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Late Pliocene age of glacial deposits at Heidemann Valley, East Antarctica: evidence for the last major glaciation in the Vestfold Hills

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Abstract: A Pliocene (2.6–3.5 Ma) age is determined from glacial sediments studied in a 20 m long, 4 m deep trench excavated in Heidemann Valley, Vestfold Hills, East Antarctica. The age determination is based on a combined study of amino acid racemization, diatoms, foraminifera, and magnetic polarity, and supports earlier estimates of the age of the sedimentary section; all are beyond ^{14}C range. Four till units are recognized and documented, and 16 subunits are identified. All are ascribed to deposition during a Late Pliocene glaciation that was probably the last time the entire Vestfold Hills was covered by an enlarged East Antarctic Ice Sheet (EAIS). Evidence for other more recent glacial events of the 'Vestfold Glaciation' may have been due to lateral expansion of the Sørsdal Glacier and limited expansion of the icesheet margin during the Last Glacial Maximum rather than a major expansion of the EAIS. The deposit appears to correlate with a marine deposition event recorded in Ocean Drilling Program Site 1166 in Prydz Bay, possibly with the Bardin Bluffs Formation of the Prince Charles Mountains and with part of the time represented in the ANDRILL AND-1B core in the Ross Sea.

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Key words: amino acid racemization dating, diatoms, foraminifera, magnetic polarity, origin, Sørsdal Glacier, trench excavation

Introduction

Compared with West Antarctica and proximal parts of East Antarctica, including the central Transantarctic Mountains, McMurdo Dry Valleys, Ross Sea and McMurdo Sound areas, very little is known of the Late Cenozoic glacial history of most of coastal East Antarctica. Evidence for the fluctuation of the ice sheet margin throughout this broad sector has been confined to widely separated sets of observations in coastal oases (for example Amery Oasis, Vestfold Hills, Bunger Hills), scattered mountain ranges (for example Prince Charles Mountains), and seismic surveys and drilling on the continental shelf and slope (Adamson & Pickard 1986, Pickard *et al*. 1988, Domack *et al*. 1991, Adamson & Colhoun 1992, Fitzsimons & Domack 1993, Goodwin 1993, Hirvas *et al*. 1993, Harris *et al*. 1996, Melles *et al*. 1997, Gore 1997, Augustinus *et al*. 1997, Whitehead *et al*. 2006).

At Vestfold Hills, (Fig. 1) there is still uncertainty regarding the extent of ice cover during the Last Glacial Maximum (Gore & Colhoun 1997). New evidence presented here suggests that glaciation of Vestfold Hills was limited to a region within a few kilometres of the present ice edge between 12.5 and 9.3 ka, as determined from a date of 11.4 ka on marine sediments on the inner shelf (Domack *et al*. 1991), ^{14}C dated lake sediments (Bronge 1989), ^{14}C dated marine shell fragments in ice-thrust moraines adjacent to Sørsdal Glacier (Fitzsimons & Domack 1993), and two ^{26}Al ages on glacial boulders within 2 km and 5 km of the ice (Fabel *et al*. 1997). Cosmogenic exposure-age dating of striated dolerite dykes using ^{36}Cl and adjacent gneiss bedrock using ^{10}Be have given values of from 30 ka close to the ice sheet, to around 100 ka near the coast, but there was poor correspondence locally between dated samples (Stone *et al*. 1993, Fabel *et al*. 1997). The large local variability and older than expected ages were explained as preservation of an inheritance signal due to non-uniform and insufficient erosion of the bedrock by the passage of ice during the Vestfold Glaciation.

The lack of deep exposure in glacial sediments throughout Vestfold Hills has constrained obtaining stratigraphic evidence for periods of glaciation. In 1989, Hirvas *et al*. (1993) excavated four pits on the northern margin of Heidemann Valley (Fig. 1). The stratigraphy

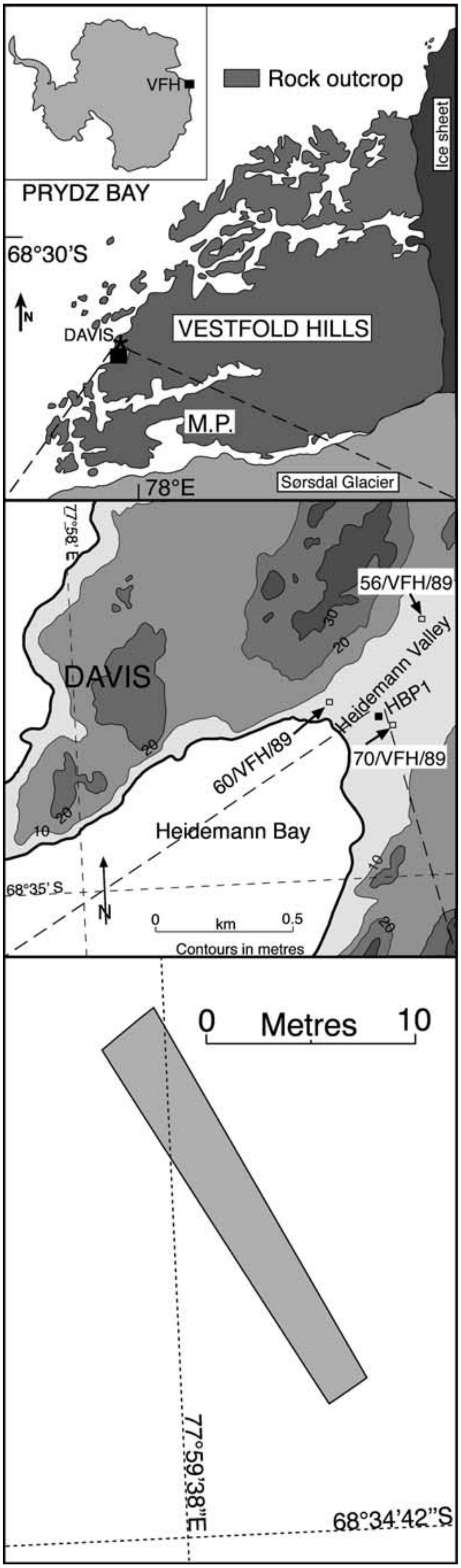

Fig. 2. The Heidemann Valley trench after excavation. Human figure for scale.

