Garwood Valley, Antarctica: A new record of Last Glacial Maximum to Holocene glaciofluvial processes in the McMurdo Dry Valleys

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ABSTRACT

We document the age and extent of late Quaternary glaciofluvial processes in Garwood Valley, McMurdo Dry Valleys, Antarctica, using mapping, stratigraphy, geochronology, and geochemical analysis of sedimentary and ice deposits. Geomorphic and stratigraphic evidence indicates damming of the valley at its Ross Sea outlet by the expanded Ross Sea ice sheet during the Last Glacial Maximum. Damming resulted in development of a proglacial lake in Garwood Valley that persisted from late Pleistocene to mid-Holocene time, and in the formation of a multilevel delta complex that overlies intact, supraglacial till and buried glacier ice detached from the Ross Sea ice sheet. Radiocarbon dating of delta deposits and inferred relationships between paleolake and Ross Sea ice sheet grounding line positions indicate that the Ross Sea ice sheet advanced north of Garwood Valley at ca. 21.5 ka and retreated south of the valley between 7.3 and 5.5 ka. Buried ice remaining in Garwood Valley has a similar geochemical fingerprint to grounded Ross Sea ice sheet material elsewhere in the southern Dry Valleys. The sedimentary sequence in Garwood Valley preserves evidence of glaciofluvial interactions and climate-driven hydrological activity from the end of the Pleistocene through the mid-Holocene, making it an unusually complete record of climate and paleoenvironmental conditions from the terrestrial Antarctic.

INTRODUCTION

The McMurdo Dry Valleys of Antarctica preserve an ~14-m.y.-old record of the complex interactions between glaciations and the land surface (Sugden et al., 1993). Determining the dynamics of ice-sheet advance and retreat in Antarctica during the Pleistocene-Holocene transition has become a topic of interest because of its potential for informing predictions of ice-sheet response to future episodes of warming (Conway et al., 1999). The McMurdo Dry Valleys are an ideal environment in which to date the record of Last Glacial Maximum (LGM) ice-sheet processes because, while they are currently ice-sheet free, the McMurdo Dry Valleys preserve glacial drift and till units from multiple glacial periods and from multiple ice-sheet sources (including both East and West Antarctic Ice Sheets) (Brook et al., 1995; Denton et al., 1989; Hall and Denton, 2000; Stuiver et al., 1981).

In order for glacial till and/or stranded glacier ice to be deposited within the McMurdo Dry Valleys, the Ross Ice Shelf (Fig. 1), fed by the East and West Antarctic Ice Sheets, must have been thicker during glacial periods. In particular, the ice sheet needs to have been grounded (here, referred to as the Ross Sea ice sheet when in a grounded state) with sufficient thickness to drive ice flow upslope into the McMurdo Dry Valleys (Stuiver et al., 1981).

Direct dating of glacial tills can be challenging in the absence of exogenous markers like volcanic ash (e.g., Marchant et al., 2002). Consequently, research in the Ross Sea region and Transantarctic Mountains has focused primarily on dating the lacustrine effects of ice sheets—the formation of lakes and their deposits during times when valley mouths were blocked by the expanded Ross Sea ice sheet (e.g., Clayton-Greene et al., 1988; Conway et al., 1999; Dogel, 1985; Denton et al., 1989; Hall and Denton, 2000; Hall et al., 2000a, 2002; Hendy et al., 1979; Péwé, 1960; Prentice et al., 2008; Stuiver et al., 1981)—and the isostatic responses—marine shell deposits uplifted by isostatic rebound postglaciation (Hall et al., 2000a). This first dating strategy largely relies on dating algal mats and lacustrine carbonates from fluvial deltas perched on valley walls. The lake levels required to have formed these deltas are higher than the overflow heights for modern McMurdo Dry Valleys closed basin lakes (Doran et al., 1994). Accordingly, for the elevated deltas and shorelines to have formed, the grounding line for the Ross Sea ice sheet must have been north of the McMurdo Dry Valleys, allowing the ice sheet to plug the lower ends of the valleys, resulting in the formation of glacier-dammed lakes. For the lakes to have drained, the grounding line must have retreated south of the McMurdo Dry Valleys, allowing local base level to return to sea level (Stuiver et al., 1981).

This glacial dam model has motivated extensive mapping and dating of shorelines and paleolake delta deposits in the McMurdo Dry Valleys in order to decipher the late Quaternary history of the Ross Sea ice sheet. Pleistocene and Holocene paleolakes have been mapped using this method in the northern McMurdo Dry Valleys: Taylor Valley (Hall and Denton, 2000; Hall et al., 2000a; Hendy et al., 1979; Higgins et al., 2000), Wright Valley (Hall and Denton, 2005), Victoria Valley (Hall et al., 2002); and in the southern McMurdo Dry Valleys abutting the Royal Society range: Marshall Valley (Dogel, 1985) and Miers Valley (Clayton-Greene et al., 1988). Notably, Garwood Valley (Figs. 1 and 2), located north of Marshall and Miers Valleys, has not been mapped in detail, although deltaic deposits were observed by Péwé (1960), who named the paleolake inferred to have produced the deposits “Glacial Lake Howard.” Interestingly, Hendy (2000) reported that no evidence had yet been identified supporting the existence of an LGM-age paleolake dammed by the Ross Sea ice sheet in Garwood Valley, suggesting that delta deposits identified by Péwé (1960) in Garwood Valley are likely of Holocene, rather than late Pleistocene, age (Hendy, 2000; Stuiver et al., 1981).

Here, we report on the stratigraphy of recently exposed glaciofluvial deposits on the floor of Garwood Valley, Antarctica (Figs. 2 and 3). We show that the Garwood Valley paleolake and
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delta deposits are unusual in the McMurdo Dry Valleys in that they span the complete sequence from ice damming of Garwood Valley, through paleolake growth and decay, to modern-climate modification processes in a single outcrop. They preserve ice and sediments that can be geochemically correlated with Ross Sea ice sheet material and proglacial lake sediments collected from neighboring valleys. From stratigraphic interpretation and dating of these deposits, we infer the glaciofluvial processes and the climate conditions in the McMurdo Dry Valleys during the transition out of the LGM. In particular, we test the working hypothesis that, during the LGM, a tongue of the grounded Ross Sea ice sheet entered Garwood Valley, producing a glacier-dammed lake that drained or dried out several times, and that ultimately, the grounded ice in the valley became decoupled from the Ross Sea ice sheet and ablated in place, becoming mantled with ablation till and eolian sediments.

GEOLOGICAL CONTEXT

Garwood Valley (78.026°S, 164.144°E) is a coastal Dry Valley located between the Royal Society Range and the Ross Sea, west of the Brown Peninsula (Figs. 1 and 2). The valley extends ~13 km from its head in the Shangri-La region adjacent to the Joyce Glacier east to its mouth at the shore of the Ross Sea. At its widest, Garwood Valley is ~3.5 km across and has a steep-walled, U-shaped cross section. Surface elevations on the valley floor range between sea level and ~400 m, while the valley is bounded by ridges that approach elevations of ~1000 m, separating it from Marshall Valley (to the south) and Salmon Valley (to the north). The Garwood Glacier is located ~8 km inland from the coast, at an elevation of ~200 m, and it divides the valley into upper and lower sections. Here, we report on glaciofluvial features in the lower portion of the valley between the modern Garwood Glacier and the Ross Sea.

