Glaciovolcanic evidence for a polythermal Neogene East Antarctic Ice Sheet

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ABSTRACT

A paradigm has existed for more than 30 years that the basal thermal regime of the East Antarctic Ice Sheet in Victoria Land made a fundamental transition from wet-based to cold-based either at ~14 Ma or after ~2.5 Ma. Basal thermal regime is important because it determines the potential for unstable behavior in an ice sheet, with profound implications for global sea levels. We have studied the environmental characteristics of volcanic centers scattered along 800 km of the Ross Sea flank of the Transantarctic Mountains. The volcanoes were largely erupted subglacially. They preserve evidence for the coeval paleo-ice thicknesses and contain features diagnostic of both wet-based and cold-based ice conditions. By dating the sequences we are able to demonstrate that the basal thermal regime varied with time between ~12 Ma and present. Its spatial organization was also considerably more complicated than previously inferred. It was polythermal overall and probably comprised a geographically and temporally varying coarse temperature patchwork of frozen-bed and thawed-bed ice, similar to the East Antarctic Ice Sheet today. Thus, an important shift is required in the prevailing paradigm describing its temporal evolution.

INTRODUCTION

The Neogene glacial history of Antarctica is incompletely known and inferring volume changes associated with expansions and contractions of the world's largest ice sheet relies heavily on proxy records from numerical models and drillcores (McKay et al., 2009; Pollard and DeConto, 2009; Passchier et al., 2011). Numerical models are important tools for understanding and predicting ice sheet evolution but they are unconstrained until supported by observations. Moreover, despite the abundance of information now available from drillcores, the nature and development of the basal thermal regime of the East Antarctic Ice Sheet (EAIS) is contended vigorously (Wilson, 1995; Sugden, 1996; Miller and Mabin, 1998; Armienti and Baroni, 1999; Stroeven and Kleman, 1999; van der Wateren et al., 1999; Lewis et al., 2007; Oberholzer et al., 2008). Resolving that debate is fundamental for understanding long-term ice sheet stability and EAIS contributions to sea level change (Barrett, 2013). The Neogene period includes the Mid-Miocene Climatic Optimum (~17.0-14.5 Ma), a complex stage of fluctuating $\delta^{18}O$ records suggesting a varied Antarctic ice volume, and the Mid-Miocene Climatic Transition (~14.5-13.0 Ma), commonly regarded as marking the onset of climatic cooling and ice sheet expansion when the EAIS may have acquired the cold polar (frozen-bed) glacial regime that it displays today (Lewis et al., 2007). However, it has also been suggested that warmer conditions persisted after the Mid Miocene Climatic Transition associated with extensive deglaciation. In that view, hyper-arid polar-desert conditions only became permanently established from Late Pliocene time (Wilson, 1995). The prevailing paradigm is that the change in basal thermal regime was an essentially unidirectional step-change with arguments focusing on the timing of that change. The aim of this study is to determine the basal thermal regime of Neogene ice in Victoria Land and its evolution using information associated with glaciovolcanic sequences, in order to produce a conceptual model of its thermal organization.

ICE SHEET BASAL THERMAL REGIME

Ice sheets exist in different glacial states and are classified empirically by their basal thermal regime. The basal regime is a complicated function of several variables, including precipitation, ice thickness, ambient temperature and geothermal heat flux, which vary spatially and temporally. Cold ice (also called polar, dry-based or frozen-bed) is below the melting point, frozen to its bed and moves by internal deformation; notwithstanding minor erosional modification, cold ice largely protects the underlying landscape. Warm ice (also known as temperate, wet-based or thawed-bed) is at the melting point everywhere except in a thin surface layer and moves primarily by basal sliding; it is an efficient agent of erosion and it is associated with a wide range of glacial landforms and abundant meltwater that variably reworks any tills present. Polythermal ice (also called sub-polar) is below the melting point except in a thin wet basal layer; polythermal ice thus also has a thawed bed and moves by sliding; debris entrainment and deposition can be substantial but meltwater and fluvial activity are much less well developed than for warm ice (Hambrey and Glasser, 2012). Polythermal is also used as a descriptor for an ice sheet with a basal thermal regime that is a patchwork of frozen-bed and thawed-bed ice (Kleman and Glasser, 2007). Warm and polythermal ice masses can be hard to distinguish in the geological record and are also collectively called wet-based, a convention we follow here.

Sedimentological studies can often distinguish between different thermal regimes of paleo-ice sheets (McKay et al., 2009; Passchier et al., 2011). Sedimentary outcrop is absent in Victoria Land, and other sources of information such as drillcores are few. It may also be impossible to know if sediments related to grounding events represent ice streams or outlet glaciers (generally wet-based) or inland ice, and distinguishing how geographically representative a basal thermal regime is can be difficult and uncertain (Hambrey and Glasser, 2012). Moreover, unless fresh tephras are present, dating is by generally imprecise biostratigraphy. Dating by magnetostratigraphy relies on matching magnetic polarity patterns, does not yield absolute ages and is difficult to interpret unambiguously for shallow marine sequences with multiple hiatuses. Terrestrial glacial sediments are also typically hard or impossible to date.

