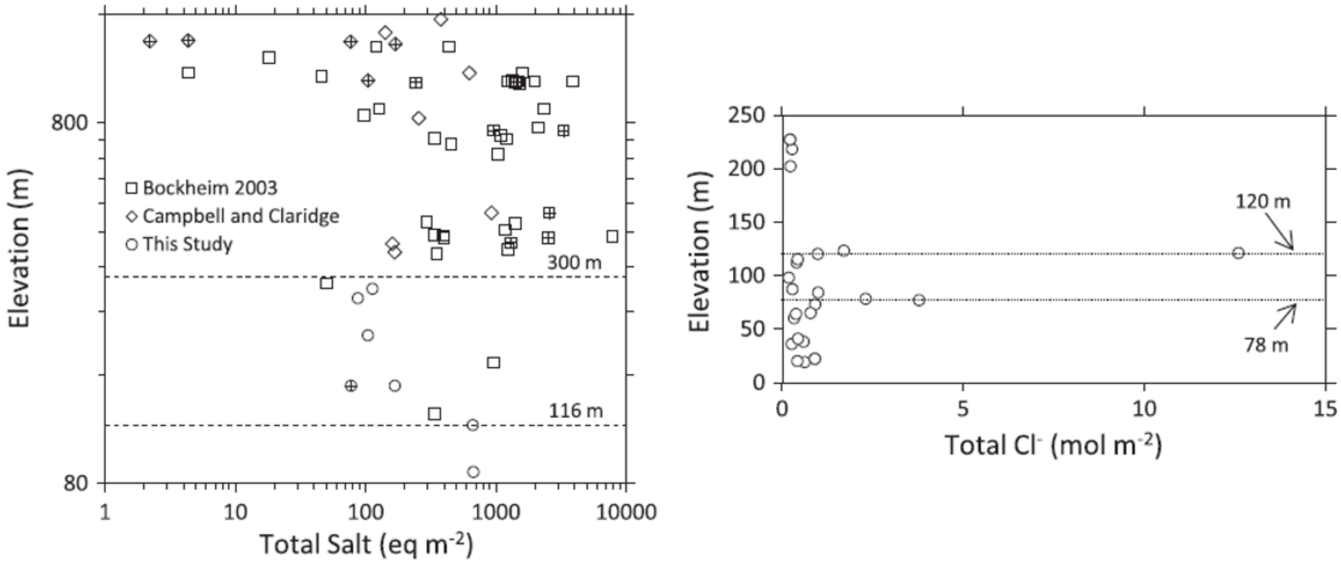

Figure 6. Total soluble salt content of Bonney Basin soils (**left**) and chloride content of Fryxell Basin soils (**right**) versus elevation. The 300 m asl line in the left plot marks the maximum proposed depth of GLW in Bonney Basin according to Toner et al. source [5], and the 116 m asl line indicates the elevation of the Suess Glacier sill. In the right plot, the 78 m and 120 m elevation lines correspond roughly to the threshold elevation of the Coral Ridge and Seuss Glacier sills, respectively. '+' symbols indicate the presence of ice cement at the sample site (modified from source [5]).

In lower Taylor Valley soils, the concentration of Cl^- is highest close to Nussbaum Riegel and below ~120 m asl, with 2 distinct spikes in concentration occurring at 78 and 121 m asl (Figure 6) [5]. The spikes in Cl^- concentration correspond roughly with the threshold elevations of Coral Ridge and the Suess Glacier sill, respectively, and may indicate that a paleolake remained at those elevations for a longer duration than it did at other elevations in lower Taylor Valley [5].

3.3. Deltas and Streams

Around 200 sandy terraces, normally considered to be perched deltas, are found at elevations up to 314 m asl throughout Taylor Valley (Figure 7) [3,4,11]. Freshwater microfossil assemblages found in several of the terraces in Fryxell Basin indicate that they are non-marine in origin [4,10]. These terraces are usually found alongside, and are often being incised by, modern stream channels, and their elevations may be like that of linear features that are hypothesized to be strandlines [6]. In general, they range from 1.5–12 m in relief, with relatively flat tops and between 10° and 30° slopes at their toe [4]. They range in area from 4–~50,000 m^2 and contain finer grained sediments (silt to fine gravel size, with sand size being dominant) capped with a gravel lag [4]. The sediments are often, but not always, laminated [4], and some sandy terraces have an irregular appearance [17]. In addition, some claim that Ross Sea Drift and large boulders are present atop some of the sandy terraces throughout Taylor Valley [4,11,15], while others have noted a lack of glacial dropstones and deposits atop these terraces [6]. Boulders were noted to be present on top of a few sandy terraces, superficially resembling deltas, along Delta Stream. However, ground penetrating radar (GPR) profiles of these deposits, discussed below, confirmed that they are not deltas [73]. It is thus unclear from the literature whether drift is present atop the perched deltas in Taylor Valley.

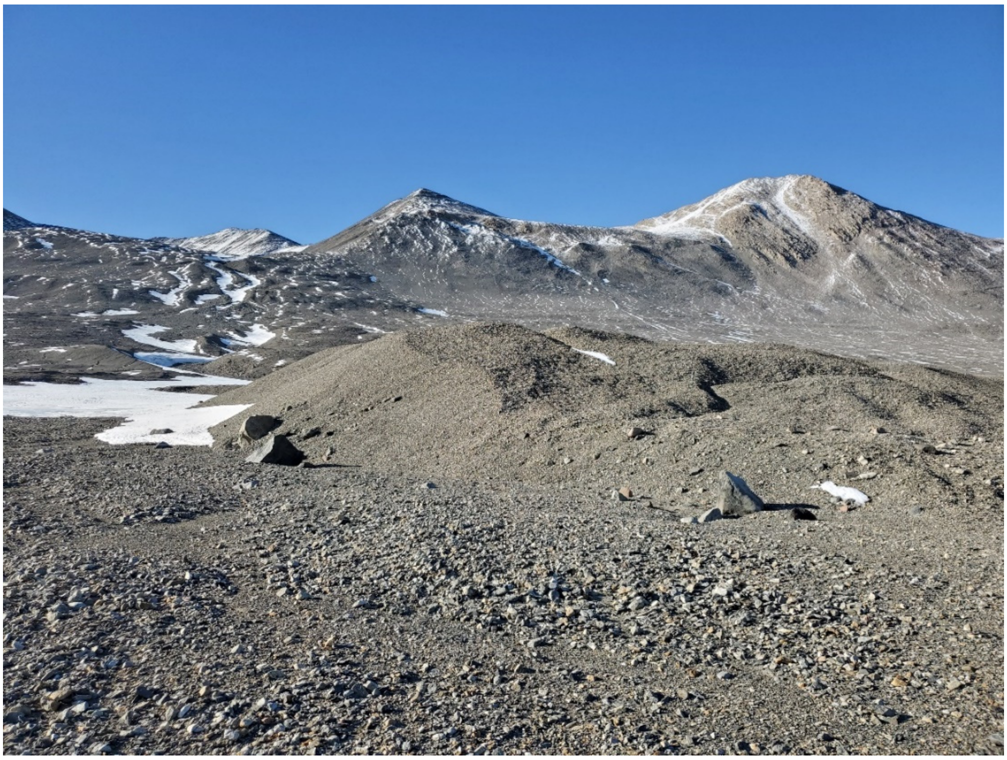

Figure 7. A sandy terrace along Huey Creek in Fryxell Basin. Image taken from the creek bed facing north. Photo credit M. Stone.

Despite these sandy terraces commonly being referred to as deltas, GPR profiles of 4 sandy terraces in lower Taylor Valley revealed that only 1 of the 4 was actually a delta [73–75]. 3 of 4 were dominantly deposited by fluvial or glaciofluvial processes, with 2 terraces along lower Delta Stream being interpreted as forming as stream channel bars during flood events, and 1 terrace at 120 m asl, also along Delta Stream, forming from Ross Sea Drift overridden by outwash from the ice sheet, thus suggesting if formed in an ice-marginal environment [73]. Based on these results, Horsman [73] hypothesizes that many of the sandy terraces throughout lower Taylor Valley that are morphologically similar to those found to have non-deltaic origins are also not deltas. Delta-like features have also been observed forming away from the MDV lake edges as the result of glacio-fluvial and niveo-aeolian processes [76].

A GPR survey of a large, sandy terrace at ~80 m asl along Crescent Stream in Fryxell Basin confirmed the feature to be a delta [73,75]. The survey further revealed a few diffraction events that may indicate the presence of buried pebbles or boulders, or pockets of fine-grained soil [73,75]. While the inclusion of coarse-grained materials in deltas has been hypothesized by some to indicate the mixing of depositional regimes due to the simultaneous deposition of the delta and an active lake-ice conveyor [17], coarse grained materials can also be deposited as part of normal delta-forming processes during high-flow events [73].

The channels of the streams throughout Taylor Valley are incised into the underlying drift, including the Ross Sea I Drift, indicating that the streams formed after the deposition of the various drift sheets [77]. These streams can flow even in below freezing air temperatures if the underlying rock and soil is above freezing [77]. This means deltas could have potentially formed from streamflow occurring during colder climates during and following the LGM [9], though others have suggested increased stream flow and delta formation more likely occurred during more recent warmer intervals [12].

3.4. Strandlines

Several types of lacustrine strandlines have been described in the MDVs with varying degrees of supporting evidence for the classification of each type. Here, we separate these strandline descriptions into three categories: delicate type, ice-push type, and bench type.

3.4.1. Delicate Type

Near-horizontal lineations delicately etched into till near Rhone and Canada Glaciers are thought by some to be strandlines from paleolakes in Taylor Valley (Figure 8) [6,7]. These delicate type strandlines fall between 120–311 m asl near Rhone Glacier [6] and reach ~46 m asl near Canada Glacier [7]. Perched deltas deposited at similar elevations near Rhone Glacier provide supporting evidence for these features to be classified as strandlines [6].

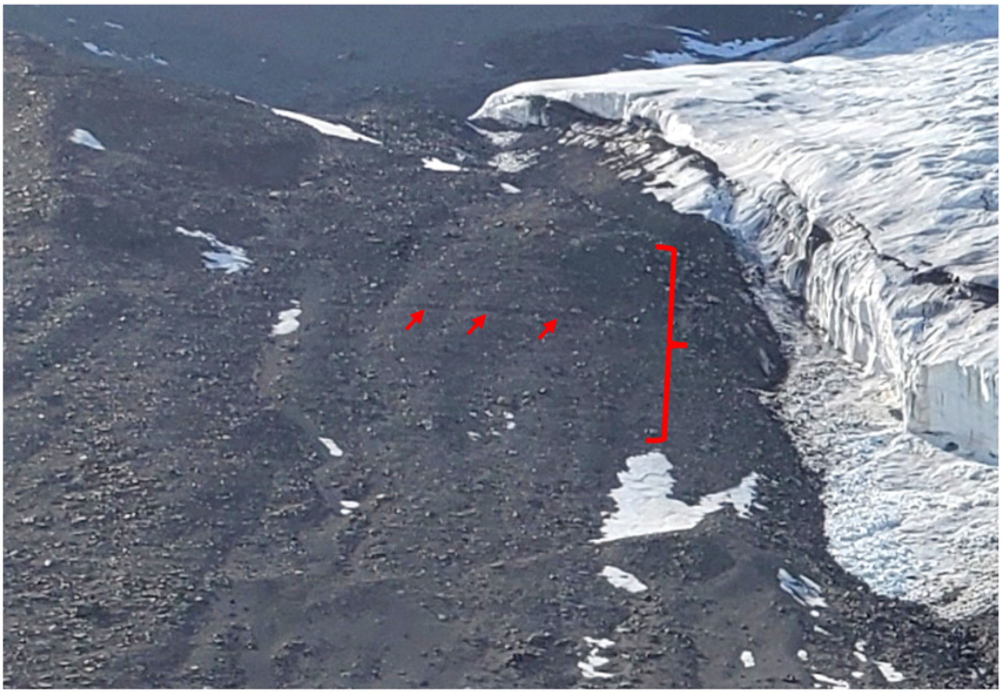

Figure 8. Delicate type strandlines (left of the red bracket) next to Rhone Glacier. The red arrows point to the most prominent of these linear features. Photo credit M. Stone.

