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Late Cenozoic Antarctic paleoclimate reconstructed from volcanic ashes in the Dry Valleys region of southern Victoria Land

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ABSTRACT

We report the discovery of numerous in situ Miocene and Pliocene airfall volcanic ashes that occur within the hyperarid Dry Valleys region of the Transantarctic Mountains in southern Victoria Land, Antarctica. Ashes that occur above 1000 m elevation rest at the ground surface, covered only by a thin ventifact pavement 1 to 2 cm thick. The ash deposits are loose and unconsolidated and show no signs of chemical weathering. Laser-fusion ^{40}Ar/^{39}Ar analyses of volcanic crystals and glass shards indicate that the ashes range from 4.33 Ma to 15.15 Ma in age. The Arena Valley ash (4.33 ± 0.07 Ma) rests on the surface of a well-developed desert pavement and ultraxerous soil profile at 1410 m elevation. Lack of geomorphic evidence of liquid water on surficial sediments coeval and older than the Arena Valley ash, together with the pristine condition of volcanic crystals and lack of authigenic clay formation, indicates a cold desert at and since 4.33 Ma. The Beacon Valley ash (10.66 ± 0.29 Ma), the Koenig Valley ash (13.65 ± 0.06 Ma), and the Nibelungen Valley ash (15.15 ± 0.02 Ma) fill the upper half of relict sand-wedge troughs that form only in cold-desert conditions. The lack of authigenic clay-sized minerals in these ash deposits, along with preservation of sharp lateral contacts with surrounding sand-and-gravel deposits, suggests that frozen conditions (without rain or well-developed active layers during summer months) have persisted in Beacon, Koenig, and Nibelungen Valleys since ash deposition. Ash-avalanche deposits that rest on rectilinear slopes contain matrix ash dated to 7.42 ± 0.31 Ma in upper Arena Valley and 11.28 ± 0.05 Ma in lower Arena Valley. Little slope development has occurred since emplacement of these ash-avalanche deposits. Such slope stability is consistent with cold-desert conditions well below 0 °C. Taken together, these ash deposits point to persistent polar conditions similar to the present at elevations above 1000 m in the western Dry Valleys region during at least the last 15.0 m.y. This conclusion contradicts the view that, during part of the Pliocene epoch, East Antarctica was largely free of glacier ice and that scrub vegetation (*Nothofagus*, Southern Beech) survived along the Transantarctic Mountain front in the Dry Valleys region and to at least lat 86°S (Webb and Harwood, 1993). Instead, it supports marine and geomorphological evidence that calls for a stable Antarctic cryosphere, much the same as today, since middle Miocene time.

INTRODUCTION

An outstanding problem in antarctic science is the development of a detailed late Cenozoic climate record. Late Cenozoic antarctic paleoclimate is based traditionally on interpretations of marine oxygen-isotope curves. Curves that show a stepwise increase in δ^{18}O values beginning ca. 40 Ma are thought to represent a decline in atmospheric temperature and an increase in ice volume on Antarctica (Shackleton and Kennett, 1975; Savin et al., 1975; Kennett, 1982; Miller et al., 1987; Kennett and Hodell, 1993). However, the discovery of in situ roots, stems, and leaves of fossil *Nothofagus* (southern beech) wood in glacial deposits (Sirius Group) in the Transantarctic Mountains (Webb and Harwood, 1987, 1991, 1993) suggested that Antarctica was quite warm until late Pliocene time. But the interpretation of these fossiliferous glacial deposits has come under considerable debate; at issue is not the existence of *Nothofagus* in Sirius Group outcrops, but whether such trees are indeed Pliocene in age as suggested by their association with biostratigraphically dated marine microfossils (Harwood, 1986; Clapperton and Sugden, 1990; Webb and Harwood, 1991; Burckle and Pokras, 1991; Sugden, 1992; Denton et al., 1993; Marchant et al., 1993a, 1993b, 1993c; Hambrey and Barrett, 1993). The purpose of this paper is to introduce a late Cenozoic paleoclimate record for the Dry Valleys region (independent from interpretations of the marine-oxygen isotope record and the Sirius Group flora and fauna) that relies on laser-fusion ^{40}Ar/^{39}Ar analyses of in situ ash deposits that occur in sand wedges (tesselations of Péwé, 1959), on ventifact pavements, and in avalanche deposits in the Dry Valleys region.

GEOGRAPHIC SETTING

The Dry Valleys represent one of the largest ice-free regions in Antarctica, covering an area of almost 4000 km^2 in the central Transantarctic Mountains (Fig. 1). The valleys are situated between the McMurdo Sound sector of the Ross Sea and the East Antarctic

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Data Repository item 9603 contains additional material related to this article.

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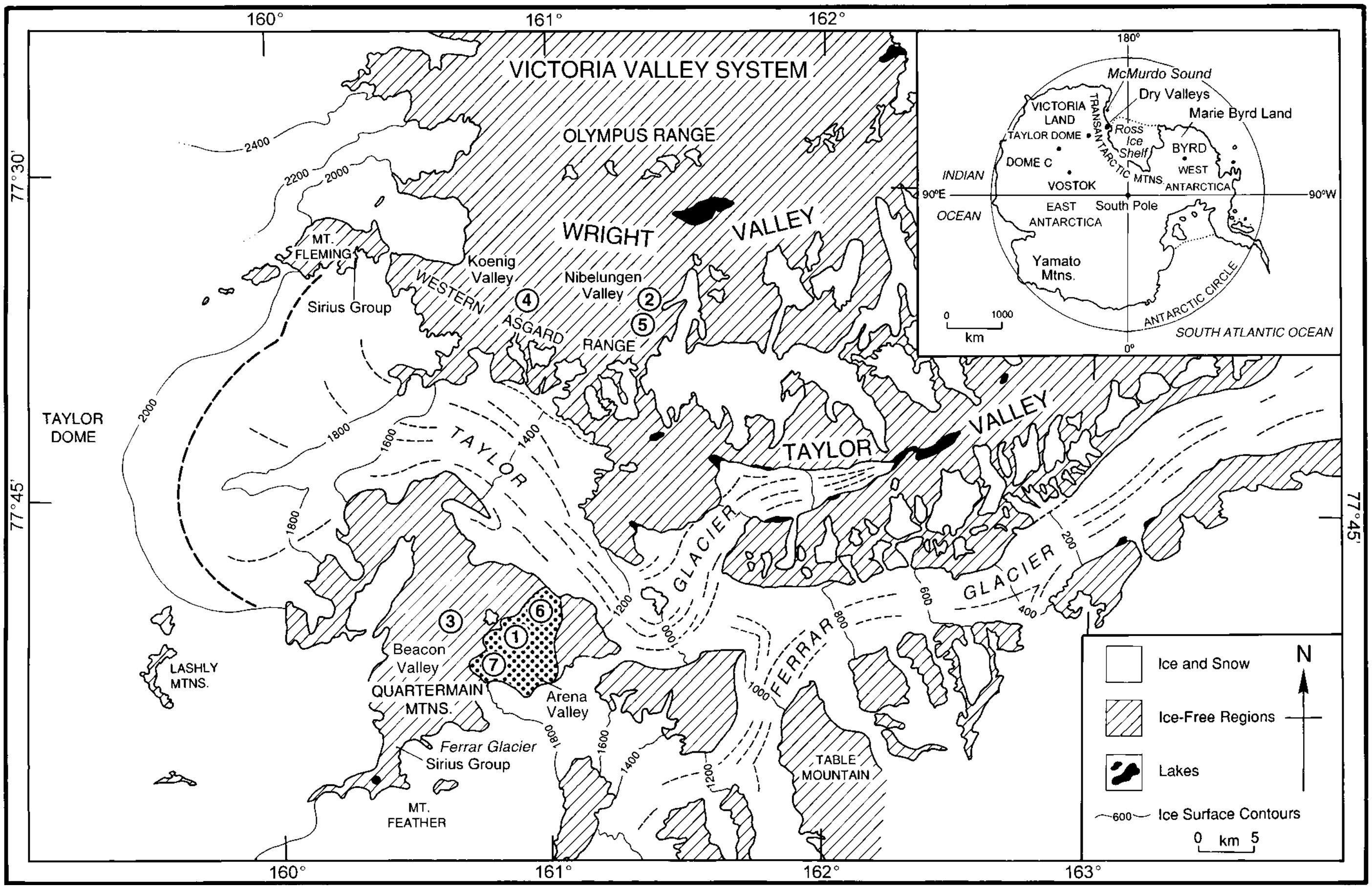

Figure 1. Location map of the Dry Valleys region of southern Victoria Land. Numbers 1–7 indicate positions of ash-fall deposits described in the text. 1, Arena Valley ash (DMS86-86B) is 4.33 ± 0.07 Ma; 2, Mount Thundergut ash (DMS90-124B) is 14.84 ± 0.28 Ma; 3, Beacon Valley ash (NPS84-327) is 10.66 ± 0.29 Ma; 4, Koenig Valley ash (DME91-41) is 13.65 ± 0.06 Ma; 5, Nibelungen Valley ash (DMS91-22) is 15.15 ± 0.02 Ma; 6, lower Arena Valley ash-avalanche deposit (DMS86-113) contains ash dated at 11.28 ± 0.05 Ma; and 7, upper Arena Valley ash-avalanche deposit (DMF86-141 and DMS86-131) contains ash dated at 6.37 ± 0.16 Ma and 7.42 ± 0.31 Ma.