Conversely, glaciovolcanic sequences are formed at geographically fixed locations during eruptions beneath slow-moving inland ice (i.e. non ice-stream; Smellie et al., 2011b). Eruptions also occur in a geological instant and, uniquely, because erupted lavas resurface the slopes of the volcano, the coeval ice then interacts with each new lava surface according to its basal thermal regime. Succeeding eruptions bury earlier surfaces and protect them from further modification. The temporal evolution of the basal thermal regime can then be documented by isotopically dating the eruptive events. However, eruptions are typically infrequent and the record is low resolution by comparison with marine sediments. Although volcano-related geothermal heat might alter the climate-related basal thermal regime, the heat fluxes are largely restricted to the summit regions of volcanoes and basal ice situated on the volcano flanks will retain its climate signature (Gulick, 1998). This is confirmed by the preservation of multiple volcanic sequences in several large volcanoes in Antarctica formed under the influence of cold-based ice (Wilch and McIntosh, 2002; Smellie et al., 2011a,b).

VOLCANISM AND ERUPTIVE SETTING IN VICTORIA LAND

Volcanic rocks are widespread in Victoria Land and form numerous large shield volcanoes 1-2 km high scattered along 800 km of the Ross Sea margin of the EAIS between Cape Adare and Mt Discovery (Fig. 1). Three major volcanic areas were investigated: the Hallett Volcanic Province (10-3.8 Ma: Armienti and Baroni, 1999; Smellie et al., 2011b); the Melbourne Volcanic Province (principally Cape Washington in the Mt Melbourne Volcanic Field; 2.88-1.73 Ma: Wörner and Viereck, 1989; Gemelli, 2009); and the Erebus Volcanic Province at Minna Hook (11.8-8.0 Ma: Fargo, 2009). Although a non-glacial subaerial environment may have prevailed at times, it was atypical for the period and an overwhelmingly glacial setting during eruptions has been suggested for all three areas based on the presence of glacial sediments, striated surfaces and, most of all, environmentally diagnostic volcanic features (Wörner and Viereck, 1989; Fargo, 2009; Gemelli, 2009; Smellie et al., 2011a,b). Inferred paleo-ice thicknesses were typically < 300 m in all areas. In each center, features in the volcanic sequences known as passage zones (an indication of paleo-ice surface or ponded water level; see below) dip away radially from their known or inferred source vents and the sedimentary interbeds generally lack nonvolcanic basement-derived erratics (Smellie et al., 2011b). Thus, the associated coeval ice formed a series of prominent ice domes on the east (Ross Sea) flank of the Transantarctic Mountains and it simply draped rather than drowned the volcanoes (Smellie et al., 2011a,b). We regard the measured thicknesses as representative of the glacial cover along the eastern margin of the EAIS. Since the local climate will have been dominated by the presence of the high Transantarctic Mountains chain, the environmental information contained in the glaciovolcanic sequences will reflect that influence. The ice domes are unlikely to have been part of an expanded thick West Antarctic Ice Sheet (WAIS) since eruptions through an ice sheet thick enough to override the topography would have created volcanic sequences with sub-horizontal passage zone surfaces rather than the dipping passage zones observed. Moreover, although an expanded WAIS would have compressed paleo-ice flow lines of EAIS outlet glaciers closer to the Transantarctic Mountains front, the volcanoes would have deflected the north-flowing ice around their eastern margins and thus prevent any significant direct contact with the WAIS (Talarico and Sandroni, 2010). Sequences at Minna Hook, Coulman Island and Cape Adare also contain rare prominent laterally extensive erosional unconformities associated with glacial sediments containing a variable proportion of nonvolcanic basement clasts. This suggests that the volcanoes were occasionally overridden by much thicker regional ice. An alternative origin for the volcanic sequences, as products of eruptions into the sea, is excluded. There are no interbedded marine sediments, and passage zones in the volcanic strata dipping radially away from their source vents is a feature diagnostic of glaciovolcanic eruptions; effusion into the sea would create horizontal passage zones (Smellie et al., 2011b, fig. 4).

