

Major middle Miocene global climate change: Evidence from East Antarctica and the Transantarctic Mountains

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ABSTRACT

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 regimes, more than 13.94 m.y. ago. This glacial record provides the first terrestrial evidence linking middle Miocene global climate cooling to a permanent reorganization of the Antarctic cryosphere and to subsequent growth of the polar East Antarctic Ice Sheet. The composite stratigraphic record constructed from field mapping and analyses of 281 soil excavations shows a classic wet-based till (Circe till, including an extensive melt-out facies), overlain by a weathered colluvial deposit (Electra colluvium), and then a series of stacked tills deposited from cold-based ice (Dido drift). Chronologic control comes from ⁴⁰Ar/³⁹Ar analyses of concentrated ash-fall deposits interbedded within glacial deposits. The shift from wet- to cold-based glaciation reflects a drop in mean annual temperature of 25–30 °C and is shown to precede one or more major episodes of ice-sheet expansion across the region, the youngest of which occurred between 13.62 and 12.44 Ma. One implication is that atmospheric cooling, following a relatively warm mid-Miocene climatic optimum ca. 17 to 15 Ma, may have led to, and thus triggered, maximum ice-sheet overriding.

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INTRODUCTION

The Antarctic cryosphere prior to late Neogene time was substantially different from that of today. The volume of the East Antarctic Ice Sheet varied significantly over time scales as short as 100 k.y. (Pekar and DeCanto, 2006; Barrett, 2007), and glaciers in the Transantarctic Mountains were wet based (Marchant et al., 1993; Sugden et al., 1995). The transition to cold-based glaciers, with internal ice temperatures closely matching mean annual temperatures (MAT) <<0 °C (Holdsworth and Bull, 1968), marks a fundamental step in the development of the modern Antarctic cryosphere. Until now terrestrial records documenting the style and 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 and includes deposits from both wet- and cold-based glaciers. Multiple deposits of in situ volcanic ash provide limiting ages for this transition and bracket subsequent episodes of ice-sheet expansion.

The importance of this terrestrial glacial record arises from its relation to the middle Miocene climate transition, the second of three key steps in Cenozoic climate cooling (Zachos et al., 2001). The relative timing of this cooling as recorded in offshore records, along with our evidence for the development and expansion of a polar East Antarctic Ice Sheet and for a thermal change in local high-elevation glaciers in the Transantarctic Mountains, is critical to

understanding the full role of the Antarctic cryosphere in this global climate event. Comparison of this new glacial record to high-latitude records elsewhere on the continent (e.g., Rocchi et al., 2006) and to offshore marine records (e.g., Shevenell et al., 2004) will help establish the time-transgressive nature of the middle Miocene climate transition and define its role in altering landscape development in mountainous regions of Antarctica (e.g., Hickey et al., 2003; Sugden and Denton, 2004; Stern et al., 2005).

Physical Setting

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'E to 161° 45'E; Fig. 1). Peaks in the range appear as flat-topped inselbergs, the highest of which reach 2000 m. The western Olympus Range is composed of thick formations of Beacon Supergroup sandstone (Barrett, 1981) and sills of Jurassic Ferrar Dolerite (Kyle et al., 1981). The overall morphology of the range shows evidence for ancient fluvial and glacial erosion, but the relative importance of each erosive process remains the focus of ongoing studies (Denton et al., 1993; Sugden et al., 1995; Prentice et al., 1998). The focus here is on the glacial record from Circe-Rude Valley (an informal name from Prentice et al., 1998) at the western boundary of the range (Fig. 1).

Circe-Rude Valley is a broad, north-facing valley ~6 km long by 4.5 km wide. It is bounded to the west by a major coastal-facing escarpment (the main Dry Valleys escarpment of Sugden et al., 1995), to the northwest by

Rude Spur, and to the east by Mount Electra and Mount Circe (Fig. 1). The valley floor averages 1400 m in elevation but drops to 1200 m in the west, where a shallow trough, as wide as 1 km, opens to McKelvey Valley. Circe-Rude Valley is the only valley in the western Olympus Range bounded by a high, near-continuous headwall. All other valleys show breached and/or low-elevation headwalls.

Circe-Rude Valley is free of glacier ice except for a single, unnamed alpine glacier that extends outward from the western valley wall (Fig. 1). The accumulation zone is positioned where wind-blown snow from the polar plateau collects and augments local precipitation (Fig. 1). The glacier is ~1 km long and a maximum of 1 km wide; it is cold based and ablates by sublimation. A narrow ice-cored moraine topped by dolerite boulders and cobbles marks the glacier terminus. The boulders and cobbles originate from rockfall from surrounding cliffs; some clasts travel englacially before arriving at the surface via sublimation of overlying ice. The cold-based thermal regime prevents the addition of all but a minute quantity of material to the glacier sole (e.g., the extremely small erosion rates calculated by Cuffey et al. [2000] for one modern alpine glacier in the eastern Dry Valleys).

There are few published measurements of climate conditions in the western Olympus Range. The nearest record comes from Lake Vanda, which is southeast of the western Olympus Range and 125 m elevation (Fig. 1). At this site, MAT is measured as -19°C and mean annual precipitation is ~45 mm of water equivalent (Schwerdtfeger, 1984; Doran et al., 2002). Based on a dry adiabatic lapse rate of $9.8^{\circ}\text{C}/\text{km}$, the MAT in Circe-Rude Valley is probably $\sim 30^{\circ}\text{C}$. Using meteorological observations from multiple sites in the Dry Valleys, Doran et al. (2002) predicted mean summer temperatures (December–February) of -10 to -15°C in Circe-Rude Valley.

METHODS

We mapped unconsolidated deposits in Circe-Rude Valley during austral summers from 1999 to 2004. Sedimentological characteristics of mapped deposits are based on analyses of 281 soil pits, each ranging from 1 to 3 m deep. We collected multiple sediment samples at each excavation. Clasts (>16 mm) were separated from matrix by dry sieving in the field and later examined at Boston University for evidence of glacial molding, striations, wind abrasion, and surface staining. The fine fraction (<16 mm) was analyzed using standard wet and dry sieving procedures.

Volcanic ash observed in the field was collected separately and placed in sealed whirl-pack