Regionally, the bedrock underlying the southern McMurdo Dry Valleys (Salmon, Garwood, Marshall, Miers) is composed of Skelton Group metasediments and igneous intrusives of Precambrian to Cambrian age (Dagel, 1985). The Royal Society Range that forms the head of Garwood Valley is composed of Devonian to Triassic Beacon Supergroup sandstones, intruded by sills of the Ferrar Dolerite (Dagel, 1985).

Glaciologically, Garwood Valley has been affected both by local alpine glaciers, such as the Garwood, Joyce, and nearby Koettlitz Glaciers, as well as by the East/West Antarctic Ice Sheet or Ross Sea ice sheet invading up the valley from the Ross Sea. At least two distinct widespread tills are present above 500 m in the lower valley, dated by cosmogenic methods to 272 ± 7 ka and 104 ± 3 ka (Brook et al., 1995). These old till ages are interpreted to reflect inheritance of cosmogenic nuclides from till parent rocks, or to represent tills emplaced by grounded ice during the preceding glacial periods (Brook et al., 1995). Initial observations by Péwé (1960) of the glaciofluvial deposits along the valley floor (those analyzed here) led him to infer glaciation of Garwood Valley by an expanded lobe of the nearby Koettlitz Glacier at ca. 6 ka.

Regionally, the presence of porphyritic anorthoclase phonolite (“kenyte”) in the widely distributed (and commonly ice-cored) Ross I drift unit, which fringes the coastal margin of the McMurdo Dry Valleys from Taylor south to Miers (Stuiver et al., 1981), has led to a broad consensus that the source of this glacial deposit was Ross Sea ice sheet material that transported Ross Archipelago volcanics (typified by “kenyte” from Ross Island) to the south and west. On the basis of radiocarbon-dated algal mats, lake carbonates, and marine mollusks associated with glaciofluvial features related to this ice advance, the Ross Sea ice sheet grounded in the McMurdo Dry Valleys ca. 28,860 ± 14C yr B.P. (Denton et al., 1989; Denton and Marchant, 2000; Hall and Denton, 2000; Stuiver et al., 1981), or slightly later (ca. 18–22 ka; Joy et al., 2011) as the ice sheet advanced. The grounding line for the Ross Sea ice sheet is thought to have returned south of the McMurdo Dry Valleys by 6500 ± 14C yr B.P. (Conway et al., 1999; Denton et al., 1989; Hall and Denton, 2000; Stuiver et al., 1981). The recession date is inferred, in part, from dating of two algal mat samples collected within the glacial till deposit at the mouth of Garwood Valley (see next section) dated to 6190 ± 80 and 6580 ± 50 14C yr B.P. (Stuiver et al., 1981). In subsequent sections, we integrate our...
stratigraphic analysis and inferred glaciofluvial processes with this regional model of glacial activity during the Pleistocene and Holocene.

GARWOOD VALLEY SURFACE FEATURES

Garwood Valley contains numerous surface units similar to those mapped in Miers and Marshall Valleys (Clayton-Greene et al., 1988; Dagel, 1985); unique features include their size, spatial distribution, exposure, and stratigraphic continuity. Field mapping, light detection and ranging (LiDAR) topography (Schenk et al., 2004), and IKONOS satellite image data form the basis for a new surficial geologic mapping of Quaternary glaciofluvial units within lower Garwood Valley (Figs. 2 and 3).

This mapping shows that the lower end of Garwood Valley is dominated by the down-valley till unit, typically mapped as the Ross I drift (Stuiver et al., 1981) or the M3 drift unit (Richter, 2011). The surface of the till is composed of an angular

Figure 2. Context map showing Garwood Valley surface units and figure locations. Inset shows the Ross Sea region, the southern McMurdo Dry Valleys (arrow), and the location of Garwood Valley (red dot). GG—Garwood Glacier. Base map is light detection and ranging (LiDAR) topography slopeshade. LiDAR data serve as the basis for the plotted contours.

Figure 3. Topographic transects in Garwood Valley. Light line shows the main trunk of Garwood River. Dark line shows valley surface profile (dotted line in Fig. 2). Inset shows a higher-resolution view of the delta complex, with locations of mapped stratigraphic section and elevations of exposed ice. The dashed line interpolates the ice-sediment contact between outcrops. Topography was extracted from 4 m/pixel light detection and ranging (LiDAR) data (Schenk et al., 2004).
pebble-cobble-boulder desert pavement overlying unsorted silt and sand with sporadic larger clasts. Desert pavement cobbles are predominantly dark volcanics (dolerite and/or fine-grained phonolite) and orange metasediments, with sparse granite and sandstone boulders. Porphyritic anorthoclase phonolite (“kenyte”) is common in the down-valley till. Hyaloclastite breccias containing phonolitic glass are also present in the down-valley till. The lithic assemblage in the till is interpreted to indicate a dual source for till clasts that combines Ross Sea volcanic complex mafic rocks with granites, sediments, and metasediments derived from the Transantarctic Mountains south of Garwood Valley (Stuiver et al., 1981).

The down-valley till is universally underlain by massive glacier ice with a smooth, planar contact between the ice and the overlying sediments, suggesting that it is a supraglacial ablation till, rather than a subglacial till that has been exhumed. As noted by Pollard et al. (2002), the till is typically ~10–20 cm thick, although, in places, it thickens up to 1–2 m; however, all soil excavations conducted by the authors on the down-valley till between 2009 and 2012 have exposed buried ice beneath till. The down-valley till is extensively modified by thermokarst ponds (referred to as kettles by Pollard et al., 2002), resulting from melting of the underlying ice and evaporation of the meltwater. As a consequence of containing a massive ice core, the down-valley till unit has steep flanks and a generally convex-up surface profile (Fig. 3).

The up-valley till unit covers the valley floor between the down-valley till and the Garwood Glacier. The up-valley till shares many attributes with the down-valley till. The desert pavement at the top of the till is composed primarily of angular pebbles and cobbles, with boulders present less commonly than in the down-valley till. The underlying sand-silt matrix is much the same; however, it is generally slightly more oxidized than the down-valley till. While all rock types present in the down-valley till are present in the up-valley till, “kenyte” is less common in the up-valley till, and it is not present in the northwesternmost third of the unit (the furthest up-valley). Where porphyritic anorthoclase phonolite (“kenyte”) is present in the up-valley till, it is typically fragmented. Hyaloclastite is extremely rare in the up-valley till, and, where present, it is strongly weathered. Although only locally exposed by Garwood River erosion and shallow soil excavations, the up-valley till is also underlain by massive ice, suggesting that it, too, is a supraglacial till. Thermokarst ponds are not present in the up-valley till, and it has a relatively uniform, down-valley surface slope (Fig. 3). Contacts between the valley walls, the up-valley till, and adjacent surface units are generally topographically smooth. The presence of two tills in Garwood Valley is consistent with observations in the McMurdo Dry Valleys of two or more till units associated with the Ross Ice (Denton and Marchant, 2000).

After the till units, the most notable surface feature in Garwood Valley is the large deltaic relic complex located in the center of the valley (Figs. 2 and 4). The three stepped deltas that form the complex are ~650 m in total length and ~280 m at their widest. The surfaces of the deltas step lower in the down-valley direction, from 45 m a.s.l. (middle delta), to 20 m a.s.l. (lower delta). A small, isolated packet of till (interpreted as up-valley till) outcrops at the surface between the middle delta and the lower delta.

The deltas have a complex stratigraphy (see next section), but they are overwhelmingly composed of bedded, coarse, quartzofeldspathic sand. The surfaces of the deltas are topped with a desert pavement composed of rounded and subrounded pebbles that are predominantly representative of local metasediments, suggesting a source of deltaic sediments from within Garwood Valley. Modern sand-wedge polygons dissect the upper several meters of the deltas. The delta complex is bounded by modern alluvium, which embays it on three sides and is in contact with the up-valley till to the northwest. The contact of the delta deposits with the up-valley till is sharp and is defined by a change in slope, lithology, grain size, and grain shape.

