ENTRAINMENT OF GLACIOMARINE SEDIMENTS AND FORMATION OF THRUST-BLOCK MORAINES AT THE MARGIN OF SØRSDALE GLACIER, EAST ANTARCTICA

SEAN J. FITZSIMONS

Department of Geography, University of Otago, PO Box 56, Dunedin, New Zealand

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ABSTRACT

The morphology, sedimentology and structure of moraines at the margin of an outlet glacier in east Antarctica are described, and contemporary depositional processes in a marine inlet adjacent to the ice margin are examined. Results indicate that the principal moraines are thrust-block moraines produced by basal freezing and deformation of glaciomarine sediment as the outlet glacier expands into a marine inlet. Preservation of detailed glaciomarine sedimentary structures and beds of marine shells suggests that the sediment was frozen during entrainment, transportation and deposition. The presence of low-angle faults in the moraines show that the moraines consist of an *en echelon* arrangement of thrust plates. The sedimentology, structure, thickness of the thrust plates, and inferred entrainment processes are consistent with Weertman's ice–debris accretion hypothesis for debris entrainment at the edge of cold ice sheets. A model of thrust-block moraine development produced by this study provides a framework for the interpretation of radiocarbon dates from marine macrofossils in the moraines. The model may also be useful in the interpretation of similar moraines in coastal east Antarctic oases and other polar marginal marine environments.

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INTRODUCTION

In east Antarctica, glaciation and deglaciation of coastal oases appear to be achieved by marginal fluctuations of outlet glaciers (Fitzsimons, 1991). Together with ice shelves, outlet glaciers are the most sensitive elements of large ice sheets and respond relatively quickly to changes in climate and sea level. Former positions of outlet glaciers and ice shelves in coastal east Antarctic oases are established by dating marine macrofossils preserved in lateral moraines (Fitzsimons and Domack, 1993; Fitzsimons and Colhoun 1995). At Vestfold Hills in coastal east Antarctica (Figure 1), radiocarbon dates from moraines adjacent to the Sørsdal Glacier have produced anomalous ages. Figure 2 shows that the oldest date is from the moraine closest to the ice margin and the youngest date is from the outermost moraine. This unusual pattern could be explained in a number of ways, including contamination and reworking of the shells, and erosion and redeposition of glaciomarine sediment by the Sørsdal Glacier. The validity of the dates has been reported elsewhere (Fitzsimons and Domack, 1993). The primary purposes of this paper are to establish the glaciological and depositional processes involved in the formation of the moraines and to provide a framework for the interpretation of radiocarbon dates from moraines adjacent to east Antarctic outlet glaciers. Establishing these processes is a necessary step in the reconstruction of the late glacial and Holocene ice-margin fluctuations.

Understanding the glaciological processes and radiocarbon dates involves documenting the sedimentology and structure of the moraines, interpreting depositional environments, and explaining the glaciotectonic and thermal conditions during entrainment, transportation and deposition of the moraine debris. After the research methods and field area are described, the characteristics and age relationships of the moraines and glaciomarine

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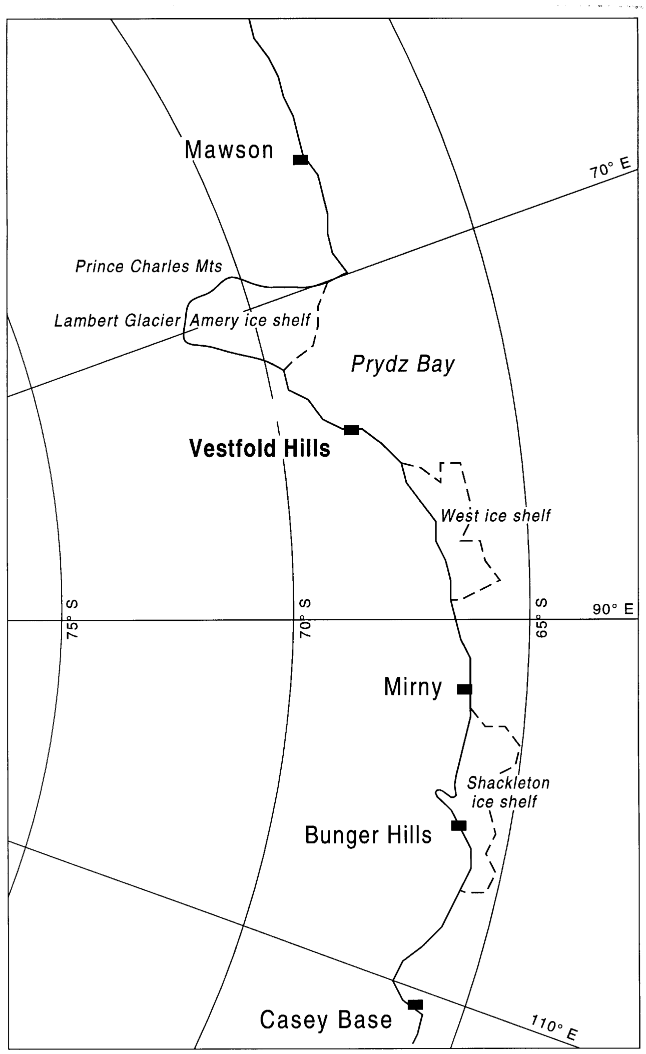

Figure 1. Location map of the Vestfold Hills oasis.