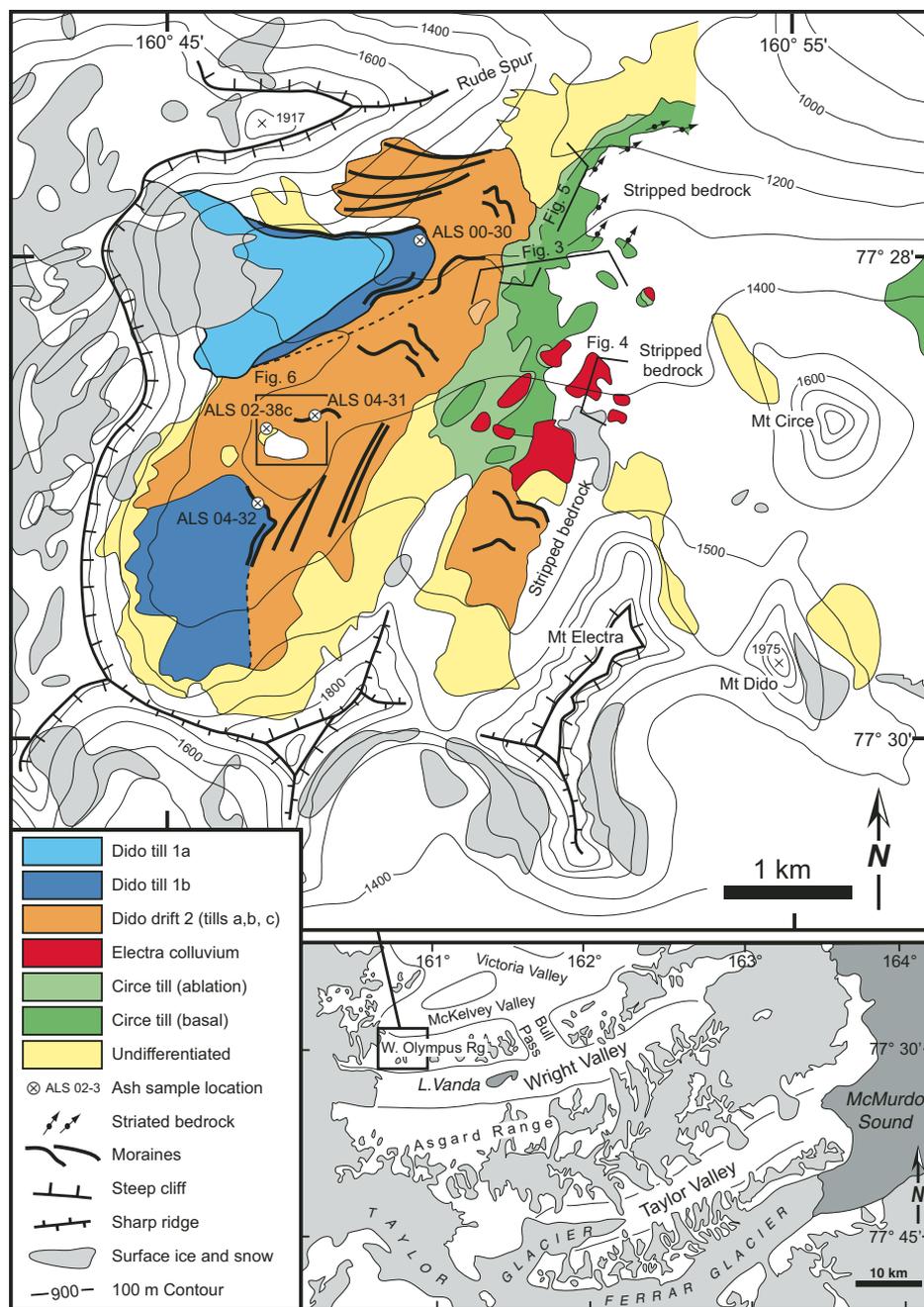


Figure 1. Glacial geologic map of Circe-Rude Valley (top) and general location map for western Olympus Range (lower right). Locations for Figures 3, 4, and 5 (shown as numbered brackets that open in the direction of view) and Figure 6 (shown as an enclosed box) are plotted.

bags. Aliquots were washed in deionized water and shard morphology was analyzed using binocular microscopes at $60\times$. Mineralogical homogeneity was assessed for each sample by visually assigning an origin (volcanic or nonvolcanic) to at least 5000 grains placed on a series of gridded slides. Individual sanidine crystals separated for $^{40}\text{Ar}/^{39}\text{Ar}$ dating were hand-picked from washed aliquots; crystal selection was made

on the basis of crystal habit, cleavage, and size. Samples were coirradiated with the Fish Canyon sanidine monitor standard in the Cd-lined in-core facility at the Oregon State reactor. Ages were calculated relative to a Fish Canyon age of 28.02 Ma (Renne et al., 1998). Single-step laser fusion $^{40}\text{Ar}/^{39}\text{Ar}$ analyses for individual grains were processed at the Lamont Doherty Earth Observatory Argon Geochronology Lab using

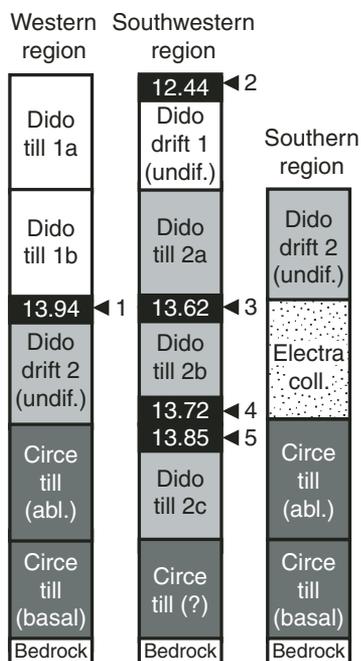


Figure 2. Generalized stratigraphy of surficial deposits in the western, southwestern, and southern regions of Circe-Rude Valley. Relative deposit thickness is not representative of deposit thickness in the field. Black triangles indicate the age and stratigraphic position of five dated ash-fall deposits. The lowermost deposit in all three areas is a wet-based till, older than 13.94 Ma, that we term the Circe till (or equivalent). A weathered, colluvial deposit, termed the Electra colluvium, that also predates 13.94 Ma (see text), overlies the Circe till in the southern region. A suite of tills deposited from cold based ice, collectively termed the Dido drift, overlies the Circe till and/or Electra colluvium. Tills within the Dido drift are subdivided into two groups: group 2 tills show significant evidence for postdepositional erosion, whereas group 1 tills lack such evidence (see text); tills within both groups are subdivided further on the basis of surface morphology, outcrop pattern, and/or superposition (undif.—undifferentiated; abl.—ablation till member).

a CO₂ laser. Analytical data for each analysis are given in Data Repository Table DR1¹. Ages were calculated from Ar isotope ratios corrected for mass discrimination, interfering nuclear reactions, procedural blanks, and atmospheric Ar contamination.

RESULTS

Circe-Rude Valley contains deposits from ancient, locally derived, wet-based glaciers (Circe till) and a younger suite of genetically related tills deposited from cold-based alpine glaciers (collectively termed the Dido drift). A weathered diamicton of nonglacial origin (Electra colluvium) separates these two broad classes of glacial deposits in stratigraphic section (Fig. 2). The distinction between the 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 (Cuffey et al., 2000) that flow by internal plastic deformation; they ablate mostly by sublimation (Bull and Carnien, 1970) and deposit loose gravel-rich tills that contain only angular clasts (Atkins et al., 2002).

Circe Till

The Circe till is 1–4 m thick and overlies striated and molded bedrock in the center of Circe-Rude Valley. Exposures form an irregular, highly dissected map pattern with small outliers dotting the valley floor (Figs. 1 and 3). Till margins terminate on weathered bedrock, showing either a steep outward-facing escarpment as much as 4 m high or a thin feathered edge that grades to an array of scattered cobbles (Fig. 3). The bedrock molding and striations below Circe till point to a gradual change in ice-flow direction downvalley, grading from N45°E on the bench northwest of Mount Circe to N65°E near the lip of the valley (Fig. 1).

Most excavations through Circe till display two prominent members: a lower, compact mud-rich diamicton, and an upper, considerably less compact, stratified diamicton with well-developed sand and gravel lenses. The basal member is as much as 2.5 m thick; it contains sandstone and dolerite clasts set within a