Figure 2. A. Oblique aerial view looking southward into Arena Valley, Quartermain Mountains. In the background is Mount Feather, which at 2985 m elevation is the highest peak in the Quartermain Mountains. An outcrop of the Sirius Group occurs at 2650 m elevation on the northeast flank of this mountain. In the foreground are cold-based moraine loops associated with Pliocene-Pleistocene fluctuations of Taylor Glacier into lower Arena Valley (Marchant et al., 1994). Well-developed rectilinear slopes occur on valley walls (see text and Fig. 2K). B. The Arena Valley ash deposit in west-central Arena Valley (DMS86-86B). The ash is 30 cm thick and overlies a buried ventifact pavement and a weathered colluvial deposit (devoid of volcanic material). The Arena Valley ash is isotopically dated at 4.33 ± 0.07 Ma (Table 2). This ash deposit, like all other ash deposits in the Dry Valleys region, is loose and unconsolidated, contains <5% clay, and is easily scooped out by hand. C. The vertical face of the Arena Valley ash has been cut back to expose the underlying ventifact pavement. D. Active sand wedge polygons in the western Dry Valleys region; snowfall fills troughs between polygon centers. A premise of our volcanic ash dating is that during volcanic eruptions ash fall is trapped in deep thermal contraction cracks, just as snowfall is trapped in active cracks today (see text). E. Cross section cut through a relict sand-wedge trough in the western Asgard Range. Note the near-vertical stratification of the sands and gravels that fill the sand wedge. A similar sand wedge filled with volcanic ash is shown in Figure 2F. F. Cross section cut through the Beacon Valley ash deposit (NPS84-327). The ash is ~45 cm wide at the surface. Note sharp stratigraphic contacts with oxidized sands and gravels. The Beacon Valley ash is isotopically dated at 10.66 ± 0.29 Ma. G. Cross section cut through the Koenig Valley ash deposit (DME91-41). Ash (center stripe) is ~10 cm wide. Note vertically oriented ventifacts to the left of the ash wedge. The Koenig Valley ash is isotopically dated at 13.65 ± 0.06 Ma. H. Cross section cut through a relict sand wedge. Note V-shaped gravel deposit at the center of the wedge, shallow linear depression at the ground surface tracing the former wedge, and sorting across the surface of the wedge. The Nibelungen Valley ash (DMS91-22) lies banked against large gravel clasts situated below the trowel; the trowel is ~25 cm long. The Nibelungen Valley ash is isotopically dated at 15.15 ± 0.02 Ma.

polar plateau. Ice from interior East Antarctica drains north around the Dry Valleys region by MacKay Glacier and south by Mullock Glacier. Within the Dry Valleys region, deep canyons expose nearly flat-lying Devonian-to-Triassic-age Beacon Supergroup sedimentary strata and an underlying basement complex of Precambrian igneous and meta-igneous rocks. The main transverse valleys (Taylor, Wright, and Victoria System) are separated by the Asgard and Olympus Ranges and by the Quartermain Mountains (Fig. 2A). These are sandstone-and-dolerite capped mountain blocks that trend east-west and rise above 1800 m elevation. Land surfaces within these mountain blocks lack deep regolith and instead show only a thin, patchy veneer of glacial till, talus, and colluvium; sandstone bedrock crops out extensively along the floor of most of the valleys.

The Dry Valleys now feature a hyperarid, cold-desert climate. Mean annual temperature and precipitation, both recorded at ~100 m elevation in central Wright Valley, approach −20 °C and 80 mm water equivalent, respectively (Schwerdtfeger, 1984). Assuming a lapse rate of 1 °C per 100 m elevation rise (Robin, 1988), the mean annual temperature within the Asgard Range, Olympus Range, and Quartermain Mountains approaches −30 °C to −35 °C. High-velocity katabatic winds drain across intervalley mountain blocks and are channeled through deep valley troughs toward the Ross Sea. Alpine glaciers occur where wind-blown snow is concentrated in the lee of topographic highs. Because they are small and occur in a hyperarid cold-desert climate, these glaciers are frozen to underlying beds and are nearly free of debris (Meserve Glacier in Wright Valley has a basal temperature of −18 °C, Bull and Carnein, 1968). In contrast, the larger outlet glaciers can attain basal-melting conditions; portions of Taylor Glacier are wet-based (Robinson, 1984). Glaciers and snow patches lose mass predominantly by sublimation (Chinn, 1980), although some melting (<10% of ablation) occurs in places below ~1000–1400 m elevation. (Melt water occurs at progressively higher elevations toward the coast; this rise in elevation may reflect the combined effects of reduced katabatic winds, which are more persistent in the western Dry Valleys, and maritime climates toward the coast [Marchant and Denton, 1996].)

The hyperarid, cold-desert environmental conditions above 1000 m elevation in the western Dry Valleys region foster the development and preservation of sand wedges, tightly knit surface pavements with ventifacts that show extensive quartzification (Weed and Norton, 1991), and thin talus relicts unmarked by rills, channels, debris flows, and levees. It is in association with these morphologic features that most of the ashes occur in the Dry Valleys.

DRY VALLEYS ASHES

We have mapped 75 different ash deposits and dated 50 using laser-fusion ^{40}Ar/^{39}Ar techniques; seven volcanic deposits that we consider type sections for the Dry Valleys region are described below.

Ash on Buried Desert Pavements

Description. Ash-fall deposits on buried desert pavements rest conformably and with sharp planar contacts on preexisting in situ ventifacts. The basal sections of such ash deposits lack contamination, whereas the upper sections commonly show increasing amounts of detrital contamination and deformed bedding.

The Arena Valley ash (sample DMS86-86B; Fig. 2B) crops out in central Arena Valley in the Quartermain Mountains on the surface of an extensive colluvial deposit (1410 m elevation) exhibiting a well-developed desert pavement and ultraxerous soil profile (Marchant et al., 1993a, 1993b). The Arena Valley ash is ~25 cm thick and covers a circular area with a radius of ~10 m. It rests with a sharp planar contact on a well-developed in situ desert pavement formed of an interlocking mosaic of gravel-sized ventifacts (Fig. 2C). The ventifacts are commonly pitted and exhibit siliceous crusts and 5–10 mm quartz rinds, suggesting subaerial exposure in a desert environment (Weed and Norton, 1990). A similar desert pavement now overlies the Arena Valley ash and prevents wind deflation.

The Arena Valley ash includes a lower basal unit, a middle cross-bedded unit, and an upper ash-rich diamicton. The lower unit is structureless and consists of a thin lens (0.5 cm to 1.0 cm) of coarse-grained (0.5 mm to 1.0 mm) glass shards and volcanic crystals. The middle unit ranges from 5 to 10 cm thick and, in places, shows alternating cross-bedded layers of fine (0.01 mm to 0.31 mm) and very coarse-grained (0.5 mm to 2.0 mm) ash. The upper unit, ~15 cm thick, is composed of 95% ash, 3% detrital sand grains, and 2% gravel-sized ventifacts of Beacon Supergroup sandstones and Ferrar Dolerite. All units within the Arena Valley ash contain <2.5% clay-size sediment. Glass shards, which show a bimodal grain-size distribution, are angular and unweathered.

Mount Thundergut ash (sample DMS90-124B) is situated at ~1500 m elevation at the base of Thundergut Mountain in Nibelungen Valley, western Asgard Range. Unlike the Arena Valley ash, which crops out at the ground surface, Mount Thundergut ash lies buried beneath 60 cm of coarse glacial till (Nibelungen till of Marchant et al., 1993b). In stratigraphic section, the 2-cm-thick ash layer ash rests directly on a buried ventifact pavement (composed of angular, cobble-sized sandstone and dolerite clasts). Ventifacts show thick desert varnish and extensive pitting, indicating exposure in a desert environment prior to burial beneath Nibelungen till. The Mount Thundergut ash, which is concentrated in gaps and spaces between adjacent ventifacts, contains <5% clay-sized grains. The overlying till lacks volcanic ash (Marchant et al., 1993c).