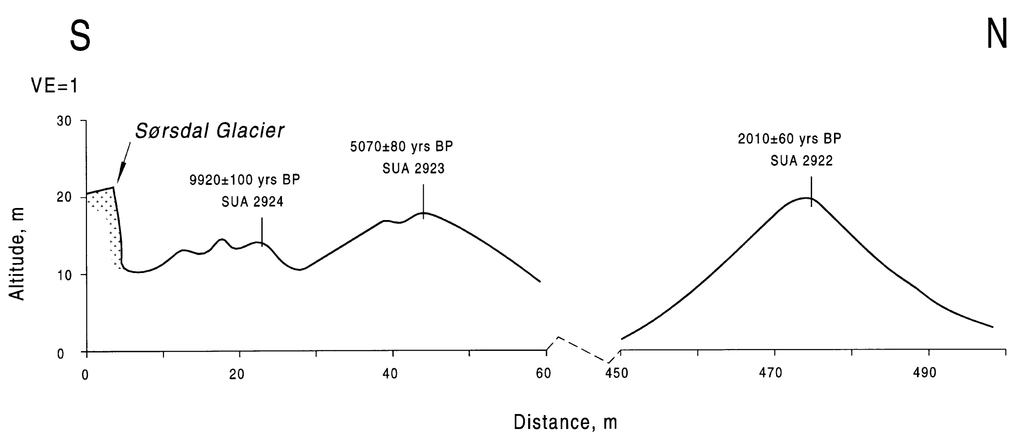

Figure 2. Profile of moraine ridges at the northern margin of the Sørsdal Glacier showing the location of three radiocarbon dates from layers of marine shells.

deposits are presented. This is followed by a consideration of the theoretical background to the entrainment of thrust blocks and presentation of a depositional model for the formation of those moraines.

FIELD AREA AND METHODS

The Vestfold Hills is a small (420 km^2) ice-free area in Princess Elizabeth Land (Figure 1). It is the third largest ice-free area in Antarctica, after the Dry Valleys of southern Victoria Land and the Bunger Hills of Wilkes Land. The mean annual temperature of Davis Station is –10·2°C (Schwerdtfeger, 1970) and the climate is, on average, warmer than other Antarctic stations of similar latitude (Burton and Campbell, 1980). Although there are no precipitation data, snowfall is believed to be light (<250 mm water equivalent). The Vestfold Hills form a complex low-relief topography up to 158 m a.m.s.l. on gneissic rocks. The landscape containes numerous fresh and saline lakes, accumulations of debris in the valley floors, and some moraine ridges. Contemporary depositional processes at the ice margin are controlled by the maritime climate of the terminus area which gives rise to widespread summer melting. In consequence, depositional processes are dominated by mass movements of glacigenic sediments (Fitzsimons, 1990).

To understand the origin of the moraines, exposures and pits dug in the crests of the moraines were examined in detail and sedimentary characteristics were recorded in the field in 1990 using the scheme described by Eyles *et al*. (1983). A wide range of data on sedimentary structures and characteristics of the sediments was recorded in order to characterize the lithofacies. The data included measurements of particle size, clast shape, lithology, sedimentary structures, glaciotectonic structures and pebble fabric. Pebble fabric in diamicts was measured from the orientation and dip of prolate-shaped clasts greater than 2 cm in length. Measurements were plotted on lower hemisphere Schmidt nets and contoured according to the method of Kamb (1959). The data were analysed using the eigenvector method of Mark (1973), where eigenvector V_1 gives the direction of maximum clustering and V_3 indicates the direction of minimum clustering and is perpendicular to both V_1 and V_2. Normalized eigenvalues or significance values, S_1, S_2, S_3, indicate the degree of clustering of the eigenvectors V_1, V_2, V_3, and are calculated by dividing the eigenvectors by the total number (N) of sample measurements. Particle size analyses on samples from the major facies types were performed using sieves and a hydrometer. Shells in growth position and worm tubes from laminated glaciomarine sediments were collected and sent to the University of Sydney radiocarbon laboratory. An Antarctic reservoir correction of 1300 years, based on dating of living organisms by Adamson and Pichard (1986), was applied.