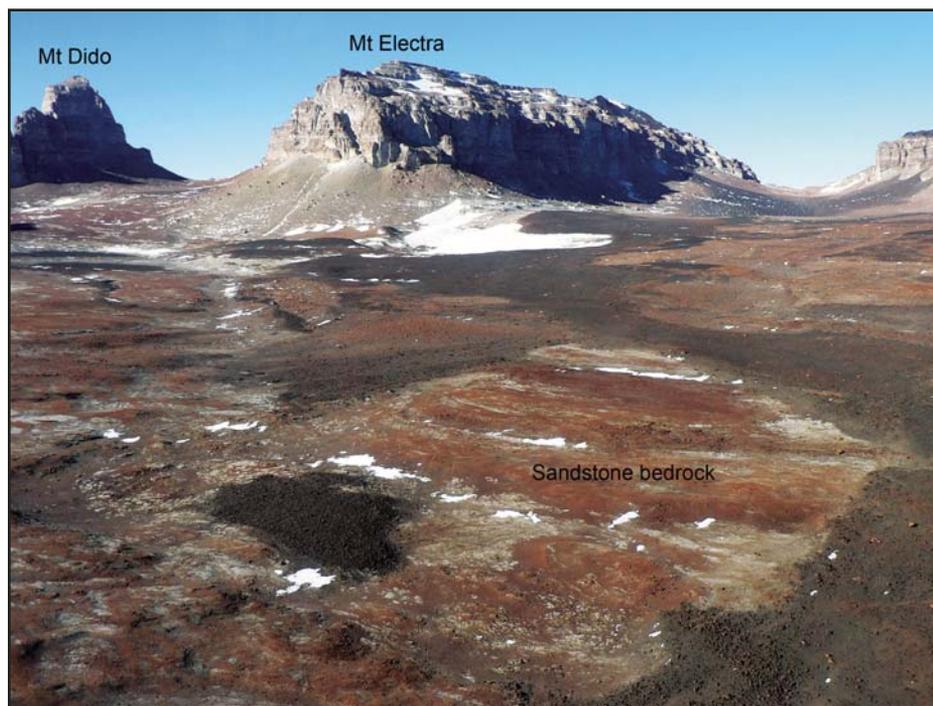


Figure 3. Oblique aerial photograph of Circe-Rude Valley; view is to the southeast (angle of view and location are depicted in Fig. 1). Scale varies in the image; foreground field of view is approximately 700 m. The light colored surfaces are exposed bedrock. Dark patches in foreground are outliers of the Circe till and/or dissected Electra colluvium. The unusual outcrop pattern of the Circe till and/or Electra colluvium, showing serrated margins and distant outliers, suggests erosion of formerly more extensive deposits. One suggested cause is basal freeze-on beneath a polythermal ice sheet that overtopped the western Olympus Range during mid-Miocene time (e.g., Denton et al., 1993). Eolian dissection alone cannot produce the observed patterns, as even boulders (>2 m in size) appear to have been removed.

¹GSA Data Repository Item 2007206, Table DR1, ⁴⁰Ar/³⁹Ar analytical data, is available at www.geosociety.org/pubs/ft2007.htm. Requests may also be sent to editing@geosociety.org.

TABLE 1. SEDIMENTOLOGICAL CHARACTERISTICS OF MAPPED DEPOSITS IN CIRCE-RUDE VALLEY

Unit	Texture (matrix <1.6 cm)			Clasts/kg of matrix (>1.6 cm)	Glacial surfaces (clasts)		Weathering characteristics (clasts)		Internal stratigraphy
	Gravel (%)	Sand (%)	Mud (%)		Molded (%)	Striated (%)	Wind abraded (%)	Stained surfaces (%)	
Dido drift 1 <i>n</i> = 14	26	71	3	21	0	0	<1	11	Unstratified and unsorted; open void spaces at depth
Dido drift 2 <i>n</i> = 31	22	75	3	19	0	0	1	7	Unstratified and unsorted; minor pockets of sorted wind- blown sand; open void spaces at depth
Electra colluvium <i>n</i> = 17	27	67	6	17	0	0	9	79	Unstratified and unsorted; clasts/kg and staining decrease with depth
Circe drift <i>n</i> = 43	10	75	15	3	34	7	0	4	Well-sorted and bedded horizons in upper ablation-till member; none in lower member

Note: Dido drift 1 includes samples from atop buried glacier ice; *n*—number.

greenish yellow muddy sand matrix (Table 1). Although spatially variable over short distances (<10 m), clast lithology matches that of underlying bedrock in Circe-Rude Valley. Most clasts are striated and many show a preferred orientation, with long axes parallel to the long-valley axis and underlying bedrock striations. The upper member of the Circe till is as much as 1.5 m thick; it contains imbricated clasts and cross-bedded sand consistent with deposition from water moving northward down the valley axis. Observed stratigraphic contacts between the upper and lower members of the Circe till are generally sharp, but in some excavations are intercalated. We found no evidence for a weathering horizon between the upper and lower members of the Circe till.

We interpret the lower member of the Circe till as a lodgment till deposited from wet-based ice. The orientation of underlying bedrock striations and the absence of far-traveled erratics suggest that the ice was of local origin, accumulating locally along the valley headwall, or possibly as a small ice cap along the spine of the range. Because the till lacks moraine ridges or other ice-marginal features, the geographic extent of the glaciation remains unknown, but it is plausible that glaciers descending from the headwall of Circe-Rude Valley may have merged with eastward-flowing valley glaciers occupying McKelvey Valley, as suggested by Prentice et al. (1998). We interpret the upper member of the Circe till as an ablation till. Its stratification implies significant modification from water, most probably derived from melting at the former ice surface. In the absence of a buried soil and/or weathering horizon separating upper and lower members, both members likely reflect deposition during a single glacial event, although the absence of a soil profile could be explained by erosion during one or

more episodes of glacial advance. Based on the radiometric age of volcanic ash deposits that stratigraphically overlie the till (see following), deposition predates 13.94 Ma.

Electra Colluvium

The Electra colluvium is an aerially restricted unit that now crops out as isolated, flat-topped mesas in the eastern half of Circe-Rude Valley (Figs. 1 and 3). Each mesa has steep margins that stand 1–3 m above Circe till and/or scoured bedrock (Fig. 4). Most mesas are 100–1000 m² in area, but one is as large as 40,000 m². Electra colluvium overlies Circe till with gradational contacts; no weathering horizons were observed between units. Field surveys indicate that the upper surfaces of all mesas have a uniform northward dip of 6–7° (Fig. 4).

The Electra colluvium is composed of highly angular dolerite clasts set within a loose matrix of coarse-grained, reddish brown sand grains and dolerite grus (Table 1). The dolerite was likely derived from erosion of a former sill of Ferrar Dolerite that once capped Mount Electra. Most of this sill is now gone from Mount Electra, but the sill still caps mountain peaks immediately to the west. Clasts within the upper 50 cm of the unit are interlocking and appear to have shattered in place from the weathering of large boulders and cobbles. Near-surface clasts show extensive modification from wind erosion and pitting. Overall, these textural and morphologic characteristics are similar to those of dissected colluvial deposits mapped in the nearby Asgard Range (Marchant et al., 1993), 15 km south of the western Olympus Range. We conclude that the Electra colluvium was most likely deposited as a colluvial sheet graded to valley walls at the southeast corner of Circe-Rude Valley, and perhaps elsewhere in

the valley. Erosional remnants closest to Mount Electra have the appearance of truncated, low-angle talus slopes (Fig. 4).

Dido Drift

Overview

The Dido drift is a collection of patchy, and in some cases overlapping, tills deposited from cold-based alpine glaciers in Circe-Rude Valley (e.g., tills 1a and 1b, as well as 2a, 2b, and 2c; see Fig. 1 and following text). Individual tills range from a single layer of isolated cobbles to widespread till sheets as much as 3 m thick. The latter are commonly grain-supported diamictons composed of loose mixtures of sand, gravel, cobbles, and angular boulders (Table 1); open void spaces occur at depths >30 cm. Moraine ridges, which also commonly display open void spaces at depth, are associated with most Dido tills. These ridges may delineate well-defined recessional sequences, or, less commonly, bound the margins of individual till sheets as terminal moraines (Figs. 1 and 5). In stratigraphic section, tills comprising the Dido drift appear as fining-upward sequences, separated by faint weathering horizons and/or in situ ashfall (Fig. 6). The local relief and morphology of Dido drift near the headwall of Circe-Rude Valley suggest that stacked tills there may reach a cumulative thickness of ~30 m. The pattern of tills in map view, as well as the spatial arrangement of terminal and recessional moraines, suggest that glaciers depositing Dido drift originated from three locations along the headwall of Circe-Rude Valley, here designated as western, southwestern, and southern regions (Fig. 1).