The volcanic outcrops are dominated by ‘a‘ā lava-fed deltas (the commonest sequence type), and sheet-like sequences (Smellie et al., 2011a, 2013). ’A’ā lava-fed deltas are wedge-like prisms of volcanic rocks that form when subaerial ‘a‘ā lava advances into pooled water (Smellie et al., 2013). They are divided structurally into subaerial ‘a‘ā lava topsets overlying chaotic or crudely stratified water-lain hyaloclastite breccia foresets; the lavas and hyaloclastite are separated by a broadly planar surface called a passage zone that is a proxy for the water level or ice surface coeval with eruption and whose characteristics are diagnostic of eruptive setting (Smellie, 2006). Sheet-like sequences comprise relatively thick (tens of meters) mafic or felsic lava and hyaloclastite overlying thinner sedimentary beds, typically diamictite, conglomerate and/or sandstone (Smellie, 2008). The modes of formation of these and other glaciovolcanic sequences and how they can be used to deduce parameters of associated ice, such as basal thermal regime and ice thickness, are well known and numerous examples have been published (Smellie and Skilling, 1994; Smellie, 2006, 2008;

Wilch and McIntosh, 2007; Smellie et al., 2009, 2011a,b, 2013; Edwards et al., 2011). For example, syn-eruptive variations in passage zone elevation together with evidence from the morphology of underlying bedrock surfaces and presence or absence of glacial and fluvial sediments can be used to deduce the thermal regime, whereas the thickness of subaqueous volcanic lithofacies produced during a single eruption is a good proxy for ice thickness.

GLACIOVOLCANIC SEQUENCES AND EVIDENCE FOR BASAL THERMAL REGIME

Glacial features observed in Victoria Land volcanic sequences include sharp eroded surfaces that are polished, striated or molded (fig. 2 in Data repository). The surfaces are overlain locally by massive diamictite with clasts that may be abraded, facetted and/or striated. Some deposits show trails of angular clasts and pervasive low-angle jointing indicative of shearing characteristic of basal tills. Stratified volcaniclastic beds up to a few meters thick commonly overlie the diamictites and are formed of juvenile vitroclastic detritus deposited from flowing water (i.e. they are fluvial). The associated ice was thus not frozen to its bed when the sediments were emplaced. These features are ubiquitous associated with ‘a‘ā lava-fed deltas at Minna Hook and much less common sheet-like sequences in northern Victoria Land. The ice was erosive and the presence of fluvial beds indicates that meltwater flowed at the ice:bed interface as a sheet or in tunnels. A wet-based thermal regime is indicated. The fluvial deposits are mainly monomict, composed of juvenile glassy clasts. They are thus syn-eruptive. Conversely, polymict fluvial deposits formed by erosion of lithified pre-existing sequences are rare suggesting that meltwater was generated mainly during the eruptive episodes and it was otherwise relatively scarce. Therefore, the basal thermal regime may have been polythermal, rather than warm. Such an interpretation for the Minna Hook volcanics, at least, is supported by interpretations of marine sediments of the same age recovered in drillcore nearby in McMurdo Sound (McKay et al., 2009).

The widespread lava-fed delta sequences in the Hallett Volcanic Province and at Cape Washington differ from those at Minna Hook. For example, the surfaces between the individual Hallett and Melbourne deltas are essentially uneroded; they also lack fluvial sediments and diamict; and they are rough on a scale of a few decimeters, characterized by essentially unmodified ‘a‘ā lava rubble (clinkers; fig. 2b in Data repository). However, with their passage zones dipping radially away from their source vents, they were also demonstrably glacially emplaced (Smellie et al., 2011a). The absence of diamicts (tills), fluvial sediments and glacially eroded surfaces in a glacial setting suggests mean annual temperatures < 0°C and an essentially protective ice cover frozen to its bed, i.e. a cold-based thermal regime (Smellie et al., 2011b). An alternative hypothesis, that the volcanic strata are the products of numerous eruptions over a short space of time in which erosion by ice was insufficient to leave an imprint, is unlikely as a general explanation. The erosion rates of wet-based glaciers are typically millimeters per year (Hallet et al., 1996) and will rapidly leave a record. $^{40}Ar/^{39}Ar$ dating also suggests that ample time was available between eruptions (Fargo, 2009; Gemelli, 2009; Smellie et al., 2011a,b).