Interpretation. The high concentration of volcanic ash and the lack of significant nonvolcanic contaminants in the basal portions of both the Arena Valley ash and the Mount Thundergut ash, together with the preservation of intact bubble vesicles (in glass shards) and underlying ventifact pavements, suggest primary ash-fall deposition with little, if any, postdepositional reworking. The admixture of sand grains, ventifacts, and ash in the upper unit of the Arena Valley ash suggests slight postdepositional reworking and/or penecontemporaneous slumping of adjacent colluvial deposits onto the air-fall ash; cross-bedding in the middle unit represents slight eolian transport during initial ash-fall deposition. The desert pavement overlying the Arena Valley ash probably formed by deflation of the upper unit and the resulting concentration of the enclosed ventifacts onto the ash surface. Both the Arena Valley ash and the Mount Thundergut ash are likely to represent a very small volume of the total ash fall; most of the ash was likely dispersed and transported out of the valleys by katabatic winds.

Ash in Sand-Wedge Deposits

Description. The surface of unconsolidated sediment in the western Dry Valleys region shows a complex array of sand-wedge polygons separated by deep V-shaped troughs (Fig. 2D). The polygons, which form by periodic contraction of perennially frozen ground, are similar to ice-wedge polygons of the Arctic, except that interpolygonal troughs are filled with vertically stratified sand-and-gravel deposits rather than ice (Péwé, 1959; Berg and Black, 1966; Black, 1976; Watson, 1981; Svensson, 1988). A key distinction is between active and relict sand-wedge polygons, although both types now occur in the Dry Valleys region. Active polygons show distinct surface morphology consisting of deep furrows between high-relief centers, whereas relict polygons are only recognizable in stratigraphic section as V-shaped, vertically stratified sand-and-gravel deposits (Fig. 2E). Relict polygons develop as the loci of thermal contraction of the underlying frozen ground changes over time. Such polygons, no longer associated with thermal contraction, are quickly infilled with slumped sand-and-gravel deposits, which cover and protect preexisting ash fall trapped in interpolygonal troughs. The largest active interpolygonal sand-wedge troughs in the Dry Valleys are up to 3 m deep, but most range between 30 and 90 cm deep; upstanding cobbles and boulders commonly line the margins of these active troughs. Ash fall occurs only in ~1% of examined relict sand wedges; active sand-wedge troughs lack volcanic ash. Where present, volcanic ash commonly occurs in narrow veins or within wide V-shaped wedges between oxidized sand-and-gravel layers.

The Beacon Valley ash (sample NPS84-327) crops out at 1300 m elevation at the base of a gentle slope (10°) in east-central Beacon Valley, Quartermain Mountains. The V-shaped ash deposit (~1 m^3) rests with sharp planar contacts between conformable layers of near-vertically stratified sand and gravel (Fig. 2F). The ash wedge, tapering downward, is ~45 cm thick at the surface and dips ~15° up-slope.

The Beacon Valley ash is composed predominantly of poorly sorted and angular pumice. Individual glass shards show intact bubble vesicles. The ash is bimodal, with a maximum grain size of ~1.5 mm. The Beacon Valley ash contains ~5% detrital-quartz sand grains/dolerite grus and ~1%–2% gravel ventifacts. Ventifacts occur predominantly along ash margins and show a preferred near-vertical orientation.

The Koenig Valley ash (DME91-41) crops out at 1250 m elevation in central Koenig Valley, western Asgard Range. In stratigraphic section, the deposit shows a narrow vertical stripe of unweathered volcanic ash (10 cm wide) between conformable layers of oxidized sand and gravel (Fig. 2G). The ash contains <3.0% clay-sized grains. Ventifacts occur predominantly along ash margins and show a preferred near-vertical orientation.

The Nibelungen Valley ash crops out at 1450 m elevation in upper Nibelungen Valley. The top of the ash deposit, which is situated ~3 cm below the ground surface, lies against a large upstanding cobble and is bounded on one side by oxidized sands and gravel (Fig. 2H). The ash deposit (40 cm^3) lacks nonvolcanic detritus; glass shards show intact bubble vesicles; clay-sized grains compose <4.5% of the ash deposit. In cross section, oxidized sands and gravels that border the ash form a vertically stratified, wedge-shaped deposit that tapers downward to a depth of 85 cm.

Interpretation. The high concentration of volcanic ash in the Beacon Valley, Koenig Valley, and Nibelungen Valley ashes, the intact bubble vesicles, and the sharp planar contacts with surrounding sediments all suggest primary ash-fall deposition. The overall deposit morphology (including ash wedges and adjacent stratified sand-and-gravel layers) strongly suggests that the Beacon Valley, Koenig Valley, and Nibelungen Valley ashes represent direct ash fall into active thermal-contraction cracks that have since been infilled with eolian sand and slumped ventifacts (e.g., Péwé, 1959; Berg and Black, 1966). Figures 2I and 2J show additional relict sand wedges filled with volcanic ash.

Ash-Avalanche Deposits

Two ash-avalanche deposits occur in Arena Valley in the Quartermain Mountains. Both emanate from cliffed bedrock couloirs at the heads of rectilinear slopes, are lobate in plan view, are convex in cross-profile, and contain at least 30% volcanic ash in the matrix fraction (<2.0 mm). They are similar to pumice flows first described by Kuno (1940).

The lower Arena Valley ash-avalanche deposit (sample DMS86-113) is 350 m long and 50 m wide. It occurs on the east-facing rectilinear valley wall near the mouth of Arena Valley (Fig. 2K). The deposit extends downslope from a narrow bedrock couloir at ~1650 to 1625 m elevation, overlies undifferentiated colluvium, and terminates two-thirds of the way down the valley wall at ~1100 m elevation. Lateral contacts between the avalanche deposit and adjacent colluvium are sharp and are marked by an abrupt change in surface slope. In cross profile, the central core of the avalanche deposit rises ~3 m above adjacent colluvium. The avalanche deposit thickens downslope to a maximum of slightly >1.5 m.

In hand-dug sections, the lower Arena Valley ash-avalanche deposit shows a chaotic admixture of unweathered sandstone gravel (10%), dolerite ventifacts (15%), quartz sand and dolerite grus (30%), granite erratics (<1%), and coarse-grained (1.0–1.5 mm) volcanic ash (45%); clasts show no preferred orientation (Figs. 2L and 2M). The ash is phonolitic and includes fibrous glass shards and euhedral anorthoclase crystals.

A second ash-avalanche deposit occurs on the east-facing valley wall at the head of Arena Valley (samples DMF86-141 and DMS86-131). This deposit shows multiple lobes that branch from a central tongue (200 m long and 20 m wide). The central tongue extends downslope from narrow bedrock couloirs and terminates 5 m above the bedrock floor of Arena Valley (at ~1425 m elevation); it shows an asymmetric cross profile with the steep side facing upvalley. Sandstone boulders occur at the margins of individual lobes. In stratigraphic section, the avalanche deposit exhibits a chaotic internal assortment of dolerite ventifacts and grus, quartz sand, pitted sandstone gravel, and volcanic ash (35% to 45% of the matrix fraction). It overlies eroded remnants of undifferentiated colluvium with gradational stratigraphic contacts.

Interpretation. The geomorphic setting, morphology, and poor sorting together suggest rapid emplacement of ash-avalanche deposits over preexisting colluvium. Avalanche deposits most likely originated from collapse of unstable accumulations of volcanic ash (either trapped in bedrock couloirs or resting on oversteepened valley slopes) that incorporated preexisting unconsolidated deposits. Ash-avalanche deposits in Arena Valley probably formed at or

Figure 2. (*Continued*). I and J. Cross sections cut through relict sand-wedges with volcanic ash in Beacon Valley. A single layer of surface ventifacts has been removed to show a portion of the lateral extent of each ash deposit. The ash wedge in I is 35 cm wide at the surface; ^{40}Ar/^{39}Ar analyses indicate an age of ca. 4.0 Ma. The large ash-fall deposit filling the relict sand wedge in J has an ^{40}Ar/^{39}Ar age of ca. 9.95 Ma. The high peak in the background is Mount Feather. K. Oblique aerial view of lower Arena Valley showing lobate ash-avalanche deposit on steep rectilinear valley wall. The avalanche deposit is overlain by moraines and drift associated with Pliocene-Pleistocene advances of Taylor Glacier into Arena Valley (see also Fig. 2A and Marchant et al., 1994). Note that the geomorphic form of the avalanche deposit is preserved beneath the drift. Ash within the avalanche deposit is isotopically dated at 11.28 ± 0.05 Ma (DMS86-113). L and M. Hand-dug sections cut into the lower Arena Valley ash-avalanche deposit (L) and adjacent colluvium (M). Note that clasts within the colluvium are oriented with a-axes parallel to the present surface slope; clasts within the avalanche deposit show no preferred orientation. N. Small glacier in Mount Cook National Park, New Zealand, showing dynamic surficial sediments alongside ice margins. The atmospheric 0 °C isotherm lies between the accumulation area in the background and the ablation area in the foreground. In the ablation area, valley walls show active rills, levees, debris flows, and slumps. In sharp contrast, the western Dry Valleys region lacks these morphologic features (see Fig. 2A). If the 0 °C isotherm rose from its present theoretical position in the Dry Valleys (at ∼600 m below sea level [Robin, 1988]) onto the ice sheet surface, then it seems unlikely that ashes would be preserved on steep valley slopes. Rather, preservation of the ashes strongly suggests that the 0 °C isotherm never rose up through the Dry Valleys region during at least the last 15.0 Ma. Because most glaciological models rely heavily on development of surface-melting ablation zones to remove the East Antarctic Ice Sheet, we argue that the above data suggest East Antarctic Ice Sheet stability during the last 15 m.y. (see text).

near times of volcanic eruptions because katabatic winds would have dispersed unprotected and exposed volcanic ash, and because ash probably would have become unstable and avalanched shortly after initial buildup in steep bedrock couloirs.