Western Region

Glaciers originating from the western region, where the modern glacier originates today,

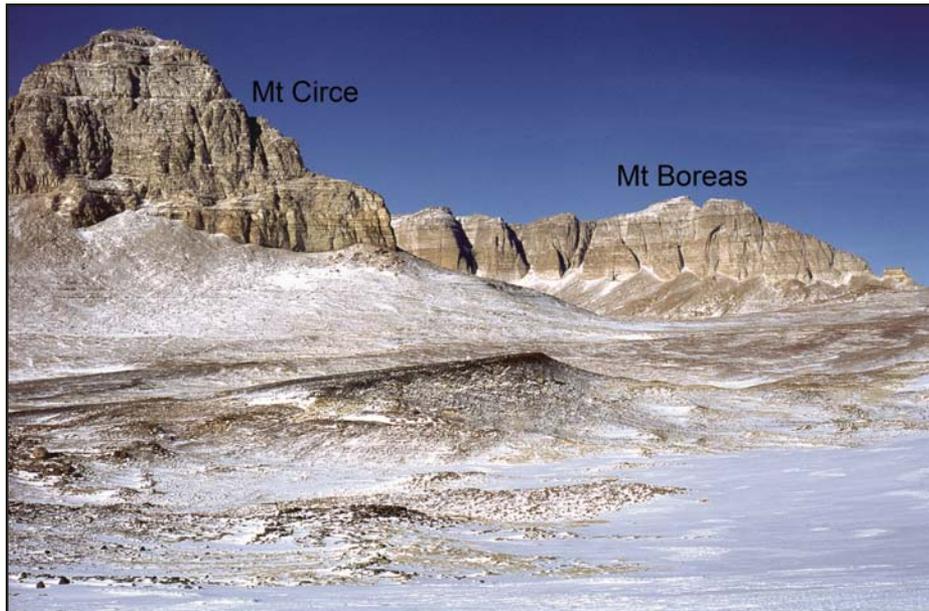


Figure 4. An upstanding remnant of the Electra colluvium; view is to the southeast (angle of view and location are depicted in Fig. 1; sloped surface of colluvium is 110 m long). The surface of Electra colluvium dips northward at $\sim 7^\circ$, away from the base of Mount Electra (not shown in photograph).



Figure 5. Composite photograph showing left-lateral moraines of Dido till 2 (undifferentiated) on the wall of Rude Spur (angle of view and location are depicted in Fig. 1; scale varies in the image, face of Rude Spur is approximately 2 km wide). Black arrows point to successive moraines, the highest of which is located ~ 350 m above the valley floor. Dido tills 1a and 1b are also visible at left.

produced at least three overlapping tills. We differentiate these tills on the basis of surface morphology and superposition. The oldest and stratigraphically lowest of these tills (Dido till 2, undifferentiated; see following and Fig. 1) extends farthest downvalley, terminating at an erosional boundary ~3.5 km from the headwall. Between ~2.5 and ~3 km from the headwall this till grades from a continuous sheet of mixed sand, gravel, cobbles, and boulders to a scattering of isolated boulders atop Circe till and weathered bedrock. A stratigraphically younger till (Dido till 1b; see following and Fig. 1) directly overlies the matrix-rich portion of this older till; it crops out as perched cobbles and boulders that collectively terminate in a well-defined loop ~2.25 km from the valley headwall (Figs. 1 and 5). The third and youngest till (Dido till 1a) overlies a core of glacier ice and terminates ~2 km from the valley headwall. The surface of this upper till, which is composed of relatively large cobbles and boulders, some surrounded by matrix sands, displays prominent contraction-crack polygons. There is no evidence for stratification or for morphologic features (e.g., thermokarst, rills, kames) that would suggest melting of subsurface ice.

Southwestern and Southern Regions

Glaciers emanating from the southwestern and the southern regions of the valley headwall deposited tills with near-identical sedimentologic characteristics, precluding clear subdivision based on map patterns, as was done for tills in the western region. Instead, the tills in the southwestern and southern regions are differentiated stratigraphically as fining-upward sedimentary packages, each bounded by planar contacts, weathering horizons, or in at least one location by a deposit of air-fall ash (ALS 04–31d; Figs. 1 and 6). The weathering horizons are extremely faint and appear as an increase in the hue of oxidized sand and grus at the contact between stacked till sheets. Moraines that mark the surfaces of tills range from upstanding boulder-capped ridges to faintly aligned surface clasts (Fig. 7).

Postdepositional Erosion

Some of the tills composing the Dido drift show evidence for significant postdepositional erosion, analogous to that observed for the Circe till and Electra colluvium, whereas others appear fully intact. Based on the presence or absence of this erosion, we subdivide the Dido drift into

two groups. The first group includes tills that lack evidence for erosion; tills in this group are Dido till 1a and Dido till 1b. These tills occur <~2 km from the valley headwall, show well-defined distal margins, and are noted as shades of blue in Figure 1. In contrast, group 2 tills, which include Dido tills 2a, 2b, and 2c, show extensive dissection, including irregular drift boundaries and enclosed basins, and are noted as a tan color in Figure 1. The enclosed basins are tens to hundreds of meters in diameter, show steep inward-facing margins, and, in places, expose weathered bedrock. Where exposed, this bedrock is entirely devoid of overlying boulders and cobbles; even the largest boulders commonly found in nearby outcrops of Dido drift are absent. The implication is that the erosive agent was capable of entraining boulders and cobbles, and so wind deflation alone cannot account for the formation of enclosed basins (see following). One particularly large basin cuts through a stratigraphic section of Dido tills 2a, 2b, and 2c, and exposes an underlying outcrop of wet-based till that is most probably correlative with the Circe till (Fig. 6).

We interpret all tills in Dido drift as being deposited from cold-based alpine glaciers that