Data-driven evidence for how delicate type strandlines form is absent from the literature. However, Hendy et al. [17] hypothesize that ice-covered lakes may develop "subtle" step-and-trend shorelines due to windblown deposition of fine-grain sediment into open moats and slumping of saturated unconsolidated sediment along the shoreline. Minimal amounts of open water around the lake ice cover limits wave action, which limits the development of these step-and-trend shorelines. Step-and-trend shorelines are hypothesized to develop preferentially on steeper slopes, which facilitate slumping, and to contain sorted sediment due to the aeolian influences on their formation [17].

3.4.2. Ice-Push Type

Ice-push type strandlines form when pressure from lake ice formation along a lake edge, or impact from floating lake ice, leaves an imprint on the lakeshore. This type of strandline is common above Lake Vanda in Wright Valley, and active formation of ice-push type strandlines has been observed along the western shore of that lake [78]. By comparing the grain size distribution of various elevation strandlines above Lake Vanda to other colluvium collected in the area, Jones et al. [78] found the two were indistinguishable in all but one sample, suggesting that ice-push alone is responsible for most strandline formation, with no influences from grain-sorting processes such as wave action (Figure 9). The single sample that was distinguishable from colluvium was well sorted, which they attribute to fluvial influences due to its proximity to a shallow channel.

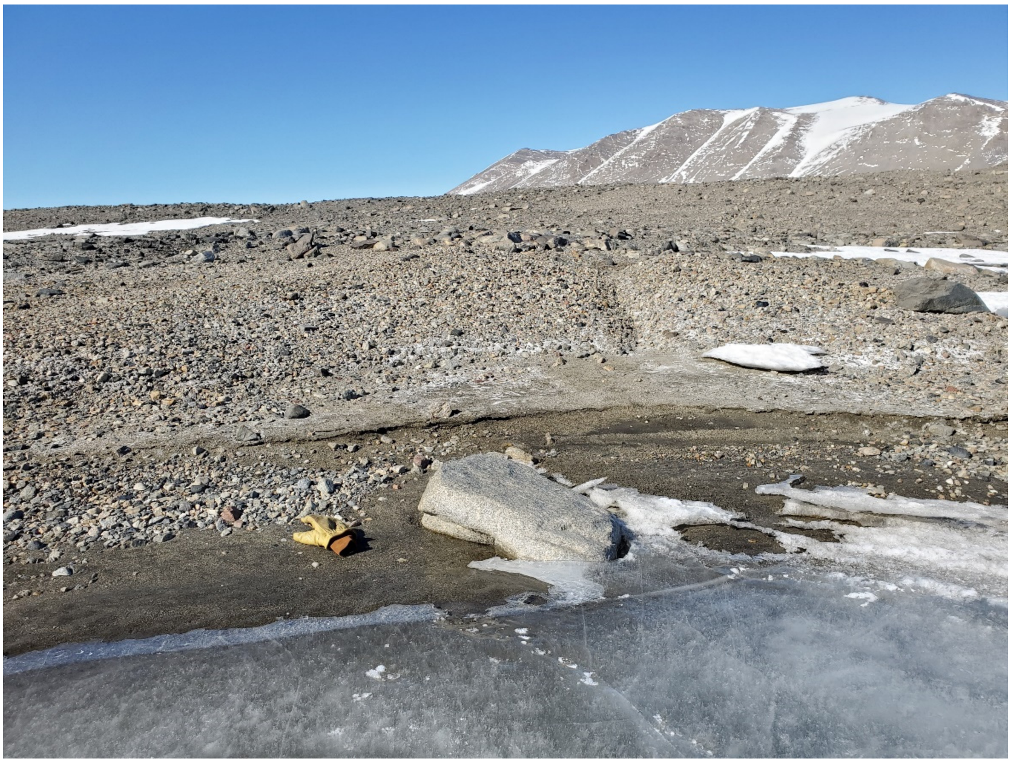

Figure 9. An ice push strandline along the shore of modern Lake Fryxell marking the 2014 lake level (highest in the modern record for Lake Fryxell [79]). Photo taken in January of 2022 facing east. Photo credit M. Stone.

The strandline study of Jones et al. [78] is significant as it is the only data-driven study of strandline formation in the MDVs known to the authors. Thus, ice-push type strandlines are the only strandline type identified in the region that are confirmed to be of lacustrine origin. Ice-push type strandlines are notably absent above Lakes Bonney and at higher elevations above Lake Fryxell in Taylor Valley [18], though some ice-push strandlines have been noted along the lakeshore of Lake Fryxell within a few vertical meters of its modern lake level (e.g., [73]), and signatures of buried ice-push strandlines were not identified in a Bonney Basin survey of soils above and below the proposed GLW highstand level of 336 m asl [19].

3.4.3. Bench Type

Bench type strandlines are large scale (several meters to tens of meters across), semi-continuous, near-horizontal linear features present throughout Taylor and several other MDVs (Figure 10). These features were first identified as potential strandlines of Glacial Lake Llano in Bonney Basin by Angino et al. [80] and were later attributed to GLW. Although Dort [81] states that these features were determined to not be strandlines, and instead are lateral moraines from an earlier expansion of Taylor Glacier, they provide no supporting evidence for this claim. A photograph capturing these features in Bonney Basin was published by Denton & Armstrong [8], who definitively labeled these features as strandlines, despite providing no supporting evidence for the claim. Since then, these features have interchangeably been referred to as lateral moraines (e.g., [48]), strandlines (e.g., [82]), or both (e.g., [83]) depending on the context of the publication.

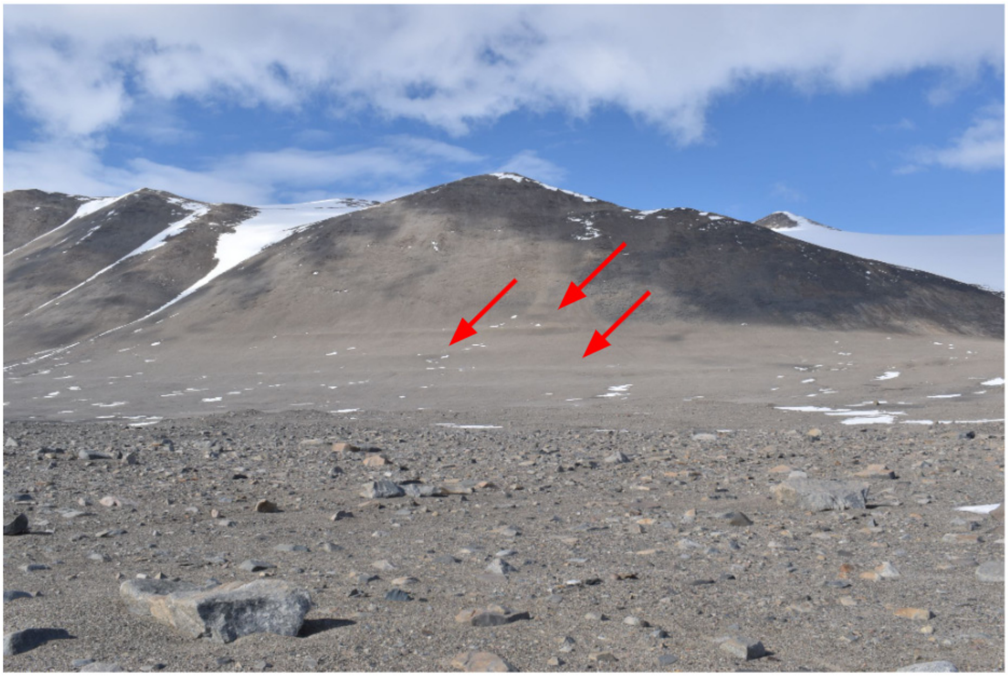

Figure 10. Bench type 'strandlines' (marked by red arrows) along the south wall of Fryxell Basin. Photo credit M. Stone.

In lower Taylor Valley, bench type strandlines are hypothesized to have formed via lake ice conveyor movement of debris away from the RIS grounding line atop the GLW ice cover and its subsequent deposition in the moats of the paleolake [4,9,15,17], though they may also be produced through the erosion of the pre-existing landscape by unspecified lacustrine processes [4]. As the debris is transported across the lake ice cover, fine grained sediments are thought to pass through the lake ice, leaving mostly coarse-grained material to be deposited in the moats. This coarse-grained material incorporates lake edge algae, minerals, and other lacustrine features as it is deposited, which may help distinguish these strandlines from moraines [4,17].

Moat deposition via lake ice conveyor is hypothesized to not occur at the same rate in all parts of a lake. According to the model, the most prominent strandlines should form on the side of the lake that is opposite the lake-glacier contact [17], though in lower Taylor Valley the most prominent bench type strandlines are on the north and south walls of the valley adjacent to the proposed RIS grounding line at Coral Ridge. Around the rest of the lake, moat deposition is thought to be sporadic, being made up by the amalgamation of individual mounds and ridges [4,17]. These lake ice conveyor-based bench type strandlines are discontinuous, sub-horizontal, and have several meters of relief along the former lake shoreline [4].

The span over which lake ice conveyor-based strandlines amalgamate into distinctive features is not specified in the literature, though this process is thought to require long-term lake level stability [17]. Thus, the formation of such prominent bench style strandlines at high elevations in lower Taylor Valley is surprising given that higher lake levels are less stable than lower ones due to the increased amounts of ablation that come with having a larger lake surface area [20].

The preservation of the bench style strandlines in lower Taylor Valley may reflect their relative age. While some authors claim they are well preserved [16], suggesting they formed relatively recently, others have noted excessive amounts of ventification in the boulders covering these features, suggesting that they are very old [84], potentially predating the Ross Sea I glaciation.

Despite the bench style strandlines of Bonney Basin being the first described in Taylor Valley [80], the mechanism of the formation of these strandlines is unclear. It has been suggested that lake ice conveyors were in operation in Bonney Basin at times during the hypothesized span of GLW [48]. Thus, the Bonney Basin bench strandlines may be attributed to lake ice conveyor deposition as well. The features may also have been formed by unspecified erosional processes occurring along the lake edge [4,83].

Konfal et al. [83] hypothesized that the bench style strandlines in Bonney Basin formed from shoreline slump and aeolian deposition in the moats, leading to a step-and-trend morphology. However, this hypothesis is based on the shoreline formative processes proposed by Hendy et al. [17], who clearly state that shorelines formed in this way are "subtle". The step-and-trend model of shoreline formation thus seems unlikely to be applicable to the meter-scale bench style shorelines in Bonney Basin.

If the bench features of Taylor Valley are not strandlines, they may be lateral moraines from former advances of the RIS in lower Taylor Valley [5,6], and from former advances of Taylor Glacier in Bonney Basin [48]. A glacial origin for these bench features will be explored in greater detail in Section 4.3.