SOURCE AREAS

The chemical composition and grain-size distribution of Dry Valleys ashes permit identification of potential volcanic source areas. Table 1 and Figure 3 show microprobe chemical analyses and grain-size histograms of several Dry Valleys ashes. For comparison, we also show various grain-size and geochemical data of glass shards from volcanic horizons within the Byrd (Kyle et al., 1981; Palais, 1985) and Dome Circe (Kyle et al., 1981, 1982) ice cores, as well as ash from the surface ice near the Allan Hills in southern Victoria Land and near the Yamato Mountains in Queen Maud Land (Nishio et al., 1984, 1985; Katsushima et al., 1984). The Dry Valleys ashes were analyzed with a MAC 400 Microprobe using Bence and Albee (1968) corrections (using simple silicate and oxide standards), an accelerating potential of 15 kV, and a beam current of 20 nA. An internal glass standard was analyzed as an unknown to test accuracy. To minimize potential alkali loss we used a beam size of 20 μ. Figure 4 shows an SiO_2-Na_2O + K_2O diagram, which plots the composition of glass shards from several Dry Valleys ashes along with compositional fields of volcanic rocks from the McMurdo Volcanic Group, Marie Byrd Land, and the south Sandwich Islands (LeMasurier and Thomson, 1990).

Our results indicate that Dry Valleys ashes are geochemically similar to alkaline volcanic rocks found either in the McMurdo Volcanic Group (Kyle, 1990) or in Marie Byrd Land (LeMasurier and Thomson, 1990). The coarse texture and bimodal grain-size distribution of Dry Valleys ashes (Fig. 3), both of which independently suggest deposition close to volcanic regions (Carey and Sigurdsson, 1982; Fisher and Schmincke, 1984), limit potential source areas to eruptive centers in the McMurdo Volcanic Group. The McMurdo Group includes all volcanic centers within the Melbourne, Hallet, and Erebus Volcanic Provinces (Kyle, 1990); the most likely sources for the Dry Valleys ashes are the numerous alkali volcanoes of the nearby Erebus Volcanic Province. Phonolitic ashes are not the product of basaltic cinder cones that occur in central and upper Taylor Valley (McCraw, 1962; Wilch et al., 1993).

ISOTOPIC DATING

The isotopic ages of the Dry Valleys ashes were determined by laser ^{40}Ar/^{39}Ar total fusion and incremental-heating analyses of volcanic crystals and glass shards removed from individual ash deposits. Pristine euhedral volcanic crystals were handpicked from ash samples using a binocular microscope, treated with 7% hydrofluoric acid in an ultrasonic cleaner for 5 min (to remove any altered clays or attached glass), followed by 10 min in distilled water, and then irradiated in the hydraulic rabbit core of the Omega West research reactor at Los Alamos National Laboratory for 4 hr. Calculated mean ages are based on single- and multiple-crystal analyses measured on a Mass Analyzer Product 215 noble-gas mass spectrometer, calibrated with monitor minerals Fish Canyon Sanidine and MMhb-1. Summarized in Table 2, the results indicate that the ashes range in age from 4.33 Ma to 15.15 Ma (complete results are given in the GSA Data Repository[1]). We also dated glass shards from several ash deposits. In nearly all cases, the age obtained for the glass fraction was older than the age of volcanic crystals extracted from the same deposit. We attribute the older glass age to excess argon or to the mobility and subsequent loss of potassium during slight low-temperature hydration (e.g., Cerling et al., 1985). In our opinion, laser-fusion ^{40}Ar/^{39}Ar analyses of individual and multiple volcanic crystals yield the most accurate ages. Hence, we rely on crystal analyses to date individual volcanic eruptions. An important point is that each deposit is composed of a single volcanic ash; ashes of different isotopic ages are not mixed together.

DISCUSSION

The preservation of in situ, unweathered, and unaltered surficial ash-fall deposits in the western Dry Valleys region of Antarctica has important implications for paleoclimate and glacial history. Ash-

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[1] GSA Data Repository item 9603 is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

TABLE 1. MAJOR ELEMENT ANALYSES (MAC 400S MICROPROBE) OF VOLCANIC GLASS FROM DRY VALLEYS ASHES

Ash sample	Arena Valley ash DMS86-86B	Beacon Valley ash NPS84-327	Upper Avalanche deposit DMS86-131		Koenig Valley ash DMS91-41		Nibelungen Valley ash DMS91-22		Byrd Station ice core*		Dome Circe ice core[†]		Allan ash[§]		Yamato ash[§]	
N	6	5	5		6		6		21		16		12		14	
	wt%	wt%	wt%	S.D.	wt%	S.D.	wt%	S.D.	wt%	S.D.	wt%	S.D.	wt%	S.D.	wt%	S.D.
SiO_2	57.3	58.2	57.38	0.68	60.00	0.66	60.98	0.83	63.61	0.59	61.67	0.64	44.23	2.25	57.92	0.71
TiO_2	0.3	0.3	0.14	0.02	0.72	0.04	0.64	0.30	0.37	0.07	0.52	0.04	3.76	0.47	1.00	0.09
Al_2O_3	20.1	19.9	19.83	0.36	15.51	0.19	15.36	0.30	15.46	0.51	14.11	0.38	16.29	1.37	13.98	0.82
FeO**	4.3	4.5	6.24	0.11	6.96	0.34	7.25	0.05	6.81	0.91	8.79	0.36	10.19	0.78	11.03	0.44
MnO	0.3	0.2	0.42	0.03	0.38	0.02	0.40	0.03	0.20	0.03	N.A.	N.A.	0.22	0.06	0.23	0.07
MgO	0.3	0.3	0.09	0.03	0.48	0.05	0.23	0.03	0.02	0.01	0.06	0.03	4.06	1.02	2.81	0.37
CaO	1.5	1.2	0.64	0.02	0.87	0.03	1.02	0.05	0.91	1.14	1.21	0.07	9.91	2.37	7.57	0.25
Na_2O	7.9	8.7	7.23	1.3	6.71	0.37	5.67	0.49	9.65	0.22	6.58	0.76	4.29	0.86	2.71	0.25
K_2O	5.0	5.7	3.60	0.26	4.68	0.16	4.09	0.16	4.84	0.13	4.40	0.16	2.95	0.50	0.39	0.06
P_2O_5	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0.07	0.03	1.57	0.24	0.12	0.07
Cr_2O_3	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0.01	0.01	0.01	0.01
NiO	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0.03	0.03	0.05	0.05
Total	97	99	95.6	2.81	96.3	1.86	95.6	2.24	102	3.61	97.4	2.47	97.5	9.96	97.8	3.19

Note: N = number of samples analyzed; S.D. = standard deviation; N.A. = not applicable (analysis not run). Analyses of Arena Valley ash and Beacon Valley ash kindly provided by W. C. McIntosh.

*Ash layer at 1436 m depth (Tube No. 915). Data from Palais (1985).

[†] Mean of analyses from six ash layers (788 m, 1457 m, 1487 m, 1500 m, and 1711 m). Original data from Kyle et al. (1981). Adapted from Palais (1985).

[§] Data from Katsushima et al. (1984).