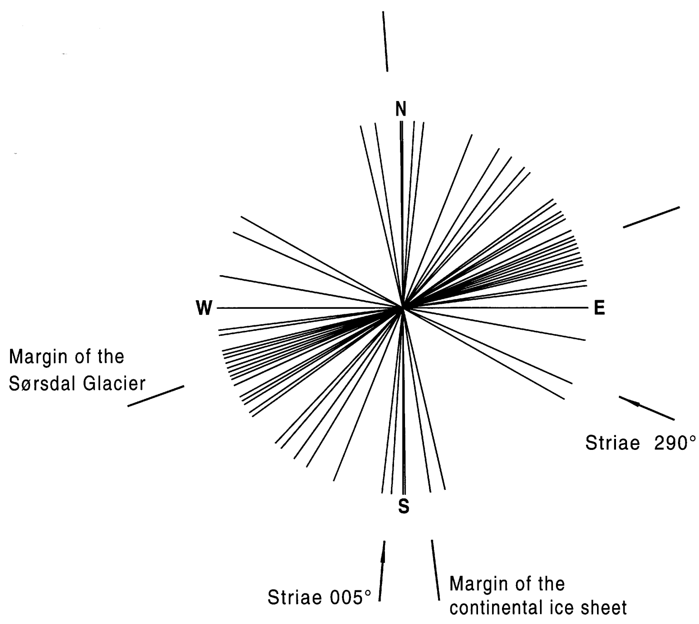

Figure 3. Trends of the principal moraine ridges of the Vestfold Hills together with the trend of the margin of the Sørsdal Glacier and the margin of the continental ice sheet.

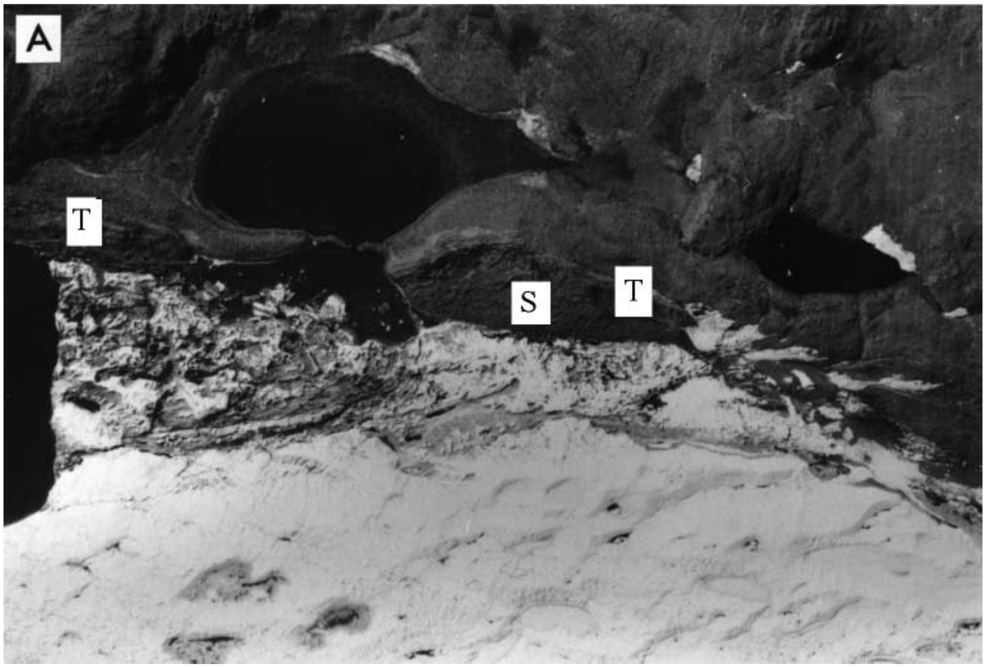

Figure 4. (A) Vertical aerial photograph of moraines on the shore of a marine inlet adjacent to the margin of the Sørsdal Glacier. The rounded ridge that forms the small embayment is older than the moraine with the tension cracks (T) and slumped surface (S). The oval marine inlet is 300 m wide. (B) Thrust-block moraines adjacent to the edge of the Sørsdal Glacier showing the topographic expression of the *en echelon* arrangement of the thrust blocks. The depression between the ridges is 1·5 m deep.

RESULTS

Measurements of strikes of the moraine ridges show a multimodel distribution (Figure 3). One principal direction is parallel to the northern margin of the Sørsdal Glacier, a relatively fast-flowing outlet glacier (c. 600 m a^{-1}) that has a floating margin. The second is parallel to the edge of the continental ice sheet which flows relatively slowly (<1 m a^{-1}). Several moraines of different ages are recognizable at the ice margin (Figure 4). Moraines close to the ice margin are distinguished by tension cracks and slumping on the surface of the ridges, features which indicate the presence of an ice core (Figure 4).