3.5. Subsurface Evidence for Paleolakes

Airborne electromagnetic (AEM) data collected in lower Taylor Valley indicates a zone of lower resistivity, interpreted to be unfrozen sediment, that extends well beyond the limits of modern Lake Fryxell (Figure 11) [85]. The depth to this low resistivity zone increases with elevation forming a gradient (Figure 11). The zone itself may be a talik that formed beneath a paleolake, with the permafrost gradient representing the gradual exposure of formerly submerged sediments during the lake's final drawdown stage [14,55,85].

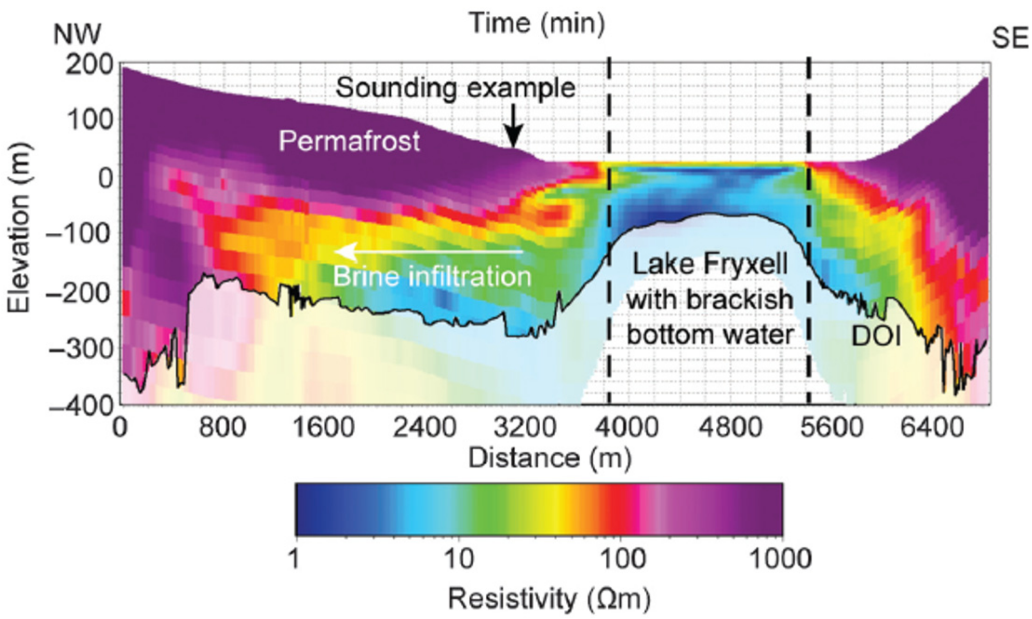

Figure 11. Resistivity cross section across Lake Fryxell. Vertical dashed lines indicate the surface extent of Lake Fryxell. Note the low resistivity zone, hypothesized to be a remnant talik from an ancient high-level lake, that extends well beyond the limits of modern Lake Fryxell (modified from source [85]).

This low resistivity region extends east and west of Lake Fryxell and is thought to also indicate a saline groundwater system that begins at Lake Hoare and extends to the McMurdo Sound, dipping beneath both Canada Glacier and Coral Ridge [55,56]. A groundwater system also exists beneath Taylor Glacier and Lake Bonney [55,86]. However, indicators of groundwater connectivity in the resistivity data collected between Lake Bonney and Lake Hoare are notably absent [55]. Although groundwater was observed in Dry Valley Drilling Project (DVDP) drill hole 10 at New Harbor, and is suspected to have existed just below the terminal depth of DVDP drill hole 11 at Coral Ridge (based on reduced sediment cohesion at the base of that core), no notable groundwater was observed in DVDP drill hole 12 from the south shore of Lake Hoare, despite that hole being drilled all the way to bedrock [87].

The pore waters of DVDP core 11 at Coral Ridge are non-connate in nature [88], which may be attributed to the flushing of the core's sediment by waters draining from GLW into the McMurdo Sound [87,88], or could be a product of flushing by the groundwater system. DVDP core 12 pore waters become isotopically lighter with depth and salinity increases with depth, indicating downward freezing of the pore waters at the core site [89].

4. Glacial Evidence

The presence of the RIS in the mouth of lower Taylor Valley is essential in explaining any historic lake levels that reached above the elevation of the valley mouth threshold at Coral Ridge. Glacial positions during the Ross Sea I glaciation also dictate the maximum spatial extent a paleolake in Taylor Valley could have occupied. A discussion of evidence for past glacial positions and movements in Taylor Valley is therefore necessary for understanding the history of lakes in Taylor Valley.

Here, we will examine the glacial drift sheets present in Taylor Valley; the lake ice conveyor hypothesis for drift sheet distribution; the types, distribution, and formation of relevant glacial features found in Taylor Valley; and the isostatic rebound resulting from ice mass loss following the LGM to understand the valley's glacial history and its implications for the valley's paleolakes.

4.1. Drift Descriptions and Extents

Several drift sheets are present in Taylor Valley. The Bonney Drift consists largely of metamorphic and granitic rocks, including Irizar Granite, that are local to the MDVs. It also contains a lesser amount of Beacon Sandstone and dolerite clasts [7,90]. The drift has ventifacts and, possibly, well-developed desert pavement, suggesting a very old age [7,80], though the desert pavement has also been suggested to be let-down drift from a lake ice conveyor operating atop GLW [48]. Hummocks composed of Bonney Drift, found on the floor of Bonney Basin between Lake Bonney and Suess Glacier, have a crescent-like shape. This shape is morphologically like the toe of modern Taylor Glacier, suggesting Taylor Glacier was responsible for their deposition and providing evidence that Taylor Glacier is responsible for the Bonney Drift [48]. East dipping moraines and ice-marginal channels preserved on the walls of Bonney Basin also provide evidence for Taylor Glacier, rather than alpine glaciers or the RIS, being the source of the Bonney Drift [48], though local alpine glaciers may have played a role in Taylor Glacier's advance and thus may be responsible for some of the drift's composition [9].

The Bonney Drift occupies the area of Taylor Valley between the snout of Taylor Glacier and Canada Glacier. It extends up to ~375 m asl near Rhone Glacier and descends to an upper limit of ~300 m asl between Suess and Lacroix Glaciers [4,48]. This upper limit is defined by lateral moraines on the valley walls and large, triangular flatiron features present in the region between the Lacroix and Suess Glaciers [48]. Although Canada Glacier is suggested as an eastern limit for the Bonney Drift, the surface drift of the Lake Hoare region is unique from the rest of the Bonney Drift (discussed later in this section), and a clear eastern limit for the Bonney Drift has not been defined.

The Ross Sea Drift is considered younger than the Bonney Drift and is attributed to expansions of the RIS into lower Taylor Valley (Figure 12) [4]. The Ross Sea Drift contains kenyite (Kenyite is a porphyritic anorthoclase phonolite extrusive igneous rock, of which the only known source in the region is Mount Erebus [91]), basalt, dolerite, and sandstone erratics, all with allochthonous sources east of Taylor Valley [3,4,92]. The drift can be stratified, contains ice-cored deposits, and is often bounded by an end moraine in the MDVs, although in Taylor Valley, this is not the case [6]. In Taylor Valley, the drift contains cross-valley and longitudinal ridges and is capped by numerous perched delta deposits [4,6].

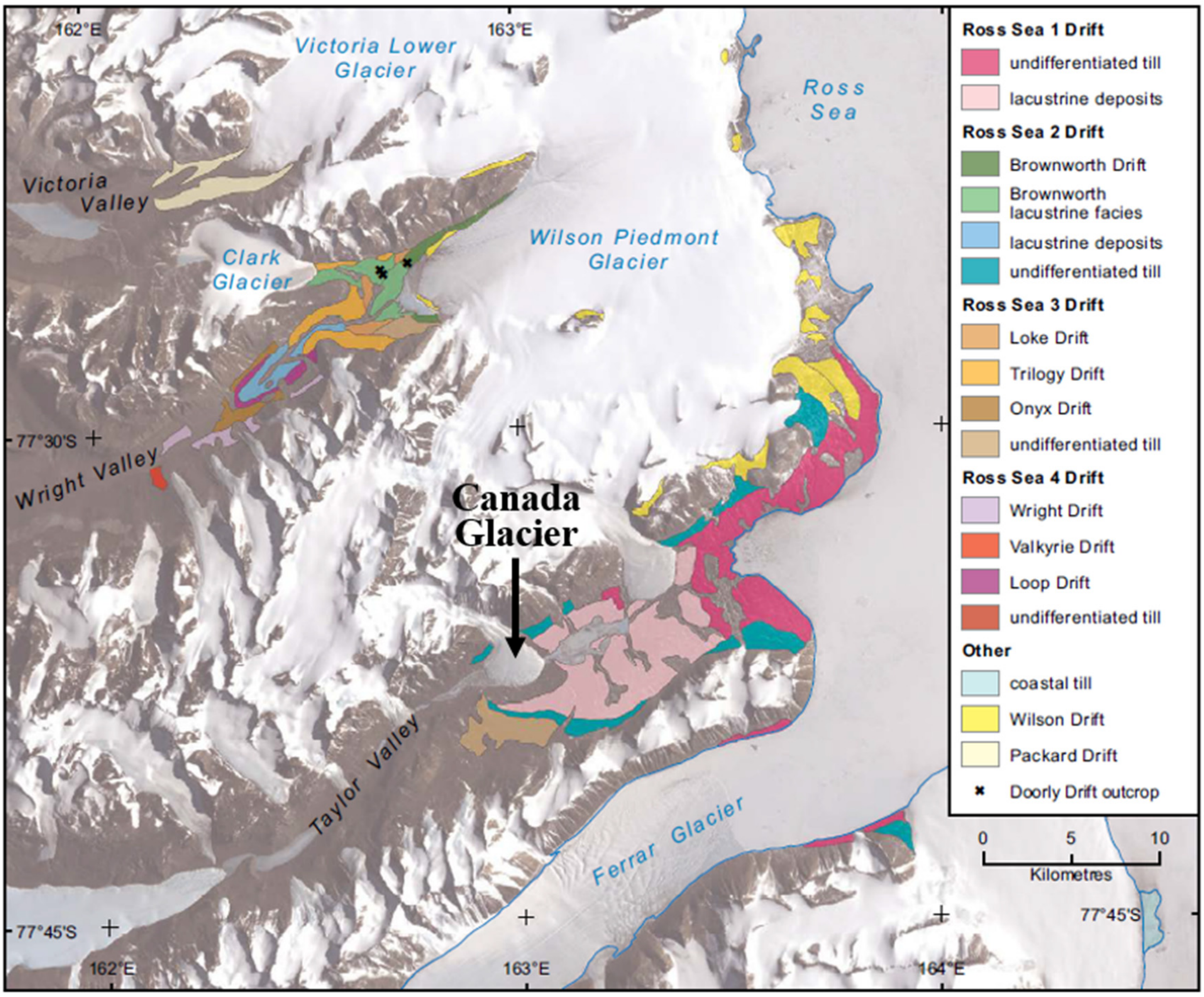

Figure 12. Distribution of various drift sheets in the McMurdo Dry Valleys. The western part of Taylor Valley is occupied by Bonney Drift (not indicated on map). Note the unmapped drift directly south of Canada Glacier. This region has been mapped as both Bonney Drift (e.g., [84]) and Ross Sea Drift (e.g., [6]) (modified from source [93]).

Several Ross Sea Drift sheets from different Ross Sea glaciations exist in Taylor Valley (Figure 12). The Ross Sea I Drift is distinguished from older Ross Sea Drifts based on spatial relationships, the subdued surface morphology of the older drifts (indicating that the formerly ice-cored deposits of these older drifts have undergone sublimation, causing the landscape to flatten), and different degrees of weathering and ventification in the deposits [3,6].

