

Major middle Miocene climate change and the extinction of tundra communities: Evidence from the Transantarctic Mountains

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Summary We present a glacial record from the western Olympus Range, East Antarctica, that documents a permanent shift in the thermal regime of local glaciers, from wet to cold based, between 14.11 and 13.94 million years ago (Ma). The record includes classic wet-based tills interbedded with fossil-rich glaciolacustrine deposits overlain by a series of cold-based drifts. Chronologic control comes from ⁴⁰Ar/³⁹Ar analyses of six *in-situ* volcanic ash deposits. The shift from wet- to cold-based glaciation reflects a drop in mean annual temperature of 20 to 30 °C and is shown to precede one or more major episodes of ice-sheet expansion across the region sometime between 13.62 and 12.44 Ma. Major implications are 1) that atmospheric cooling preceded, and thus may have triggered, maximum overriding of the polar East Antarctic Ice Sheet and 2) that complex terrestrial communities became extinct in this sector of the Transantarctic Mountains at ~14 Ma.

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Introduction

The Antarctic environment prior to late Neogene time was substantially different from that of today. The East Antarctic Ice Sheet maintained temperate margins (Barrett, in press), glaciers in the Transantarctic Mountains were wet based (Marchant et al., 1993), and tundra-type terrestrial communities existed within 500 km of the South Pole (Ashworth and Cantrill, 2004). The transition to cold-based glaciers, with internal ice temperatures closely matching mean annual temperatures (MAT) well below 0 °C, marks a fundamental step in the development of the modern Antarctic cryosphere and corresponds to a boundary between past relatively mild climate conditions and modern polar-desert conditions. Until now terrestrial records documenting the precise timing of this transition were lacking. Here we present a new record from the western Olympus Range, southern Victoria Land, Antarctica, that spans this transition. The record includes deposits from both wet- and cold-based glaciers as well as numerous glaciolacustrine deposits preserving fossils from ancient tundra communities. Multiple interbeds of *in-situ* volcanic ash provide limiting ages for this transition, afford an age for fossil assemblages, and bracket subsequent episodes of ice sheet expansion.

The western Olympus Range is part of the divide between upper Wright Valley and McKelvey Valley, and is situated near the center of the McMurdo Dry Valleys region (77° 30'S; 160° 40' to 161° 45'E). Peaks in the range appear as flat-topped inselbergs, the highest of which reach 2000 m. There are no published reports of climate for western Olympus Range. Based on nearby measurements the MAT is probably about -30 °C with mean summer temperatures (December-February) of -10 to -15 °C (Doran et al., 2002). Annual precipitation is likely <100 mm of water equivalent.

Glacial stratigraphy

Extensive mapping conducted during austral summers from 1999 to 2007 and analyses of over 450 soil pits show that the western Olympus Range contains deposits from ancient, locally derived, wet-based glaciers (Circe till) and an overlying, younger suite of genetically related tills that were deposited from cold-based alpine glaciers (collectively termed Dido drift). The distinction between Circe till and Dido drift is obvious in the field because wet- and cold-based alpine glaciers produce markedly dissimilar deposits. Wet-based glaciers are powerful erosive agents that mold and striate bedrock surfaces over which they slide. They deposit mud-rich tills that contain molded, striated, and polished clasts. In contrast, cold-based glaciers are extremely weak erosive agents that flow by internal plastic deformation; they ablate mostly by sublimation and deposit loose gravel-rich tills that contain only angular clasts.

Deposits from wet-based glaciers: Circe till

Circe till is from 1 to 4 m thick and rests on striated and molded bedrock throughout the western Olympus Range (Fig 1). Exposures form an irregular, highly dissected map pattern suggestive of one or more episodes of post-depositional erosion. Circe till is a classic wet-based till comprised of a lower mud-rich diamicton with striated clasts derived from local bedrock. In places the till grades upward into a stratified facies with well-developed lenses of sorted sand and gravel. Circe till lacks terminal moraines, thus precluding the determination of its maximum geographical extent. The only moraines associated with the till come from the eastern half of the study area where groups of arcuate,