The Garwood River, which is fed by run-off from the Garwood and Joyce Glaciers, cuts through these units as it flows to the Ross Sea. Where the river cuts the up-valley till, the channel is tens of meters wide, >4 m deep, and steeply V-shaped. Observations of exposed ice in the channel walls (see “Other Ice-Sediment Relationships” section) and of river passage through undercut banks and/or tunnels through the up-valley till indicate that this portion of the river is affected by fluvial thermokarst formation in which relatively warm Garwood River water melts buried ice and undercuts the up-valley till, leading to surface subsidence.

Finally, in the vicinity of the relict deltas, the modern Garwood River and discharge from several snow-fed gullies on the valley walls form a surface unit of modern alluvium. Recent deposition is chiefly in broad flats adjacent to and downstream of the delta complex. Modern alluvium is predominantly quartzofeldspathic sands with millimeter-scale horizontal bedding; however, finer particles, including silts and clays, are deposited by some distributary streams.

**GARWOOD VALLEY DELTA COMPLEX STRATIGRAPHY**

The stratigraphy of the Garwood Valley delta complex has been recently exposed by lateral erosion of the Garwood River. Taking advantage of these recent and short-lived exposures (they are rapidly being covered by colluvial and eolian deposits), we documented the stratigraphy of each of the three deltas during the austral summers of 2009–2012, with particular attention to relationships between sedimentary units within the delta complex, and between the sedimentary units and underlying massive ice (Tables 1–3).

The upper delta is spatially extensive, but it has sparse exposure, owing to its topographic isolation from the Garwood River, which has laterally eroded into the middle and lower deltas (Fig. 4). As a result, the flanks of the upper delta are generally mantled in steep, dry talus. A small outcrop of the upper delta was measured on the northeastern edge of the unit, where it is partially eroded by a small gully.

The base of the upper delta outcrop consists of medium to coarse sand and pebbles interpreted as fluviodeltaic sediments. Above the sands, a dark silty layer grades into a light-toned silt-clay
interbedded with eolian sediments, and overlying lacustrine units (compared to unmodified drift/till in G21 and G23) and the presence of compressive fractures in G16 interpreted to indicate deformation of wet sediment. The onset of lake ice conveyor activity may have resulted from hydrological changes (expansion of the lake) or for glacio logical reasons (re-advancement of the ice sheet). The lower delta is smaller than the middle delta, but it is also well exposed by recent Garwood River erosion (Fig. 8; Table 3). Abundant algal mats in the lower delta also provide multiple radiocarbon dates (see section on “Synthesis of Delta Complex Stratigraphy”).

The lower delta, like the middle delta, has a sandy-silty-cobbly gravel as the lowest exposed unit, which is interpreted as a glacial till modified by lake ice conveyor processes, based on the presence of fine-grained interbeds. Above the till, a silt-sand layer coarsens upward into a sandy gravel, which we interpret as lacustrine sands grading upward into a braided channel deposit. A cross-beded sand-silt unit overlies the sandy gravel and is interpreted as a deltaic topset deposit. Above this, the lower delta is capped by a gravelly sand fluvial unit that has been dissected at the top to form a pebble-rich desert pavement.

The stratigraphy of the lower delta leads to a general interpretation that it formed after the middle delta, in a proglacial lake setting, as deltaic deposition advanced to lower portions of the lake in response to lake-level lowering caused by thermokarst downcutting of the ice plug and/or ice-sheet lowering. The emplacement of the lower delta represents the final phase of lacustrine deposition in Garwood Valley (outside of modern thermokarst ponds), as it is topographically lower than any other delta surface in the mapped section of the valley. Based on the absence of evaporite deposits associated with the lower delta, further downcutting of the ice plug subsequent to the formation of the lower delta is inferred to have resulted in the final draining of glacial lake Howard.

Do the upper and lower till units described in the middle delta correlate with surface units mapped in the “Garwood Valley Surface Features” section? We note that the till island preserved between the middle and the lower delta and the down-valley till (Fig. 9) shares a similar lithology and low degree of weathering with the down-valley till. Likewise, the down-valley till...
Fluvial-lacustrine sediments forming deltaic foresets

Lacustrine deposit (deltaic bottomset)

Lake ice "conveyor" deposit (Clayton-Greene and Hendy, 1987; Hall et al., 2000b)

Lake ice "conveyor" deposit, similar to G15, that underwent compaction during the loading of the unit by G15

Transitional facies between fluvial-lacustrine deposits (see below) and conveyor-modified till

Lacustrine deposits

Lacustrine deposits

Fluvial deposit that modifies the underlying lacustrine material

Low-energy lacustrine sediments

Subaerial glacial till, largely unmodified by lacustrine conveyor process. Evidenced by the presence of intact sand wedges in the till. Relict sand wedges are only found in this unit in Garwood Valley. The increase in cobble and gravel abundance toward the top of the unit may indicate desert pavement formation by eolian removal of fines

Lower portion of a till unit of similar composition to G21. Together, this unit, G23, and G21 constitute a lower till package, in contrast to the conveyor-modified till package comprised by G15 and G16
Gravel, cobbles, and pebbles. The gravel is subangular to subrounded and is composed of diverse lithologies including mafic volcanics and orange metasediments. The maximum clast size is 8–12 cm.

Desert pavement

Fine to medium-size sand with interbedded silt. The unit has wavy, subparallel bedding defined by grain-size variations. The sand is light tan or buff and is composed mostly of quartz, with some feldspar. Medium to medium-coarse sand packages are interbedded within the fine to medium-size sand and contain ~1-cm-thick lamina and cross-bedding. The unit is meltwater-saturated in some locations and discharges at the outcrop face. Rip-ups of algal mat fragments are common in this layer. The lower contact of this unit is sharp and subplanar and is defined by a thick black algal mat.

Fluvio-deltaic deposits forming deltaic topsets

Sandy gravel. Prominent 5-cm-thick sand lenses climb to south in the gravel and pinch out. These sands overlie frozen gravel lenses. The gravel is matrix-supported in bedded coarse sand. The largest gravel clasts are 6–8 cm and are composed of diverse lithologies, including mafics, metamorphics, and quartzites. The gravels and the sand lenses are poorly sorted, with subtle stratification running parallel to unit boundaries. Pebble long axes parallel this subtle, subhorizontal bedding. The lower contact of this unit is gradational over 5 cm, climbs to south, and is locally deformed.

High-energy fluvial/braided channel deposit

Silty clay coarsening up to silt and very fine sand. The light-brown, silty clay is strongly bedded into parallel, <5 mm clay layers separated by silt and very fine sand beds <2 mm thick. White clay beds cap the unit with 2–3-mm-thick internal clay laminae, and similar clay beds are present at the base of the unit. Contacts within the silt beds and the bounding clays are gradational. In the lower clay, parallel bedding is defined by grain-size variations with sandy partings. The clay is friable along bedding planes and is well sorted. Pebbles and/or dropstones that deform the clay beds are present in the clays. The deposit is substantially invaded by modern segregation ice lenses. The lower contact of the unit is sharp and climbs slightly to southeast (down-valley).

Low-energy lacustrine deposit that is an extension of the G10 lacustrine unit

The unit correlates with the upper till package from the middle delta outcrop (G15 and G16).