DISCUSSION

The Victoria Land sequences show evidence for basal regime from multiple successive eruptions. Moreover, the sequences reflect inland ice (i.e. non-ice-stream) basal conditions. Thus, any ambiguity caused by including data for ice streams or outlet glaciers is removed. Moreover, the sequences are of similar thickness and extend over similar vertical intervals (mostly ~500-600 m, each composed of products of several eruptions) thus excluding any topographic influence on basal regime variability (Stroeven and Kleman, 1999). The observed differences in thermal regime are therefore likely to be real. Our results are summarized in Figure 2 (see also tables 1 and 2 in Data repository). They are consistent with those of marine sedimentary investigations of drillcores for the same time period that show a much coarser pattern of alternating thermal regimes within a broadly progressive change from wet-based to cold-based ice in younger strata (McKay et al., 2009; Passchier et al., 2011; Fig. 2). Taken together with those studies, we are now able to document the recurrence of wet-based ice within the Miocene on multiple occasions and at multiple localities scattered within a zone 800 km in length. The new glaciovolcanic data suggest that between ~12 and 9 Ma, wet-based ice prevailed at Minna Hook whereas cold-based ice conditions occurred during the same period (at ~10 Ma) in the Hallett Volcanic Province. After ~8 Ma, periods of wet-based ice were present but uncommon within a generally cold-based regime in the Hallett Volcanic Province and Melbourne Volcanic Field. The results clearly conflict with the prevailing paradigm of a single step-wise change from wet-based to cold-based ice. Instead we suggest that, rather than the entire ice sheet switching between thermal regimes through time, the bed of the Neogene EAIS at any time was probably a patchwork or mosaic of variably deforming ice with different basal regimes, i.e. a polythermal ice sheet. Whilst our interpretation applies to Victoria Land, it is likely that it can also be extended to the rest of the EAIS, similar to how thermal regime in the present EAIS is now envisaged (Pattyn, 2010; Kleman and Glasser, 2012). Stroeven and Kleman (1999) also argued for a polythermal Neogene EAIS in Victoria Land based on theoretical grounds and observations in Scandinavia applied to a high-relief terrain, but their model relies on the presence of a very thick, topography-drowning EAIS that is unlike the much thinner glacial cover that our evidence indicates existed for much of the period (Smellie et al., 2011b).

Our study also potentially provides a powerful first-order explanation for the conflicting and currently irreconcilable results of published surface exposure and landscape evolution studies in Victoria Land, which suggested a widely varying timing for the supposed step-change transition to a cold-based ice sheet (i.e. at ~14 Ma: Lewis et al., 2007; between 8.2 and 7.5 Ma: Armienti and Baroni, 1999; prior to 3.5 Ma: Oberholzer et al., 2008; or after ~2.5 Ma: van der Wateren et al., 1999). Under our new hypothesis, the apparent occurrence of wet-based conditions at different times in different places may simply reflect the presence of geographically limited and possibly transient patches of wet-based ice within an overarching polythermal (temperature mosaic) basal thermal regime. The geographical mix of thermal regimes suggested by the sedimentary and, particularly, glaciovolcanic studies will make the dynamics of the Neogene (and present-day) EAIS difficult to model successfully. However, our study shows that glaciovolcanic records in Antarctica have the potential to enhance significantly our understanding of Neogene EAIS development.

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FIGURE CAPTIONS

Figure 1. Locations of glaciovolcanic centers studied in Antarctica. MZS – Mario Zuchelli Station (Italy); MCM – McMurdo Station (USA).

Figure 2. Summary diagram illustrating variations in basal thermal regime over time in Victoria Land based on information derived from glaciovolcanic and sedimentary sequences. Error ranges for most data points are within the size of the depicted symbol or are shown as vertical lines. Sources for sedimentary sequences: CRP1-3 (Barrett, 2007); AND-1B (McKay et al., 2009); AND-2A (Passchier et al., 2011).

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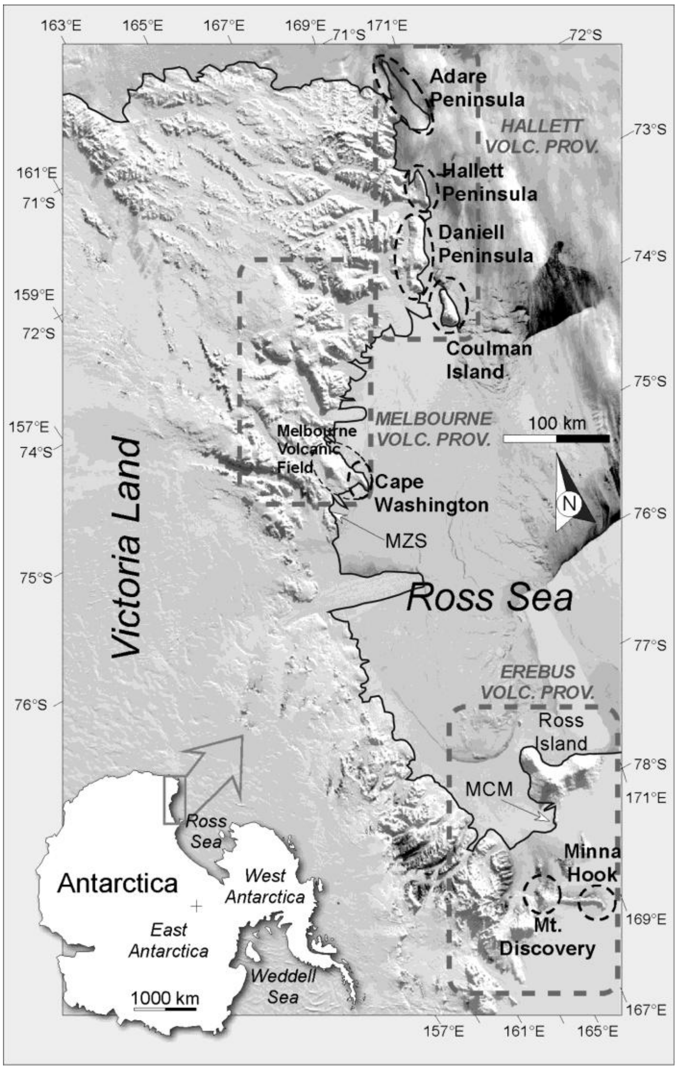