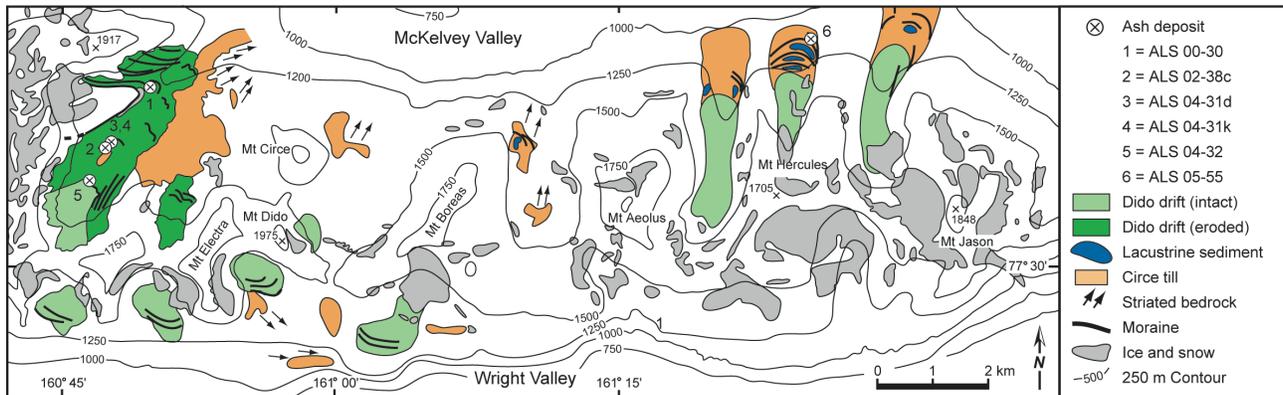


Figure 1. Map of glacial deposits in the western Olympus Range.

cross-valley moraine ridges are positioned at north-facing breaks in slope (where ice surfaces would have received the most exposure to high-angle sun; Fig. 1). These moraines form well-defined recessional sequences that include glaciofluvial and glaciolacustrine deposits. The lacustrine deposits are of great interest because many contain beds of concentrated freshwater diatoms as much as 10 cm thick and extraordinarily well-preserved macrofossils including mosses, insects and ostracods (see Ashworth et al., this volume). All of these lacustrine deposits are comprised of laminated silt, sand and clay and many include glacial dropstones. They are all positioned adjacent to up-slope moraine flanks at elevations of 1150 to 1450 m. Based on the maximum extent of lacustrine deposits at each site, lakes ranged in size from < 5 to ~80 m in diameter.

We interpret the basal diamict of Circe till to be a lodgement till deposited from wet-based ice. The orientation of underlying bedrock striations, as well as the absence of far-traveled erratics, together suggest that the ice was derived from cirque glaciers or a small ice cap. The stratified melt-out facies implies significant modification from water, most probably derived from melting at the former ice surface under warmer-than-present climate conditions. As glaciers retreated, moraines developed in north-facing, intermountain valleys. Where melt water was impounded behind these moraines, small lakes formed, many of which supported a complex assemblage of plants and animals.

Deposits from cold-based glaciers: Dido drift

Resting directly atop Circe till is Dido drift, a collection of patchy, and in some cases, overlapping tills deposited from cold-based alpine glaciers in the western Olympus Range. Individual tills range from a single layer of isolated cobbles to till sheets as much as 3 m thick. The latter are commonly grain-supported diamictos comprised of loose mixtures of sand, gravel, cobbles, and angular boulders. Numerous moraine ridges in Dido drift delineate well-defined recessional sequences, or, less commonly, bound the margins of individual till sheets (Fig. 1). Till sheets making up Dido drift can be divided into two groups based on the presence or absence post-depositional erosion analogous to that observed for Circe till. Group 1 includes Dido tills that lack evidence for erosion (light green in Fig. 1). In contrast, group 2 tills show extensive dissection including irregular drift boundaries and enclosed erosional basins, 10's to 100's of meters in diameter, that expose underlying bedrock (dark green in Fig. 1). One particularly large basin cuts through a stratigraphic section of Dido drift that includes three separate tills and two volcanic-ash interbeds; the section also exposes an underlying outcrop of wet-based till most probably correlative with Circe till (Fig. 2).

We interpret all tills in Dido drift as being deposited from cold-based, alpine glaciers. The pattern of tills in map view, as well as the spatial arrangement of terminal and recessional moraines, suggest that glaciers originated from protected alcoves positioned at valley headwalls. Modern cold-based glaciers in the western Olympus Range and elsewhere in the Dry Valleys provide a good analog for the origin of Dido drift. Today, these glaciers carry only englacial and supraglacial debris that falls onto the glacier from surrounding cliffs; sublimation of ice releases englacial material, which slowly accumulates at the ice surface producing a loose deposit with large voids (e.g., Schäfer et al., 2000; Marchant et al., 2002).