Massive ice locally underlies the lowest till in the middle delta. The massive ice is most evident although the massive ice beneath the lowest till (G12) has been removed by fluvial thermokarst erosion. In the middle delta, massive ice extends beneath the lower till to the middle delta outcrop (Fig. 11). Massive ice is present in the upper till package as the stratigraphic expression of the (modified) down-valley till. Massive ice beneath overlying massive ice in the McMurdo Dry Valleys, and overlying till beds, may be unique in the McMurdo Dry Valleys.

A submerged portion of the lowest till in Garwood Valley is preserved in the form of massive ice beneath the basal units in the middle delta complex, we see evidence of lake ice conveyor deposits interbedded with fine-grained lake deposits. This relationship, in which basal glacier ice lies a submerged remnant of the lower till iden-


tified in a subsurface remnant of the lowest till directly beneath the (modified) down-valley till. In addition, extant massive ice is present beneath overhanging and ice-cemented till, face in 2009, exposing bright white ice-cored massive ice beneath overlying massive ice (Figs. 10A and 10B). In addition, extant massive ice is present beneath overlying massive ice (Figs. 10A and 10B).

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OTHER ICE-SEDIMENT RELATIONSHIPS

A surprising result of the stratigraphic analysis of the Garwood delta complex is that massive ice underlies the glacial till (inferred to be of Ross Sea ice sheet origin; see “Chronology” section) and lacustrine deposits. Is this pattern repeated elsewhere in the valley? Two locations shed light on ice-sediment relationships: the Garwood Valley ice cliff and the little ice cliff. The Garwood Valley ice cliff provides a vivid illustration of fluvial sediments overlying massive glacier ice and till (Fig. 12). Similar in appearance to the down-valley massive ice outcrop presented in Stuiver et al. (1981), the ice cliff adjacent to the delta complex is a location where a sedimentary unit abutting the up-valley till precipitously steps down to the modern Garwood River braid plain, with a change in elevation of 10–15 m occurring over a horizontal distance of 2–3 m.

Although access to the sediment-ice contact at the top of the ice cliff is precluded by the dramatic relief, the stratigraphy of the interface was evaluated using fallen blocks containing the contact. The ice cliff material is largely composed of clean and variably bubbly glacial ice with low debris content (except for in places where bands of ice-cemented sands are present in horizontally bedded packages ~10–30 cm thick). Above the ice, there is a pebble- and cobble-rich unit supported by a brown silty sand matrix. The pebbles are largely angular mafic volcanics, are concentrated toward the top of the unit, and are sparsely distributed throughout. Above the cobbles, there are coarse sands and granules that are plane-bedded with varying degrees of dip and festoon cross-bedding. Sand packets are typically several centimeters thick and are traceable for several meters across the top of the ice cliff. The cobble-rich unit is in conformable contact with the ice, and it has a sharp, but undulating contact, typical of the contact between buried ice and overlying sediment in the down-valley till. The overlying sandy layer invades the underlying cobble-rich unit over a several-centimeter gradational contact. Upward, the sands give way to a pebble-based
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desert pavement at the top of the sediments above the ice cliff.

These ice-capping sediments form a small, but distinct and planar surface unit that abuts the up-valley till at a topographically smooth, but compositionally sharp contact. The sediments above the ice cliff form a relatively flat-lying surface that is ~3 m lower than the upper delta topmost surface. Taken together, we interpret these relationships to indicate that the Garwood Valley ice cliff represents a location where stranded ice-sheet ice, overlain by till, was inundated and then buried by fluviodeltaic sediments associated with the delta complex. The ice cliff represents a simplified, marginal portion of the delta complex, and it illustrates the conformable contacts between buried ice, till, and fluviodeltaic sediments.

In contrast to this ice-sediment depositional environment, the little ice cliff, an outcrop located down-valley from the delta complex, provides insight into the relationship between the down-valley till and fluvial erosion (Fig. 13). The little ice cliff is an ~4-m-high exposure of massive ice embayed by the modern Garwood River braid plain, opposite the main body of the down-valley till. The ice contains stringers of sand, similar to those observed at the ice cliff, but which are generally thinner than 10 cm. A sharp upper contact marks the transition between the little ice cliff ice and overlying sediments. The sediment cover is dominated by yellow-tan sand and silt, containing sparse angular cobbles. The sands have subtle, subhorizontal bedding defined by varying degrees of sediment cohesion. The clast density increases toward the top of the sediment cover. Most clasts are mafic volcanics, and they range in size from pebbles to ~40 cm boulders. Many clasts have carbonate rind surfaces.

On the basis of its textural and compositional similarity with the down-valley till present across the modern Garwood River, we interpret the little ice cliff to be a portion of the down-valley till that was separated from the main body of the unit by Garwood River fluvial and thermal erosion (fluvial thermokarst). The presence of down-valley till upslope of the little ice cliff, grading into a topographically smooth contact with the valley-wall bedrock, suggests that there has not been significant fluvial and/or thermokarst erosion upslope of the little ice cliff. Rather, it suggests that the primary conduit for discharge for the modern Garwood River, and,

Figure 7. Relict sand wedges preserved in the lower till and in fluvial units contemporaneous with the lower till. (A) Sand wedge polygons (box and arrows) in the lower till. Inset shows a contrast-stretched image of the boxed sand wedge showing vertical laminations of sand, suggesting the sand wedge formed in situ and has been preserved intact. Sand wedges are ~1 m wide. (B) Sand wedges in a fluvial unit coeval with the lower till. Sand wedges are ~50 cm wide.

Figure 8. (Left) The lower delta outcrop. Scale bar at left shows 50 cm vertical gradations. (Right) Stratigraphy and age control for the lower delta. For sand, vf is very fine, f is fine, m is medium, c is coarse, and vc is very coarse. For gravel, gran indicates granules, pebb indicates pebbles, cobb indicates cobbles, and boul indicates boulders.

In contrast to this ice-sediment depositional environment, the little ice cliff, an outcrop located down-valley from the delta complex, provides insight into the relationship between the down-valley till and fluvial erosion (Fig. 13). The little ice cliff is an ~4-m-high exposure of massive ice embayed by the modern Garwood River braid plain, opposite the main body of the down-valley till. The ice contains stringers of sand, similar to those observed at the ice cliff, but which are generally thinner than 10 cm. A sharp upper contact marks the transition between the little ice cliff ice and overlying sediments. The sediment cover is dominated by yellow-tan sand and silt, containing sparse angular cobbles. The sands have subtle, subhorizontal bedding defined by varying degrees of sediment cohesion. The clast density increases toward the top of the sediment cover. Most clasts are mafic volcanics, and they range in size from pebbles to ~40 cm boulders. Many clasts have carbonate rind surfaces.

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Figure 9. Composite sketch of the Garwood Valley delta complex based on field observations and annotated based on stratigraphic interpretations.

Figure 10. Contacts between sediment and ice. (A) A portion of the middle delta with the lower till indicated by pointing. White dot indicates the location from which part B was photographed. (B) View looking beneath the undercut middle delta. Till sediments are in an undulating contact with bright white ice. Exposed ice is bounded by dashed lines. Thickness of exposed ice is ~20 cm. (C) Exposed ice (bounded by dashed lines) beneath a portion of the middle delta. Height of exposed ice is ~1 m. (D) Undercutting of the lower delta by the modern Garwood River. Main channel flow direction is indicated by the white arrow. Flow from under the delta is indicated by the black arrow. Fluvial thermokarst erosion is common in Garwood Valley. Aluminum ladder in background (above white arrow) for scale. Ladder is ~4 m long.