Figure 1

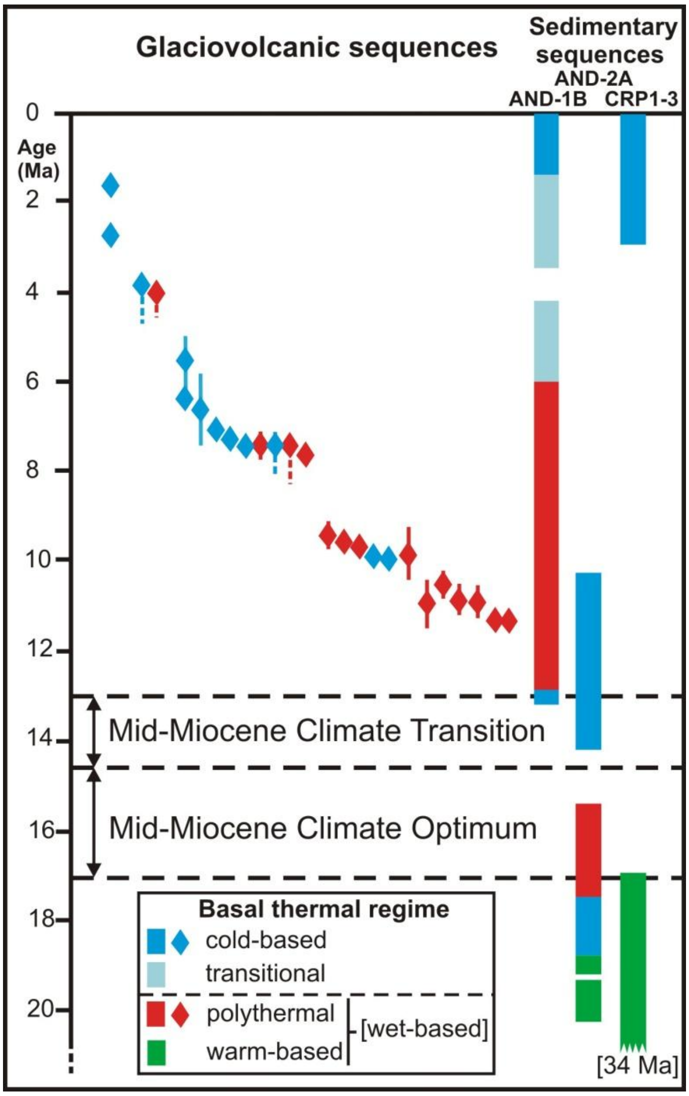
Glaciovolcanic sequences
Sedimentary sequences
AND-2A
AND-1B
CRP1-3
Age (Ma)
0
2
4
6
8
10
12
14
16
18
20
Mid-Miocene Climate Transition
Mid-Miocene Climate Optimum
Basal thermal regime
cold-based
transitional
polythermal
warm-based
[wet-based]
[34 Ma]

Figure 2

Supplementary Information for:

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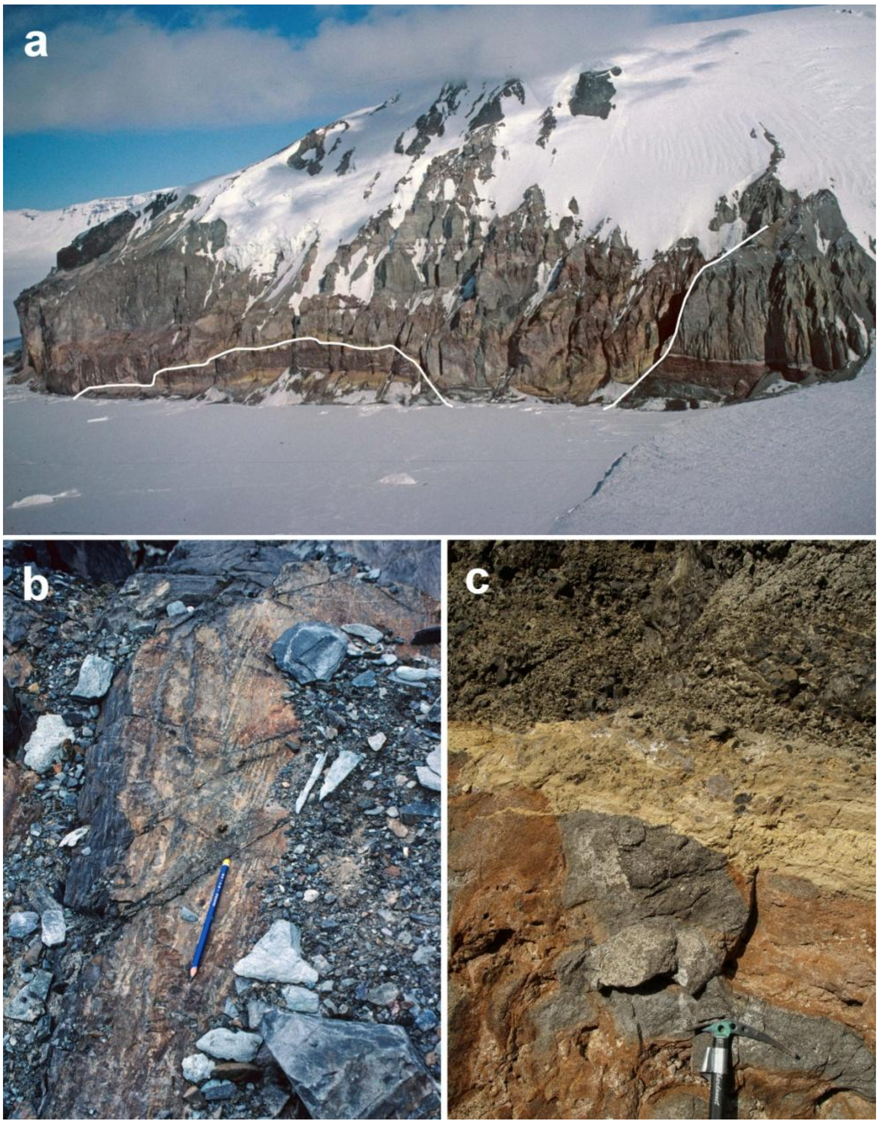

Figure 1. Glaciovolcanic sequences and related features indicative of the basal thermal regime of the EAIS in Victoria Land. 1. Wet-based ice features: (a) prominent erosional unconformity in felsic sheet-like sequences at northern Mandible Cirque, Daniell Peninsula; sequence is ~600 m thick; (b) striated metamorphic basement surface underlying volcaniclastic rocks, west of Hallett Peninsula; striations parallel to pencil; (c) cross section through sharp erosional surface truncating mafic lava pillow (grey) overlain by yellow fluvial sandstones and grey hyaloclastite breccia at Minna Hook.