recorded in three of the pits seemed to show the separation of an older from a younger till. In Pit 70/VFH/89, the lower and upper tills were separated by a 20–50 cm thick bed of shelly gravel considered by Hirvas *et al*. (1993) to represent a marine transgression. They referred the postulated marine interval to an interglacial termed the Davis Interglacial which thermoluminescence and amino-acid dating suggested to be greater than 300 ka or perhaps greater than 1 Ma old. Colhoun (1991) questioned the validity of inferring an interglacial stage from such a thin bed of shelly gravel. He noted that all the shelly material seemed to be fractured although it is suggested that some of the contained bivalve *Laternula* could have been almost *in situ*. Hence allocation of the thin shelly gravel beds to an

Fig. 1. Locality maps. 60/VFH/89 etc. are sites of excavations referred to in Hirvas *et al*. (1993). Heidemann trench is indicated by the black square. Co-ordinates relate to Universal Transverse Mercator Grid Zone 44. Horizontal Datum WGS 72. M.P. = Marine Plain.

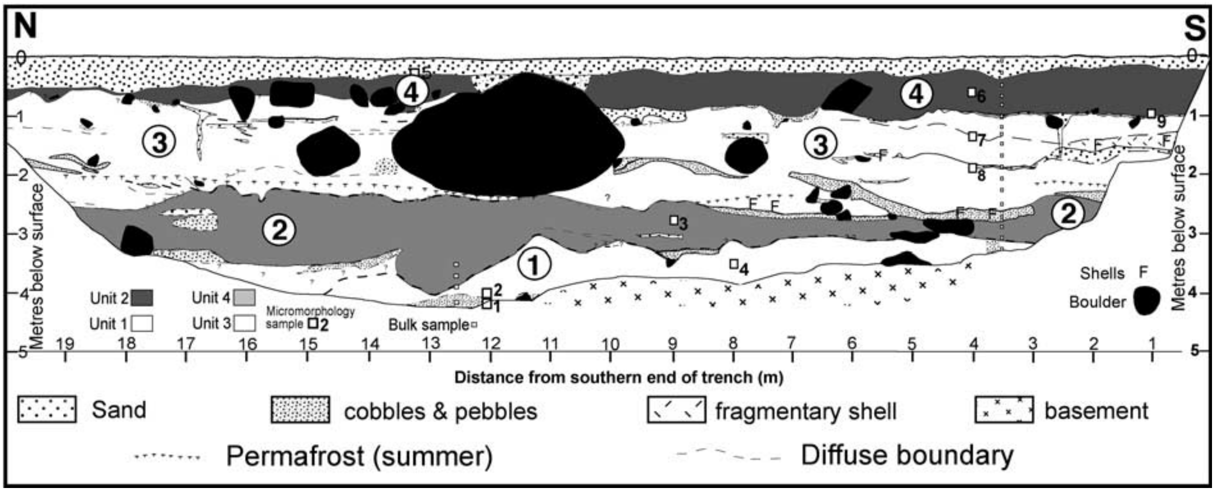

Fig. 3. Stratigraphy of the Heidemann Valley Trench. Boulders shown in black. Circled numbers are Till Units 1–4. Small squares with numbers are micromorphology samples, not studied here. Bulk micropalaeontology samples in vertical section at southern end of trench, are shown as smaller squares.

interglacial interval is stratigraphically difficult. Attempts to radiocarbon date the shell fragments have provided minimum ages close to the practical limits of radiocarbon dating, suggesting an older age for the sediments.

In March 1997, a trench was excavated across part of Heidemann Valley (Figs 1 & 2) adjacent to Heidemann Bay and normal to the WSW direction of the regional ice flow. The purpose was to examine the stratigraphy and structure of the glacial and any associated deposits, and to obtain shell samples for radiocarbon, microfossil, and amino-acid racemization dating (Fig. 3) and to determine the magnetic polarity. It was hoped to resolve whether or not there was good stratigraphic evidence for a Davis Interglacial proposed by Hirvas *et al*. (1993) as >1 Ma representing a climatic interglacial stage, and to resolve problems relating to the range of ages obtained from the fossil shell material. This paper presents the results and their significance for former glaciation of Vestfold Hills.

The limited dated evidence for Vestfold Hills that has bearing on the glacial deposits exposed in the Heidemann Valley trench indicates that after deposition of the mid-Pliocene marine deposits bearing Cetacea (Quilty 1991, Quilty *et al*. 2000, Harwood *et al*. 2000, Fordyce *et al*. 2002) and other fossils on Marine Plain, most of the bedrock hills of the oasis were exposed to cosmogenic rays that gave minimum values of 100 ka with the later Vestfold ice expansion (Vestfold Glaciation) which probably lasted from after 30 to about 13 ka being confined to marginal areas close to the present ice sheet and Sørsdal Glacier. The fossil data from the Heidemann Bay trench plus the Pliocene marine deposits that have been preserved by permafrost at Marine Plain may indicate that the central part of Vestfold Hills has been covered only once by ice since the Late Pliocene and that during much of the Pleistocene it may have remained as an unglaciated, very dry oasis comparable with the Dry Valleys of the McMurdo Sound region.

Table I. Summary of grain size analyses from Heidemann Valley trench (dry weights rounded to 0.1%; range of values given for multiple samples). N = number of samples.