**Total Fe as FeO.

fall deposits, which trap and preserve the soils, sediments, and landforms on which they fall, can be used to resolve local climate conditions (temperature, soil moisture) at the ash site during ash-fall deposition. In addition, the preservation of detailed sedimentary features (bedding in the ash, sharp stratigraphic contacts, and vertically stratified sand-and-gravel deposits) suggests that ash deposits have not been overridden by wet-based, erosive glaciers. In Iceland, where ash-fall deposits drape over preexisting microrelief, the former existence of patterned ground (thufur) is recognizable in stratigraphic section because ash layers conform to the undulating paleo–land surface (Gerrard, 1985). The specific type of patterned ground, when analyzed in conjunction with soil texture and development, yields detailed information on local paleoclimatic conditions at the time of ash deposition. Tephra layers in Iceland commonly contain abundant plant roots, stems, and twigs, indicating the presence of vegetation at the time of volcanic eruption and, possibly, vegetation changes (if numerous ash-fall layers occur in stratigraphic succession). Ash-fall deposits in the Dry Valleys region lack associated vegetation, a fact that alone provides an important clue for reconstructing late Cenozoic regional paleoclimate.

Cold-Desert Ventifact Pavements

Today, ventifact pavements in the western Dry Valleys region are ubiquitous (Selby, 1971, 1974, 1985). Modern pavements, composed of interlocking sandstone and dolerite cobbles, form by deflation of fine-grained debris and the resulting concentration of coarse gravel and cobble lags at the ground surface (although other mechanisms may be additionally responsible; e.g., Cooke et al., 1993). Under the present hyperarid, cold-desert climate, ventifact pavements are highly resistant to erosion; sandstone bedrock exposed in the Dry Valleys may deflate at a rate of 3–5 m/10 m.y. (Marchant et al., 1993b, 1993c), whereas gravel-and-cobble ventifact pavements appear stable for up to 15 m.y. (Marchant et al., 1993b). This stability is due in part to the development of thick coats of protective varnish on the outer rock surface and the precipitation of secondary silica cements on sandstone clasts (quartzification of Weed and Norton, 1991). Of course, pavement stability also relies on lack of significant melt water and precipitation, both of which could wash surface pavements downslope in overland flow and/or promote extensive gullying in channelized flow. None of the modern ventifact pavements above 1000 m elevation in the western Dry Valleys region is associated with levees, channels, debris flows, mudflows, or other geomorphic evidence of liquid water.

Ancient ventifact pavements, buried by ash fall millions of years old, are identical to modern pavements of the Dry Valleys region. Buried pavements in Arena and Nibelungen Valleys show interlocking sandstone and dolerite clasts and are nowhere associated with geomorphic evidence for liquid water. We postulate that hyperarid, cold-desert conditions, similar to the present, existed in Arena and Nibelungen Valleys at 4.33 Ma and 14.84 Ma, respectively, and that such conditions have persisted up to the present time. If atmospheric temperature had warmed significantly since ash-fall deposition, then surface melt, precipitation, or cryoturbation near the ground surface would have disturbed ventifact pavements and overlying ashes (particularly the Arena Valley ash, which occurs at the present ground surface).

One can argue that the maximum potential mean annual air-temperature rise in Arena Valley during the last 4.33 m.y. was <3 °C (Marchant et al., 1993a). This temperature estimate is based in part on the modern distribution of levees, debris flows, mudflows, and channels in the Dry Valleys region; these geomorphic features, which attest to the presence of liquid water, are common below 800 m in the western Dry Valleys, where mean annual air temperatures are above −27 °C (Schwerdtfeger, 1984). The mean annual air temperature at the ash site in Arena Valley is about −30 °C (this temperature estimate for Arena Valley is based on a recorded mean annual air temperature of −19.8 °C at 123 m elevation in Wright

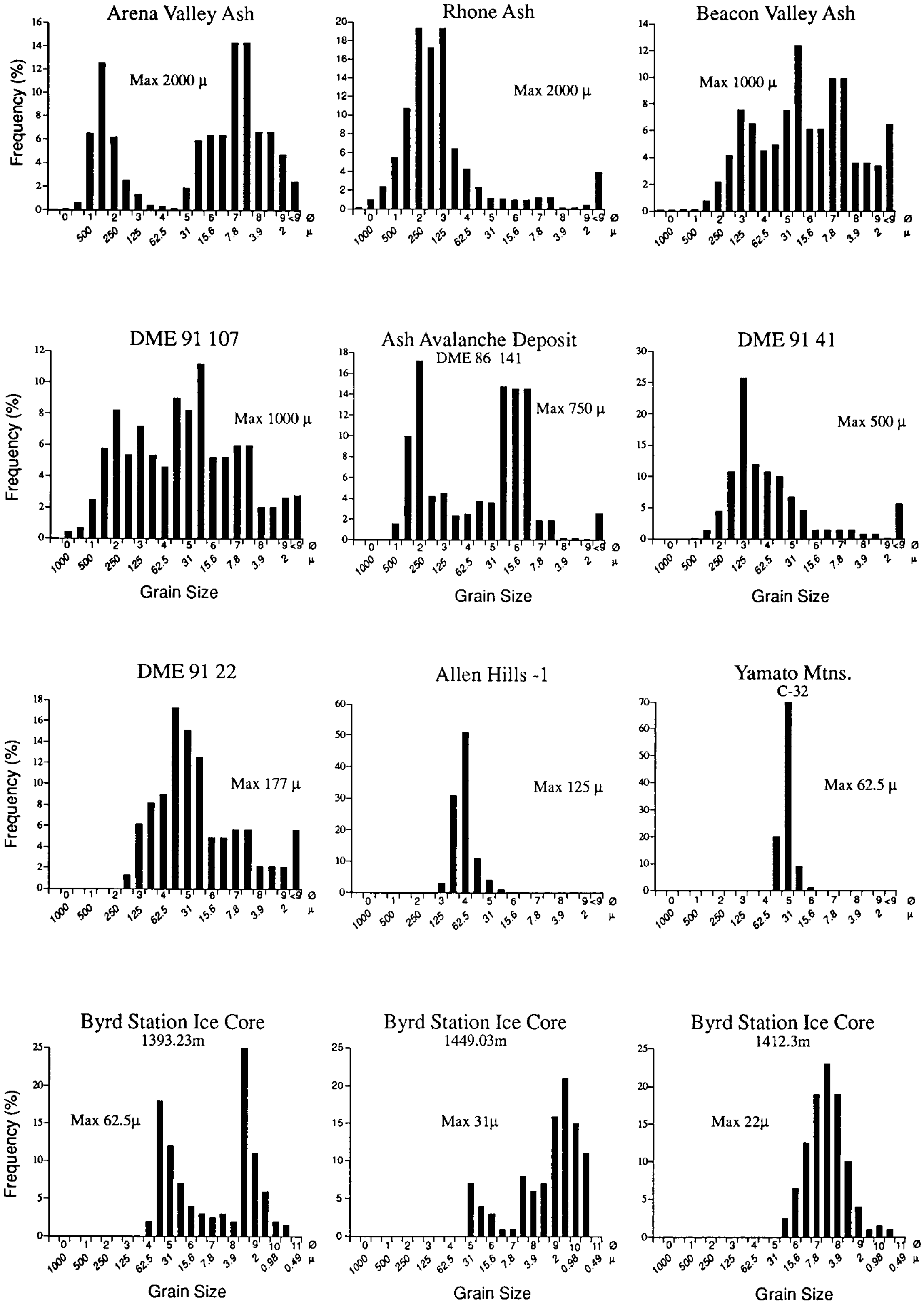

Figure 3. Grain-size distribution of selected Dry Valleys ashes. For comparison, we also show various grain-size data of glass shards from volcanic horizons within the Byrd (Palais, 1985; Kyle et al., 1981) and Dome Circe (Kyle et al., 1981, 1982) ice cores, as well as ash from the surface ice near the Allen Hills in southern Victoria Land and near the Yamato Mountains in Queen Maud Land (Nishio et al., 1984, 1985; Katsushima et al., 1984). The Rhone ash (not described in text) comes from central Taylor Valley.

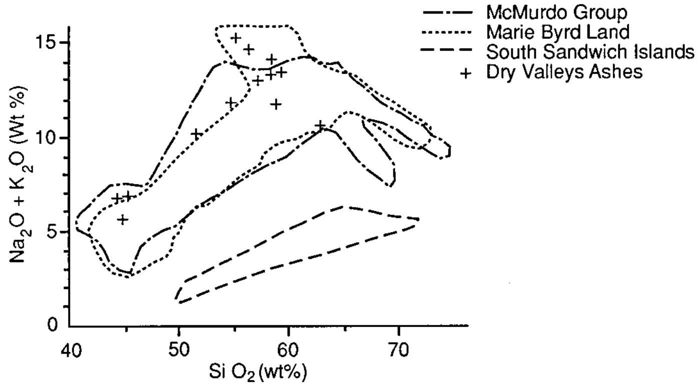

Figure 4. Summary total alkali versus silica diagram showing Dry Valleys ashes as well as compositional fields for volcanic rocks from the McMurdo Group, Marie Byrd Land, and South Sandwich Islands (adapted from LeMasurier and Thomson, 1990, p. 7).