Chronology

Our numerical chronology comes from $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of six ash fall deposits interbedded with mapped units. In all cases, ash deposits used for chronologic control are comprised of exclusively angular glass shards and include only 3.5 to 0.5% non-volcanic contaminants. Reworking of ash into these deposits is unlikely based on the absence of both rounded glass shards and non-volcanic, wind-blown material. Uniformly precise radiometric ages support this interpretation. Locations of ash deposits are shown in Figure 1.

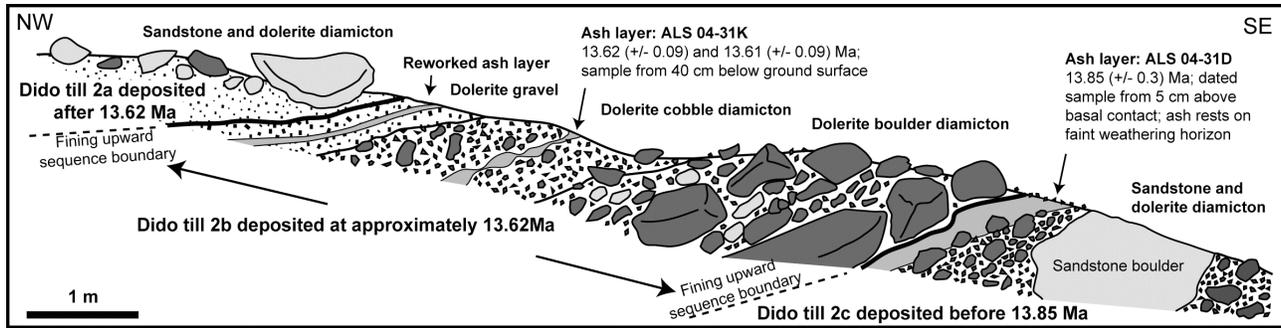


Figure 2. Cross-sectional diagram of till sheets and ash deposits.

The age of Circe till and associated lacustrine deposits

Two volcanic ash deposits place limiting ages on the deposition of Circe till. Sample ALS 05-55 is an ash bed resting conformably within diatom-rich lake sediments 2 km north of Mt Hercules. The bed is 3.5 cm thick and is oriented parallel to surrounding lacustrine laminations. The bed maintains a uniform thickness over a distance of at least 6 m and shows sharp upper and lower contacts. We interpret the ash to have fallen directly into a small moraine-dammed lake. Preliminary analyses of laser-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ dating of sanidine crystals from the ash shows that the bed is 14.11 ± 0.11 Ma.

ALS 02-38c is a near-horizontal bed of ash. It rests conformably between an underlying compact wet-based till (most likely correlative to Circe till) and overlying Dido drift. The bed is 10 to 30 cm thick and extends laterally 15 m. The lower contact is sharp, whereas the upper is gradational over a distance of 2 to 5 cm. We conclude that ALS 02-38c comes from air-fall ash that collected in a small topographic depression atop wet-based till. Following deposition, the bed was buried beneath non-erosive cold-based glacier ice. Radiometric dating of sanidine crystals yields an age 13.72 ± 0.02 Ma.

Together these two ash deposits indicate 1) that Circe till is at least middle Miocene in age, 2) that glaciers depositing Circe till had retreated from their maximum positions by 14.11 Ma, and 3) that a diatom flora (and likely a more complex biota in nearby lakes) persisted in this part of the TAM until ~ 14 Ma.

The age of Dido drift and the transition to cold-based glaciation

Four volcanic ash deposits place limiting ages on till sheets making up Dido drift. Sample ALS 00-30 comes from a downward-tapering wedge of ash that penetrates group 2 drift. In map view, the ash deposit forms a Y shape extending laterally about 3 m; it extends downward >40 cm. Based on its morphology and surrounding sand-wedge sediments, we interpret the ash to lie at the center of a relict sand-wedge deposit marking the former intersection of three contraction-crack polygons. Laser-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ dating of sanidine crystals shows that the ash is 13.94 ± 0.75 Ma.