Ross Sea Drift is constrained to lower Taylor Valley. The northern limit of the Ross Sea I Drift may be defined by a lateral moraine that fringes the Asgard Range, dropping from ~400 m asl near Hjorth Hill to ~58 m asl near Canada Glacier [6]. The northern upper elevation limit of Ross Sea I Drift may also be defined by a ~350 m asl east-dipping moraine on Hjorth Hill [3], though it is unclear if this moraine is the same as the aforementioned moraine. Older Ross Sea Drifts reach elevations as high as ~620 m asl near the valley mouth, indicating that advances of the RIS prior to the Ross Sea I glaciation were larger. On the south wall of Taylor Valley, the limit of the Ross Sea Drift is marked by well-preserved lateral benches. The western limit of the Ross Sea I Drift in Taylor Valley is difficult to identify as it is not defined by a prominent terminal moraine [6]. Hall et al. [4] suggest the Ross Sea Drift extends to the south-east shore of modern Lake Hoare, whereas Cox et al. [93] map the Ross Sea Drift as terminating on the southern margin of a moraine ring several hundred meters south of Canada Glacier's toe. The region between Canada Glacier and the moraine ring has been mapped as containing Bonney Drift by some (e.g., [4,84]) and as containing Ross Sea Drift by others (e.g., [6]), though the moraine ring itself was likely formed by Canada Glacier (Figures 12 and 13) [6,7].

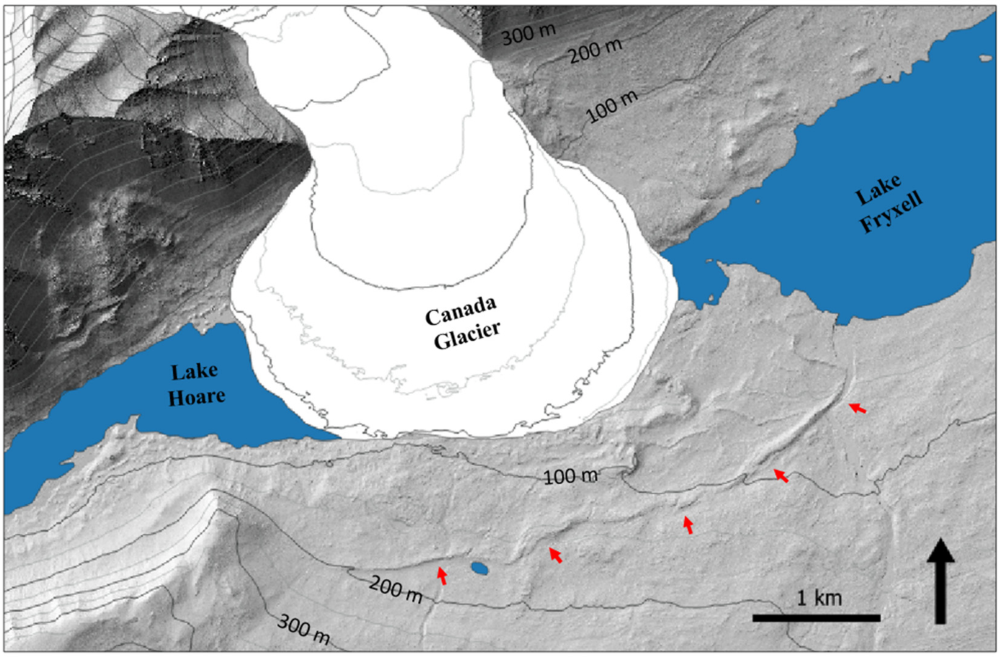

Figure 13. Hillshade image showing the moraine ring (indicated by red arrows) off the toe of Canada Glacier (hillshade produced from digital elevation model created by [94]).

Despite its importance as the dividing location between the Fryxell and Bonney Basins, and thus the Ross Sea and Bonney Drifts, respectively, published studies of drift distribution in the Lake Hoare region are limited. Glacial drift in this region is defined by kame topography [80]. It contains clasts composed of local bedrock and so is compositionally similar to the Bonney Drift, but the presence of moraines with fair to good preservation make it distinguishable from the much older Bonney Drift [7]. The drift in this region may result from deposition by a piedmont glacier [80] that formed as the result of a recent alpine glacier advance and subsequent retreat [7]. Indeed, an alpine glacier advance and subsequent minor retreat following or during the deposition of the Ross Sea I Drift is indicated by the presence of the Alpine I Drift, which is found adjacent to the snout of nearly every alpine glacier, is largely unweathered, and is commonly ice-cored [4,7].

The Wilson Drift, attributed to the expansion of the Wilson Piedmont Glacier, is found just north of Taylor Valley along the coast (Figure 12) [95]. Based on the distribution of the Ross Sea and Wilson Drifts on Hjorth Hill, Hall & Denton [95] hypothesize that an expanded Wilson Piedmont Glacier merged with the Taylor Valley lobe of the RIS during the Ross Sea I glaciation.

4.2. Lake Ice Conveyors

Lake ice conveyors, which distribute glacial drift across a proglacial lake via a moving lake ice cover, have been hypothesized as a major means of drift distribution in many of the MDVs (Figure 14) [15]. In contrast to traditional means of glacial drift distribution, where drift is emplaced largely by a glacier itself and thus the drift distribution reflects the extent of past glacial ice, lake ice conveyors are hypothesized to be able to transport debris far away from a glacier's terminus [15,17].

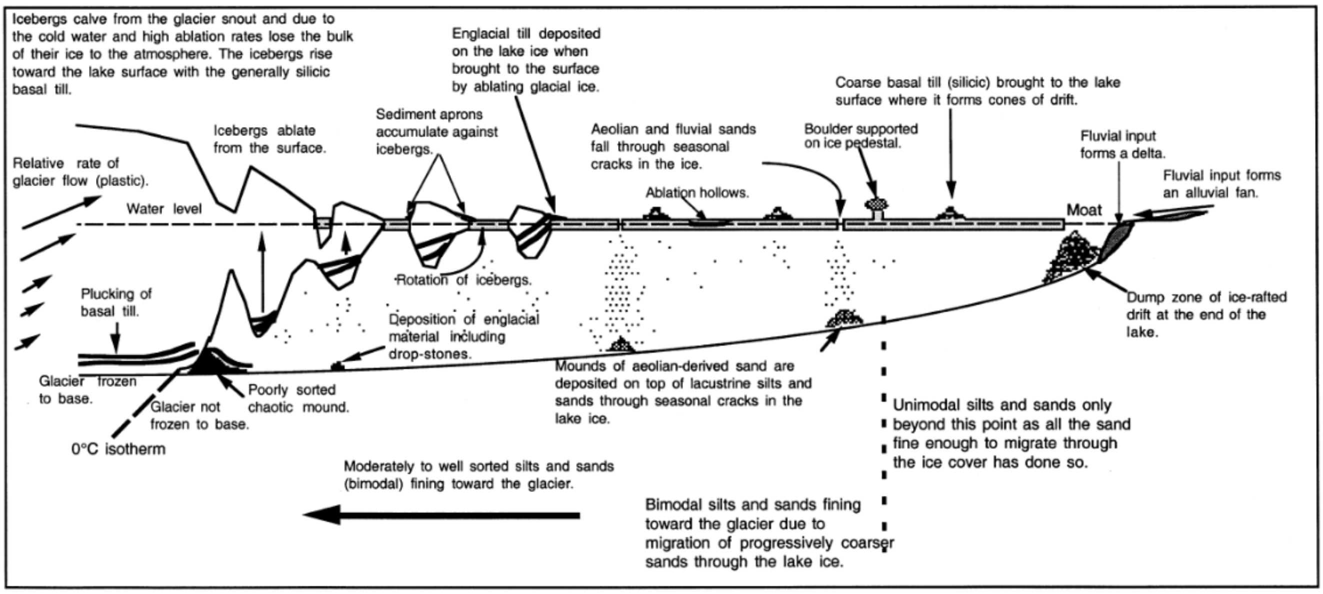

Figure 14. Conceptual diagram depicting hypothesized lake ice conveyor processes and deposition (from source [17]).

Lake ice conveyors can only exist on proglacial lakes with a perennial lake ice cover [15]. They are thought to best develop in proglacial lakes in contact with a large calving front of a fast-moving, frequently calving glacier. Glacial calving is considered the primary driver of lake ice movement in a conveyor system [17,96]. Calved glacial ice becomes trapped in place by the lake ice cover, forming ridges on the lake ice [17]. Continued calving pushes the ice ridges, along with the rest of the lake ice cover, further away from the glacier, distributing glacial debris across the proglacial lake [17].

In a lake ice conveyor system, calving may be triggered by the release of stress from the lake ice that is hypothesized to coincide with the formation of open-water moats along the lake shore during the austral summer [17]. The development of open moats also provides space along the distal shoreline to facilitate ice cover movement away from the glacier front [4]. Glacial calving may additionally be facilitated by the undercutting of the calving front via an 'inverted convection cycle' hypothesized to form in ice-covered proglacial lakes during the summer [17].

The ice ridges derived from glacial calving make up the first of three ice cover zones present in a lake ice conveyor system [17]. In this first zone, some of the debris trapped in glacially-derived ice is thrusted below the 0 °C isotherm in the lake during ridge formation. The ice surrounding this debris melts, depositing unsorted debris on the lake floor, hypothetically forming lines that run parallel to the glacier front [17]. The ice ridges on the lake ice cover decrease in size away from the glacier front due to ablation (Figure 14) [17]. Further from the glacier front, the second ice cover zone is composed of sediment bands left behind by fully ablated ice ridges. These sediment bands cause differential melting of the lake ice cover, resulting in depressions in the lake ice called 'ablation hollows' [17]. Furthest from the glacier front, the third zone is marked by the appearance of ice-cored debris cones [17,96], the formation of which is discussed later in this section.

Identifying geomorphologic signatures of past lake ice conveyor deposition relies on identifying a suite of landforms rather than individual ones, and not every landform will be deposited by every lake ice conveyor due to differences in conveyor momentum, sediment supply, lake level stability, moat area, and operation time [15]. Landforms associated with lake ice conveyor deposits include cross-valley ridges, grounding line mounds and moraine banks, longitudinal ridges, moat lines in the form of sub-horizontal benches on valley walls and buried lake ice [15]. Most are discussed in detail in other sections of this work. In general, sediment and landforms deposited via lake ice conveyors are thought to drape over underlying topography and to generally consist of fine-grained sediment, which can be laminated or massive, capped by poorly sorted coarse material [15]. As lake ice moves away from a glacier front, fine grained debris is lost through the lake ice cover and the abundance of debris on the ice cover decreases. This results in a net increase in grain size, and a decrease in deposit thickness, away from the grounding line [17]. Lake ice conveyor deposits are thought to often contain evaporites and desiccated algae [15].

Based on the presence of several lake ice conveyor associated landforms in Taylor Valley, the lack of glaciotectonic deformation in the Ross Sea Drift sediment deposited west of Coral Ridge, the lack of similarity between the morphology and sedimentology of the Explorers Cove Basin and the area west of Coral Ridge, and the inability of radiocarbon dates from algae layers collected from cross-valley ridges to produces a sensible chronology of RIS retreat from the Fryxell Basin, Hall et al. [4] hypothesize that the RIS grounded along, and did not penetrate west of, Coral Ridge (Figure 1). They assume that all Ross Sea Drift west of Coral Ridge was deposited via a lake ice conveyor atop GLW. The narrowing topography at the western end of the Fryxell Basin is hypothesized to have prevented lake ice conveyor deposition west of Canada Glacier [15].