Depth in section (cm)	N	Sediment unit	>2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	250–125 μ	125–63 μ	<63 μ
0–35	2	Marine deposits	2.4–2.5	4.1–6.0	9.4–13.4	17.1–22.2	36.9–37.2	17.2–27.3	2.6–7.2
35–90	3	Till 4	10.3–28.0	8.7–11.0	11.8–15.5	15.1–17.5	17.1–22.2	12.6–18.1	4.9–6.0
90–95	1	Sand & gravel	45.4	12.3	11.7	11.9	11.6	5.7	1.6
95–255	7	Till 3	14.6–28.7	6.9–14.8	11.7–15.9	12.6–15.5	13.0–22.0	10.9–17.7	2.4–11.8
185–190	1	Sand & gravel with shell fragments in Till 3	31.8	12.5	15.5	14.6	18.1	6.1	1.5
255–270	1	Sand & gravel with shell fragments on surface of Till 2	33.6	15.8	15.6	13.3	11.8	7.9	1.9
270–370	4	Till 2	5.3–42.0	9.6–14.0	10.7–24.8	8.8–21.1	10.3–16.8	12.7–15.5	2.8–10.6
320–330 & 380–420	3	Till 1	14.3–35.5	5.4–16.5	11.7–17.8	9.0–18.4	10.3–24.3	11.3–14.4	5.7–10.2

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Table II. Selected chemical analyses of stratigraphic units. All measurements in ppm. Conductivity in Micro Siemens.

Depth (cm)	Sediment unit	Conductivity	PH	Ca	Mg	K	Na	Cl	SO_4
20–30	Marine deposits	1.09	6.3	43.4	31.1	44.8	1142.7	1622.3	200.9
60–70	Till 4	1.62	6.2	38.7	35.0	46.9	1646.8	2551.9	305.1
90–95	Sand & gravel	1.37	5.7	54.0	100.0	76.6	1268.4	2123.7	218.3
120–130	Till 3	3.00	5.6	66.2	118.3	138.9	2904.4	5008.9	520.6
220–230	Till 3	4.32	6.1	108.3	394.5	192.85	3863.6	7373.7	537.2
280–290	Till 2	4.63	6.3	125.8	420.8	214.3	4250.0	6802.4	629.5
320–330	Till 1	6.58	6.2	325.0	540.5	288.6	6185.0	10583.2	1234.5

The Pliocene is of increasing interest in discussion of the evolution of Antarctic and global palaeoenvironment. Miller *et al*. (2005) illustrated the dramatic change in oxygen/carbon isotope signals as the Antarctic glacial environment evolved through the 3.5–2.5 Ma interval, to the modern cyclical pattern of variation within a limited range. Haywood *et al*. (2009) summarized the Miocene/Pliocene history of the Antarctic but the Late Pliocene was not covered to the same depth as was Middle Miocene–Early Pliocene.

Material and methods

To obtain data that would reveal the conditions under which the shell-bearing glacial deposits were formed, and new material for dating, a trench, 20 m long, approximately 4 m wide, and 4 m deep, was excavated into the permafrost. The stratigraphy and structure of the sediments revealed in the south-west wall of the excavation are shown in Fig. 3. To characterize glacial sediment facies, the sediments were sampled mainly for particle size analysis near the southern end and, to complete the record, just north of the centre of the trench. Shell fragments were extracted for radiocarbon and amino-acid racemization dating. Particle size analysis of the sediments was conducted at the University of Newcastle, NSW, Australia, by dry sieving using Endecott sieves in the size ranges from > 16 mm to 63 μm. Summary aggregated results of dry weight percentage are shown in Table I. Selected chemical analyses were also made of samples of some of the stratigraphic units (Table II) Conductivity and pH values were measured in the ratio 1:5 sediment:distilled water. Ca, Mg, K, Na, Cl and SO_4 were measured by a Waters ion chromatograph. Microfossils were studied at the Australian Antarctic Division (PQ) and the University of Tasmania (JW).

Siliceous microfossils were identified with an Olympus light microscope from strewn slides mounted with Norland optical adhesive (refractive index = 1.56). A list of species was collated by scanning systematically 16 slides at low magnification (400 x) and high magnification (1000 x) for taxonomic identification. The biostratigraphic range of the fossils assists in constraining the age of the sample. The Southern Ocean Zonation of Harwood & Maruyama (1992), revised to the Berggren *et al*. (1995) timescale, has been applied.

Quantitative abundance data were collected by scanning systematically the microfossil slides. The use of raw and concentrated slides, and the typically fragmented nature of the fossils, precluded the collection of absolute abundance data. Therefore, qualitative indices ranging from 0 to 6 are used to describe fossil abundance:

0 = no specimens or fragments observed,
1 = at least one specimen or fragment per slide,
2 = a few specimens or fragments per slide,
3 = numerous specimens or fragments (< 10) per slide,
4 = many specimens or fragments (> 10) per slide,
5 = a specimen or fragment every few fields-of-view (at x400 magnification), and
6 = numerous specimens or fragments on every field-of-view (at x400 magnification).

A sample of approximately 12 g was taken from each of the 16 units identified here but data from the samples

Table III. AMS radiocarbon ages, Heidemann Valley Trench. Carrara marble used to estimate correction for sample preparation background contamination. Sample 'IAEA C1 marble' designates a material with infinite ^{14}C age. pMC is % modern carbon and represents ratio of radiocarbon content of sample normalised to that in Oxalic acid standard (OX-I). Final pMC values obtained after normalisation to Oxalic standard, mass and §^{13}C correction, and chemistry background. Ages given as conventional radiocarbon ages, not calendar ages. AMS facility is as described in Fink *et al*. (2004). Limiting ages and that for NDFB (not distinguishable from background) determined according to Stuiver & Polach (1977).