Valley and an average lapse rate of 1 °C/100 m elevation rise; Schwerdtfeger, 1984; Fortuin and Oerlemans, 1990). The preservation of the in situ Arena Valley ash deposit, together with the lack of debris flows, levees, and channels on the surface of widespread till and colluvial deposits in Arena Valley (that are coeval and older than the ash; Marchant et al., 1993b), indicates that surficial sediments have not been modified by liquid water; hence, mean annual air temperatures in Arena Valley failed to rise above −27 °C during the last 4.3 m.y. (This estimate allows for a maximum potential air temperature rise of 3 °C in Arena Valley during the last 4.3 m.y. [Marchant et al., 1993a].) By the same argument, the maximum mean annual air temperature rise in Nibelungen Valley during the last 14.84 m.y. (at the buried ventifact site) is ~5 °C.

Sand-Wedge Deposits

Today, active sand wedges are ubiquitous morphologic forms that penetrate till, colluvium, and bedrock regolith in the Dry Valleys region (Péwé, 1959; Black, 1976). Along the coast, where mean annual air temperatures approach −14 °C (and snowfall is greater than it is inland; Schwerdtfeger, 1984), active sand wedges commonly contain conformable ice lenses. Such wedges, known as composite wedges (Black, 1976), represent a transition between traditional ice wedges, which form in humid permafrost conditions (Péwé, 1966, 1973), and sand wedges, which form only in very cold and dry continental climates (Romanovskij, 1973; Péwé, 1959; Black, 1976). Péwé (1973) argued that ice wedges in Alaska require mean annual air temperatures of −6 to −8 °C and that sand wedges are likely to form only in arid regions with high winds, no vegetation cover, and mean annual temperatures below those required for ice-wedge formation.

Ancient sand wedges, infilled with ash fall millions of years old, are identical to active sand wedges in the Dry Valleys region. The implication is that environmental conditions at the time of ash-fall deposition were similar to the hyperarid, cold-desert conditions of today. The preservation of sharp stratigraphic contacts, vertical bedding, and primary sedimentary structures in all sand wedges, along with the absence of deformation structures related to cryoturbation, suggests that hyperarid, cold-desert conditions have persisted in the Dry Valleys since middle Miocene time (15.15 Ma), the isotopic age of the oldest ash fall in a sand-wedge deposit (Nibelungen Valley ash).

Arena Valley Ash-Avalanche Deposits

Ancient ash-avalanche deposits that rest on steep hillslopes (28° to 35°) attest to long-term slope stability, with little, if any, colluviation in Arena Valley since middle Miocene time. If colluviation had occurred after ash-fall deposition, then avalanche deposits would be buried beneath younger talus/colluvium or washed downslope. In general, hillslope development in mountainous polar regions is greatest where mean annual air temperatures oscillate around the 0 °C isotherm and where precipitation is high, both of which help facilitate extensive rock degradation through freeze-thaw mechanisms. The preservation of in situ ash-avalanche deposits in Arena Valley indicates that here mean annual air temperatures failed to reach 0 °C during the last 11.28 m.y. and that precipitation

TABLE 2. SUMMARY OF LASER TOTAL FUSION $^{40}Ar/^{39}Ar$ ANALYSES OF DRY VALLEYS ASHES

Geomorphic setting	Ash deposit	Sample number	*N*	Crystal*	Glass*	Age† (Ma)
Desert pavements	Arena Valley ash	DMS-86-86B	18	Individual volcanic crystals		4.33 ± 0.07 S.D.
	Mount Thundergut ash	DMS-90-124B	4	Multiple volcanic crystals		14.84 ± 0.28 S.D.
		DMS-90-124B	5		Multiple glass shards	15.24 ± 0.08 S.D.
Sand wedges	Beacon Valley ash	NPS-84-327			Multiple glass shards	10.66 ± 0.29 S.D.
	Koenig Valley ash	DMS-91-41	5	Multiple volcanic crystals		13.65 ± 0.06 S.D.
		DMS-91-41	11		Multiple glass shards	14.75 ± 0.03 S.D.
	Nibelungen Valley ash	DMS-91-22	10	Multiple volcanic crystals		15.15 ± 0.02 S.D.
		DMS-91-22	11		Multiple glass shards	14.24 ± 0.05 S.D.
Avalanches	Lower Arena Valley ash-avalanche deposit	DMS-86-113	3	Multiple volcanic crystals		11.28 ± 0.05 S.D.
		DMS-86-113	5		Multiple glass shards	12.90 ± 0.06 S.D.
	Upper Arena Valley ash-avalanche deposit	DMF-86-141	3	Multiple volcanic crystals		6.37 ± 0.16 S.D.
		DMF-86-141	6		Multiple glass shards	7.38 ± 0.14 S.D.
		DMS-86-131	5	Multiple volcanic crystals		7.42 ± 0.31 S.D.

*The terms *multiple crystal* and *multiple glass shards* indicate that the isotopic age is based on fusion of two to four volcanic crystals or glass shards in each sample *(N)*.

†Inverse variance weighted mean; S.D., standard deviation; *N*, number of samples analyzed; a complete list of all age data is available in the GSA Data Repository (see footnote 1 in text).

was probably very low. Moreover, as neither the ash-avalanche deposits nor the adjacent colluvium on valley walls show geomorphic evidence of liquid water (rills, levees, debris flows, channels), it is likely that mean annual air temperatures in Arena Valley failed to rise above −27 °C during the last 11.28 m.y. (minimum mean annual air temperature where substantial melt water now occurs in the western Dry Valleys region; see also Fig. 2N and Marchant and Denton, 1996).

Chemical Stability of Volcanic Ashes

Volcanic glass is unstable at the ground surface and alters to clay at a rate dependent on atmospheric temperature and the abundance of pore water (rates increase at high atmospheric temperatures and high pore-water pressures; Lowe and Nelson, 1983; Lowe, 1986). For example, under humid temperate conditions in New Zealand, which are compatible with growth of *Nothofagus*, volcanic ashes older than ca. 50 000 years have weathered to >60% clay (Birrell and Pullar, 1973; Lowe et al., 1983; Lowe, 1986). The Dry Valleys ashes contain <5% clay (Fig. 3) and volcanic crystals lack evidence for chemical etching (Fig. 5). The absence of significant clay-sized grains in Miocene and Pliocene surficial ash deposits suggests that warm and wet climate conditions probably never advanced up into the western Asgard Range and the Quartermain Mountains in at least the last 15 m.y. Rather, the chemical stability of surficial ashes is consistent with persistent, hyperarid cold-desert climate (similar to the present) since middle Miocene time.

Implications for Antarctic Glacial History

Two vastly different hypotheses have been developed with regard to late Cenozoic East Antarctic Ice Sheet dynamics (see Sugden et al., 1993). The first, based on the ecology of warm-water marine diatoms and *Nothofagus* within Sirius Group glacial deposits in the Transantarctic Mountains, postulates limited ice cover in East Antarctica during much of Pliocene time (Webb et al., 1984, 1986; Webb and Harwood, 1987, 1991, 1993; Barrett et al., 1992; Hambrey and Barrett, 1993). The fundamental assumption of this hypothesis is that reworked marine diatoms within the Sirius Group originated in ocean basins in the interior of East Antarctica and were subsequently transported beneath wet-based ice to the Transantarctic Mountains (which then supported scrub *Nothofagus*) by an expanded East Antarctic Ice Sheet. In sharp contrast, the second hypothesis postulates that the present East Antarctic Ice Sheet devel-