As lake ice conveyors do not deposit in all parts of a lake at the same rate or at the same time and may function intermittently, they can explain the differential weathering observed in patches throughout the Ross Sea Drift [11,15]. This is thought to justify the appearance of a near-random spatial and temporal distribution of radiocarbon dates from samples collected throughout the Ross Sea Drift under the assumption that those dates reflect the true ages of the sampled deposits and are not influenced by any significant radiocarbon reservoir effect [15]. No published map demonstrates the distribution of the relative ages of Ross Sea Drift patches based on weathering characteristics, nor does any published data exist that demonstrates a correlation between the weathering characteristics of a sample site and the radiocarbon age of a sample collected from that site.

4.3. Moraines

As the glaciers of the MDVs are generally thought to be cold-based, landscape alteration occurs at much lower rates as compared to regions with wet-based, more temperate glaciers [97,98]. The development of depositional features, such as moraines, is largely dependent on the amount of debris carried by a glacier. While processes such as basal sliding and entrainment of the underlying substrate beneath cold-based glaciers can provide some of the necessary debris [97], due to their low erosion rates, much of the rock found in and atop cold-based glaciers comes from rock falls that deposit directly onto a glacier's surface [98]. In regions like the MDVs, where rock falls are infrequent, glacial ice is largely free of debris, usually resulting in limited and non-continuous moraine development unless a glacier's terminus remains stationary for a long duration [98]. This may explain why prominent terminal moraines are absent off the toe of several of Taylor Valley's alpine glaciers [77,97,98], and why a terminal moraine of the RIS has not been identified west of Coral Ridge [6]. Alternatively, the low frequency of prominent terminal moraines may be attributed to previous advances of some glaciers terminating in a body of water [77] or to the glaciers currently being at their greatest extent. The former is because glacier toes floating on top of a water body tend to calve frequently and retreat rapidly toward the lake edge [27], leaving little time for glacial debris to accumulate and form moraines on the lakebed.

Despite the challenges of producing end moraines in an environment such as the MDVs, small moraines are found forming at the toe of many alpine glaciers [80], and more prominent, older moraines can be found a few to several hundreds of meters in front of the snout of several local alpine glaciers. Many of these older moraines are composed of largely unweathered materials and they are commonly ice-cored [4,9].

An ice-cored moraine directly adjacent to the toe of Suess Glacier, which has a relief of ~12 m, contains algal mat deposits and bedded sands [4,99]. Additional moraines have been noted between the Suess and Canada Glaciers, with moraines west of Lake Hoare being concave west, and more eastern moraines being concave east [4].

The moraine ring off the toe of modern Canada Glacier overrides pre-Ross Sea I Drifts (Figure 13) [6]. The presence of a layer of apparent Ross Sea I Drift atop the moraine may indicate Canada Glacier retreated prior to the RIS overriding that area [6]. However, confusion surrounding the drift between Canada Glacier and the moraine, discussed above, may indicate a mixing of Ross Sea Drift and other drifts in that area. Thus, the Ross Sea Drift in identified on the moraine may be misleading and may have been redistributed into the moraine by the advance of Canada Glacier following the drift's initial deposition.

Moraines and related glacial features also preserve a history of ice sheet movements in Taylor Valley. Several bench-like features exist on the walls of Taylor Valley (Figure 10) and are most prominent in the Fryxell and Bonney Basins. Although some authors suspect some of these features may be strandlines (e.g., [8,17,83,84]), many of these features, including some of the near-horizontal ones, are thought to be lateral moraines from past glacial advances [48,77,81,83]. However, similar linear, bench-like features on the walls of Victoria Valley were found to be the result of slope failures rather than glacial deposition [76]. These slope failures occurred more than 100 kyr BP based on ^{10}Be exposure ages and were likely triggered by glacial scouring [76]. Thus, some benches are post-glacial mass-movement features, not moraines. Regardless of if they formed as moraines or post-glacial mass-movement features, these bench features can serve to approximate glacial margins during past glacial advances. Murrell [84] noted excessive ventification of boulders deposited on some of these bench features in lower Taylor Valley, indicating some of them are very old. Other benches may have formed more recently: on the south wall of lower Taylor Valley, one unspecified bench is hypothesized to mark the southern limit of the Ross Sea I Drift [6].

On the north wall of lower Taylor Valley, a lateral moraine beginning ~400 m asl near Hjorth Hill and dipping westward to ~58 m asl near Canada Glacier may mark the maximum western extent of the RIS during the Ross Sea I glaciation, and the upper limit of Ross Sea I Drift [6]. A moraine located ~350 m asl, also on Hjorth Hill, has also been suggested to mark the upper limit of the most recent Ross Sea Drift [3,4]. While it is unclear whether the two moraines on Hjorth Hill are one in the same, the latter is thought to be part of a moraine embankment that crosses Coral Ridge and connects to a less prominent moraine on the south wall of the Valley [4].

According to Hall et al. [4,15], Coral Ridge is a moraine embankment and marks the western limit of RIS-derived grounding line features such as till, waterlain diamicton, and glaciotectonic features in Taylor Valley. These features are exposed in outcrops along Commonwealth Stream where it cuts through Coral Ridge [4]. However, a GPR survey of Coral Ridge did not reveal any laterally continuous bedding buried within the ridge, suggesting that the grounding-line features are not laterally continuous throughout the ridge [74]. Thus, the outcrops along Commonwealth Stream may not be representative of the composition of Coral Ridge as a whole, nor indicative that the entire ridge was deposited as part of a terminal grounding line. The GPR transect further revealed any bedding within Coral Ridge is not crosscut by the Coral Ridge scour [74], which is presumed to have formed from waters flowing between Fryxell and Explorers Cove Basins during and following the retreat of the RIS from the valley mouth [6,9,33].

Lateral moraines on the walls of Bonney Basin are attributed to expansions of Taylor Glacier [48]. A prominent moraine on the north wall of Bonney Basin, between 306 and 310 m asl, marks the upper limit of the Bonney Drift [48]. The lateral moraines of several alpine glaciers appear to merge with this prominent moraine, suggesting a synchronous expansion of Taylor and several local alpine glaciers, at least in the Bonney Basin [48,100].

On Hjorth Hill, an interlobate moraine containing both Ross Sea and Wilson Drifts indicates that the RIS and Wilson Piedmont Glacier expanded synchronously and merged at the mouth of Taylor Valley during the Ross Sea I glaciation [95].

4.4. Cross-Valley Ridges

Cross-valley ridges are linear ridges running perpendicular to a valley's axis that are superimposed on the landscape, varying in width and rising 0.3–3.0 m above the underlying topography [4,6,15]. These ridges can be either straight or concave, with the concave direction facing dominantly east toward the valley mouth in Taylor Valley [4,80]. They can occur in parallel series exhibiting both regular and irregular spacing [6]. In Taylor Valley, cross-valley ridges are commonly found east of Lake Fryxell, ~1.5 km south of the terminus of modern Commonwealth Glacier [4,6,80].

Proponents of the lake ice conveyor hypothesis suggest that cross-valley ridges form from debris-laden glacial ice incorporated into the cover of a proglacial lake with an active lake ice conveyor. The debris is formed into debris bands on the ice cover as the glacial ice sublimates [17]. These debris bands are deposited directly onto the valley floor during lake drawdowns, resulting in the formation of distinct cross-valley ridges. The curved shape of some cross-valley ridges is hypothesized to be due to differential speeds across the moving lake ice cover [15]. As the debris is set directly on the underlying landscape, there is minimal disturbance to underlying sediment [15,17].

Two hypotheses exist for the composition of cross-valley ridges formed via lake ice conveyor deposition. Ridges may contain stratified windblown sediments and be capped by coarse debris [4,15]. It is not clear how the stratification of these deposits would survive the feature toppling off the lake ice cover and into the moat during lake drawdown periods. Ridges may also consist of largely unsorted coarse debris and may incorporate or rest atop stratified lacustrine sediment and algal mats when they form [17]. The latter hypothesized composition is problematic as the sedimentological composition of moraines are very similar to that described for lake ice conveyor derived cross-valley ridges. Therefore, geomorphological signatures from the surrounding landscape are considered the primary means of distinguishing the two deposit types [15,17].

In lower Taylor Valley, the morphology of the cross-valley ridges, along with the veneer of McMurdo Volcanic Group rocks on the surface of many of the ridges, may instead suggest the features were deposited as recessional moraines by the RIS [101]. A GPR survey across a few of these features showed some contain fine-grained, near-horizontally strata capped by gently dipping (~3°) prograding scalloped linear beds, interpreted as migrating ripple deposits, near the surface [74,101]. The presence of migrating ripples indicates unidirectional flow was occurring at the time of deposition, and the incorporation of small boulders within the ripples rules out aeolian deposition [101]. This suggest that some cross-valley ridges form as the result of two depositional processes, with streamflow attributed to depositing the near-horizontal strata at the base of the deposit first, followed by the deposition of the scalloped beds by some unknown unidirectional flow process. This assessment led Arcone et al. [74] to hypothesize that the features may have formed in lateral meltwater channels adjacent to the RIS.

GPR surveys of other cross-valley ridge features, also found in Taylor Valley to the north-east of the suspected lateral meltwater channel ridges, do not contain the scalloped bedding found in the other ridges, but do contain gently dipping linear bed forms. These north-eastern ridges are therefore suspected to be the result of different depositional processes than the other cross-valley ridges [74].

4.5. Longitudinal Ridges

In the MDVs, longitudinal ridges are defined as sinuous ridgelines that generally trend along the strike of a valley's axis and are draped over the underlying topography [15]. Hook and ring structures may occur along the margins of these features [4]. In Taylor Valley, longitudinal ridges are described as having 2–15 m of relief above the surrounding landscape and being laterally continuous for up to >1 km. They may be composed of both local bedrock and kenyite and basalt erratics [4]. Cross-valley ridge structures have been observed superimposed atop longitudinal ridges [4,15], indicating that some of the longitudinal ridges likely formed prior to the overlying cross-valley ridges.

Some authors attribute the formation of longitudinal ridges to supra-lake-ice streams [4,15] and/or supraglacial fluvial drift [17]. Both refer to meltwater streams originating at a glacial source (e.g., the RIS) and flowing over a lake ice cover, concentrating, and transporting both glacial and lake ice debris as they flow. These streams are hypothesized to be able to melt through a lake ice cover, and, once this occurs, to continue to cut through the ice cover in the upstream direction via headward melting. During this process, their sediment load is deposited on the lake floor, draping over the underlying topography [4,15,17]. A second proposed mechanism for the deposition of longitudinal ridge deposits is the direct deposition of these streams or their lake ice cover deposits onto the valley floor during lake level drop [17].

Regardless of the depositional mechanism, the passage of supra-lake-ice stream sediments through the lake water column, whether in deep parts of the lake or in the moat during lake level drop, and the differential melting and ablation commonly observed on lake ice covers, should prevent any flow signatures from being preserved in the final deposit, and should lead to the formation of conformable bedding controlled by the shape of the underlying terrain [74]. However, GPR profiles collected from a prominent longitudinal ridge located to the southeast of modern Lake Fryxell in lower Taylor Valley displayed non-conformable bedding indicative of progradation in several places within the deposit [74].

The presence of progradational flow structures identified within GPR profiles from a prominent longitudinal ridge in lower Taylor Valley may indicate that the feature was deposited as an esker [74]. While some authors suspect that meltwater discharge from the RIS into Taylor Valley was dominantly from the ice sheet's surface [39], making the formation of eskers unlikely, this belief is not ubiquitous in the literature and several authors have suggested that eskers are present in lower Taylor Valley [4,33,74].