Figure 11. A shoreline (arrows) incised in the down-valley till. The shoreline sits slightly above a terraced delta that is at nearly the same elevation as the lower delta, located across the modern Garwood River braid plain.
Figure 12. The Garwood Valley ice cliff. (A) Wide-angle view of the ice cliff, looking south from the Garwood River braid plain. White arrow indicates location of JLA10IC1. Large box indicates location of B; small box indicates location of C. (B) The ice cliff with people for scale. Bedded fluviodeltaic deposits above a coarse till layer are clearly visible. Talus cones formed from ice and sediment shed from above sit at the front of the ice cliff. (C) Close view and simplified stratigraphy of the ice cliff. Till sits atop massive buried ice; deltaic sediments sit atop the till.
likely, for the paleo–Garwood River and/or Glacial Lake Howard, was through an eroded portion of the Ross Sea ice sheet ice dam that constitutes the down-valley till.

SYNTHESIS OF DELTA COMPLEX

stratigraphy

Based on these stratigraphic observations and resulting inferences, we have correlated units among the upper, middle, and lower deltas to produce a composite picture of Garwood Valley delta complex stratigraphy (Fig. 9). Grain-size distribution summaries of units identified in this study are given in Figure 14. A schematic illustration of the glacial, hydrological, and geological processes that formed the Garwood Valley delta complex and surface units is presented in Figure 15.

At the base of the complex, a lower till unit overlies intact massive ice and was generated as a sublimation/melt-out lag deposit. At the surface, we map this unit as the up-valley till. The presence of a supraglacial till deposit in central Garwood Valley implies the emplacement of a large ice plug into the valley during LGM time. The best evidence for a Ross Sea ice sheet source for the ice dam is the similarity between the glacial till sediments in Garwood and the glacial till sediments mapped throughout the northern Dry Valleys (which, by virtue of geometry, cannot have been dammed by the Koettlitz Glacier; Stuiver et al., 1981; Denton et al., 1989; Hall and Denton, 2000). The sediments in the till units (mapped extensively in the past as the Ross I drift) are composed overwhelmingly of Ross Sea extrusive volcanics, rather than of Royal Society Range metasediments and intrusive volcanics. The Koettlitz Glacier is not a strong candidate for the source of Ross Sea volcanic sediments; rather, we interpret the geology of the up-valley and down-valley tills to indicate that, during the LGM, the Ross Sea ice sheet was the dominant ice source for the Garwood Valley plug. Accordingly, in order for the ice dam to have formed, the Ross Sea ice sheet grounding line must have been located up to or north of the mouth of Garwood Valley.

A reentrant lobe of Ross Sea ice sheet ice, capped by sublimation lag deposits (the down-valley till), dammed the Garwood River, resulting in deposition of lacustrine deposits upstream of the dam. Depositional energy was sufficiently low to preserve till sedimentary structures, including sand wedges, as it flooded the lower/up-valley till. As the lake (Glacial Lake Howard) (Péwé, 1960) grew, calving of icebergs and down-valley till sediments from the glacier led to the deposition of glacial drift onto the lake ice, which was then rafted and deposited by the conveyor process (Clayton-Greene and Hendy, 1987; Hall et al., 2000b), forming the upper till in the middle delta.

Preservation of the deeply ice-cored down-valley till (including the presence of unconsolidated sedimentary features at the till surface such as the shoreline terrace) indicates that the ice overlain by the down-valley till was stranded at some point in Garwood Valley. Once cut off from the main Ross Sea ice sheet, it was too thin to flow rapidly and drain back out of the valley mouth and became dead ice.

Eventually, deltas formed in the ice-dammed lake in the Garwood Valley. First the upper delta formed. Lake level then dropped, which we interpret as a resulting from downcutting through the dead-ice plug, resulting in the middle delta forming in a lower and down-valley position. A similar sequence followed to produce the lower delta. In order for the lake water to have drained, ice levels had to be lower outside of Garwood Valley. Because the mouth of Garwood Valley is at sea level, the Ross Sea basin into which the Garwood Valley drains has to have been free of grounded ice at the time of lake lowering, or else the lake would have continued to have been dammed by the high Ross Sea ice sheet ice. From the elevation of the deltas, approximate lake levels and areas (Fig. 16) can be estimated. Lake area dropped from 7.1 × 10^5 m^2 during formation of the upper delta, to 2.9 × 10^5 m^2, and, finally, to 1.3 × 10^5 m^2 during formation of the lower delta (for comparison, total delta surface area is ~1.1 × 10^5 m^2).

The only unit in the complex that shows clear evidence for a period of subaerial modification is the lower till package, inferred on the basis of preserved sand wedges (which occur only in this unit in the delta complex and which form over ~10^3 yr time scales under persistent dry conditions). This, coupled with the absence of massive gypsum layers and large calcite crystals (common to Miers and Marshall Valley paleolake deposits) (Clayton-Greene et al., 1988; Dagel, 1985), suggests that the Garwood Valley paleolake (Glacial Lake Howard) never fully desiccated. This argues against major periods of evaporation (and attendant changes in lake chemistry) as the major driver of lake-level reduction, although climate-driven change to lake water budget and attendant lowering of lake level are possible explanations of the change in water level that resulted in the end of deposition on the upper delta and the formation of the middle delta. Rather, the evidence for extensive fluvial thermokarst erosion in the valley, coupled with the winding path of the Garwood Valley.
River through the remnant ice-cored portions of the down-valley till (Fig. 2), suggests that lake lowering most likely resulted from localized breaching of the ice dam and discharge to the Ross Sea. This delta expansion and lake-level down-drop suggest that the Ross Ice Shelf grounding line had retreated south of Garwood Valley by the time that deposition ceased on the upper delta and transitioned to the middle delta, allowing paleolake water to drain.

**CHRONOLOGY**

Tying the relative chronology determined from the stratigraphic observations to absolute ages is key to determining the significance of the Garwood Valley sediment and ice deposits with respect to behavior of the Ross Sea ice sheet. During the course of the stratigraphic measurements and observations, we collected 21 samples of carbonaceous materials that were radiocarbon dated by accelerator mass spectrometry (Table 4). Most dated materials were samples of algal mats preserved within lacustrine and fluvial deposits. Also analyzed were six samples of lacustrine carbonate and a feather contained in glacial till. The chronologic information provided by these results is presented as both radiocarbon years (14C yr B.P.) and as calendar years (cal. yr B.P. or ka, depending on precision) based on the Fairbanks et al. (2005) and INTCAL (Stuiver and Reimer, 1993; Reimer et al., 2009) radiocarbon calibration curves. These dates build upon previous radiocarbon dating of materials collected near the mouth of Garwood Valley (Denton and Marchant, 2000;...
Two major challenges exist for interpreting radiocarbon age data in the McMurdo Dry Valleys: (1) determining whether samples from perennially ice-covered lakes are from shallow-water environments that are in regular exchange with atmospheric CO₂ through seasonal moats or are from deep-water deposits that are cut off from atmospheric CO₂ due to strong density stratification (and would thus, appear older—the “residence effect”) (Doran et al., 1999; Hall and Henderson, 2001; Hendy and Hall, 2006); and (2) determining the correspondence between algal mat ages and lacustrine carbonate ages—do algal mats show evidence of incorporation of inheritance of old carbon from glacial or geological sources (the “inheritance effect”)?