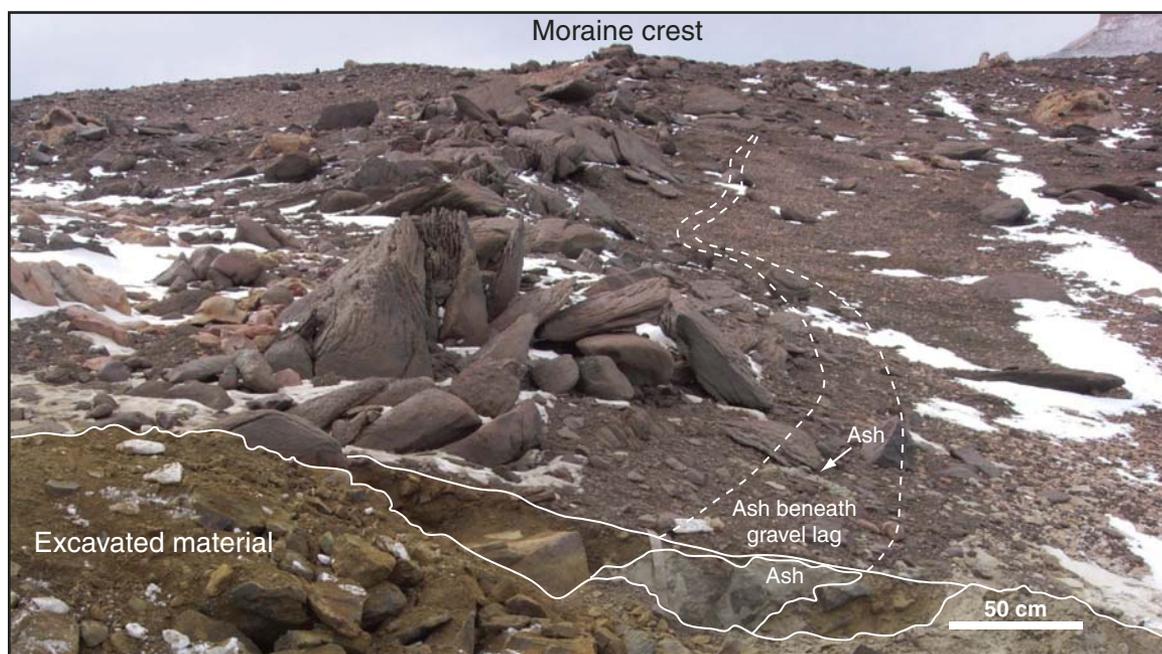


Figure 7. Photograph showing a soil excavation across the moraine ridge at the northern margin of the most prominent hollow in the southwestern section of Circe Rude Valley (see Figs. 1 and 6 for precise location). The excavation exposes a conspicuous ash layer between two diamictons. The ash layer can be traced laterally for at least 120 m. $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of 13 individual sanidine crystals from this ash layer (ALS-04-31d) yielded an age of 13.85 ± 0.3 Ma (Table 2; Table DR1 [see footnote 1]). Dido till 2c is below the ash layer and Dido till 2b is above the ash; the large dolerite boulders along the moraine crest are ~2 m in diameter and are part of Dido till 2b. The stratigraphic sequence was likely produced when cold-based alpine glaciers repeatedly terminated at or very near this location. See text for details on ash deposition.

once occupied bedrock alcoves along western, southwestern, and southern portions of Rude-Circe Valley. The stratigraphically youngest till in the western region (Dido till 1a) provides a good analog for the origin of similar, though more distal tills throughout Circe-Rude Valley. This till is today cored by glacier ice, and although no other till retains such an ice core, the preponderance of open voids at depth in all Dido tills is consistent with the loss of excess subsurface ice (i.e., ice volume > pore space) at depth. The loss of excess ice in coarse-grained deposits enables clasts to be brought together, slowly producing an intricate openwork texture with large voids. We postulate that the tills composing Dido drift were produced by sublimation of cold-based alpine glaciers containing englacial debris. The debris likely originated as rockfall onto former ice accumulation zones, just as is the case for the modern alpine glacier at the valley head today. If this scenario is correct, then tills within Dido drift are best described as sublimation tills (e.g., Schäfer et al., 2000; Marchant et al., 2002).

Chronology: Volcanic Ash Deposits

Our numerical chronology comes from $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of multiple ash-fall deposits interbedded within mapped units. Previous reports documenting the age of glacial deposits in the Dry Valleys based on $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of ash-fall deposits (e.g., Marchant et al., 1993, 2002; Sugden et al., 1995) have sparked debate (van der Wateren and Hindmarsh, 1995) primarily because exploratory results from theoretical surface-process studies appear to be inconsistent with long-term preservation of ash fall at the ground surface (Hindmarsh et al., 1998; Sletten et al., 2003; Ng et al., 2005). To help clarify the debate, we give a detailed account of the geomorphic setting, age, and location of dated ash deposits; as demonstrated here, the results suggest that active-layer cryoturbation has been largely inoperative in the western Olympus Range for at least the past 13.94 m.y., or at least it has been unable to modify the original setting of ash deposits over this duration (see also Marchant et al., 1996).

Volcanic ash deposits in Circe-Rude Valley (Fig. 1) occur in three distinct morphologies: (1) as infill within relict sand-wedge troughs and associated thermal-contraction cracks (e.g., Marchant et al., 1996, 2002); (2) as laterally extensive beds between, and within, tills; and (3) as small pods that fill voids in Dido drift.

ALS 00–30: Infill Within a Relict Sand-Wedge Deposit

Sample ALS 00-30 comes from the western region and is part of a downward-tapering wedge of ash that truncates Dido till 2 (undifferentiated

with respect to being till 2a, till 2b, or till 2c, see Fig. 1). The ash wedge is at the center of a relict sand-wedge deposit marking the former intersection of surface troughs from three contraction-crack polygons (Fig. 8). In map view, the ash deposit forms a Y shape extending ~3 m (Fig. 8); including surrounding sands, the ash deposit extends downward at least 1 m into Dido till 2 (Fig. 8).

Morphologic examination of the ash at 60× shows that individual glass shards are coarse-silt to medium-sand sized. The shards possess delicate, needle-like extensions and fragile bubble-wall vesicles (Fig. 9). The ash deposit as a whole is clean, containing <1.5% nonvolcanic contaminants. We consider these data to indicate that sample ALS 00-30 comes from in situ ash fall trapped within the intersection of three former sand-wedge troughs within polygonally patterned ground (Fig. 8). Volcanic sanidine crystals from this deposit yield an age of 13.94 Ma (Table 2; Data Repository Table DR1 [see footnote 1]) and provide a minimum age for deposition of Dido till 2 in the western region. The deposit also indicates that wet-based, local alpine glaciers have not developed in this region for at least the past 13.94 m.y.

ALS 02-38c: Ash Bed Between Wet-Based Till and Dido Drift

Sample ALS 02-38c comes from a near-horizontal bed of ash, 10–30 cm thick, that in stratigraphic section overlies a compact, stratified wet-based till (most likely correlative to Circe till) and underlies Dido till 2b in the southwestern region (Figs. 1 and 6). The bed of ash can be traced laterally for at least 15 m. Glass shards are silt- to fine-sand sized and are light gray. The bed contains <2.0% nonvolcanic contaminants. Its basal contact is sharp, but there is no evidence to suggest that the ash buried a long-exposed weathered horizon. However, its upper contact with overlying Dido till 2b is gradational, the upper 2–5 cm of the ash deposit being a mixture of volcanic grains (glass and crystals) and Dido till 2b (Fig. 6). We conclude that ALS 02-38c comes from air-fall ash that collected in a small topographic depression. Following deposition, the bed was buried beneath nonerosive, cold-based glacier ice. The radiometric dates of sanidine crystals from this deposit average 13.72 Ma (Table 2; Table DR1 [see footnote 1]) and provide a minimum age for underlying wet-based till and a maximum age for Dido till 2b (see Fig. 6 for details).

ALS 04-31d: An Ash Bed Between Two Tills in Dido Drift

Sample ALS 04-31d comes from an inclined bed of ash that in stratigraphic section is

between stacked Dido tills 2c and 2b; together the tills and intervening ash compose a portion of a prominent moraine ridge in the southwestern region of Circe-Rude Valley (Figs. 1, 6, and 7). The bed of ash, visible near the base of an excavation cut into this moraine (Figs. 6 and 7), is 20–60 cm thick; it can be traced laterally for at least 120 m along the proximal slope of the moraine (Fig. 7). The ash bed exhibits some stratification; the lower 10 cm displays a fining-upward sequence that shows shards decreasing in size from coarse sand to coarse silt. The remainder of the ash bed is generally unsorted, but, in places, cross-lamination occurs in the lee of large boulders that extend upward from underlying Dido till 2c (Fig. 6). Glass shards are angular, show intact spires, and are light gray to colorless. The concentration of nonvolcanic contaminants averages 0.8%.

Based on mineralogical homogeneity, graded bedding, and preservation of delicate features on glass shards, we interpret the lowermost few centimeters of the ash to be an in situ air-fall deposit that collected on the flank of a boulder-strewn moraine. The fine cross-laminations observed in the upper portion of the bed suggest minor drifting of air-fall ash; had the ash been reworked substantially, however, it would most likely show considerable morphologic evidence for glass-shard abrasion and a much greater percentage of nonvolcanic grains. The radiometric dates for sanidine crystals within this deposit average 13.85 Ma (Table 2; Table DR1), providing a minimum age for underlying Dido till 2c and a maximum age for overlying Dido till 2b (Fig. 6).