4.6. Debris Mounds

Debris mounds are found below ~150 m asl throughout lower Taylor Valley [4]. These debris mounds are hypothesized to provide evidence for a proglacial lake ice conveyor that operated atop GLW [4,15]. These mounds are 0.5–3 m in height and typically have a surface area of <100 m^2, with larger mounds occurring more proximal to Coral Ridge and smaller mounds occurring further to the west [4,15]. Several non-exclusive mechanisms have been proposed for how debris mounds form via lake ice conveyors, with some forming on the lake bottom, known as grounding-line mounds [17], and others forming as lake edge deposits or let-down deposits during periods of lake level fall.

Grounding-line mounds are hypothesized to form in lake ice conveyor systems from rock and sediment rain out from debris-laden ice calved from the conveyor driving glacier. Unlike the typical, sorted sediment that passes through a lake ice cover, rock and sediment deposited in these grounding-line mounds are not restricted to specific grain sizes, and the deposits often incorporate lacustrine algae and sediment as they form [17]. This is because the base of the calved ice falls below the ice-water interface level of the rest of the lake, and thus melts until it reaches the equilibrium depth, releasing any debris entrained in ice below that depth to the bottom of the lake in the process [4,17]. The size of grounding-line mounds is thought to decrease away from the grounding line, though grounding line fluctuations can lead to inconsistencies in this pattern, and prolonged operation of a lake ice conveyor can lead to the amalgamation of these mounds into a moraine embankment [17].

Lake-edge-deposited debris mounds are hypothesized to form from debris deposited on top of lake ice from a glacier driving a lake ice conveyor [96]. The debris can form into ice-cored debris cones and be transported via the moving ice cover to eventually reach the lake's moat, depositing as the moat melts during the austral summer (Figure 14). If the lake ice conveyor stops operating, the ice-cored debris cones will become stranded on the lake ice and will be deposited at let-down drift when lake levels drop [17,96]. Let-down drift refers to debris trapped on or in a lake ice cover that is set directly on to the valley floor during lake level lowering. Debris mounds deposited as let-down drift often have a cup-in-saucer morphology due to being deposited directly atop fine-grained lacustrine sediment [17].

Some debris mounds are said to contain stratified sediments capped with coarse materials [15]. This type of mound may form where coarse materials trapped on the lake ice cover are deposited over stratified lacustrine sediments, either in the moat or as let-down drift [15].

4.7. Core-Based Evidence for Past Glacial Movements

The magnetic mineralogy and Curie temperatures of sediment within DVDP cores 8 and 10 at New Harbor and core 11 at Coral Ridge indicate the presence of McMurdo Volcanic Group minerals in all but the lowest parts of the cores, suggesting that the upper sediments were deposited during or following expansions of the RIS into the mouth of Taylor Valley [102]. A comparison of the lithology of sediments within these cores to regional source materials, and an analysis of sediment microfabrics and surface textures also indicate a Ross Sea provenance for much of the sediment within the cores [103].

Although the depth of the base of sediments associated with the Ross Sea I glaciation is the subject of some debate, studies of DVDP cores collected from New Harbor generally find evidence for the presence of syn- and post-Ross Sea I glaciation sediments attributed to the RIS near the top of those cores [102,104–107]. Magnetic susceptibility zones identified within DVDP cores 8, 10, and 11 should provide broad chronological constraints for each core and allow correlation between those cores [102]. However, confusion surrounding magnetic susceptibility in the top few meters of core 11 at Coral Ridge prevents detailed interpretation of its history and how it relates chronologically to the New Harbor cores. Although Purucker et al. [102] places the base of the Brunhes Epoch 79 m below the surface in DVDP core 11, a relatively thin reverse polarity zone is found a few meters from the surface in the core, capped by a normal polarity zone that starts just 2 m below the surface. Six of eight samples collected from the reverse polarity zone display steep reverse polarity inclinations, and two of those samples passed the Q-test for coherence of magnetization, leading Elston & Bressler [107] to conclude that only the top 2 m of the core were deposited during the Brunhes Epoch. This suggests that Coral Ridge may have been extant and near its current elevation prior to the Ross Sea I glaciation rather than much of the ridge being primarily a grounding line deposit from the RIS during the Ross Sea I glaciation (e.g., [4]). A reanalysis of core 11's magnetostratigraphy was unable to precisely define the magnetozone boundaries in the top 100 m of core [108], and biostratigraphic analyses and $^{40}Ar/^{39}Ar$ dated ash horizons only constrain the top ~200 m of the core to the past ~3 Myr [109,110]. The vastly different depths for the base of the Brunhes Epoch proposed by Purucker et al. [102] and Elston & Bressler [107] have major implications for the interpretation of the history of Coral Ridge and RIS movements in lower Taylor Valley. Unfortunately, there is currently no clear consensus on which epoch boundary depth is correct.Subaqueous, likely lacustrine deposits were identified in DVDP core 12 from the shore of Lake Hoare. However, the upper most sediment in the core is terrestrially deposited glacial till [111], meaning the most recent event recorded in that core is a likely glacial advance over, and subsequent retreat from, the core site rather than a paleolake. Magnetic and gamma radiation profiles of DVDP core 12, along with investigations of the core's clay mineralogy, reveal that the entire core is composed of material that is distinctly different from the portions of DVDP cores 8, 10, and 11 that are attributed to RIS deposition [88,102,112]. Further, magnetic mineralogical and Curie temperature studies of magnetic minerals sampled from DVDP core 12, and a higher relative gamma radiation content throughout core 12 relative to the further east Taylor Valley cores, both indicate a more local source for core 12's sediment, originating somewhere in the MDVs [88,102].

5. Discussion

Strandlines and perched delta deposits played a key role in the initial development of the GLW hypothesis [7]. Both were thought to indicate former lake levels in Taylor Valley, and strandlines provided evidence that perched deltas formed in a single large lake. Despite their importance, we find no sound evidence that high elevation linear features throughout Taylor Valley are strandlines. Likewise, the assumption that most-to-all sandy terraces are perched deltas has been invalidated [73]. In the absence of these 2 key pieces of evidence, we begin our discussion of the paleo-lacustrine history of Taylor Valley during the last glacial period from its most basic point: by investigating if and how enough water was produced during the last glacial period to supply a lake the size of GLW.

It is likely that wind-driven temperature increases [20] and solar radiation both played important roles in meltwater production in the MDVs during the Ross Sea I glaciation, but whether one process dominated over the other is not yet known. Regardless, this melt was likely produced in the shallow subsurface of the ice sheet [17,27,31], and melt production was likely helped or hampered by the absence or presence of fresh snow, or the presence or absence of wind-blown sediment, respectively [16,28,30,31].

It is generally agreed that the RIS provided the bulk of the meltwater supporting high-level paleolakes in Taylor Valley, with smaller and less consistent inputs from local alpine glaciers [4,6,9]. The expansive RIS provided a major catchment for meltwater to form and accumulate, but physical evidence for how this meltwater was transported to and discharged into Taylor Valley is lacking. Although the RIS generally sloped toward the

MDVs, sedimentological evidence for waters flowing along the ice sheet margin toward the valleys is absent [34], and ice marginal channels have not been identified in lower Taylor Valley [18]. If the GLW hypothesis is correct, this lack of ice marginal channels is surprising given the extremely high discharge rates that would have been necessary to sustain the paleolake [18,20], and the fact that relatively small alpine-glacier-fed streams have incised through Ross Sea I Drift producing large, deep, and very apparent stream channels in less time than the proposed span of GLW.

Physical evidence for subglacial discharge from the RIS into Taylor Valley is unsubstantial. Modern MDV glaciers are generally thought to be cold based [98], and low ice temperatures within these glaciers are thought to inhibit the formation of internal drainage networks [20]. Given the colder regional temperatures of the Ross Sea I glaciation [23,24], the development of an internal drainage network within the RIS, and thus subglacial discharge of melt into Taylor Valley, seems unlikely [27]. However, it could be hypothesized that high meltwater flux into the subsurface of the RIS, as would be necessary to sustain a lake the size of GLW, could carry enough heat to overcome the cold ice temperatures of the ice sheet's subsurface, allowing an internal drainage system to develop [27]. Thus, while seemingly unlikely, the prospect of subsurface discharge from the RIS into Taylor Valley cannot be ruled out.

Deciphering the origins of longitudinal ridges in Taylor Valley may provide some insight into how RIS meltwaters were discharged into Taylor Valley. If these features were initially deposited onto a lake ice cover as supra-lake ice streams, this would imply surface discharge from the RIS since such streams flow onto a floating ice cover from the surface of an adjacent ice sheet [17]. If the longitudinal ridges are eskers [6,33,74], this implies subglacial discharge from the ice sheet. GPR surveys of a longitudinal ridge feature did not provide conclusive evidence as to the feature's origin, though the results of these surveys do suggest the ridge was not deposited by a supra-lake ice stream [74]. The superposition of cross-valley ridges atop longitudinal ridges in Taylor Valley implies the longitudinal ridge was deposited before the cross-valley ridges [15]. This depositional sequence makes sense in the lake ice conveyor model, with cross-valley ridges formed on the lake ice cover being superimposed on the underlying longitudinal ridge during a lake drawdown stage [15,17]. This sequence also makes sense in the case that the longitudinal ridge is an esker, with the esker being deposited by the ice sheet, then cross-valley ridges, formed as moraines or other ice-marginal features [74], being deposited on top of the esker as the ice sheet retreated. Clearly more research is needed into the origins of the longitudinal ridges in Taylor Valley.

Regardless of how meltwater produced on or near the ice sheet's surface found its way into Taylor Valley, direct glacial melting through contact between the RIS and the waters of any paleolake connected to it seems likely [17] and may have been a major contributor to the net influx of water to the lake. The exposed face of the ice sheet in Taylor Valley may also have contributed significant volumes of meltwater to the valley [22,27].

Evidence for water moving between the Explorers Cove and Fryxell Basins over Coral Ridge is abundant. The Coral Ridge scour descends towards both the Fryxell and the Explorers Cove Basins, and it is probable that both basins independently overflowed at some point in time. The RIS necessarily would have dammed the Explorers Cove Basin for a lake capable of overflowing the Coral Ridge threshold to exist in that basin, and it is likely that this occurred during the final retreat of the RIS from the mouth of Taylor Valley [4,11]. West to east overflow could have occurred at any time during or following the retreat of the RIS from the valley mouth. GPR surveys across the Coral Ridge scour do not reveal any laterally continuous bedding being cross cut by the scour [74]. Laterally continuous bedding would be expected to be deposited in the calm waters of a lacustrine environment.

Therefore, it is unlikely the ridge was ever submerged in a lake for any significant amount of time, meaning it is probable that lake levels above the Coral Ridge threshold elevation did not occur once the RIS had retreated east of the ridge [74].

No evidence at or adjacent to the sill at Suess Glacier indicates that waters ever overflowed from Fryxell into Bonney Basin, or vice versa [9]. While it is possible that some of these features were present at the location of the sill but have since been advanced over by Suess Glacier, the discharge over the sill would have been extraordinary for Bonney Basin to fill, and should have resulted in erosional features, such as scours and stream channels, appearing downslope from the sill in Bonney Basin. Three possible scenarios may explain the lack of evidence for overflows around the Suess Glacier sill. (1) The paleolake waters of a RIS proglacial lake spilled over the sill from Fryxell into Bonney Basin to fill the valley, leaving behind geomorphologic signatures that were later stripped away by wind [50], after which the more delicate features (e.g., debris cones) in the region of the sill were deposited. (2) Taylor Glacier and the alpine glaciers of Bonney Basin provided enough meltwater to fill, but not significantly overflow, Bonney Basin at the same time as RIS fed waters in Fryxell Basin reached the sill height, preventing any notable overflow from occurring in either direction across the sill and thus resulting in a lack of overflow signatures developing at or near the sill [9]. (3) The waters of the paleolake in lower Taylor Valley did not cross the sill at Suess Glacier, either because the sill was blocked (e.g., by glacial ice) or because the lake level did not ever reach sill height. This would imply that paleolakes in the Bonney and Fryxell Basins existed and operated independent of one another.