Sample	ANSTO code	Unit	Depth (cm)	^{13}C (%)	pMC	Years (BP)	Error
VHB01	OZD807	3	130	-0.41	1.02 ± 0.08	36834	630
VHB02	OZD808	2	370	1.02	0.56 ± 0.11	41651	1578
VHB03	OZD809	1	380	0.39	0.48 ± 0.17	42889	2845
VHB04	OZD810	1	380	-0.41	0.69 ± 0.09	39974	1048
Chem.	Graphite	blank			0.1 ± 0.05	~55 ka	

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Table IV. Degree of amino acid racemization (total acid hydrolysate) in fossil molluscs from Heidemann Valley Trench. CV = coefficient of variation. Figures in right-hand five columns are amino acid D/L ratios. ALA = alanine, ASP = aspartic acid, LEU = leucine, PRO = proline, VAL = valine.

Laboratory code	Sample	Depth (cm)	ALA	ASP	LEU	PRO	VAL
UWGA-1098	HP-18, VHB-01	160(3)	0.548 ± 0.002	0.526 ± 0.01	0.269 ± 0.002	0.346 ± 0.017	0.231 ± 0.002
UWGA-1101	HP-18, VHB-02	260(3)	0.389 ± 0.009	0.494	0.216 ± 0.102	0.253 ± 0.085	0.217 ± 0.012
UWGA-1100	HP-18, VHB-03	370	0.505 ± 0.002	0.457 ± 0.024	0.242 ± 0.004	0.334 ± 0.033	0.234 ± 0.005
UWGA-1099	HP-18, VHB-04	380(1)	0.555 ± 0.009	0.465 ± 0.069	0.274 ± 0.026	0.297 ± 0.035	0.242 ± 0.009
ar Mean D/L			0.499 ± 0.077	0.486 ± 0.031	0.250 ± 0.027	0.308 ± 0.042	0.231 ± 0.0101
CV%			15.4	6.4	10.8	13.6	4.3

studied in Hirvas *et al*. (1993) have also been included. Standard Techniques were employed. Other non-diatom fossil groups were also recorded. General results of examination of foraminifera are presented here and the foraminiferal fauna will be documented elsewhere.

Radiocarbon dating of four microfossil shell samples was undertaken by AMS at the ANTARES AMS Facility (Fink *et al*. 2004) at the Australian Nuclear Science and Technology Organization (ANSTO) (Table III). The shell fragments of each sample were washed in dilute hydrochloric acid to remove coarse-grained material. The etched fragments were cleaned with deionised water for 20 min three times in an ultrasonic bath to remove further surface contamination. The samples were dried in an oven at 60°C for two days before hydrolysis to CO_2 using 85% phosphoric acid and conversion to graphite using the Zn/Fe method (Hua *et al*. 2001). The mass of graphite was 1.5–2 mg which is sufficient to make mass-dependent background corrections unnecessary for young samples (Hua *et al*. 2003) but more important for old samples as is the case here. All necessary background subtractions were made with correct propagation of errors to determine if final reduced ^{14}C pMC values were to be designated as defined ages with associated errors, as minimum age limits or as indistinguishable from background. A small proportion of graphite from each sample was employed for the determination of $^{13}C\%$ using a stable isotope mass spectrometer. All AMS ^{14}C measurements for the four samples were carried out in repeated sequence, and normalized to an Oxalic II standard which was determined to a precision of 0.4% (Fink *et al*. 2004).

Amino acid analyses of four samples was undertaken at the School of Earth and Environmental Sciences, University of Wollongong (Table IV). The degree of racemization (total acid hydrolysate) of the amino acids alanine (ALA), aspartic icid (ASP), leucine (LEU), proline (PRO) and valine (VAL) was measured in large fragments of an unidentified fossil marine hiatellid bivalve mollusc (cited by Hirvas *et al*. 1993, as *Hiatella arctica*) characterized by thick shell and umbo. Shell surfaces were cleaned with a dental drill, followed by washing in distilled water in an ultrasonic bath. A dilute acid etch (2 mol HCl) was subsequently undertaken to remove the outer shell surfaces (~5–10% by mass) of the shells that had been in contact with the host sediment. Samples were subsequently hydrolysed for 22 hours at 110°C in 8 mol HCl. Following cation exchange isolation of the amino acid residues, samples were freeze-dried and then derivatized. Gas chromatography of the N-pentafluoroprionyl D, L-amino acid 2-propyl esters was performed using a Hewlett-Packard 5890A Series II gas chromatograph with a flame ionization detector and a 25 m coiled, fused silica capillary column coated with the stationary phase Chirasil-L-Val. Full details of the analytical protocol used in this study are reported elsewhere (Murray-Wallace 1993). Enantiometric ratios were determined based on peak area calculations. Current mean annual temperature (CMAT) at the sample site, a relevant consideration for the interpretation of the amino acid results is typically cooler than -7.5°C.

Because the trench was excavated in permafrost, an oriented column of the section was collected and returned to Hobart in order to determine the palaeomagnetic record (normal or reversed magnetic polarity) contained in the sediment. The oriented column consists of eight, 0.5 m long segments, each about 10 x 6 cm in section. Two samples were taken from each segment. Throughout collection, storage, transport and analysis, samples were kept frozen. The column segments are held frozen at the Australian Antarctic Division headquarters in Kingston, Tasmania. Magnetic polarity analyses were conducted at Geoscience Australia (then Australian Geological Survey Organization: AGSO), Canberra. The oriented samples (Table VI & VII) were subject to stepwise increase in alternating field in 20–30 steps from 2 to 160 nT. Data are held by PGQ.

Results

Lithostratigraphy

The trench stratigraphy shows a thin, surface bed of Holocene marine deposits underlain by four units of till (Fig. 3). The surface of the permafrost after the trench was opened occurred at ~1 m.

The surface marine deposits (Quilty & Franklin 1997) are 0.3–0.7 m thick and consist of a sequence of fine to medium sand that is slightly coarser near the base. Less than 2.5% consists of granules and small gravel, and < 7.2% consists of silt and clay (< 63 μm). In places, low-angle cross-bedding and horizontal laminae are present. A sharp horizontal boundary (unconformity) separates the

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Table V. Distribution of diatoms in samples from Heidemann Valley (*in Harwood & Maruyama 1992).