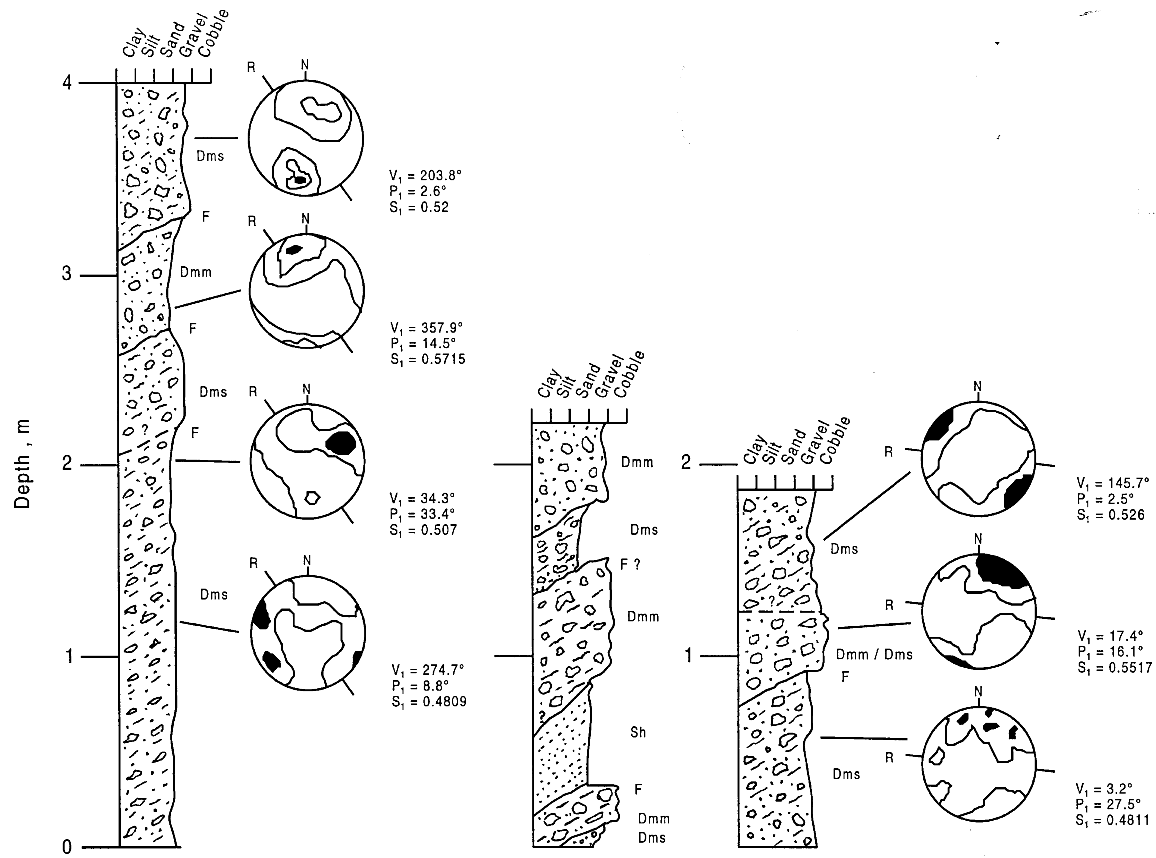

Figure 5. Graphic sedimentary logs of sections in the thrust-block moraines. The contour interval of the Schmidt nets is two standard deviations. V_1 and P_1 give the azimuth and plunge of the principal eigenvector, respectively, and S_1 gives the strength of clustering about the principal eigenvector.

Sedimentology and structure of the moraines

Exposures show that moraine sediment consist of two basic facies: stratified diamicts (Dms) and massive diamicts (Dmm; Figure 5). The dominant facies is a matrix-supported, stratified diamict with a mud matrix and particles up to 0·7 m in diameter (Figure 6A). Stratified diamicts range from relatively undeformed sediments, consisting of laminated mud with dropstones, to highly deformed sediments. Deformation structures observed in stratified diamicts range from gentle warping to boudinage and intense folding. Several beds of intact shells occur in the stratified diamict, and many larger clasts have intact worm tubes cemented to their surfaces. Shell fragments occur throughout the deposits. Particle size analysis of the stratified diamicts shows that they are very poorly sorted and some samples consist of more than 50 per cent mud (Figure 7).