The first hypothesis seems unlikely as erosional features such as scours and stream channels would not easily be stripped away. In addition, evidence from the water columns of both lobes of Lake Bonney indicate a lifetime of west to east flow [40,57–59], with no known publications providing evidence for east to west flow (e.g., waters flowing from Fryxell Basin into ELB, then into WLB) at any point during the lake's history.

The second hypothesis may be supported by the soluble salts found in Taylor Valley soils [5]. These indicate Taylor Glacier-derived waters filled Bonney Basin up to the elevation of the Suess Glacier sill, and in lower Taylor Valley, lake levels remained near the sill elevation for a long duration, suggesting the threshold elevation influenced the levels of lakes in both parts of the valley [5]. The relatively low salinity of soils between 116 and 300 m asl in Bonney Basin are hypothesized to result from rapidly changing lake levels, which, as Toner et al. [5] note, would likely be due to fluctuations in the RIS grounding line in lower Taylor Valley rather than evaporation. Thus, the soluble salts of Taylor Valley's soils suggest a RIS proglacial lake existed in lower Taylor Valley and rose to an elevation above the Suess Glacier sill, entering Bonney Basin [5]. Bonney Basin was already filled to the threshold elevation by waters from Taylor Glacier at this time, so the RIS derived waters from lower Taylor Valley simply formed a layer on top of the likely saltier and denser waters occupying Bonney Basin [5]. Lake levels in Bonney Basin then fluctuated in response to RIS grounding line fluctuations, and, as the RIS began to retreat in lower Taylor Valley, lake levels dropped and the RIS-derived waters above the sill elevation in Bonney Basin flowed back into lower Taylor Valley, leaving only the saltier Taylor Glacier-derived waters in Bonney Basin [5]. This hypothesis explains how δD trends in the water columns of Lakes Bonney and Fryxell indicate different histories for those water bodies despite them being part of the same lake during the GLW stage [50], why studies of Lake Bonney have suggested a history of entirely west to east flow [40,57–59], and why the salts in Lake Bonney's water column are generally attributed to Blood Falls, not to GLW [53,54,57].

Despite the supporting evidence for the second hypothesis, the lack of substantial evidence for a Ross Sea I glaciation-era paleolake occupying the Lake Hoare area offers support for the third hypothesis. Lacustrine algae have been recovered from laminated sediments from a moraine east of Suess Glacier, but radiocarbon ages of these samples, which represent their maximum age, show they were deposited during the Holocene well after the hypothesized retreat of the RIS from the valley mouth, and thus they do not come from any valley-wide proglacial lake [11]. The presence of this Holocene-aged lacustrine algae also explains the presence of LDOM in the Lake Hoare area without having to attribute the organic matter to GLW [71]. No strandlines or perched delta deposits exist in the Lake Hoare area, and no remnant talik is apparent beyond the boundaries of the modern lake despite one being present beyond the boundary of modern Lake Fryxell [87]. There is also no record of GLW preserved in the water column of Lake Hoare [50].

Surface deposits between Canada and Suess Glaciers appear to have a glacial rather than lacustrine origin. Drift in that region consists of local bedrock and is said to have a kame topography [9], and the uppermost sediment from DVDP core 12 consists of diamicton that was not deposited in a lake environment [111]. A large ice cored moraine exists just east of Suess Glacier, marking a recent former extent of that glacier [4]. Several cross-valley ridges also exist between the two glaciers, with the eastern ridges being concave east toward Canada Glacier, and the western ridges being concave west toward Suess Glacier [4]. The fact that these ridges are composed of local drift rather than Ross Sea Drift, and the fact that some of these ridges are concave west, suggests these are recessional moraines and not lake ice conveyor deposits from GLW [4,48]. These moraines are relatively well preserved [7], suggesting they are relatively young, and, given their proximity and directionality, these moraines can likely be attributed to Suess and Canada Glaciers.

Evidence supports both hypotheses 2 and 3 for why no overflow signatures exist at the Suess Glacier sill. Although these 2 hypotheses seemingly contradict one another, terrestrial and lake core evidence from Lake Hoare suggests both are accurate. Subaqueous, likely lacustrine deposits were identified immediately beneath the terrestrially deposited diamict at the top of DVDP core 12 from the south shore of Lake Hoare [111]. Likewise, the deepest sediments of the longest lake sediment core extracted from Lake Hoare contain volcanic glass hypothesized to have come from the RIS and thought to have been deposited in GLW [67]. Both the lacustrine material in DVDP core 12 and the Ross Sea Drift bearing deposits in the Lake Hoare core may have been deposited around the time when lake waters from lower Taylor Valley rose above the Suess Glacier sill elevation and entered Bonney Basin. Above these basal sediments in the lake core, the increasing TS suggestive of lake level lowering [67] may correspond to the retreat of the RIS in lower Taylor Valley and the resulting drop in lake level to below the elevation of the Suess Glacier sill [5]. The poorly rounded gravel bearing unit above the aforementioned lake drawdown unit [67] in the lake core may have been deposited by an advance of Canada and Suess Glaciers into the Lake Hoare area, eventually filling the basin with ice and resulting in isolated lakes in Bonney Basin and in lower Taylor Valley [7]. The decreasing isotopic weight and increasing salinity of DVDP core 12 pore waters with depth, originally attributed to permafrost formation following the loss of GLW from the region [88,89], may be explained by the downward freezing of pore waters of formerly inundated sediment overridden a cold-based glacier. The glaciers then retreated intermittently, leaving behind recessional moraines, and a lake formed in the area of modern Lake Hoare, explaining the presence of LDOM there along with the Holocene-age lacustrine algae incorporated into the ice cored moraine adjacent to Suess Glacier [11,71].

The advance of the alpine glaciers in the Lake Hoare area following the retreat of the RIS from the western part of lower Taylor Valley may be further supported by evidence from the region south of Canada Glacier. Here, confusion surrounds the origin of the surface materials between Canada Glacier and a moraine ring several hundred meters off the glacier's toe (Figure 13). Surface drift in this region has been noted as both Ross Sea Drift [4,6] and Bonney Drift [4,84], presumably due to the presence of clasts associated with both drift sheets. This can be explained by the local-bedrock-clast-bearing Canada Glacier advancing over and reworking previously deposited Ross Sea and Bonney Drifts. If true, the cross-cutting relationship between this Canada Glacier Drift and the Ross Sea Drift (Figure 12) confirms Canada Glacier advanced following the deposition of the Ross Sea I Drift.

An alpine glacier advance during or following the advance of the RIS into lower Taylor Valley is supported by the presence of ice-cored moraines off the toe of several alpine glaciers in Taylor Valley [9]. Although ice-cored moraines can persist for thousands of years in the Antarctic environment [113], it seems unlikely that that ice within a moraine would survive long-term submergence beneath the liquid bottom waters of a high-level paleolake. Thus, if a valley-wide paleolake did exist, Taylor Valley's ice-cored moraines either formed afterwards, or the lake was less extensive than hypothesized and these moraines formed beyond the paleolake's limits. This has led some authors to suggest these features are relatively young, attributing them to minor fluctuations of the various glacial fronts during a post-LGM alpine glacier advance [9]. They could equally result from alpine glaciers advancing during or prior to the Ross Sea I glaciation and not retreating until the recent past.

The interfingering of the Ross Sea I and Wilson Drifts and the presence of an interlobate moraine containing the two drift sheets on Hjorth Hill indicate that the RIS and Wilson Piedmont Glacier expanded synchronously during the Ross Sea I glaciation (Figure 12) [95], further providing evidence for an alpine glacier advance during the Ross Sea I glaciation. Although this synchronous expansion is attributed to dropping sea levels [3], much of the modern piedmont glacier does not reach the coast in areas blanketed in Wilson Drift. Instead, the expansion of the Wilson Piedmont Glacier during the Ross Sea I glaciation may have been driven by the expansion of the alpine glaciers feeding into it.

The merging of Taylor and alpine glacier moraines in Bonney Basin indicates both advanced synchronously, suggesting that Taylor and alpine glaciations occur at the same time [48,100]. This is problematic as Ross Sea and Taylor glaciations are known to occur out of phase with one another [9], yet here we find evidence for alpine glaciers expanding during the Ross Sea I glaciation. We offer 2 hypotheses that may explain this discrepancy. (1) It is possible that alpine glaciers do not operate synchronously, but instead advance and retreat independently based on local conditions. Indeed, a study of grounding line fluctuations in modern MDV alpine glaciers found they are advancing and retreating out of phase with one another [114]. Perhaps alpine glaciers in lower Taylor Valley and the coastal MDVs advanced due to an increase in deposition of wind-blown snow and ice coming from the extensive RIS, while further inland (e.g., in Bonney Basin), alpine glaciers retreated in response to the lower regional precipitation rates of the Ross Sea I glaciation [23]. (2) An alternative hypothesis is that Taylor and the alpine glaciers were more advanced in Bonney Basin at the start of the Ross Sea I glaciation than previously thought, with both retreating throughout the Ross Sea I glaciation. This may explain how the glaciers of Bonney Basin were able to produce enough melt water to fill the basin to the elevation of the Suess Glacier sill [5,9]. If the WLB sub-basin was occupied by Taylor Glacier at the start of the Ross Sea I glaciation, it would explain the absence of LDOM in that area [71]. Assuming the sandy terrace around WLB are perched deltas, perhaps they formed in ice marginal ponds adjacent to Taylor Glacier or formed in the main lake occupying Bonney Basin as Taylor Glacier retreated and lake levels dropped. Neither of the above hypotheses are mutually exclusive, and more research is needed to determine the validity of both hypotheses.

5.1. Paleolacustrine History of Lower Taylor Valley

The paleo-lacustrine history of lower Taylor Valley warrants its own discussion given the large quantity of paleo-lacustrine data collected from that part of the valley. There is ample evidence for the existence of a higher than present paleolake in lower Taylor Valley, including the presence of a large remnant talik extending well beyond the margins of modern Lake Fryxell [14,55,85], confirmed delta deposits well above present Lake Fryxell lake levels [4,73], lake core evidence [61,62], presence of LDOM [71], and soil salinity data [5]. The prevalence of Ross Sea Drift throughout lower Taylor Valley [4,61,93] and the presence of Ross Sea Drift attributed marine salts in the bottom waters of modern Lake Fryxell [54] indicate the paleolake in lower Taylor Valley was likely proglacial to the RIS.

As noted in the previous section, soil salinity data suggests waters from the lake in lower Taylor Valley rose above the Suess Glacier sill elevation and entered Bonney Basin during an early stage of the lake's history [5]. Lake levels then fluctuated between 116 and 300 m asl in Bonney Basin in response to RIS grounding line fluctuations in lower Taylor Valley, and eventually the RIS retreated eastward enough to cause lake levels to fall below the sill elevation [5]. The soil salinity data suggests that during this drawdown, lake levels persisted near ~120 m asl in lower Taylor Valley for an extended period, and lake levels in lower Taylor Valley likely never rose above ~120–140 m asl [5]. Although sandy terraces, historically all considered to be perched delta deposits, exist in lower Taylor Valley well above 140 m asl [4,6,10], investigations into the origins of these features reveals many of them may be fluvial or glacio-fluvial features and thus are not indicators of past lake levels [73]. In addition, assuming the RIS penetrated west of Coral Ridge (discussed below), even if some high-level sandy terraces are perched deltas, they may have formed in isolated lakes and ponds next to the ice sheet and do not necessarily represent a past level of a basin-wide paleolake [5,62,74].