Diatom species	Samples 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Actinocyclus sp.								1	2						1	
Actinocyclus ingens									1							
Actinocyclus ingens var. A*									1					1		
Actinocyclus octonarius var. *asteriscus*							1						2		2	1
Achnanthes brevipes							2	1		2						
Amphora sp.	1							1		1						
Arachnoidiscus sp.				2											1	
Cocconeis costata				2		2		1			2					
Cocconeis fasciolata	2					2	2	1		2	2	1			3	3
Coscinodiscus spp.	6	4	6	5	5	5	6	4	6	4	5	5	5	5	5	6
Dactyliosolen antarcticus													1			
Diplonies sp.			3	1		2					3				2	
Diplonies bomboides		2			2		3	3	4		3		2		3	4
Diplonies subovalis																
Eunotia sp.													1			
Eucampia antarctica				1					2							1
Fragilariopsis sp.																1
Fragilariopsis kerguelensis															1	
Fragilariopsis sublineata				2			1		2					2		
Grammatophora charcotti										2						
Hyalodiscus sp.							2						2		3	2
Isthmia sp.		1											1		2	
Melosira sp.			1	1						1	1					
Navicula sp.													1			
Melosira sol var. *marginalis*																
Probosica sp. cf *alata*						1				2						
Pseudodenticulata sp.				1					2	2	1	1				
Radialiplicata sol	4	1	4	4		3	3	3	4	3	4	3	1	3	4	2
Raphonies sp.					1											
Rhizosolenia sp. B*																1
Rhizosolenia hebetata group														1		
Rhizosolenia styliformis group							1									
Stellarima microtrias					1				3	2		2		2	2	2
Syndera sp.										1						
Thalassiosira spp.						1				3					2	1
Thalassiosira antarctica											1					
Thalassiosira insigna						1			1	1						
Thalassiosira oliverana										4						
Thalassiosira torokina					1								2			1
Thalassiothrix/Thalassionema/Trichotoxon	2	1	2	2			3	2		2				2		2
Trachyneis aspera	3		2	5	4	4	3	3	3	4			1		4	1
Diatom cysts													1			
Sponge spicules	4	4	4	5	5	5	5	4	5	5	5	2	6	6	5	6

surficial sand deposits from the underlying till and there is no mixing of deposits. The boundary forms the surface of the glacial deposits and the base of the transgressive Holocene marine deposits.

The underlying till beds comprise four units, 0.2–2.0 m thick, that are not all discretely bounded.

Till 1 is 0.25–> 1 m thick and, like all the overlying units, has a poorly sorted sandy matrix. Over the southern half of the trench, the lower surface appears to be close to bedrock that is likely to lie at shallow depth below the base of the entire trench, consistent with the findings of Hirvas *et al*. (1993). It is more compact than any of the overlying till units and contains more cobbles, particularly in the northern part of the trench. Near the deepest point, a shelly gravel lens has considerable silt and clay in the matrix.

Till 2 is 0.5–1.5 m thick and is more massive than Till 3. It contains only a few thin lenses of sand and gravel. Although it contains more pebbles and cobbles than Till 3 or 4, it also is composed mainly of poorly sorted sand. Shells and shell fragments occur extensively in the till, and there is a pocket of shelly gravel on the surface of Till 2 between 2.55–2.70 m (Table I). The boundary between Till 2 and Till 1 is irregular.

Till 3 is 1.5–1.75 m thick and has very similar grain-size distribution to that of Till 4, predominantly composed of sand. It consists of numerous layers indicating that it was

Table VI. Samples studied for determination of magnetic polarity.

Core segment	Sample no.	Cm from top of core segment	Height from section base (cm)
1	S11	40	360
1	S12	10	390
2	S1	40	310
2	S2	20	330
3	S7	15	285
3	S8	40	260
4	S5	15	235
4	S6	35	215
5	S3	10	190
5	S4	40	160
6	S9	10	140
6	S10	35	115
7	S13	15	85
7	S14	45	55
8	S15	20	30
8	S16	45	5

deposited as several beds that are separated in places by distinct boundaries and in others by faint and diffuse boundaries. Throughout Till 3 there are several thin discontinuous lenses of small cobbles, pebbles, sand and silt that occur associated with the boundaries in the till. Several lenses show evidence of horizontal lamination indicating water deposition. Till 3 contains the majority of the shell fragments and foraminifera. They are widely distributed, but occur mainly in distinct local concentrations. Parts of the till exhibit iron oxidation probably due to the considerable concentration of gravel lenses in the southern third of the trench. The surface of the permafrost, however, occurs within Till 3 and favours reducing conditions below it.

The uppermost *Till 4* is up to 0.75–0.80 m thick. It consists of sand with little silt and clay (Table I) and in places, is faintly iron-stained. It has a discrete lower boundary with a concentration of large boulders near and on the boundary with Till 3, particularly in the northern part of the section (Fig. 2a & b). Thin lenses of sand and fine gravel also occur at the base of Till 4 and on Till 3 indicating aqueous deposition involving local erosion of the surface of Till 3. Of particular note are two wedge-shaped

Table VII. Results of palaeomagnetic analysis. Arrowhead on core box always points down. Axis of arrow is parallel to axis of core. Head of arrow is in plane parallel to back of core box.