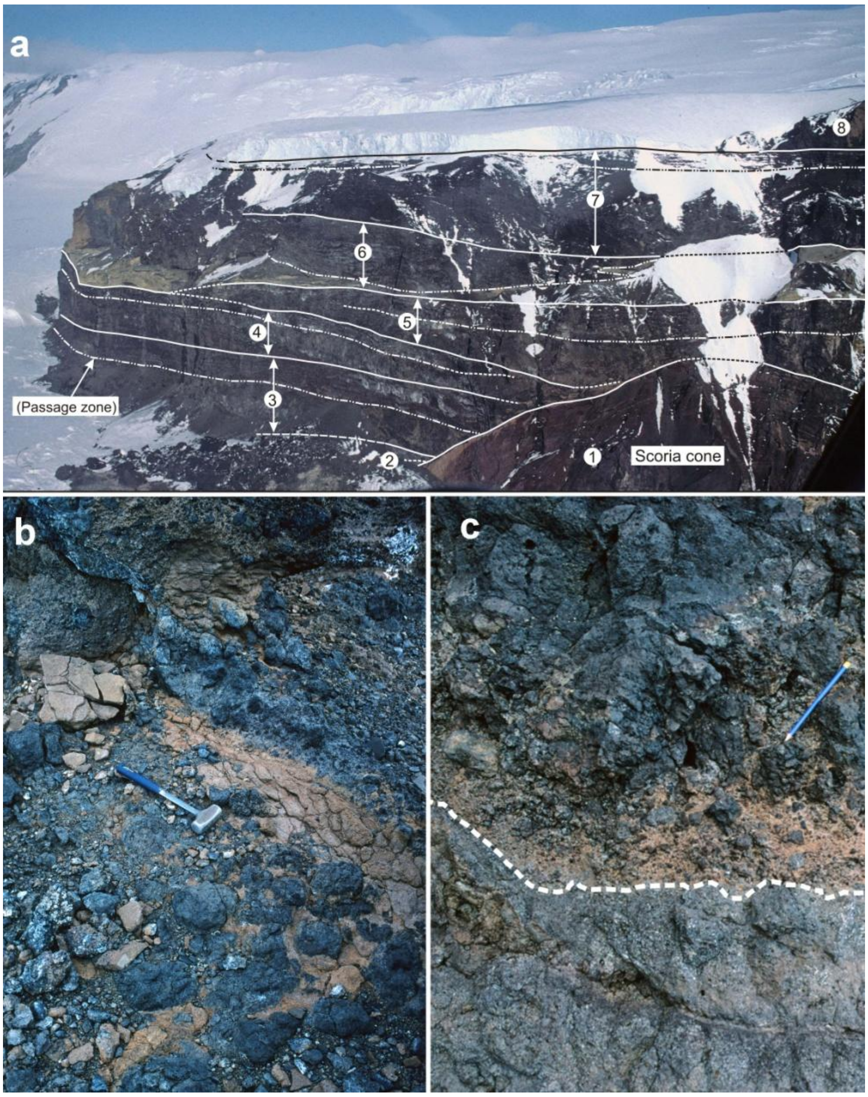

Figure 2. Glaciovolcanic sequences and related features indicative of the basal thermal regime of the EAIS in Victoria Land. Cold-based ice features: (a) ~600 m section of multiple lava-fed deltas (numbered 2-8) lacking erosion and interbedded glacial sediments overlying an erosionally unmodified basal scoria cone; Cape Phillips, Daniell Peninsula; (b)-(c) plan and cross sectional views of a rough-textured surface between two lava-fed deltas, showing a general lack of glacial erosion and (in b) presence of essentially unmodified lava clinkers; northern Daniell Peninsula.

Table 1. Inferred basal thermal regimes and age of ice associated with glaciovolcanic sequences in Victoria Land

Locality	Age (Ma)*	Interpreted thermal regime	Comments
Cape Washington	2.88±0.008 – 1.73±0.04	**Cold-based**	Multiple lava-fed deltas (2 dated)
Cape Adare, Adare Peninsula (eruptions)	c. 3.8	**Cold-based**	Sequence examined at top only, by helicopter elsewhere; age by K-Ar only
Cape Adare, Adare Peninsula (unconformity within sequence)	>3.8	**Wet-based**	Prominent erosional glacial unconformity within volcanic sequence; age uncertain (by K-Ar only); probably caused by expanded much thicker ice sheet
←		**Substantial time gap**	→
West of Cape Daniell, Daniell Peninsula	6.34±0.05 – 5.6±0.5	**Cold-based**	Multiple lava-fed deltas; top & base deltas dated; youngest dated by K-Ar
North Cotter Cliffs, E Hallett Peninsula	6.60±0.80	**Cold-based**	Multiple lava-fed deltas; only one delta dated; by K-Ar
North of Salmon Cliff, W Hallett Peninsula	7.05±0.04	**Cold-based**	Multiple lava-fed deltas; only one delta dated
Roberts Cliff, W Hallett Peninsula	7.26±0.05	**Cold-based**	Multiple lava-fed deltas; only one delta dated
Redcastle Ridge, W Hallett Peninsula	7.41±0.04	**Cold-based**	Multiple lava-fed deltas; only one delta dated
Northern Coulman Island (unconformity within sequence)	c. 7.4	**Wet-based**	Age by K-Ar; probably caused by expanded much thicker ice sheet
Coulman Island (eruptions)	7.2±1.0 – 7.6±0.8	**Cold-based**	Multiple lava-fed deltas; ages by K-Ar
West Edisto Inlet (Herschel Tuffaceous Moraine), W of Hallett Peninsula	c. 7.4	**Wet-based**	Lacustrine sequence infilled by ash turbidites situated on the flank of a valley-filling glacier; age similar to or older than nearby Hallett Peninsula sequences
Tucker Glacier	7.61±0.05	**Wet-based**	Thermal regime possibly reflects that of expanded adjacent outlet glacier
←		**Substantial time gap**	→
Minna Hook (7)	9.40±0.30	**Wet-based**	
Minna Hook (6)	9.53±0.07	**Wet-based**	Felsic dome with hyaloclastite breccia base and basal diamict (till) on glacially eroded surface
Mandible Cirque, Daniell Peninsula	9.68±0.05	**Wet-based**	Felsic dome with hyaloclastite breccia base and basal diamict (till) on glacially eroded surface
Cape Jones, Daniell Peninsula	9.87±0.09	**Cold-based**	Minor erosion but no diamict or fluvial sediments; volcano slopes pristine above c. 400-600 m a.s.l.
Cape Phillips, Daniell Peninsula	9.95±0.07	**Cold-based**	Minor erosion but no diamict or fluvial sediments
Minna Hook (unconformity within sequence)	c. 10.38 – 9.40	**Wet-based**	Age bracketed by dated units; probably caused by expanded much thicker ice sheet
Minna Hook (5)**	c. 11.47 – 10.39	**Wet-based**	Age bracketed by dated units
Minna Hook (4)**	10.50±0.30	**Wet-based**	
Minna Hook (3)**	c. 11.2 – 10.5	**Wet-based**	Age bracketed by dated units
Minna Hook (unconformity within sequence)	c. 11.2 – 10.6	**Wet-based**	Age bracketed by dated units
Minna Hook (2)**	c. 11.40 – 11.20	**Wet-based**	Age bracketed by dated units

Minna Hook (1)	c. 11.40 – 11.21	**Wet-based**	Age bracketed by dated units

* All ages by ^{40}Ar-^{39}Ar except where otherwise indicated in comments; from Fargo (2009), Gemelli (2009) and Smellie et al. (2011); see Table 2 for analytical details of ages.