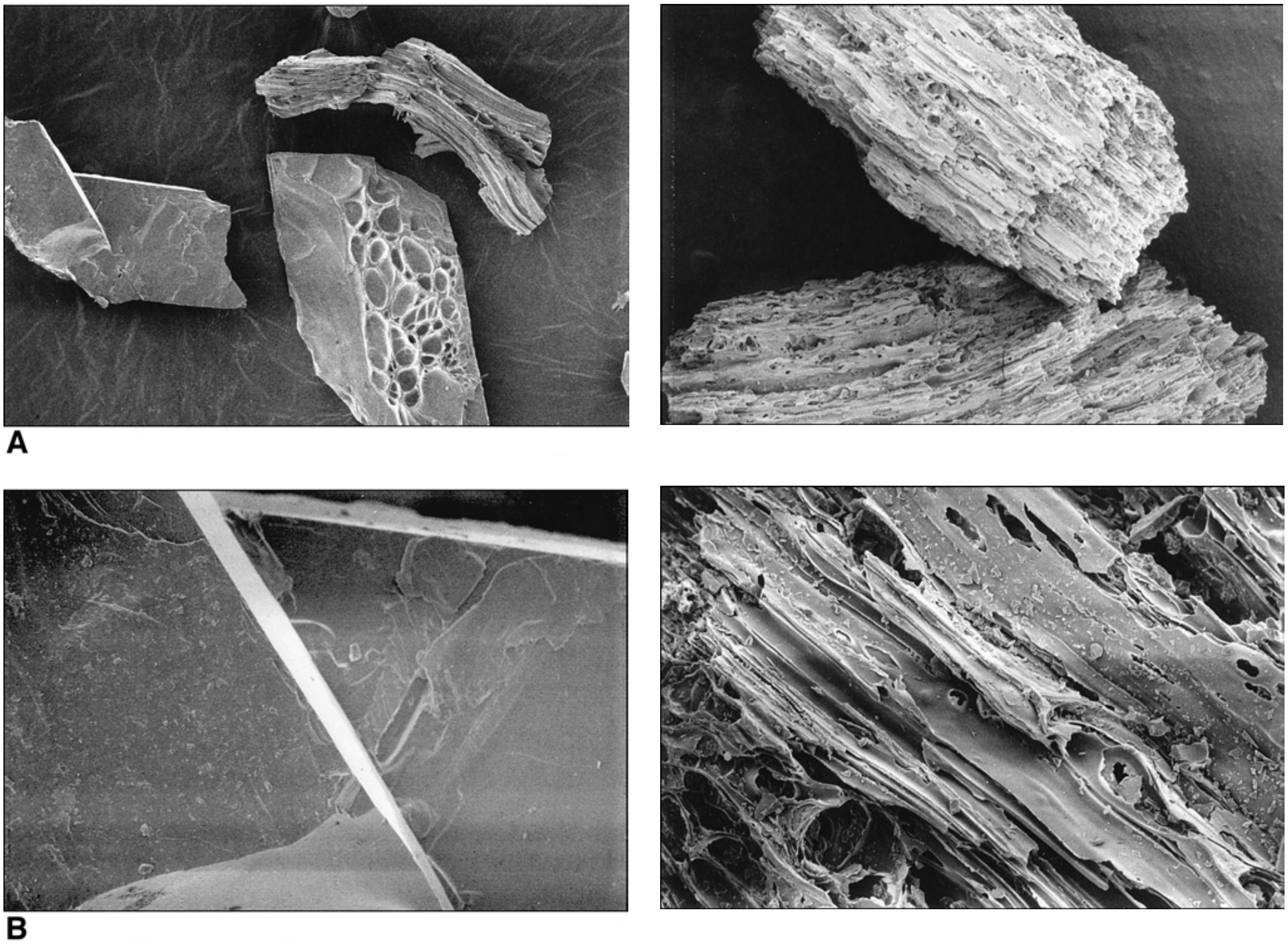

Figure 5. Scanning electron microscope images of glass shards and anorthoclase crystals from the Arena Valley ash. A and B show unweathered anorthoclase crystals and glass shards at ∼200 and 700 magnification, respectively; volcanic crystals lack evidence for chemical etching, and glass shards are not altered to clay minerals.

oped by middle Miocene time and has since been relatively stable under persistent cold-desert conditions (Shackleton and Kennett, 1975; Savin et al., 1975; Miller et al., 1987; Kennett, 1982). This latter hypothesis is based predominantly on interpretations of the marine-oxygen isotope record, although recent interpretations of the carbon isotope record, ice-rafted detritus around Antarctica, and the distribution of planktonic microfossils in the Southern Ocean also point to the climatic stability of Antarctica and an enduring East Antarctic Ice Sheet throughout Pliocene time (Kennett and Hodell, 1993). We argue here that preservation of detailed sedimentary/geomorphic features of in situ, surficial ash deposits suggests that wet-based, erosive glaciers could not have covered ash sites since volcanic deposition. The implication is that the wet-based glaciers required for deposition of the Sirius Group, which crops out well above the elevation of the Dry Valleys ashes (the Sirius Group occurs at 2650 m elevation on Mount Feather in the Quartermain Mountains [Figs. 2A and 2J] and at 2300 m elevation on Mount Flemming in the western Asgard Range), must predate the isotopic age of the oldest in situ surficial ash deposit in the western Dry Valleys region. If this is correct, then Sirius Group deposition at Mount Feather and Mount Flemming antedates 15.15 Ma. Hence our data favor the hypothesis of East Antarctic Ice Sheet stability since middle Miocene time.

Implications for Antarctic Vegetation History

The late Cenozoic vegetation history of Antarctica is based traditionally on drill-core data derived from the Deep Sea Drilling Project (DSDP) and the Dry Valley Drilling Project (DVDP). Pollen recovered from these cores, particularly from DSDP site 270, suggests that temperate forest vegetation including *Nothofagus*, and podocarpaceous conifers colonized coastal regions along the Transantarctic Mountain front in early Tertiary time (Kemp and Barrett, 1975; Hill and Truswell, 1993). Hill (1989) concluded that *Nothofagus* persisted in coastal regions in the Ross Embayment until late Oligocene, a conclusion based on the recovery of a fossil *Nothofagus* leaf between glacial beds dated as late Oligocene in the CIROS 1 drillhole in McMurdo Sound. However, fossil *Nothofagus* twigs, leaves, and stems associated with Sirius Group deposits of postulated Pliocene age (see above) in the Dominian Range (85°S, 500 km from the South Pole) and in the Dry Valleys (Taylor and Wright valleys and on Mount Feather; Webb and Harwood, 1993) call for survival of *Nothofagus* until late Pliocene/early Pleistocene time.

Is *Nothofagus* growth along the Transantarctic Mountain front until late Pliocene/early Pleistocene time consistent with our interpretation of hyperarid, cold-desert climate conditions since middle Miocene time in the Dry Valleys region? This question can be addressed by first outlining the ecological requirements of modern *Nothofagus* and then comparing these requirements to our Dry Valleys paleoclimate record. *Nothofagus*, which today does not inhabit Antarctica, has strict ecological requirements. The trees cannot survive mean annual temperatures below 5 °C or minimum temperatures below −19 °C for even a few hours. *Nothofagus* requires temperatures substantially above 0 °C to reproduce and a "plentiful supply of liquid water during summer" (Hill and Truswell, 1993, p. 71). *Nothofagus* cannot migrate long distances across salt water, and its seeds are not aerodynamic; therefore, dispersal requires land bridges (Sakai, 1981; Webb and Harwood, 1993). Mercer (1986) suggested that southernmost Chile, featuring "Magellanic tundra," represents the best modern analog for the Transantarctic Mountain front during intervals of postulated Pliocene *Nothofagus* growth and limited ice cover in East Antarctica.

In view of the paleoclimatic inferences associated with the Dry Valleys ashes and the strict ecological tolerances of modern *Nothofagus*, we argue that trees were eliminated from the Transantarctic Mountains by 15.15 Ma. Because Antarctica had separated from South America by ca. 30 Ma (Lawver et al., 1992), isolating Antarctica and permitting the development of the Circum-Antarctic Current by the Oligocene/Miocene boundary (Wright and Miller, 1993), we argue that *Nothofagus* could not recolonize Antarctica after Oligocene time even if late Miocene and/or Pliocene atmospheric temperatures in the Transantarctic Mountains had warmed appreciably. Our only explanation for *Nothofagus* twigs, leaves, and stems associated with Sirius Group deposits in the Dominion Range is that they, along with the Sirius Group, are incorrectly dated as Pliocene in age. At issue is the exact method of emplacement for marine diatoms in Sirius Group deposits. If the diatoms were emplaced by glacier ice, then it follows that the Sirius Group is late Pliocene in age (Webb and Harwood, 1993); however, if the diatoms were incorporated into Sirius Group deposits after glacial deposition (by some mechanism other than glacier ice—wind, for example), then it is possible that the Sirius Group and associated vegetation predate late Pliocene age. (For a more complete discussion, see also Burkle and Pokras, 1991; Denton et al., 1993; Marchant et al., 1993c; and Sugden et al., 1995.) On the basis of the volcanic ash data presented above, it is our opinion that the youngest Sirius Group vegetation in the central Transantarctic Mountains most likely dates to early Tertiary–late Oligocene time, consistent with the vegetation record from CIROS-1 and site DSDP 270.