Core	Top edge orientation (°MN)	Back inclination (°)	Side inclination (°)
1	52 (view N)	85	82
2	44 (view N)	78	
3	263.5 (view S)	82	
4	32 (view N)	81	86
5	228 (view S)	73.5	86
6	21.5 (view N)	88	82
7	36 (view N)	83.5	90
8	22 (view N)	82	78

cracks that penetrate Till 3 from near the surface with Till 4. The crack near the southern end is 75 cm deep and sand filled; that near the northern end is 85 cm deep and is filled with silt. The cracks terminate upwards in lenses of sand and silt from which the sediment filling them was derived. The combined evidence of the boulders on the contact, lenses of washed sand and gravel (see Table I: 0.90–0.95 m bed with 45.4% of granules and pebbles), and in-filled cracks suggests that the boundary between the two units was exposed for sufficient time for the surface of Till 3 to have been cracked either by desiccation or ice-vein development, to have been eroded perhaps partially to expose the boulders on its surface, and for the water-laid sand and gravel to be deposited. The association of these features with the exposure of the surface of Till 3 is emphasized by the absence of deep cracks and water-lain sediment within Till 4.

The sequence of excavated glacial deposits appears to overlie shallowly the bedrock floor of Heidemann Valley. It can best be interpreted as showing a compact basal till, Till 1, overlain by a series of less well consolidated flow till units, Tills 3 and 4. To what extent Till 2 forms part of the deposits at the ice sheet base rather than the flow tills is difficult to judge. It has more of the characteristics of Till 1 than Tills 3 and 4 by containing more pebbles and cobbles, being more massive and containing less sandy and gravelly lenses. The boundary between Tills 1 and 2 may have been eroded as have the boundaries between Tills 2 and 3, and Tills 3 and 4. Within Till 3, the discontinuous boundaries and abundance of sandy and gravelly lenses with shell fragments are characteristic of the flow till processes that can be observed during melting of buried ice masses near the terminus of glaciers today, with redistribution of the overlying sediments as flow till deposits and small areas of water-deposited sediment. Fitzsimons & Domack (1993) reported such processes from nearby Sørsdal Glacier.

The sequence of deposits contains a significant component of marine sediments throughout the units. The most obvious is the abundance of shell fragments particularly in Tills 2 and 3, and their local concentration through washing within the sandy and gravelly lenses. The lenses are identical with that described by Hirvas *et al.* (1993) from the nearby pit 70/VFH/89 to the north, which separates a lower from an upper till unit and is associated with deformed clay on an erosional boundary. Much of the pebble and cobble clast component in Tills 1 and 2 in the Heidemann Valley Trench is probably also derived from contemporary marine sediments that would have floored the adjacent bay and lower part of the valley at times of high sea level, thus providing a local source for their incorporation into the glacial sediments.

Chemical analyses of the sediments showed slight variation in pH in the range 5.6–6.3 with the lowest values in the gravel lens at 90–95 cm and subjacent till

(Table II). The chemical elements all show increasing values with depth except for the inversion of values for Na, Cl, and SO_4 between Till 1 and the underlying sand and gravel lens at 90-95 cm.The inversion of values suggests that the finer grained and more compact till matrix retains ions longer than the underlying gravel that would permit their more rapid downward translocation to Till 3.

Chronostratigraphy

Radiocarbon dating

The age values (Table III) obtained from the shell materials are all so close to the practical limits of the radiocarbon dating method that they must be considered as of radiocarbon infinite age, and unfortunately, provide no understanding of the age of the shell materials, and presumably also, of the microfaunal materials incorporated within the tills and gravels described. To attempt to get a better indication of their age, amino-acid racemization was undertaken.

Amino acid racemization

The results indicating the extent of racemization of the different amino acids within the single shell specimens from Antarctica conform with the relative rates for each amino acid previously noted for other marine shell species (ALA > ASP > PRO > LEU ≥ VAL: Murray-Wallace 2000, Table I). The degree of racemization for the individual amino acids between specimens is generally concordant with coefficients of variation less than 15%. Mean D/L ratios are given in Table IV.

A numeric age for the fossil shells from Antarctica was determined using the integrated rate equation for racemization:

$$\ln\left[\frac{1 + D/L}{1 - D/L}\right] = -2kt$$

where *D/L* is the D/L ratio for the fossil of unknown age, *k* is the *in situ* racemization rate constant and *t* is age. The numeric age was calculated based on the mean D/L ratio for valine, a slow racemizing amino acid. Linear reversible first-order kinetics would apply to these fossil shells in view of the relatively low degree of valine racemization and the very low effective diagenetic temperatures they would have experienced. An *in situ* racemization rate constant (*k*) was derived by modelling mathematically the degree of racemization that would be expected in a fossil sample if it were of last interglacial age (125 ka) from Antarctica with a CMAT of -7.5°C and comparison of the fossil of known age and D/L ratio. The degree of racemization determined in a specimen of the fossil mollusc *Glycymeris striatularis* (Lamarck, 1819) of last interglacial age from Broadmeadows Tasmania (CMAT = 12.5°C; Murray-Wallace 2000) was used as a framework for comparison in this calculation. As racemization rates are known effectively to double with every 5°C difference in temperature (Davies & Treloar 1977), a theoretical degree of racemization for the amino acid valine for the last interglacial for Antarctica was determined to be D/L = 0.01125 (expressed as raw data). On this basis, a racemization rate constant $k = 9.00038 \times 10^{-8}$ was derived. Based on the mean D/L ratio for valine (D/L = 0.231 ± 0.010) from the four Antarctic shell specimens, a numeric age of 2.61 ± 0.39 Ma is assigned to the fossil shells analysed in this study. The uncertainty term accounts for a 1°C uncertainty in the effective diagenetic temperature history of the fossil molluscs. If the CMAT of -10.2°C is used in the calculation, the derived age for the shells is 3.49 ± 0.53 Ma.

Biostratigraphy

The distribution of diatoms is shown on Table V and details of distribution of foraminifera will be given elsewhere.

Diatoms

Diatoms proved the most useful microfossils biostratigraphically. Sparse siliceous diatom and sponge spicule fragments occur within the samples and comprise < 5% of the sediment (from visual estimate). Biogenic silica analyses undertaken upon samples from several sedimentary sections within Heidemann Valley yielded values of ∼0.25% to 12%, with one anomalous value of 40% (Quilty & Franklin 1997). As in these sections, the abundance of siliceous fossils in the current study also varied, but has not been quantified.