Soil salinity data again shows lake levels fluctuating (or at least not existing for a long enough duration to allow excessive evapoconcentration to take place) between 121 and 78 m asl (approximately the Coral Ridge threshold elevation) [5]. Evidence for fluctuating lake levels also exists in the long sediment core extracted from Lake Fryxell in the section of core that proceeds the suspected final drawdown of GLW and the retreat of the RIS from the valley mouth [62]. Fluctuating lake levels help explain the presence of well-preserved, shallow water diatoms in this section of the core [45]. Following this period of lake level fluctuation, a spike in Cl^- in soils 78 m asl suggests the lake remained at or near the level of the Coral Ridge threshold for an extended period, allowing evapoconcentration to take place [5].

5.2. Mechanism of Drift Distribution in Lower Taylor Valley

The means by which the Ross Sea I Drift was distributed in lower Taylor Valley is intrinsically linked to our understanding of the dynamics of GLW. Proponents of the lake ice conveyor hypothesis suggest that the RIS remained grounded along Coral Ridge and GLW lake levels were dominantly controlled by changes in meltwater production on the RIS [4,15,16]. Alternatively, the drift may have been deposited by the RIS itself, with lake levels responding to changes in the grounding line position of the ice sheet [5,6,9].

Investigations into the origins of geomorphologic features cited as support for both hypotheses have not produced substantial evidence to support one hypothesis over the other. While GPR profiles from longitudinal and cross-valley ridge features have revealed strata that seemingly supports non-conveyor deposition, they have not provided strong evidence to define a clear origin for those features [74]. A major issue is that, while modern lake ice conveyors are documented in the MDVs and we have a clear understanding of how lake ice conveyor deposits appear on the lake ice surface [17], the composition of lake ice-conveyor deposits on the lakebed or resulting from lake drawdown (i.e., let-down drift) are purely hypothetical [15,17]. To our knowledge, no studies of these modern lakebed deposits have taken place. Without a clear understanding of how these deposits should appear, it is not fully possible to support or deny if a deposit results from a lake ice conveyor by studying the deposit on its own.

The superposition of coarse-grained materials over fine-grained lacustrine deposits, with sediments draped across previously deposited landscape features, is thought to be a major signature of past lake ice conveyor deposition [4,15,17]. However, this type of lacustrine deposit would also be expected in the 'ice substitution' model of Doran et al. [115]. In this model, glacial ice in contact with a proglacial lake sublimates while, simultaneously, lake ice forms below the glacial ice. As sublimation continues, debris from the glacier is set down on top of the newly formed lake ice [115]. Lake ice filtering allows fine grained materials to pass through the lake ice cover, while coarse materials remain trapped on the ice surface [68,115]. In the ice substitution model, we would also therefore expect fine grained materials to be deposited on the lakebed over previously existing landforms submerged by the proglacial lake, with coarse materials from the lake ice cover being deposited on top of those fine materials during lake drawdown and/or the removal of the lake ice cover. The western limit of Ross Sea Drift may therefore mark the approximate western limit of the RIS in Taylor Valley, and the distribution of coarse over fine materials on the valley floor west of Coral Ridge may indicate a proglacial lake existed in front of the RIS throughout its retreat from its westernmost extent. This may explain the lack of diamict identified in sediment cores from Lake Fryxell [60–62]: if coarse debris from the RIS remained trapped on the proglacial lake ice surface, we would not expect any apparent diamict to have been depositing at the coring locations.

As previously discussed, low salinity in soils above the Suess Glacier sill elevation in Bonney Basin have been attributed to lake level changes responding to fluctuations of the RIS grounding line rather than drawdown via evaporation, as are the lower salinities between the approximate sill elevations surrounding the Fryxell Basin in lower Taylor Valley [5]. A decreasing west-to-east gradient of the Cl^{-} content of soils in lower Taylor Valley also provides support for the RIS retreating from deep within lower Taylor Valley rather than staying fixed at Coral Ridge [5]. The identification of a glaciofluvial deposit along Delta Stream in the western part of Fryxell Basin also suggests the RIS grounding line was west of Coral Ridge at some point [73].

There is no compelling physical evidence for lake ice conveyor deposition in Taylor Valley that cannot also be explained by the hypothesis that the RIS advanced beyond Coral Ridge and directly (or indirectly through its proglacial lake) deposited Ross Sea Drift in lower Taylor Valley. As soil salinity and GPR data supports the RIS advancing well west of Coral Ridge during the Ross Sea I glaciation [5,73], we promote the hypothesis that Ross Sea I Drift throughout lower Taylor Valley was largely distributed by the ice sheet itself, not via a lake ice conveyor.

5.3. Implications for the Radiocarbon Reservoir Effect

As described above, GLW and the subsequent isolated lakes in Bonney Basin and lower Taylor Valley were in direct contact with several glaciers throughout their lifetime, including the RIS, Taylor Glacier, and the piedmont glacier that formed in the area of modern Lake Hoare. It is also likely these lakes received direct or stream-derived melt from other alpine glaciers throughout the valley. Where the lake(s) were in direct contact with glaciers, it is likely that direct glacial melting occurred along the glacier front in the waters below the lake ice cover [17], meaning that melt would not equilibrate with the atmosphere before entering the lake. Radiocarbon dates from samples collected near grounding lines have been shown to contain very large radiocarbon reservoir contamination [38–40]. Given the evidence for a moving RIS grounding line in lower Taylor Valley [5], we cannot rule out the possibility that radiocarbon samples from lower Taylor Valley were deposited near the grounding line, and thus may contain significant radiocarbon reservoir contamination. Even if the grounding line was stagnant, the multitude of meltwater sources feeding the lake and the high level of stratification likely to have occurred at least in Bonney Basin [5], if not across the lake as a whole, would have likely resulted in the lake(s) accumulating old carbon [38]. Likewise, in lower Taylor Valley, the superposition of coarse-grained materials over fine-grained sediments suggests the paleolake retained a perennial lake ice cover [4], which could have also led to a radiocarbon reservoir accumulating in the lake waters [38].

Stream waters have been shown to equilibrate with the atmosphere quickly [35,40], which has led some to hypothesize that a reservoir correction is not needed for algal mat samples from perched delta deposits (e.g., [11]). This, however, does not account for the fact that delta deposits form in the marginal waters of a lake, where radiocarbon reservoir effects have been shown to be both spatially and temporally variable [39], or the fact that if lake levels rose above a delta's elevation, some deposits incorporated into the delta may have formed in deeper waters and be the result of non-deltaic processes. Even if the radiocarbon ages from perched delta deposits do reflect the true age of the deposit, the presence of fluvial and glaciofluvial deposits that mimic the surficial appearance of perched deltas further complicates the issue [73]. Such deposits have been mistakenly identified as perched deltas and targeted for radiocarbon dating in the past, and they may be widespread throughout Taylor Valley [73]. Thus, radiocarbon dates from sandy terraces in Taylor Valley, previously all considered to be perched deltas, may not represent the timing of past lake levels [73].In short, the impact of radiocarbon reservoir effects on the ages of organic radiocarbon samples from lake deposits in Taylor Valley is unknown, likely variable, and possibly significant. At most, radiocarbon ages can be treated as a maximum age for a deposit. In addition, until we have a better handle on the formative process responsible for the deposition of each dated sandy terrace in Taylor Valley, we strongly caution against relying on the ages of such deposits to constrain the timing (or indeed the level) of past lake levels in Taylor Valley.

6. Conclusions

Based on the amalgamation of evidence collected from Taylor Valley throughout the history of the valley's exploration, we propose that the following sequence of events provides the simplest and most up-to-date hypothesis for the history of Taylor Valley during and following the Ross Sea I glaciation.

1. The advancing RIS reached the mouth of Taylor Valley and advanced west beyond Coral Ridge. The Wilson Piedmont Glacier also advanced at this time [95]. A proglacial lake existed in front of the RIS in Taylor Valley. A lake also existed in Bonney Basin at this time, filling the basin to the Suess Glacier sill elevation. This lake was supported by melt from Taylor Glacier (and possibly local alpine glaciers as well) [5]. The position of the Taylor Glacier grounding line at this time is unclear, but it may have occupied much or all of the WLB sub-basin, still retreating from the previous Taylor glaciation. Suess and Canada Glaciers did not block the Lake Hoare area at this time.
2. The RIS further advanced to reach its westernmost grounding line west of modern Lake Fryxell. The level of the RIS proglacial lake rose above the Suess Glacier sill elevation and entered Bonney Basin, floating on top of the denser, Taylor Glacier-derived waters that already occupied Bonney Basin, and creating the valley-wide lake known as GLW. Changes in the RIS grounding line position caused lake levels to fluctuate in Bonney Basin, with maximum lake levels there reaching ~300 m asl [5].

3. The RIS retreated in lower Taylor Valley, causing lake levels to drop in Bonney Basin. Lake levels in lower Taylor Valley remained stagnant for an extended period at approximately the elevation of the Suess Glacier sill before dropping below the sill elevation due to further retreat of the RIS grounding line [5]. The lake in Bonney Basin was now isolated from the lower Taylor Valley lake and began to drop largely due to ablation. It is not clear if changes in the Taylor Glacier grounding line position also played a minor role in the lake level drop in Bonney Basin.
4. Lower Taylor Valley lake levels fluctuated in response to RIS grounding line fluctuations [5,45]. The RIS eventually may have grounded along Coral Ridge [4]. At some point, Canada and Suess Glaciers advanced to form a piedmont glacier in the area of modern Lake Hoare. Other local alpine glaciers may have also advanced.
5. The RIS retreated to a position east of Coral Ridge allowing a lake to exist in Explorers Cove Basin [4,9]. Here forward, lake levels throughout lower Taylor Valley did not go above the elevation of Coral Ridge for any significant amount of time [74].
6. The RIS retreated from the mouth of Taylor Valley, causing Explorers Cove Basin to drain and marking the end of the RIS proglacial lake in Taylor Valley. At some point before or after this RIS retreat, alpine glacier fed streams sustained a lake near the Coral Ridge threshold elevation in the Fryxell Basin [5]. At some point Canada and Suess Glaciers began to retreat from the Lake Hoare area. Other local alpine glaciers may have retreated around this time as well.
7. Subsequent lake level and glacier fluctuations outside the scope of this manuscript eventually led to the modern configuration of lakes and glaciers seen in Taylor Valley today.

Constraining the timing of the above events is difficult given the lack of reliable age data. However, radiocarbon dates from marine shells and shell fragments found in Ross Sea Drift in lower Taylor Valley may provide an upper limit for the Ross Sea Drift distribution of ~30–25 cal. kyr BP [3,11], suggesting all of the events may have occurred within the past ~30 kyr. However, the age model developed by Wagner et al. [62] for the Lake Fryxell long core suggests the RIS may have entered Taylor Valley before 45 kyr BP, thus extending the potential upper age limit for the above events. Assuming the radiocarbon age of DIC from ELB bottom waters accurately reflects the timing of the lake regaining its ice cover following a major drawdown event, ELB was well below its modern level ~8.6 14C kyr BP [40]. This means the level of the RIS proglacial lake fell below and remained below the elevation of the Suess Glacier sill (event 3 above) sometime before ~8.6 14C kyr BP. Marine shells and shell fragments from raised marine deposits at the mouth of Taylor Valley indicate the RIS had retreated from the valley by ~5 cal. kyr BP [11], constraining the timing of event 6 above.

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