Approximately 1.5 km southwest of ALS 00-30, samples ALS 04-31d and ALS 04-31k come from ash beds exposed along a sharp erosional boundary within group 2 drift. The lower bed (31d) is 20 to 60 cm thick and can be traced laterally for at least 120 m. The upper (31k) is 1 to 2 cm thick and extends laterally at least 2 m. The lower bed shows sharp contacts and rests between two till sheets comprising group 2 drifts; the upper bed shows gradational contacts and lies within a gravel-rich horizon of group 2 drift (Fig 2). Based on its age and setting, we interpret the lower bed to be an ash-fall deposit that collected on an ice-free surface at 13.85 ± 0.03 Ma. The upper bed, being conformable with surrounding drift, likely collected in a former glacier accumulation zone at 13.62 ± 0.09 Ma, traveled englacially, and ultimately returned to the surface at this location by sublimation of overlying ice.

Sample ALS 04-32 fills voids in loose till that forms part of a continuous moraine ridge comprised of Dido drift group 1. The ash extends to a depth of 35 cm and can be traced laterally for ~ 2 m. The ash likely collected at a former glacier margin and shortly thereafter filtered down into loose, ice-marginal till. Laser-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ dating of sanidine crystals shows that this ash is 12.44 ± 0.15 Ma.

Together these ash deposits show 1) that deposition of cold-based Dido drift began >13.94 Ma, 2) that deposition occurred between 13.85 and 13.62, and at 12.44 Ma, and 3) that dissection of till sheets occurred (perhaps intermittently) until between 13.62 and 12.44 Ma. Finally, the preserved morphology of an ash-filled polygon trough as well as other near-surface deposits rules out the existence of saturated active layers at these elevations in the Olympus Range since 13.94 Ma.

Conclusions and implications

Major middle Miocene cooling

The sedimentology and stratigraphy of mapped deposits in the western Olympus Range, combined with the radiometric chronology afforded by $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of in-situ volcanic-ash deposits, indicate that wet-based glaciers

occupied the range prior to 13.94 Ma. The thermal regime of glaciers shifted from wet to cold based sometime between 13.94 Ma and 14.11 Ma. The glacial record holds no evidence for a return to wet-based glaciation after the shift to cold-based thermal regimes. Given that Circe till and Dido drift were deposited from relatively small, locally derived glaciers, this transition marks a major climate deterioration. To provide a rough estimate of how much warmer it was during deposition of Circe till relative to today, we offer the following argument: 1) assuming that the bedrock elevation of Circe-Rude Valley during deposition of Circe till was comparable to that of today (e.g., 1000 to 1300 m in elevation, Sugden et al., 1995); 2) that the middle Miocene lapse rate approximated the dry adiabatic lapse rate of ~ 9.8 °C/km; and, 3) that small wet-based glaciers with extensive surface-melting zones require MATs of ~ 0 to -10 °C, we estimate that MAT during deposition of Circe till was 20 to 30 °C warmer than today.

Expansion of the East Antarctic Ice Sheet

Although Circe-Rude Valley lacks *depositional evidence* supporting major ice-volume fluctuations during the thermal transition, the widespread erosion of Circe till and Dido drift (all group 2 tills) is consistent with erosion beneath a polythermal ice sheet, first theorized by Denton et al. (1984). According to this hypothesis, localized production and refreezing of subglacial melt water beneath a thick polythermal ice sheet resulted in the selective erosion drift sheets and in the formation high-elevation melt water channel systems (see also Marchant et al., 1993; Sugden and Denton, 2004; Denton and Sugden, 2005; Lewis et al., 2006). The record in the western Olympus Range places erosion between 12.44 and 13.62 Ma, which is consistent with previous age estimates between 14.8 and 12.4 (Marchant et al., 1993; Margerison et al., 2005; Lewis et al., 2006). These results indicate that atmosphere cooling, sufficient to support cold-based alpine glaciation above 1200 m elevation in the western Olympus Range, preceded the most significant/recent mid-Miocene expansion of the East Antarctic Ice Sheet. This scenario supports recent marine isotopic evidence that sea surface cooling between 14.2 and 13.8 Ma preceded ice sheet expansion (Shevenell and Kennett, 2004; Shevenell et al., 2004).

Extinction of tundra biota

The glacial record from the western Olympus Range suggests that cold and dry Polar-desert conditions have characterized the region since at least 13.94 Ma, most likely precluding the existence of complex terrestrial life since that time. In contrast, surface melt water was abundant and tundra communities inhabited relatively high-elevation sites at 14.11 Ma. This places the final extinction of complex terrestrial ecosystems sometime between 14.11 and 13.94 Ma, at a time just before inundation beneath an expanding East Antarctic Ice Sheet.

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