The most common diatoms are *Coscinodiscus* spp. (Table III), There are also fragments of benthic diatoms from the genera *Achnanthes*, *Amphora*, *Arachnoidiscus*, *Cocconeis*, *Diploneis*, *Eunotia*, *Hyalodiscus*, *Grammatophora*, *Isthmia*, *Melosira*, *Navicula*, *Raphonies*, *Radialiplicata*, *Synedra*, and *Trachyneis*. Benthic diatoms typically live upon substrates within shallow euphotic water depths and suggest that deposition occurred within a shallow marine environment. The benthic genera *Arachnoidiscus*, *Eunotia*, *Hyalodiscus*, *Grammatophora*, and *Raphonies* are rare within extant assemblages whilst *Isthmia* may have become regionally extinct from Antarctica in the Pleistocene. Sponge spicule fragments are also common in the samples and are typically found in shallow sediments around the Antarctic continental shelf.

The fossils are highly fragmented by mechanical processes, suggestive of a robust environment, reworking, or sediment compaction and shearing due to glacial advance. As a consequence, the biostratigraphical assessment assumes glacial reworking processes may have been operative, and the maximum age of the Heidemann Valley section can only be constrained to the first occurrence datum of the youngest fossil present. This is *Fragilariopsis kerguelensis* (O'Meara) Hasle, 1958, which occurred as a single specimen within Sample 15 and constrains this and the above sample intervals to < 3.2 Ma. The presence of *Thalassiosira antarctica* Comber, 1896 could infer an age < 0.67 Ma (Bohaty *et al.* 1998) for Sample 11 and the sample intervals above this. However, this datum has been established from lower latitude oceanic occurrences on the Kerguelen Plateau (Scherer 1991), and it may become diachronously older southwards onto the Antarctic continental shelf (D.M. Harwood, personal communication 2009) where *Thalassiosira antarctica* is currently widespread (Armand 1997). Therefore, the *T. antarctica* first occurrence datum may be unreliable.

If there has been no reworking the last occurrence datum of *Thalassiosira insigna* (Jousé) Harwood & Maruyama, 1992 is applicable, such that its presence in Sample 6 would indicate this and the sample intervals below are > 2.6 Ma in age. This age interpretation conflicts with that from *T. antarctica*. Other extinct diatoms found within the Heidemann Valley section include *Actinocyclus ingens* Rattray, 1890, *A.* var. *ingens* A in Harwood & Maruyama 1992), *A. octonarius* Ehrenberg var. *asteriscus* Barron, 1975, *Isthmia* sp., and *Thalassiosira torokina* Brady, 1977. The poor preservation and low abundance of fossils has prevented the application of datums from the absent species, because their absence may not be biostratigraphic, but due to preservation or environmental reasons.

Foraminifera

Most samples are barren of foraminifera but provided some evidence of marine microfossils, usually a few sponge spicules but other specimens yielded echinoid spines or shell fragments. The sample from Unit 6 (HBP6, Till 3) yielded a small foraminiferal fauna including undescribed species. The foraminifera are consistent with a Pliocene age (post Early Pliocene because of the absence of *Ammoelphidiella antarctica* Conato & Segre) and attest to the presence of fully marine and oxygenated waters in the old valley (with fjord-like geometry) during the deposition of Unit 6. They also place shallow limits on water depth. Unit 16 also yielded a few foraminifera as did the samples of Hirvas *et al*. (1993).

The foraminiferal faunas are dominated by cassidulinid species (infaunal *Globocassidulina, Cassidulinoides,* and epifaunal *Ehrenbergina*) and epifaunal *Cibicides refulgens* de Montfort, 1808*,* similar to those recorded from parts of Prydz Bay, such as Four Ladies Bank (Quilty 1985) where waters are well oxygenated and fully marine. The presence of elphidiids such as *Elphidium* and *Cribrononion* suggests shallower water and this is supported by the presence of *Pileolina* and *Discorbinella.* The assemblage indicates that sedimentation occurred in a few tens of metres water depth, in fully marine, nutrient-rich conditions. Perhaps conditions were normally anoxic and unfavourable to foraminifera, but with brief intervals in which conditions favoured their growth. There is evidence of dissolution of carbonate on some foraminifera and echinoid spines.

Palynology

Two samples were processed for pollen and spores, but the only organic remains are a few leiospheres similar to, but less abundant than, those occurring abundantly in the Sørsdal Formation described by Quilty *et al*. (2000).

Palaeomagnetic polarity

Most samples do not give a palaeomagnetic signal reliable enough to differentiate Pliocene from younger relationships to the magnetic poles but samples 2, 5, 8 and 10 may be reliable. All samples except Sample S2 (from the upper part of segment 2, 330 cm from the base of the pillar section) retain a normal polarity. Sample S2 has a reversed polarity signal but it must be interpreted with caution. Within the amino-acid stratigraphy based age limits of 3.49–2.61 Ma, a reversed signal would suggest that deposition occurred during normal polarity Chron C2An (Berggren *et al*. 1995). Within that chron, are three normal (C2An 3n 3.55–3.3 Ma; C2An2n 3.25–3.15 Ma; C2An1n 3.05–2.6 Ma) and two short reversed intervals (C2An2r 3.35–3.25 Ma; C2An1r 3.15–3.05 Ma). It is impossible to allocate the section to an individual subchron.

Discussion

Amino acid racemization dating, diatom and foraminiferal analyses all suggest the shell material and enclosing sediment from the Heidemann Valley Trench are of Late Pliocene age, 3.5–2.6 Ma. There are no Pleistocene or younger fossils in the sediment, and cosmogenic exposure-age dating indicates absence of glaciation during at least the Late Quaternary. This age determination most probably places the section in the Late Pliocene which is being used by some (e.g. Robinson & Dowsett 2008) as an analogue for the environment into which current climate change is driving planet Earth.