ALS 04-31k: An Ash Bed Within Dido Till 2b

Sample ALS 04-31k comes from a layer of ash, 1–10 cm thick, that occurs within Dido till 2b in the southwestern region of Circe-Rude Valley (Fig. 1); the layer is exposed ~2.1 m upsection from ALS 04-31d (Fig. 6). The layer of ash, which is conformable with sand and gravel layers in Dido till 2b, extends laterally for at least 2 m. Glass shards are fine- to coarse-sand sized and are dark gray. The concentration of nonvolcanic contaminants averages 3.5%. Most shards are angular. The layer of ash shows gradational contacts (spanning 1–5 cm) with bounding layers of till; upper and lower stratigraphic contacts lack evidence for weathering horizons.

The absence of a weathering horizon above or below the ash, such as that found beneath ALS-04-31d, as well as the gradational stratigraphic contacts with bounding till point to a common depositional history for both ash and till. The simplest explanation is that the ash, like surrounding Dido till 2b, was deposited directly

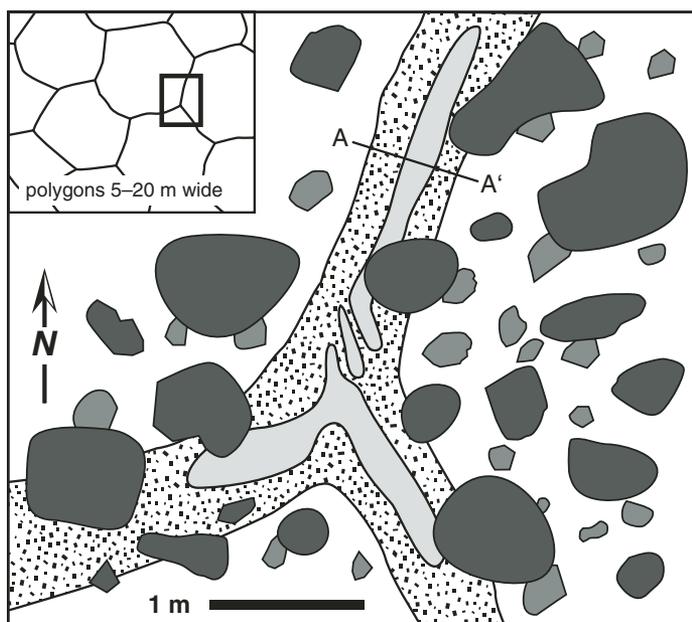
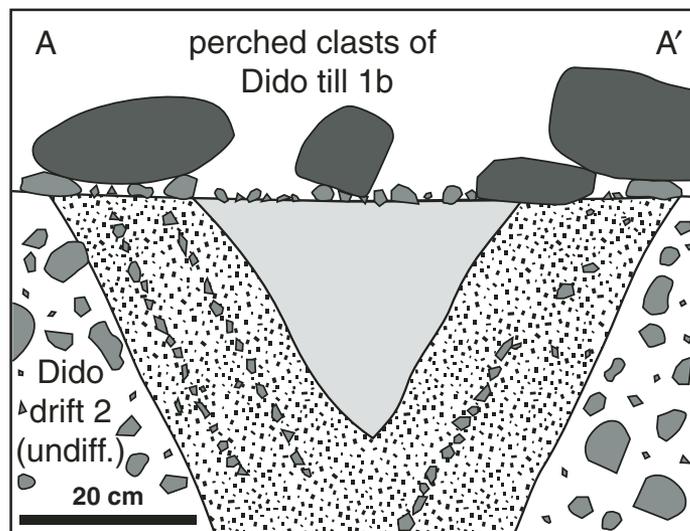


Figure 8. In situ ash fall in association with relict contraction-crack polygons. The photograph shows the intersection of three wedges of concentrated volcanic ash (white) (sample ALS 00-30, dated to 13.94 Ma) in the western region of Circe-Rude Valley (see Fig. 1 for location). Based on the morphology of the deposit, the ash was most likely deposited in troughs alongside three former polygons (see inset center panel, e.g., Marchant et al., 1996). A thin gravel layer (material that probably slumped from former trough margins) and perched clasts associated with Dido till 1b have been removed to expose the underlying ash. The white tape that is parallel with distal wedge of ash is 1.2 m. The upper right panel shows a schematic cross section (A-A') that indicates that the wedge-shaped ash deposit cuts into Dido till 2 (undifferentiated), and that perched boulders associated with Dido till 1b extend across the deposit. The sands immediately adjacent to the ash wedge are typical of relict sand-wedge polygons (e.g., Marchant et al., 1996). Overall, the deposit indicates (1) recession of glaciers to at least this location in the valley at 13.94 Ma; (2) cold, dry conditions with mean annual temperatures $< -6^{\circ}\text{C}$ at 13.94 Ma (e.g., Harry and Gozdzik, 1988; Murton, 1996); (3) minimal postdepositional reworking, such as might occur with near-surface cryoturbation and development of saturated active layers, for at least the past 13.94 m.y. (see text for details); and (4) Dido till 2 is older than 13.94 Ma and Dido till 1b is younger than 13.94 Ma.



Figure 9. Photograph of glass shards from ALS 00-30. Angular shard morphology is consistent with minimal postdepositional reworking. Evidence for chemical weathering appears minimal: glass surfaces lack evidence for hydration cracking; clay formation is very minor and found only in partially enclosed vesicles on $< 5\%$ of examined shards.

TABLE 2. $^{40}\text{Ar}/^{39}\text{Ar}$ ANALYSES OF ASH DEPOSITS FROM CIRCE-RUDE VALLEY

Sample	J		Age			MSWD	Probability	N/N _{total}
	(10 ⁻³)	±1σ	(Ma)	±1σ	±1σ [†]			
ALS 02-38c	2.6390	0.0046	13.72	0.02	0.03	0.82	0.71	23/27
ALS 04-31d	2.6145	0.0090	13.85	0.03	0.06	1.16	0.31	13/14
ALS 04-31k	2.6145	0.0090	13.62	0.09	0.10	1.48	0.13	12/14
ALS 04-31k [‡]	2.6390	0.0046	13.61	0.03	0.04	0.80	0.67	15/20
ALS 04-32	2.5993	0.0100	12.44	0.15	0.16	1.20	0.20	33/33
ALS 00-30 [§]	0.0886	0.0046	13.94	0.75	N.C.	N.C.	N.C.	N.A.

Note: Complete analytical data are given in Table DR1 (see text footnote 1). N/N_{total}—number of analyses used in calculation/total number of analyses made; MSWD—mean square of weighted deviates; N.C.—not calculated; N.A.—not applicable.

[†]Includes J parameter error.

[‡]Replicate sample collected from same ash bed analyzed separately.

[§]Because of small crystal size, results are from total fusion of ~20 crystals with cumulative weight 0.03 mg. Sample analyzed at Syracuse University Nobel Gas Isotopic Research Center. Analyses used biotite standard GA 1550 (97.9 Ma; McDougall and Harrison, 1999) and Fish Canyon sanidine standard (27.9 Ma; Steven et al., 1967; Cebula et al., 1986).

from glacier ice. If the ash landed on a former ice-accumulation zone, as we hypothesize here, then it may have been transported through the glacier for some distance before sublimation returned the ash and sediment to the glacier surface as sublimation till. In the absence of significant meltwater, slowly sublimating ice can produce tills that retain their englacial layering and sedimentology (Shaw, 1976, 1988). The ages of volcanic sanidine crystals from this layer average 13.62 Ma (Table 2; Table DR1) and provide the best date for deposition of Dido till 2b (Fig. 6).