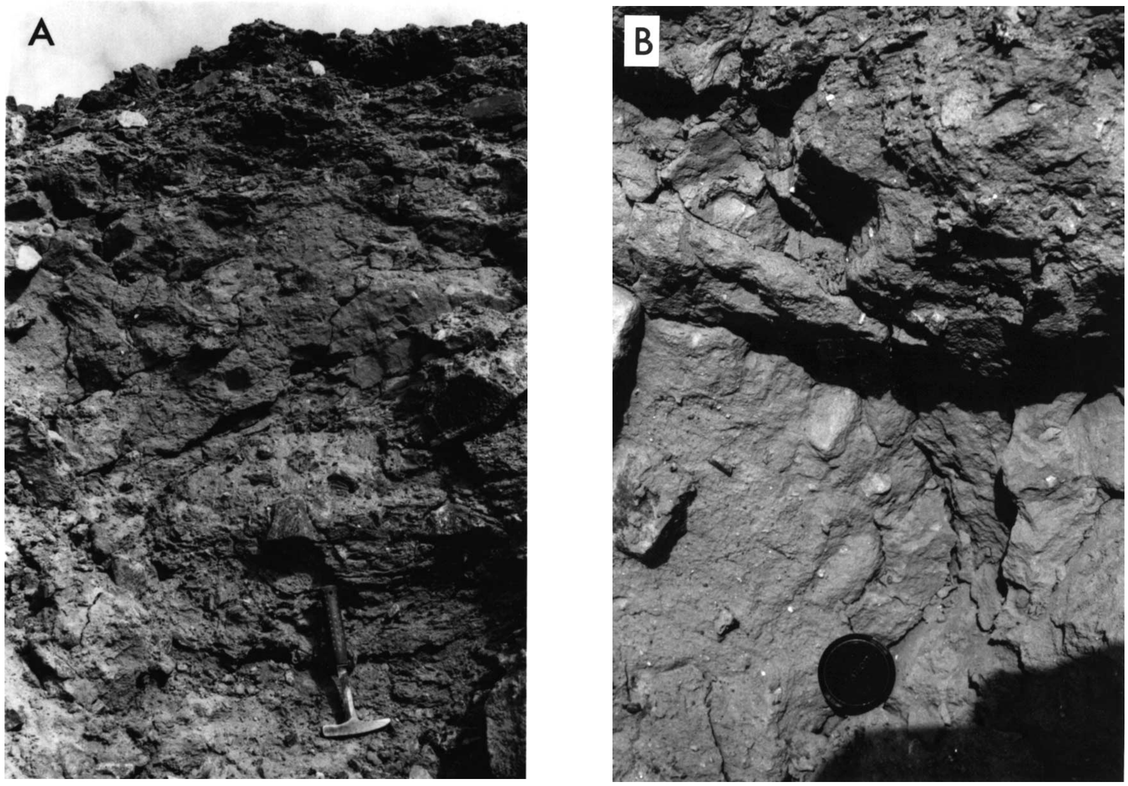

Figure 6. Moraine sediments. (A) Mud-rich stratified diamict adjacent to the hammer, overlain by massive diamict and stratified diamict. (B) Massive, mud-rich diamict; the area in shadow is a low-angle fault that represents the contact between two separate thrust blocks.

Massive, matrix-supported diamicts are also common in the moraines (Figure 5), and consist of structureless, fine-grained sandy mud with ‘floating’ gravel clasts (Figure 6B). This facies has striated clasts up to 0·8 m in diameter and abundant shell fragments dispersed in the matrix. These diamicts are very poorly sorted and contain 20 to 30 per cent mud (Figure 7).

The pebble fabrics of both the stratified and massive diamicts are weak, with S_1 values less than 0·7 (Figure 5, Table I). Stronger fabrics occur near faults that penetrate the moraine (Figure 6B) where the diamicts have been attenuated by shearing. These attenuated diamicts have fabrics with values greater than 0·7 and plot separately from the remainder of the fabric data (Figure 8). Faults that penetrate the moraine dip at 30 to 50° in an up-glacier direction (Figure 6B). They are expressed as well-preserved planar surfaces, some of which are grooved by slickensides separating diamict units that average about 0·5 m thick (Figure 5). The faults are oblique both to the bedding and to the trend of the moraine ridges (Figure 9).

Age relationships

A series of moraines at the margin of the Sørsdal Glacier record former positions of the ice edge and recent retreat from the outer moraine, which is about 500 m from the ice edge (Figure 4).

Radiocarbon dates from *Laternula* shells in glaciomarine sediment in the moraines give ages of 9920±100 a BP (SUA 2924) from a ridge about 20 m from the ice edge, 5070±80 a BP (SUA 2923) from a ridge about 40 m from the ice edge, and 2010±110 a BP (SUA 2922) from a ridge about 500 m from the ice edge (Figure 2). Because the ridges have not been overridden since they formed, the moraine closest to the ice edge is the youngest and moraine farthest from the ice is the oldest. However, the oldest radiocarbon date comes from material in the youngest moraine and the youngest date comes from the oldest, outermost moraine. This can be explained by episodic entrainment and redeposition of the fjord-bottom sediment as the outlet glacier fluctuates (Fitzsimons and Domack, 1993). The dates therefore do not reflect the age of the moraines, but record glaciomarine sedimentation when marine organisms grew in open water or under thin floating ice. Using an

Table I. Statistical summary of the pebble fabric analysis

Lithology	Sample site	V_1	Azimuth/plunge (°)	S_1	S_2	S_3
Massive diamict	F12	275	9	0·481	0·281	0·238
	F13	341	39	0·459	0·287	0·254
	F14	204	3	0·520	0·338	0·142
	F15	358	14	0·572	0·252	0·177
	F16	34	33	0·507	0·311	0·181
	F17	146	3	0·526	0·337	0·137
	F18	17	16	0·552	0·354	0·094
	F19	3	27	0·481	0·301	0·218
	F22	231	37	0·519	0·297	0·184
	F23	141	28	0·674	0·267	0·059
	F25	329	17	0·698	0·207	0·096
Attenuated diamict	F21	329	37	0·725	0·207	0·068
	F24	162	43	0·855	0·120	0·025
	F26	125	29	0.8	0·145	0·055
	F27	171	30	0·749	0·196	0·055