Do Garwood Valley radiocarbon samples represent shallow-water or deep-water deposits? All of the algal mat samples derive from sedimentary units that are interpreted as foreset deposits (Tables 1–3). These deposits are interpreted to have formed in shallow lake water as the delta advanced, and are therefore likely to have been well ventilated. The sediment was transported by the paleo–Garwood River, which was also likely to have been in ready contact with the atmosphere. Deltaic bottomset beds bearing carbonates may have formed in deeper-water environments than the algal mats, however, because the paleo–Garwood River was the primary source for water entering the lake (see Geochemistry section), it is likely that the carbonate source waters were also well exchanged prior to carbonate formation. These factors suggest that residence effects are small in Garwood Valley radiocarbon dates, based on the Doran et al. (1994) and Hendy and Hall (2006) models of stream and lake moat mixing.

Do Garwood Valley algal mats show evidence of inheritance of old carbon? Three lines of evidence lead us to conclude that while old carbon may have been incorporated into the algal mats sampled in Garwood Valley (e.g., from meltwater interactions with carbonate bedrock or old ice-sheet carbon), it does not significantly affect the derived radiocarbon ages. First, the presence of both highly depleted 1³C values for the algal mats (–24‰ to –30‰) and enriched values (–5‰ to –10‰) (Table 4) suggests that some algal mats have incorporated geological carbon (enriched in heavy 1³C), or that they may have formed without geological enrichment in the paleolake moat, where rapid CO₂ uptake associated with short growing seasons could have reduced fractionation and increased 1³C values to the –10‰ to +1‰ range (Brenda Hall, 2012, personal commun.). Regardless if the enriched algal mats are evidence of incorporation of old carbon, the position of the 1³C-enriched samples stratigraphically above the unenriched samples, coupled with younger ages for the 1³C-enriched samples compared to the unenriched samples, suggests that the effect of geological carbon input into the algal mats is small if present. Second, the radiocarbon age of a modern algal mat collected in a Garwood Valley thermokarst pond that is fed exclusively by melt of underlying Ross Sea ice sheet ice in the down-valley till unit is postbomb, indicating that there is little carbon inheritance into algal mats growing in ponds derived from melting of this portion of the Ross Sea ice sheet in Garwood Valley. In the absence of evidence for significant age offsets from old carbon reservoirs derived from bedrock or old ice, we adopt the radiocarbon ages derived from the algal mats at face value and calibrate them directly to calendar years.

In addition, ambiguity exists in the interpretation of radiocarbon ages obtained from lacustrine

### Table 4. Summary of Algal Mat and Carbonate Ages Determined by AMS Radiocarbon Dating

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type</th>
<th>Setting</th>
<th>Age (1⁰C yr B.P.)</th>
<th>1³C (‰)</th>
<th>Age (cal. yr B.P.) (F)</th>
<th>Age (cal. yr B.P.) (I)</th>
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<tbody>
<tr>
<td>JLA10CD1</td>
<td>Algal mat</td>
<td>Modern pond</td>
<td>Postbomb</td>
<td>–8.4</td>
<td>5598 ± 30</td>
<td>5606 ± 20</td>
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<td>JLA10LDA1</td>
<td>Algal mat</td>
<td>Lower delta</td>
<td>4861 ± 41</td>
<td>–9.4</td>
<td>5921 ± 36</td>
<td>5927 ± 23</td>
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<tr>
<td>JLA10LDA2</td>
<td>Algal mat</td>
<td>Lower delta</td>
<td>4899 ± 40</td>
<td>–5.6</td>
<td>5626 ± 31</td>
<td>5626 ± 28</td>
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<tr>
<td>JLA10LDA4</td>
<td>Algal mat</td>
<td>Lower delta</td>
<td>5098 ± 40</td>
<td>–24.5</td>
<td>7855 ± 62</td>
<td>7852 ± 30</td>
</tr>
<tr>
<td>JLA10LDA5</td>
<td>Algal mat</td>
<td>Lower delta</td>
<td>7020 ± 54</td>
<td>–2.4</td>
<td>13,564 ± 72</td>
<td>13,544 ± 97</td>
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<tr>
<td>G11B</td>
<td>Carbonate</td>
<td>Lower Delta</td>
<td>11,702 ± 61</td>
<td>2.4</td>
<td>13,544 ± 97</td>
<td>13,544 ± 97</td>
</tr>
<tr>
<td>G11A</td>
<td>Carbonate</td>
<td>Lower Delta</td>
<td>18,690 ± 110</td>
<td>3</td>
<td>22,297 ± 113</td>
<td>22,358 ± 75</td>
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<tr>
<td>JLA10C1</td>
<td>Algal mat</td>
<td>Ice cliff</td>
<td>6331 ± 58</td>
<td>–29.8</td>
<td>7259 ± 58</td>
<td>7277 ± 42</td>
</tr>
<tr>
<td>JLA10MDA2-R</td>
<td>Algal mat</td>
<td>Middle delta</td>
<td>4750 ± 190</td>
<td>–26.2</td>
<td>5470 ± 225</td>
<td>5502 ± 218</td>
</tr>
<tr>
<td>JLA10MDA1-1</td>
<td>Algal mat</td>
<td>Middle delta</td>
<td>5992 ± 29</td>
<td>–29.7</td>
<td>6823 ± 58</td>
<td>6836 ± 53</td>
</tr>
<tr>
<td>JLA10MDA1-W</td>
<td>Algal mat</td>
<td>Middle delta</td>
<td>6358 ± 44</td>
<td>–27.7</td>
<td>7262 ± 42</td>
<td>7282 ± 38</td>
</tr>
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<td>JLA10MDA1-B</td>
<td>Algal mat</td>
<td>Middle delta</td>
<td>6052 ± 43</td>
<td>–29.7</td>
<td>6902 ± 57</td>
<td>6904 ± 55</td>
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<tr>
<td>JLA10MDA1-2</td>
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<td>Middle delta</td>
<td>5577 ± 63</td>
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<td>6335 ± 59</td>
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<td>JLA10MDA2-P</td>
<td>Algal mat</td>
<td>Middle delta</td>
<td>4810 ± 42</td>
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<td>5561 ± 47</td>
<td>5508 ± 27</td>
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<td>G14</td>
<td>Carbonate</td>
<td>Middle delta</td>
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<td>3.8</td>
<td>10,584 ± 63</td>
<td>10,564 ± 45</td>
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<tr>
<td>G14A</td>
<td>Carbonate</td>
<td>Middle delta</td>
<td>12,326 ± 63</td>
<td>3.3</td>
<td>14,143 ± 112</td>
<td>14,168 ± 104</td>
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<tr>
<td>G18</td>
<td>Carbonate</td>
<td>Middle delta</td>
<td>4947 ± 42</td>
<td>–1.4</td>
<td>5685 ± 45</td>
<td>5681 ± 38</td>
</tr>
<tr>
<td>JLA10MDA3</td>
<td>Algal mat</td>
<td>Middle delta</td>
<td>10,920 ± 18</td>
<td>–7.5</td>
<td>12,812 ± 152</td>
<td>12,802 ± 166</td>
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<tr>
<td>G20</td>
<td>Carbonate</td>
<td>Middle delta</td>
<td>21,480 ± 140</td>
<td>1.3</td>
<td>25,805 ± 226</td>
<td>25,722 ± 260</td>
</tr>
</tbody>
</table>

Note: Ages are reported in both 1³C yr and calendar years using the Fairbanks et al. (2005) calibration curve (F) and the INTCAL calibration curve (I) (Stuiver and Reimer, 1993; Reimer et al., 2009). AMS—accelerator mass spectrometry; cal.—calendar. AMS—accelerator mass spectrometry.
carbonates formed in ice-covered lakes (typical of modern Antarctica), in which exchange with atmospheric $^{14}$C is limited by seasonal processes. Clayton-Greene et al. (1988) reported a maximum offset of 800 yr between radiocarbon dates of Miers Valley lacustrine carbonates and U/Th dating of the same carbonates. To within 1000 yr precision, then, radiocarbon dates of lacustrine carbonates may be considered an acceptable proxy for U-series dating.