Implications for Dry Valleys Landscape Development

Traditionally, the Dry Valleys landscape has been attributed to ancient glacier erosion by wet-based glaciers combined with modern salt weathering and wind deflation. Under this scenario, slow backweathering of the initial steep glacial walls produced rectilinear slopes below free faces, tentlike ridges, and residual buttes and mesas (Selby, 1971, 1974; Wilson, 1973; Denton et al., 1984; Augustinus and Selby, 1990). In fact, it has long been recognized that rectilinear slopes in the Transantarctic Mountains are not entirely the product of glacier erosion. Taylor (1914, p. 464–465) wrote that Dry Valleys slopes show "a remarkably uniform angle of ~33° . . . [that is] due less to the planation by the giant glacier-plough than to the action of King Frost" (Fig. 2A).

A problem is whether the rectilinear slopes, buttes, and mesas in the Dry Valleys region are forming today under the present cold-desert climate. Or are these morphologic forms relict, inherited from an ancient climate regime and now paralyzed under the hyperarid, cold-desert climate? The volcanic-ash data presented above strongly suggest that the Dry Valleys morphology (at least in the western Asgard Range and in the Quartermain Mountains) predates 15 Ma. As such, we argue that rectilinear slopes are not produced under the present climate and that salt-weathering and wind erosion (although effective at sculpting and fretting small-scale morphologic forms; Marchant et al., 1993c) have only slightly modified the ancient landscapes that formed prior to 15 Ma.

CONCLUSIONS

Volcanic ash-fall deposits occur within surficial sediments in the Dry Valleys region. Ashes are preserved and concentrated only when buried rapidly and protected from erosion by wind deflation. Concentrated ash deposits with little detrital contamination ($<10\%$), uniform isotopic ages and geochemical compositions, bimodal grain-size distributions, and angular glass shards with intact bubble vesicles and delicate spires represent direct ash fall from volcanic sources. Such ashes are not reworked from preexisting deposits. The chemical composition and the grain-size distribution of glass shards suggest volcanic source areas within the McMurdo Group. The most likely candidates are the numerous alkali volcanoes of the Erebus Volcanic Province.

Isotopically dated in situ ash-fall deposits afford minimum ages for the surfaces on which they rest and yield additional paleoclimatic data where associated with ventifact pavements, sand wedges, and ash-avalanche deposits. The age and stratigraphic relationship of the Arena Valley ash with an underlying desert pavement indicate that a desert climate existed in Arena Valley at 4.33 Ma. We suggest that a dry and cold climate prevailed in Arena Valley at 4.33 Ma and has persisted to the present time because surficial sediments that are coeval and older than the Arena Valley ash lack warm desert geomorphic features. The Beacon, Koenig, and Nibelungen valley ash deposits represent direct ash fall into active sand-wedge troughs. The isotopic ages of these ashes indicate that cold-desert conditions existed in their respective valleys at 10.66 Ma, 13.65 Ma, and 15.15 Ma. The inferred age and geomorphic setting of Arena Valley ash-avalanche deposits suggest that the morphologic evolution of underlying rectilinear slopes predate late Miocene time. We conclude that such slope stability (no talus development or erosion of colluvium) strongly suggests persistent cold-desert conditions in Arena Valley since 11.28 Ma. The low percentage of clay-sized grains ($<5.0\%$) in all Dry Valleys ashes indicates little chemical weathering and implies cold-desert conditions since ash deposition.

Persistent cold-desert conditions since middle Miocene time in the Dry Valleys region are inconsistent with hypotheses that call for collapse of the East Antarctic Ice Sheet from surface melting during Pliocene time, post-Miocene incursion of warm-marine waters (2–6 °C) in interior East Antarctica, Pliocene *Nothofagus* growth in the Transantarctic Mountains, and temperate glacial overriding of the Transantarctic Mountains during late Pliocene time (e.g., Webb and Harwood, 1991; McKelvey et al., 1991; Barrett et al., 1992). If our paleoclimate record is correct it implies an enduring East Antarctic Ice Sheet since middle Miocene time and makes it difficult to ascribe large-scale Pliocene sea-level fluctuations (30–40 m sea level rise) to ice-volume variations on the East Antarctic craton (e.g., Dowsett and Cronin, 1990; Krantz, 1991).

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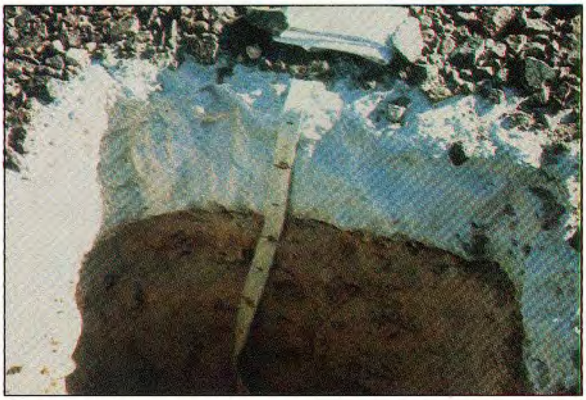

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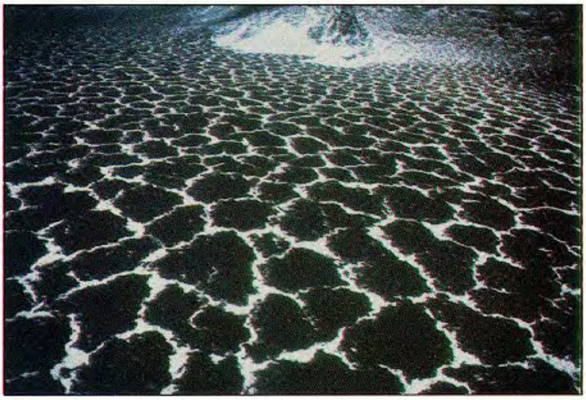

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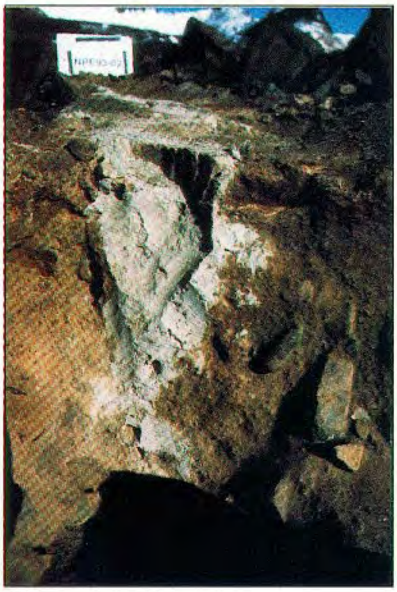

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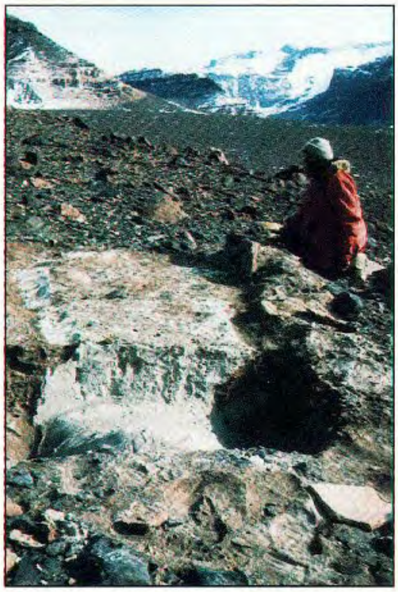

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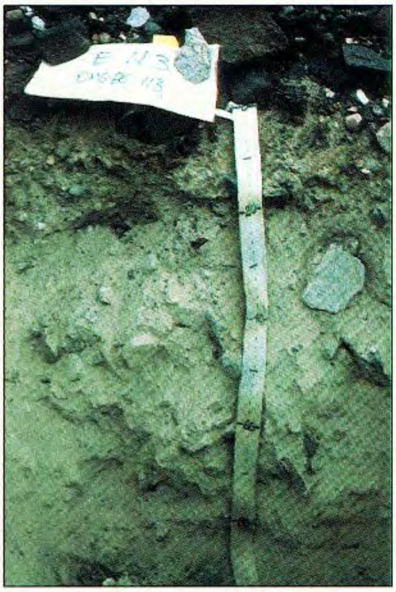

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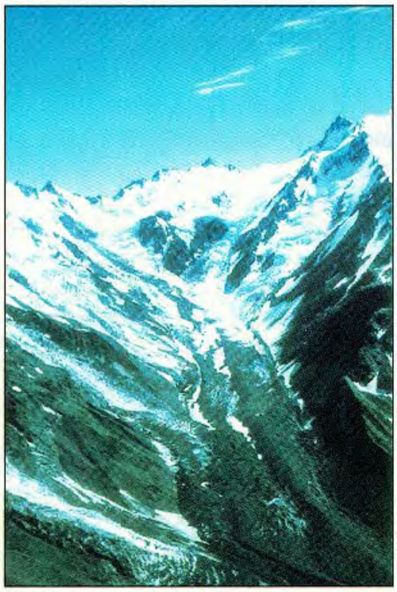

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