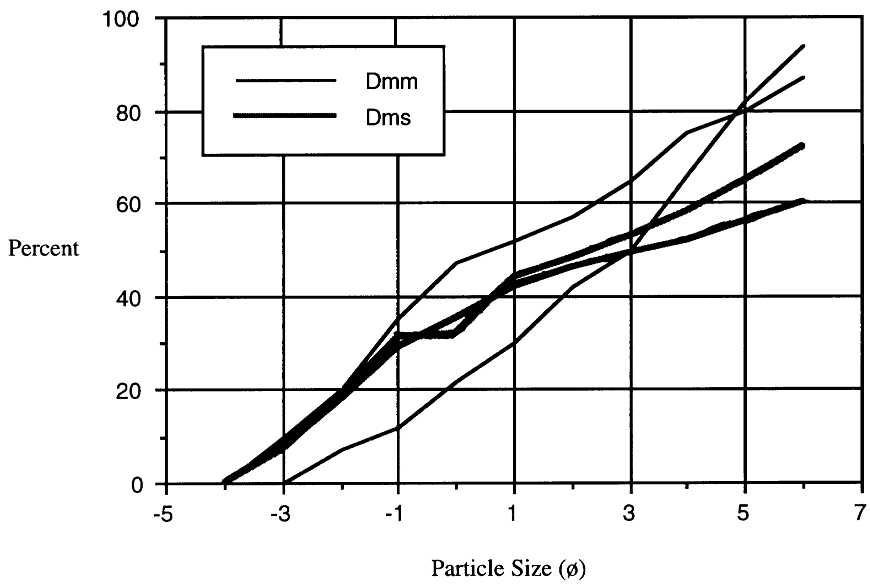

Figure 7. Particle size distributions of massive diamicts (Dmm) and stratified diamicts (Dms).

Antarctic reservoir correction of 1300 years, the three dates show that the margin of the Sørsdal Glacier was at or south of its present position by 8600 a BP and that the entire set of ridges post-dates 700 a BP. These moraines and dates suggest that the most responsive part of the ice edge, the outlet glacier, has been relatively stable throughout much of the Holocene.

DISCUSSION

Interpretation of the field data

The deposits are interpreted as glaciomarine sediments that have been entrained by an advancing ice margin as frozen blocks of substrate, and deposited on the distal shore of fjords as thrust-block moraines. The key questions in the interpretation of the deposits are the origin of the sediments and sedimentary structures, and the processes of entrainment, transportation and deposition of the moraines.

The dominance of stratified diamicts, together with the widespread occurrence of shell fragments, shell beds and worm tubes cemented to boulders, shows that the sediments were deposited in the sea adjacent to an ice margin. Low pebble fabric strength and the lack of preferred orientations parallel to the ice-flow direction are

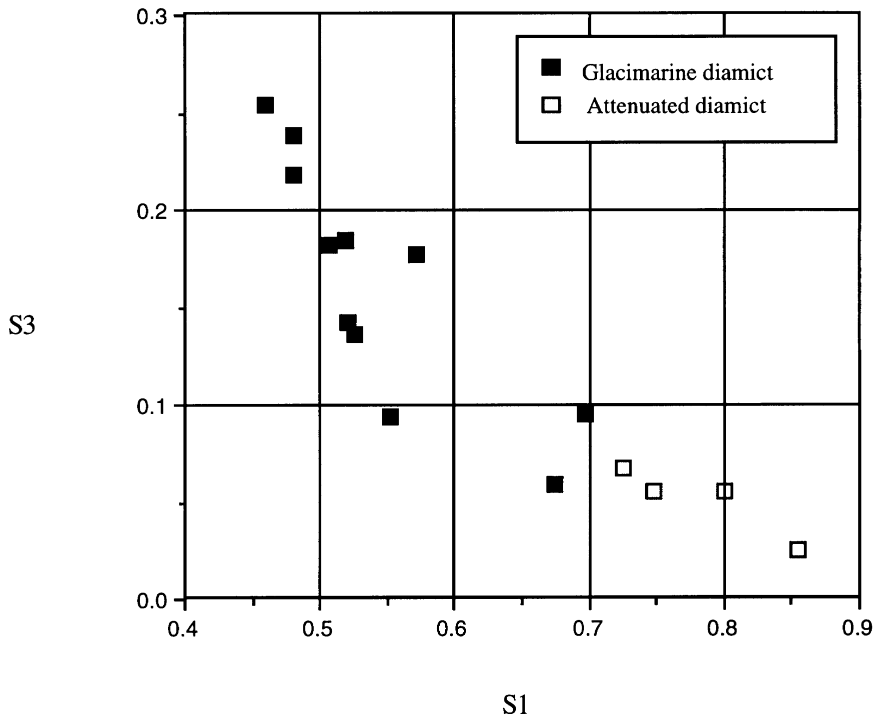

Figure 8. Comparison of the statistical distributions of pebble orientations of massive diamict, stratified diamicts and attenuated diamicts that have been deformed by overriding ice.