In light of these considerations, what does radiocarbon dating of the Garwood Valley delta complex indicate about the timing of lake and delta formation? Dates for lacustrine bottomset material span from the latest Pleistocene into the Holocene, while ages of algal mats growing in the Garwood Valley delta environments are, with two possible exceptions, Holocene in age (Table 4). The sequence suggests that Glacial Lake Howard originated during ice damming of Garwood Valley at ca. 26 ka (ca. 21,000 $^{14}$C yr B.P.). The absence of evaporates or other evidence for desiccation suggests that the lake persisted, with its level incrementally dropping until its demise sometime after 5.5 ka (ca. 4900 $^{14}$C yr B.P.). The lower till, inferred to represent the more extensive up-valley glacial drift, apparently predates the 26 ka inception of the lake, and was subject to subaerial exposure prior to lacustrine inundation. The upper till, inferred to represent sediments derived from the younger, less-weathered, down-valley till that were reworked by the lake ice conveyor process, may be as young as 13–14 ka (ca. 11,000–12,000 $^{14}$C yr B.P.) (Figs. 6 and 17).

What does the chronology indicate about the advance and retreat of the Ross Sea ice sheet grounding line? Damming of the paleo–Garwood River to produce the oldest dated carbonate beds requires the presence of an ice plug, which implies passage of the Ross Sea ice sheet grounding line north of Garwood Valley by 25.8 ± 0.2 k.y. B.P. (Table 4). This date is similar to other McMurdo Dry Valleys–derived grounding line passage estimates, ranging from ca. 23.5 k.y. B.P. in Taylor Valley (north of Garwood Valley) (Hall and Denton, 2000) to ca. 27.6 k.y. B.P. in Miers Valley (south of Garwood Valley) (Clayton-Greene et al., 1988). While the upper delta could have formed in an ice-sheet–dammed lake, with the grounding line still north of Garwood Valley, thinning of the Ross Sea ice sheet is required for partial drainage of Glacial Lake Howard, lake lowering, and the resulting growth of the middle delta. Algal mat ages from algal foresets in the middle delta span ca. 5470 to 7265 cal. yr B.P. (4750–6338 $^{14}$C yr B.P.), indicating that incision of the ice dam began by ca. 7.3 ka (ca. 6300 $^{14}$C yr B.P.). This result is consistent with an algal mat dated at 7259 ± 58 cal. yr B.P. (6331 $^{14}$C yr B.P.) from the ice-cliff deltaic sediments, which sits at an intermediate elevation between the upper and middle deltas. Continued incision soon after formation of the middle delta is suggested by the very similar ages for the lower delta, which range from 7855 to 5598 cal. yr B.P. (7020–4861 $^{14}$C yr B.P.), indicating that the Ross Sea ice sheet grounding line had moved south of Garwood Valley no later than 5.5 ka (ca. 4900 $^{14}$C yr B.P.).

Interestingly, algal mat ages from the lower delta, which is stratigraphically younger than the middle delta (Figs. 8 and 9), span ca. 5598–7855 cal. yr B.P. (4861–7020 $^{14}$C yr B.P.). In cases, these dates are older than middle delta algal mat dates. The relatively enriched $^{14}$C content of most of the lower delta algal mat samples raises the possibility that inherited (old) carbon is present in lower delta algae, thereby resulting in slightly older radiocarbon ages for the stratigraphically younger deposits. Alternatively, the draping of the lower delta on the middle delta may have reworked older middle delta algal material and redeposited/incorporated it into lower delta algal mats, resulting in anomalously old ages for the lower delta mats.

These results are consistent with previous estimates of Ross Sea ice sheet grounding line recession past Garwood Valley ca. 4750–6338 $^{14}$C yr B.P. (Conway et al., 1999; Denton et al., 1989; Denton and Marchant, 2000; Stuiver et al., 1981; Hall et al., 2004). The chronology of lake-level drop derived from this study—initial lake-level decline at ca. 7.3 ka and lake demise by ca. 5.5 ka—is consistent with chronologies developed from dating of algal mats at the mouth of Garwood Valley. Stuiver et al. (1981) concluded that the Ross Sea ice sheet grounding line was south of Garwood Valley by 6580 ± 50 $^{14}$C yr B.P. (equivalent to ca. cal. 7500 yr B.P.) and noted that ice-sheet level was at least below 25 m a.s.l. in Garwood Valley by 6190 ± 80 $^{14}$C yr B.P. (5129 ± 96 cal. yr B.P.), and they argue that this date is compatible with, but is not direct evidence of, grounding line retreat. Although it appears that downcutting through the wasting Ross Sea ice sheet and its remnants in lower Garwood Valley created the sequence of delta deposits and surfaces, what does the stratigraphy indicate about the initial growth of Glacial Lake Howard at ca. 26 ka and the subsequent transition from quiescent lacustrine deposition (carbonates and fine-grained silts) to high-energy deltaic deposition? The radiocarbon dates from our study (Table 4) are replotted over the Taylor Dome $\delta^{18}$O record in Figure 17. This plot shows that the initial formation of Glacial Lake Howard occurred definitively during the Pleistocene, near the height of the LGM at ca. 26 ka.

Colder, drier conditions are thought to have persisted in the McMurdo Dry Valleys during the LGM, resulting in reduced glacier runoff (Doran et al., 1994). This was also the period
favored for the highstand of Glacial Lake Washburn in Taylor Valley (Hall and Denton, 2000). A possible resolution to this apparent paradox (proglacial lake development during cold, low-precipitation conditions) is that modern runoff in the McMurdo Dry Valleys is primarily driven by solid-state greenhouse effects within glaciers, rather than by sensible heat exchange (Hoffman et al., 2008; Hall et al., 2010). Accordingly, it is likely that the paleo–Garwood River remained at least partially active, even during extremely cold periods, driven by insolation-dominated melting. The formation of an ice dam in Garwood Valley during a low-discharge phase for the paleo–Garwood River is consistent with the initial formation of only fine-grained deposits over the ice and till at the base of the delta complex.

The next youngest radiocarbon dates from the delta complex (including carbonates and an algal mat) correspond with isotope maxima at the close of the glacial period. These samples span ca. 12.5–14 ka, which may correspond to local warming excursions in the McMurdo Dry Valleys associated with the positive δ18O anomaly within the Antarctic Cold Reversal (ca. 12.8–14.5 ka) that produced increased runoff and changes to the paleolake depositional environment (Doran et al., 2008). Finally, the large cluster of algal mat ages from the mid-Holocene span a complex period of δ18O variability in the Ross Sea sector. These deltaic depositional periods may have been associated with peak runoff and sediment transport years, or they may reflect more complex feedbacks among temperature, precipitation, and discharge in Antarctic seasonal rivers.

In summary, the radiocarbon dates from the Garwood delta complex broadly agree with previous interpretations of Ross Sea ice sheet grounding line retreat at the close of the LGM. The detailed chronostratigraphy of the delta complex suggests the persistence of an ice-dammed lake in Garwood Valley from pre-LGM through Holocene time. Rather than being a product of a single damming, filling, and draining sequence, the delta complex suggests a multi-stage history of lake filling, with transitions between fluvial, lacustrine, and glaciolacustrine processes operating in Garwood Valley over an ~20,000 yr period.