The time interval represented by these sediments is a critical and contentious one in the context of the evolution of the EAIS, sea level and temperatures at the time. It coincides approximately with the Gauss Normal Polarity Epoch, with that surrounding the controversial issue of age of the Sirius Formation, and the question of possible small tree or shrub vegetation history on Antarctica at that time (Stroeven *et al*. 1998, Harwood & Webb 1998). The age of this section also immediately predates extinction of Antarctic thick-shelled pectenid bivalves (Berkman & Prentice 1996).

The tills in the trench appear to be of one age and are thus compatible with one episode of deposition during a major glacial advance that inundated the entire Vestfold Hills. As marine fossils occur widely through the sequence of deposits, it is not possible to define a discrete Davis Interglacial as had been suggested (Hirvas *et al*. 1993). There appears to have been only one major ice advance across the Vestfold Hills that eroded and fragmented the marine macro- and microfossils found in the till deposits. The oldest cosmogenic exposure-age assays (Stone *et al*. 1993) suggest that at least the central part of Vestfold Hills has not been glaciated since before the Late Pleistocene and implies that recent ice advances during and subsequent to the Last Glacial Maximum, termed the Vestold Glaciation

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by Adamson & Pickard (1986), were peripheral to the oasis. The suggestion that the region was not fully covered by the EAIS during the Last Glacial Maximum receives support from research on the Larsemann Hills (Hodgson *et al*. 2001, Kiernan *et al*. 2009) about 100 km to the south-west of the Vestfold Hills which indicates that the Larsemann Hills were ice-free during this time. This also had been suggested by Burgess *et al*. (1994). Gibson *et al*. (2009) have proposed that a significant part of the Vestfold Hills may also have been ice free during the LGM.

Formerly, the survival of the diatom deposits containing cetacean fossils on Marine Plain has been attributed to preservation beneath cold based ice during the Vestfold Glaciation, but the 1 m thick boulder-rich deposit that caps the marine diatomite does not have the character of a recently deposited till. It represents an ancient lag deposit that has been preserved by permafrost. This investigation thus suggests that the last glaciation of the Vestfold Hills was probably of Late Pliocene age and that the diatomite deposits of Marine Plain were preserved by a combination of long-term freezing and protection of a highly deflated boulder surface lag from a till cover of great age.

Two distinct episodes of shallow marine deposition are now known in the Vestfold Hills - 4.1–4.0 Ma at Marine Plain and 3.5–2.6 Ma in Heidemann Valley, the former by *in situ* marine deposits, the latter by marine deposits incorporated within till and gravels by subsequent ice advance. It is tempting to attempt correlation with other deposits but few are well dated.

Whitehead *et al*. (2006) reviewed the history of regional marine transgression/regression cycles in the Prydz Bay-Prince Charles Mountains region. Their marine transgression M10 (3.2/2.7–2.7/2.5 Ma) coincides very closely with the age of the sediments recovered in Heidemann Valley suggesting that the Heidemann Valley deposition is part of a broader, regional event in the Late Pliocene. It was identified in Ocean Drilling Program Site 1166. They further suggested that M10 may coincide with a marine transgression that deposited the Bardin Bluffs Formation of the Amery Oasis, although that formation is not dated well enough to distinguish which of two transgressions (M10, or M11 of 2.6–1.8/0.99 Ma) was responsible.

Miller *et al*. (2005) reviewed global eustasy throughout the Phanerozoic and showed recent isotopic data through the 9 Ma and younger time interval. The interval 3.5–2.6 Ma on that diagram coincides with their interpretation of the time that marked the beginning of the final cooling of the Antarctic to the modern, following a period of relative isotope (and supposedly ice volume) stability from the Late Miocene. This in turn coincides with the change from dominance of the 19–23 ka orbital control, to the 41 ka dominance. It also marks the rise of the Isthmus of Panama, cessation of surface water flow from the Atlantic to Pacific Ocean, and the accentuation of the Northern Hemisphere ice sheets. It may also coincide with other depositional events around the world, for example the Roe Calcarenite in southern Australia (James *et al*. 2006). This highlights the occurrence of a mid-Pliocene high sea level immediately preceding expansion of the EAIS.

Conclusions

In situ glacial sediments filling Heidemann Valley, Vestfold Hills, East Antarctica were studied from a 20 m long, 4 m deep trench excavated in 1997. Sediment was deposited in the interval 3.5–2.6 Ma (Late Pliocene), which was the last time the Vestfold Hills was subject to glaciation by an expanded East Antarctic Ice Sheet; any later glacial influence was due to lateral expansion of the Sørsdal Glacier and limited marginal expansion of the East Antarctic Ice Sheet. This hypothesis helps explain why the Early Pliocene cetacean-bearing sediments at nearby Marine Plain have been preserved *in situ* as they have not been overrun repeatedly by ice.

Dating of the sediments is based on amino acid racemization, analysis of the diatom flora and foraminiferal fauna. The sediments proved to be beyond the practical limit of the radiocarbon technique and palaeomagnetic studies suggest that deposition occurred during a period of normal magnetic polarity.

Four till units are identified in the sequence and while there is evidence of some breaks during sedimentation, there is not enough to support the concept of a separate Davis Interglacial as proposed by Hirvas *et al*. (1993).

Deposition occurred in a shallow marine bay in the interval during which Antarctic glaciation changed from the relatively stable Late Miocene–Early Pliocene phase to the modern, colder, higher ice-volume state.

Deposition coincided with that in the Prince Charles Mountains (M10 of Whitehead *et al*. 2006). It coincides approximately with the Gauss Normal Polarity Epoch.

The Vestfold Hills is emerging as a significant site for study of the Late Neogene of the Antarctic margin but to date, only part of the area has been explored in the quest for sedimentary sequences such as in Heidemann Valley and on Marine Plain. The northern part of the Vestfold Hills, beneath a thin veneer of Quaternary sediments, warrants dedicated study.

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