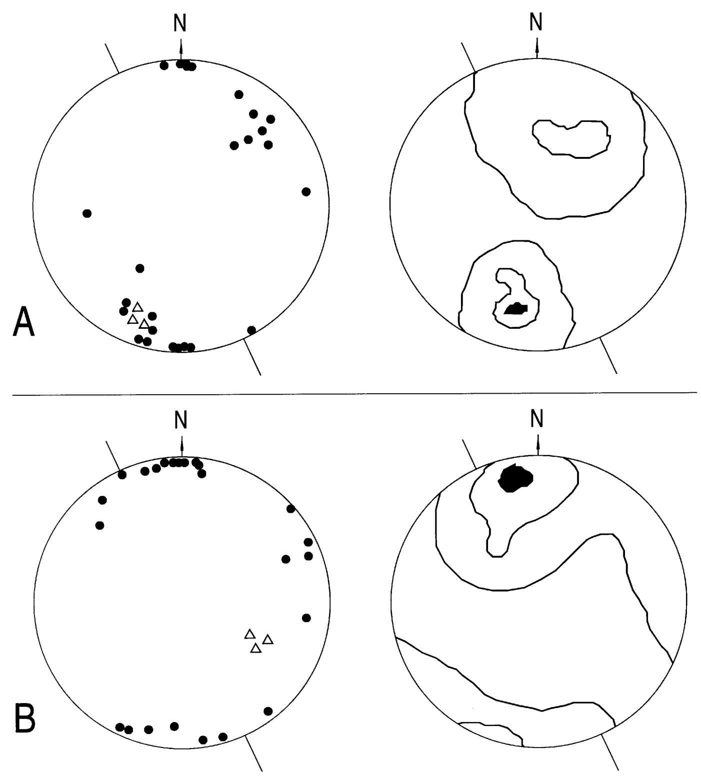

Figure 9. Scatterplots and contoured Schmidt equal-area nets for pebble orientations of faulted diamicts. Poles to the faults are shown by triangles and the trend of the moraine ridge by lines outside the net. The contour interval is 2 σ.

Table II. Average eigenvalue data for different types of deposits

Till type	S_1		S_3	
	Mean	s.d	Mean	s.d
Glaciomarine diamict (this study)	0·544	0·077	0·162	0·062
Ice-rafted diamict (Domack and Lawson, 1985)	0·543	0·075	0·155	0·054
Attenuated diamict (this study)	0·758	0·038	0·059	0·007
Lower sheared till (Allen *et al.*, 1991)	0·768	0·06	0·057	0·02
Upper sheared till (Allen *et al.*, 1991)	0·719	0·02	0·073	0·01
Thin deforming layer Fjallsjökull, Iceland (Hart, 1994)	0·847	–	0·001	–

consistent with this interpretation. In their study of the pebble fabric of ice-rafted diamicts, Domack and Lawson (1985) concluded that ice-rafted debris produces a distinct fabric signature characterized by the absence of preferred orientations, little consistency in vector orientation between sites, and a lack of a relationship to ice-flow direction. Comparision with data from Domack and Lawson (1985) shows these deposits have very similar characteristics and suggests that the glaciomarine deposits have formed by ice rafting or perhaps slumping from the ice margin (Table II).

The highest Holocene raised beach deposit in the Vestfold Hills is only 6 m above sea level (Adamson and Pickard, 1986). The Holocene age of the glaciomarine sediment, together with its position up to 20 m above sea level, indicates that the deposits have been lifted from the adjacent fjord floor. Preservation of fine laminations and beds of shells in the sediments indicates that the sediment was eroded and transported as blocks. Absence of deformation within the blocks is interpreted to mean that the sediments were frozen when entrained by the glacier.

Low-angle faults, together with slickensides and attenuated diamicts adjacent to the faults, show that the glaciomarine sediment has been entrained as a series of blocks with an average thickness of about 0·5 m (Figure 5). The reverse order of the dates and moraines (Figure 2) shows that the moraines have accumulated as successively older glaciomarine sediments were eroded from the floor of the fjord and deposited on the distal shore. Pebble fabric of the attenuated glaciomarine sediment can be compared to fabrics of sheared tills (Table II). Attenuated diamicts have high fabric strength (average S_1 = 0·758, S_3 = 0·059), which is similar to a thin deforming layer at Fjallsjökull in Iceland (S_1 = 0·847, S_3 = 0·001 (Hart, 1994)) and the Lower Sheared Till described by Allen *et al*. (1991) (S_1 = 0·768, S_3 = 0·057), all of which are considerably greater than for undeformed glaciomarine sediment (Table II). Pebbles in the attenuated diamicts were probably realigned as the block was sheared where it was detached from its substrate or at the contact with the ice, resulting in increased fabric strength.