GEOCHEMISTRY

What does the composition of Garwood Valley ice and sediment indicate about its relationship with Ross Sea ice sheet ice and LGM-age sediments located elsewhere in Garwood Valley and in neighboring valleys? How representative is Garwood Valley of glaciofluvial processes in the southern McMurdo Dry Valleys? In this section, we evaluate the chemical and isotopic compositions of Garwood Valley sediments and ice, relative to previous analyses of Garwood Valley deposits, and we compare them to samples from neighboring valleys.

First, in order to evaluate the continuity of buried ice composition in Garwood Valley, ice samples collected in 2009–2010 were analyzed for major ion composition and for δ18O and δD (Fig. 18; Tables 5 and 6). Major ion concentrations were determined by ion chromatography as described in Welch et al. (2010), resulting in a total analytical error of <4%. Stable O and H isotopes were measured using a Picarro WS-CRDS Analyzer for Isotopic Water, Model L1102-i. Samples analyzed for stable isotope ratios were splits from the major ion ice samples that were separated prior to ion chromatography (IC) analysis.

Comparisons of the major ion compositions and stable isotopes of Garwood Valley ice indicate broad similarities and intriguing differences between the Pollard et al. (2002) samples and the ice cliff/delta complex samples. Single-ended analysis of variance (ANOVA) analyses of the major ion data presented in Table 5 indicate no statistically significant (P < 0.05) differences between the buried ice at the mouth

![Figure 18. Plot of δD vs. δ18O for ice and water collected in Garwood Valley. “Levy et al. Ice”—samples collected from the ice cliff and from beneath the delta complex. “Pollard et al. Ice”—values reported by Pollard et al. (2002). Glacial Runoff—water collected downstream of the Garwood Glacier. Garwood River—modern Garwood River water collected upstream of the ice cliff.](gsabulletin.gsapubs.org)

<table>
<thead>
<tr>
<th>Sample</th>
<th>F (mg/L)</th>
<th>Cl (mg/L)</th>
<th>SO4 (mg/L)</th>
<th>Na (mg/L)</th>
<th>K (mg/L)</th>
<th>Mg (mg/L)</th>
<th>Ca (mg/L)</th>
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<td>0.12</td>
<td>7.50</td>
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<td>7.72</td>
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<td>1.17</td>
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<td>3.97</td>
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<td>10.92</td>
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<td>0.88</td>
<td>6.08</td>
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<td>JLI09G4</td>
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<td>0.28</td>
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<td>0.36</td>
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</tr>
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</table>

Note: GMI—Garwood massive ice; the number indicates the depth below the surface at which the sample was collected (see Fig. 2 for sampling area). P—probability that JLI samples and GMI samples are derived from same ice compositional population based on single-ended analysis of variance. No values are significantly different (P < 0.05), suggesting a relatively homogeneous ion load in Garwood Valley ice.
of Garwood Valley and the ice located at the ice cliff and beneath the delta complex. Compositionally, the upper valley ice and the lower valley ice are nearly identical. Nevertheless, single-ended ANOVA analyses of the O and H isotopic values (% Vienna standard mean ocean water [VSMOW]) of the two ices yield significant differences: Ice from the ice cliff area is significantly more depleted in D than down-valley ice (−241‰ vs. −219‰, P < 0.002) and is also significantly more depleted in 18O than down-valley ice (−30‰ vs. −27‰, P < 0.01). These data suggest that, while the buried Ross Sea ice sheet in Garwood Valley is compositionally homogeneous, it records a complex isotopic history of similar complexity to the modern Ross Ice Shelf (Kellogg et al., 1990), which reflects intermingled ice sources reflecting both marine and glacial origins. It is also possible that thermal and physical erosion by the Garwood River through the stranded Ross Sea ice sheet loke of buried ice has resulted in the intermingling of locally derived ice (transported as river meltwater and refrozen in place) with Ross Sea ice sheet ice, which could account for the similarity in isotopic values between some ice-cliff ice and the Garwood Glacier.

Next, how does the isotopic composition of Garwood Valley carbonates compare to those from neighboring Miers Valley, and what does that indicate about the water sources for the paleolakes in which these carbonates formed? Clayton-Greene et al. (1988) reported calcium carbonate δ18O values spanning −21‰ to −11‰ and δ13C values spanning −33‰ to −15‰, respectively (all ratios in this paragraph are Vienna Pee Dee belemnite [VPDB], similar to values reported for Glacial Lake Washburn (in Taylor Valley) by Lawrence and Hendy (1989); −30‰ to −17‰ for δ18O and −4‰ to +4‰ for δ13C. Clayton-Greene et al. (1988) interpreted these relatively enriched δ18O values (relative to buried ice or ice-sheet values) as evidence of local, meteoric sources. This ~20 k.y. history of activity is recorded in a single outcrop in Garwood Valley (the delta complex), making it an unusually complete chronostratigraphic sequence in the McMurdo Dry Valleys. Most unusually, the Garwood paleodelta outcrops sit conformably atop intact glacial till units, which in turn overlie buried massive ice deposits interpreted to be remnants of the stranded Ross Sea ice sheet emplaced in the valley during the late Pleistocene. Strikingly, the Garwood Valley delta complex and associated glacialfluvial landforms indicate that the particular geological and hydrological conditions in Garwood Valley permitted growth of a very large delta in a very small ice-dammed lake.

After initial lake formation, the earliest deposition of sediments in Glacial Lake Howard is associated with local maxima in the δ18O ice-core record at the nearby Taylor Dome, indicating deposition during periods of relative warmth in the McMurdo Dry Valleys, even during broadly colder periods during the late Pleistocene. Deposition of the complex topset/foreset units in the delta was not strongly associated with particular Taylor Dome climate modes, suggesting
complex interplay between climate and local McMurdo Dry Valleys hydrometeorology.

Glacial Lake Howard shows no evidence of complete dehydration, and rather, it is interpreted to have largely drained through breaching of the ice dam in the mouth of the valley. No gypsum plates exist in the Garwood Valley paleodelta. Likewise, subaerial sedimentary markers (remnant sand wedges) are only observed in the oldest glacial till unit immediately overlying the buried ice, and not in any other stratigraphic unit, suggesting persistent lacustrine conditions without intervening aerial periods.

Garwood Valley ice and sediment geochemical and isotopic compositions are broadly consistent with carbonate and ice compositions recorded elsewhere in the Ross Sea (Ross I) drift. Buried glacial ice is geochemically homogeneous within Garwood Valley, but it shows stable isotope variability that may indicate the presence of a horizontally distributed climate record. Garwood Valley lacustrine carbonate oxygen and carbon compositions are most consistent with lake formation dominated by the proximal melting of alpine glaciers, with minimal contributions from melting of the ice-sheet dam.

Chronostratigraphic and geochemical analyses of glaciolfluvial units in Garwood Valley result in observations and inferences that are broadly consistent with glacial reconstructions conducted elsewhere in the McMurdo Dry Valleys. Garwood Valley is unique, however, in the complexity and detail of the sedimentary record preserved from the Pleistocene-Holocene transition, and in the richness of the delta complex preserved from the Pleistocene-Holocene transition. Garwood Valley is unique, however, in the rare glaciofluvial units in Garwood Valley conducted elsewhere in the McMurdo Dry Valleys, as broadly consistent with glacial reconstructions resulting in observations and inferences that are consistent with glaciofluvial units in Garwood Valley inferred from lacustrine deposits in Victoria Valley: Journal of Quaternary Science, v. 7, no. 7, p. 697–706, doi:10.1002/jqs.691.


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Garwood Valley, Antarctica: A new record of Last Glacial Maximum to Holocene glaciofluvial processes in the McMurdo Dry Valleys

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