ALS 04-32: Ash that Fills Voids in Dido Till 1b

Sample ALS 04-32 comes from the crest of a well-formed end moraine in Dido till 1b that crosses the valley floor in the southwestern region (Fig. 1). The ash occurs as a three-dimensional network of linked pods, with the margin of each pod abutting clast-supported cobbles and boulders. Individual pods average 5–20 cm³ and collectively extend to a maximum depth of ~35 cm; interconnected pods can be traced laterally for ~2 m. The ash is coarse-silt to medium-sand sized and dark gray; glass shards exhibit delicate surface features. Nonvolcanic contaminants account for 6.5% of grains. Given the clast-supported texture of the Dido drift at this locality, the pods of ash most likely represent accumulation of ash fall moving downward through open voids. The mineralogical homogeneity of the ash and the preservation of delicate spires on individual glass shards indicate that the ash has not been reworked. Given that field observations of dated moraines deposited from cold-based ice in the Dry Valleys show that voids between clast-supported cobbles generally fill with salt-cemented eolian sands shortly after deposition (i.e., tens to hundreds of thousands years at most; Marchant et al., 1994; Staiger et al., 2006), the average radiometric date for

volcanic sanidine crystals within this deposit, 12.44 Ma (Table 2; Table DR1), provides a good estimate for the timing of moraine formation at this site.

An important point to emphasize regarding the volcanic ash chronology presented here, but one that is sometimes overlooked, is that the five dated ash deposits, which occur over a relatively small region (<5 km²) and are within a succession of stacked tills, show no inversions. All ashes appear in the correct (relative) stratigraphic sequence and there is no evidence for mixed populations. This argues strongly for little to no postdepositional erosion and transport following initial ash-fall deposition.

DISCUSSION

Depositional History of Unconsolidated Deposits and the Phases of Local Glaciation

The sedimentology and stratigraphy of mapped deposits in Circe-Rude Valley, as well as the radiometric chronology afforded by $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of in situ volcanic ash deposits, indicate that prior to 13.94 Ma, Circe-Rude Valley was occupied by wet-based glaciers; these glaciers deposited the Circe till. Striations and molded bedrock beneath the Circe till indicate that ice flowed out from the valley headwall, turning eastward near the valley mouth in a flow direction consistent with the interpretation of Prentice et al. (1998) that glaciers from Circe-Rude Valley may have merged with eastward-flowing glaciers occupying McKelvey Valley. Evidence from nearshore Oligocene–early Miocene glacial records suggests a long history of wet-based glaciation in Antarctica prior to deposition of the Circe till (Barrett, 2007). Given the erosive nature of the ice that deposited the Circe till, all traces of these earlier glacial deposits, if they existed in the western Olympus Range,

must have been eroded during (or before) deposition of the Circe till.

Following deposition of the Circe till, glacier ice retreated sufficiently to enable deposition of the Electra colluvium on top of the Circe till near the valley headwall. Based on the radiometric ages of Dido drift in the western and southwestern groups (older than 13.94 and older than 13.85 Ma, respectively), and correlation among these members with the southern group of Dido drift (which overlies the Electra colluvium), the Electra colluvium is at least middle Miocene in age, predating 13.94 Ma (Fig. 2). Following deposition of the Electra colluvium, or perhaps concurrent with the latest phases of it, glaciers again extended outward from the head of Circe-Rude Valley and deposited the multiple tills composing the Dido drift. Our interpretation that the Dido drift was deposited from cold-based glaciers is based on (1) the preservation of superposed members of the Dido drift in stratigraphic section (in some cases preserving delicate weathering horizons and in situ ash fall); (2) the sedimentological characteristics of the drift, including the absence of mud-rich matrix and glacially molded clasts; and (3) the fact that the youngest till is today forming from sublimation of underlying debris-rich glacier ice. Dated deposits of volcanic ash that occur beneath Dido drift (ALS 02–38c), on top of the drift (ALS 00–30), and within the drift (ALS 04–31d, ALS 04–31k, ALS 04–32), indicate that (1) initial deposition of the Dido drift began before 13.94 Ma; (2) by 13.85 Ma, cold-based alpine glaciers had retreated from their maximums to regions about half-way down Circe-Rude Valley; and (3) by 12.44 Ma, the margin of glaciers in the southwestern region of Circe-Rude Valley had retreated an additional 1.25 km to a position just >1 km from the headwall. Although we cannot exclude the possibility of multiple advances and retreats of cold-based alpine glaciers, and in one place stratigraphic data argue for at least one readvance (Fig. 6), the overall pattern and morphology of the Dido drift are best explained by a general recession of cold-based ice through time.

Paleoclimate

Given that Circe till and Dido drift were deposited from locally derived alpine glaciers or, for Circe till, small mountain ice caps where the effects of pressure melting and strain and/or geothermal heating are minimal, the degree to which basal and/or near-surface ice undergoes melting can be used as a rough gauge of paleoclimate conditions. The glaciers that deposited Circe till underwent extensive basal and surface melting, indicating that climate conditions were warmer than those of today. To provide a rough

estimate of the degree of warmth relative to today's conditions, we offer the following argument, assuming (1) that the bedrock elevation of Circe-Rude Valley during deposition of the Circe till was comparable to that of today (e.g., 1000–1300 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 at least 0 to -5 °C, we estimate that the MAT during deposition of Circe till was 25–30 °C warmer than today.

The stratigraphic context of surficial ash deposits in Circe-Rude Valley provides additional information on paleoclimate conditions. Ash-filled sand-wedge deposits indicate hyper-arid, cold-desert conditions at the time of ash fall (Marchant et al., 1996), with a MAT of < -6 °C (Harry and Gozdzik, 1988; Murton, 1996). An important requirement of the volcanic ash chronology presented here is that the general morphology of Circe-Rude Valley was established, largely as it appears now, by at least middle Miocene time. Excluding minor surface lowering, the landscape in the immediate area of these well-preserved ash deposits must be similar to the mid-Miocene landscape. This conclusion is based on the fact that the ash deposits are situated on valley floors, are unconsolidated, and are preserved intact at or near the ground surface (Fig. 8). Any change to the macro-scale morphology of the area would cause either erosion or burial of these deposits. Moreover, given that none of the ash deposits shows the effects of cryoturbation associated with the freeze and thaw of saturated active layers, a process very common in near-surface sediments within coastal regions in the Dry Valleys today (where MAT is ~ -14 °C) and in the Arctic (Hallet and Allard, 1998), we conclude that some, if not all, near-surface soils remained dry, without well-formed saturated active layers, for at least the past 13.94 m.y. (Fig. 8). Geochemical preservation of glass shards from these Miocene-aged deposits suggests generally cold and dry soil conditions over the past 14 m.y. Shard surfaces show no evidence for hydration cracking; clays, which commonly form from chemical alteration of volcanic glass (e.g., Lowe, 1986), are conspicuously lacking (Fig. 9).

Regional Considerations

In the Transantarctic Mountains 500 km south of the Dry Valleys, evidence for wet-based glaciation, soil development, and warmer-than-present climate conditions have been described from the Neogene-aged Meyer Desert Formation in the Beardmore Glacier drainage (Mercer,

1972; McKelvey et al., 1991; Webb et al., 1996; Retallack et al., 2001). Fossil assemblages of tundra plants and animals interbedded between diamictites indicate that mean summer temperatures had to be at least 4–5 °C for two to three months of the year and MATs in the range of -8 to -12 °C (Francis and Hill, 1996; Ashworth and Thompson, 2003; Ashworth and Preece, 2003; Ashworth and Kuschel, 2003; Ashworth and Cantrill, 2004). These values are similar to the estimates of paleotemperature that resulted in wet-based glaciation and extensive surface-melting ablation zones in the western Olympus Range. Like the western Olympus Range, the transition from wet- to cold-based glaciation is recorded in the stratigraphy of the Meyer Desert Formation. At issue, however, is the proposed age of the wet-based deposits in the Beardmore region. Interbedded marine microfossils suggest a Pliocene age (Webb et al., 1996), whereas cosmogenic nuclide ages of boulders offset by faults that crosscut cold-based moraines stratigraphically younger than the wet-based Meyer Desert Formation indicate a pre-Pliocene age of older than 5 Ma (Ackert and Kurz, 2004). The similarity in the transition from wet- to cold-based glacial deposits both in the western Olympus Range and in the Beardmore region strongly suggests a shared climatic forcing. The cosmogenic nuclide estimates would not preclude a mid-Miocene age for the wet-based glacial deposits of the Meyer Desert Formation, and agree with new geomorphological data from West Antarctica indicating that the transition there took place ca. 15 Ma (Rocchi et al., 2006).