** Despite similar or overlapping ages, the dated informally-numbered units at Minna Hook included in this table relate to different lava-fed deltas.

Table 2. Summary details of ^{40}Ar-^{39}Ar ages for volcanic sequences in Victoria Land used in this study

Sample	**Locality**	**Technique**	**Material**	**^{39}Ar% concordant segment (plateau)**	**n[a]**	**Error-weighted mean age (Ma)[b]**	**±2σ (internal error)**	**MSWD[c]**	**Total gas age (Ma)**	**±2σ (internal error)**	**Ref**
11-01-06 JS5	Cape Washington (2)	Lazer step heating	Groundmass	61.6	4	**1.729**	**0.037**	1.19	1.852	0.080	Gemelli 2009
11-01-06 JS3	Cape Washington (1)	Lazer step heating	Groundmass	60.8	3	**2.885**	**0.080**	1.63	2.958	0.037	Gemelli 2009
2-01-06 JS7	Bluff 7 km WNW of Cape Daniell, Daniell Peninsula	Lazer step heating	Groundmass	53.9	4	**6.338**	**0.050**	1.8	6.445	0.045	Smellie et al 2011
1-01-06 JS5	First bluff N of Salmon Cliff, Hallett Peninsula	Lazer step heating	Groundmass	74.9	5	**7.049**	**0.040**	0.22	7.070	0.043	Smellie et al 2011
29-12-05 JS10	Roberts Cliff, Hallett Peninsula	Lazer step heating	Groundmass	72.3	5	**7.257**	**0.050**	1.5	7.322	0.053	Smellie et al 2011
4-01-06 JS1	Redcastle Ridge, Hallett Peninsula	Lazer step heating	Groundmass	61.0	4	**7.407**	**0.043**	0.36	7.441	0.047	Smellie et al 2011
4-01-06 JS11	S flank of Tucker Glacier, 4.5 km NW of Crater Cirque	Lazer step heating	Groundmass	57.3	4	**7.605**	**0.049**	0.20	7.322	0.062	Smellie et al 2011
19-12-05 JS2	Mandible Cirque, Daniell Peninsula	Total fusion	Alkali feldspar	-	8	**9.683**	**0.051**	0.50	9.669	0.051	Smellie et al 2011
21-12-05 JS8	Cape Jones, Daniell Peninsula	Lazer step heating	Groundmass	54.4	4	**9.866**	**0.088**	1.6	10.144	0.092	Smellie et al 2011
4-01-06 JS6	Cape Phillips, Daniell Peninsula	Lazer step heating	Groundmass	-	-	No plateau	**-**	-	**9.950**	**0.066**	Smellie et al 2011
MB06-587	Minna Hook (7)	Lazer step heating	Groundmass	90.76	8	**9.4**	**0.3**	0.64	9.0	0.4	Fargo 2009
MB06-504	Minna Hook (6)	Lazer step heating	Groundmass	100	10	**9.53**	**0.07**	1.68	9.51	0.07	Fargo 2009
MB06-765	Minna Hook (4)	Lazer step heating	Groundmass	100	10	**10.5**	**0.3**	1.23	11.0	0.7	Fargo 2009
MB06-509	Minna Hook (bracketing age)	Lazer step heating	Kaersutite	100	9	**10.39**	**0.09**	0.85	10.36	0.09	Fargo 2009

MB06-761	Minna Hook (bracketing age)	Lazer step heating	Groundmass	78.88	6	**11.2**	**0.1**	5.17	11.5	0.2	Fargo 2009
MB06-763	Minna Hook (bracketing age)	Lazer step heating	Groundmass	63.72	5	**11.42**	**0.08**	1.86	11.8	0.4	Fargo 2009
MB06-546	Minna Hook (bracketing age)	Lazer step heating	Groundmass	81.8	6	**11.47**	**0.08**	4.14	11.6	0.09	Fargo 2009

[a] – number of steps or analyses used in the error-weighted mean calculation.

[b] – preferred ages indicated in bold typeface.

[c] – mean squares of weighted deviates.

Notes:

1. Ages of units not dated directly (Minna Hook only) were bracketed by dating units higher and lower in the succession.
2. All ages are relative to Fish Canyon sanidine at 28.02 Ma (Renne et al., 1998) and decay constants are after Steiger and Jaeger (1977).

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