Thermal Transition in the Western Olympus Range: 17–14 Ma

The idea that wet-based glaciers first occupied the Transantarctic Mountains and later gave way to cold-based glaciation is not new (e.g., Taylor, 1922; Denton et al., 1970; Selby and Wilson, 1971). The debate has been, and continues to be, the timing and style of this transition. Our study demonstrates that in the western Olympus Range, the transition took place before 13.94 Ma. Offshore sediment records suggest that the climate of Antarctica reached a mid-Miocene climatic optimum ca. 16–17 Ma, consistent with nearshore wet-based glaciation (Hambrey et al., 2002; Barrett, 2007), and may have remained relatively warm until (and beyond) 15 Ma (Zachos et al., 2001). Conservatively, this brackets the thermal transition in the western Olympus Range to between 17 and 13.94 Ma. Questions remain, however, regarding the style of the transition, either abrupt or gradual, and the relation of the transition to variations in the volume of Antarctic ice.

Although Circe-Rude Valley lacks depositional evidence supporting major ice-volume fluctuations during the thermal transition, the widespread erosion of the Circe till, Electra colluvium, and Dido drift (all group 2 tills) is consistent with erosion beneath a polythermal ice sheet, first theorized by Denton et al. (1984) on the basis of dissected till sheets, bedrock-floored hollows, scoured drift margins, and meltwater channels in the western Dry Valleys region. According to the Denton et al. (1984) hypothesis, production and subsequent localized refreezing of subglacial meltwater beneath a thick polythermal ice sheet resulted in deep basins and hollows in otherwise coherent drift sheets, high-elevation meltwater channel systems, and elongated tongues of reworked drift (see also Marchant et al., 1993; Sugden and Denton, 2004; Denton and Sugden, 2005; Lewis et al., 2006). Given the range of elevations for these erosional features, Denton et al. (1984) (and subsequently Marchant et al., 1993; Sugden and Denton, 2004) inferred erosion beneath a thick ice sheet that engulfed all but the highest peaks in the Dry Valleys. A conservative age for the most significant and recent overriding episode in the western Dry Valleys region is between 14.8 and 12.4 Ma (Marchant et al., 1993; Margerison et al., 2005; Lewis et al., 2006). This age range is consistent with our record from the western Olympus Range, which places overriding between 12.44 and 13.62 Ma (i.e., group 1 Dido tills, which are 12.44 Ma or younger, show no evidence of dissection, but Dido till 2b, deposited at 13.62 Ma, and overlying Dido till 2a, deposited between 13.62 Ma and 12.44 Ma, both show evidence for significant postdepositional dissection from overriding ice). Given that estimates for the timing of ice overriding are generally within the period for mid-Miocene cooling (e.g., Zachos et al., 2001), it has been tempting to link ice-sheet overriding to marked global cooling. It has been unclear, however, whether sustained atmospheric cooling preceded the most significant phase of ice-sheet expansion, or whether ice expansion, through positive feedbacks, initiated (or accelerated) global cooling.

Our 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 ice-sheet expansion (here dated for the western Olympus Range to between 12.44 and 13.62 Ma). This scenario is consistent with the general notion that initial mid-Miocene ice-sheet expansion occurred as climate began to cool, but still at a time when sea-surface temperatures were relatively warm so as to provide a suitable moisture source for ice growth (e.g.,

Shevenell and Kennett, 2004; Shevenell et al., 2004; see also Prentice and Mathews, 1991). The preservation of in situ, near-surface ash fall in unconsolidated deposits in the western Olympus Range indicates that following this last major glacial event (between 12.44 and 13.62 in the western Olympus Range), the local climate never returned to the warm conditions that may have fostered initial mid-Miocene expansion of the East Antarctic Ice Sheet.

The record for mid-Miocene volcanism from the McMurdo Volcanic Group, inferred from our dated ash-fall deposits, may provide additional support for the glacial chronology presented here. The frequency of dated eruptions leading up to and following inferred East Antarctic Ice Sheet thickening exceeds the number of dated ash-fall deposits in the Dry Valleys for any subsequent 0.5–1.5 m.y. interval (see also Marchant et al., 1993, 1996). One explanation calls for intensified volcanism related to crustal loading (and unloading) from major ice-sheet expansion(s) (e.g., Slater et al., 1998; Hanyk et al., 2005).

CONCLUSIONS

Locally derived, wet-based glaciers occupied Circe-Rude Valley in the western Olympus Range prior to 13.94 Ma. During that time, local MATs may have been as much as 25–30 °C above present values. Following the last phase of wet-based glaciation (before 13.94 Ma), cold-based alpine glaciers occupied Circe-Rude Valley at 13.85 Ma or earlier (Dido till 2c); at 13.62 Ma (Dido till 2b); at some time between 13.62 and 12.44 (Dido till 2a); and at 12.44 Ma (Dido till 1b). The transition from wet-based to cold-based local glaciation in the western Olympus Range, which occurred by 13.94 Ma, reflects one, if not the most, significant climate step in Antarctica during Neogene time.

Dissection of unconsolidated sediment and bedrock within the western Olympus Range suggest scour beneath an expanded East Antarctic Ice Sheet (e.g., Denton and Sugden, 2005), dated here to an interval between 12.44 and 13.62 Ma. These results are consistent with the general notion that initial mid-Miocene ice-sheet expansion occurred at a time when sea-surface temperatures were decreasing but still relatively warm (before 14–15 Ma), but our results show that the final and most extensive expansion across the western Olympus Range followed considerable climate cooling. Atmospheric cooling inferred from the change in glacial thermal regimes implies that MATs in the western Olympus Range (1300 m elevation) may have reached near today's value of ~–30 °C before 13.94 Ma. If so, this supports isotopic

data from Southern Ocean sediment cores that register a decrease in sea-surface temperature of 6–7 °C between 14.2 and 13.8 Ma (Shevenell et al., 2004).

An important requirement of the volcanic ash chronology presented here is that the general morphology of Circe-Rude Valley was established, largely as it appears now, by at least middle Miocene time. Given that none of the surficial ash deposits show the effects of cryoturbation associated with the freeze and thaw of saturated active layers, a process very common in near-surface sediment within coastal regions in the Dry Valleys today (where MATs are ~14 °C) and in the Arctic, we conclude that most near-surface soils in Circe-Rude Valley, if not all, remained dry, without well-formed saturated active layers, for at least the past 13.94 m.y.

Our record for mid-Miocene volcanism from the McMurdo Volcanic Group, as inferred from the abundance of ash fall dated to just before and to just after ice-sheet thickening between 12.44 and 13.62 Ma, provides additional support for our glacial chronology. Intensified volcanism during this time may be related to crustal loading (and unloading) beneath major ice-sheet expansion(s).

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Erratum

Major middle Miocene global climate change: Evidence from East Antarctica and the Transarctic Mountains

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The age of ash layer ALS-04-31D in Figure 6 and in line 5 of the caption for Figure 7 should be 13.85 ± 0.03 Ma.