Most thrust-block moraines have been deposited on the distal shores of fjords or valley sides where the outlet glacier flowed out of a sediment-filled depression. The ridges are composed of an *en echelon* arrangement of a series of well-preserved, imbricate slabs that form the structural framework of the moraines (Figure 4B). Moran *et al*. (1980) suggest that if thrust blocks are deposited near the site of thrusting, the blocks will be preserved in a relatively unmodified condition, but where they are deposited more than 2 km from the site of entrainment, the thrust sediment is likely to be deformed and primary structures destroyed. In ice-marginal sediments of former glaciers in North America and Europe, most glaciotectonic thrusting occurs in a proglacial location. Overriding leads to subglacial shearing and penetrative deformation of the thrust mass (Moran *et al*., 1980; Aber, 1982; van der Wateren, 1985; Evans, 1989).

The interpretation outline above hinges on the formation of thrust blocks that are detached and entrained by basal freezing. The problem of how relatively large masses of unconsolidated substrate can be incorporated into glaciers, and the processes involved in detachment and entrainment are explored below.

Theory

A mechanism for large-scale freezing of sediment to the base of terrestrial ice has been proposed by Weertman (1961). It is an ice and debris accretion model that depends on the relation between the 0°C isotherm and the glacier bed. When the 0°C isotherm coincides with unconsolidated material forming the glacier bed, the material is frozen onto the bottom of the ice sheet. However, Weertman concluded that there was insufficient field data to prove conclusively that moraines have formed in this way. Moran (1971) and Moran *et al*. (1980) used Weertman's hypothesis to explain the glacial geomorphology and glaciotectonic structures of the prairie area of North America. They suggest that basal melting beneath thick ice could increase pore-water pressures in unfrozen sediment, thereby decreasing shear strength and allowing the glacier to lift large blocks of sediment into flowing ice. Under steady-state conditions, the heat flow at the bottom of an ice sheet is given by Weertman as:

$$k\gamma = Q_g + Q_s + LA \tag{1}$$

where k is the coefficient of heat conductivity of ice, γ represents the vertical temperature gradient at the bottom surface, Qg is the geothermal heat, Qs is the heat of sliding, L is the latent heat of fusion, and A is the thickness of ice/sediment being frozen to or melted from the bottom surface.

Measurements and interpretation of the thrust-block moraines in the Vestfold suggest that the maximum thickness for individual thrust blocks is around 0·5 m. The thickness of material being frozen to the glacier bed can be examined by rearranging Equation 1:

$$A = \frac{k\gamma - Q_g - Q_s}{L} \tag{2}$$

Thus, for a glacier with a given velocity, the thickness of the material refrozen to the glacier bed (A) will be directly proportional to the vertical temperature gradient at the bottom surface (γ). Consequently, the thinner parts of an ice sheet are more likely to be in a freezing zone. Although γ is unknown at this location, it can be estimated using a relationship derived by Robin (1955):

$$\gamma = \frac{\Delta T}{h^*} \tag{3}$$

where ΔT is the temperature difference between the top and bottom ice surfaces, h^* is a 'compensated' thickness, which is equal to the actual thickness of the ice sheet if there is no melting or freezing at the bottom surface. For the Sørsdal Glacier, a surface temperature of −10°C and a bottom surface temperature of about 0°C is realistic, because in polar glaciers ice temperature at a depth of 10 m closely correlates with mean annual air temperature (Andrews, 1975). At the edge of the glacier, where the ice is 100 m thick, the vertical temperature gradient through the bottom surface (γ) is 1°C m^{-1}.

Using values of $1{\cdot}7\times10^5$ cal^{-1}°C for k, 72 cal cm^{-3} for L, 13 to 190 cal cm^{-2} a^{-1} for Qs, 39 cal cm^{-2} a^{-1} for Qg (Weertman, 1961), and 1°C m^{-1} for γ, a thickness of around 20 cm a^{-1} of debris could be entrained by the glacier. The 0·5 m thick thrust blocks observed in this study are consistent with the theory of ice–debris accretion outlined by Weertman.

While the freezing model outlined above explains the potential for the development of thrust-block moraines, the development of a shear surface in unconsolidated substrate must also be considered. Proglacial thrusting has been attributed to rising pore-water pressure in the substrate and/or failure along a decollement layer which may develop within or at the base of the permafrost, segregated ice lenses in the substrate, or clay layers in permafrost (Mathews and Mackay, 1960).

In the steady-state relationship outlined by Equations 1 and 2, the entrainment of sediment depends on the position of the 0°C isotherm with respect to the bottom of the ice mass. If the 0°C isotherm lies below the ice base, and is in unconsolidated sediment, the frozen block of sediment can be detached along the frozen–unfrozen boundary. However, the difficulty is that the shear strength of most unconsolidated sediment is generally considerably greater than the shear stress exerted by ice (Moran *et al*., 1980; Paterson, 1981; Drewry,

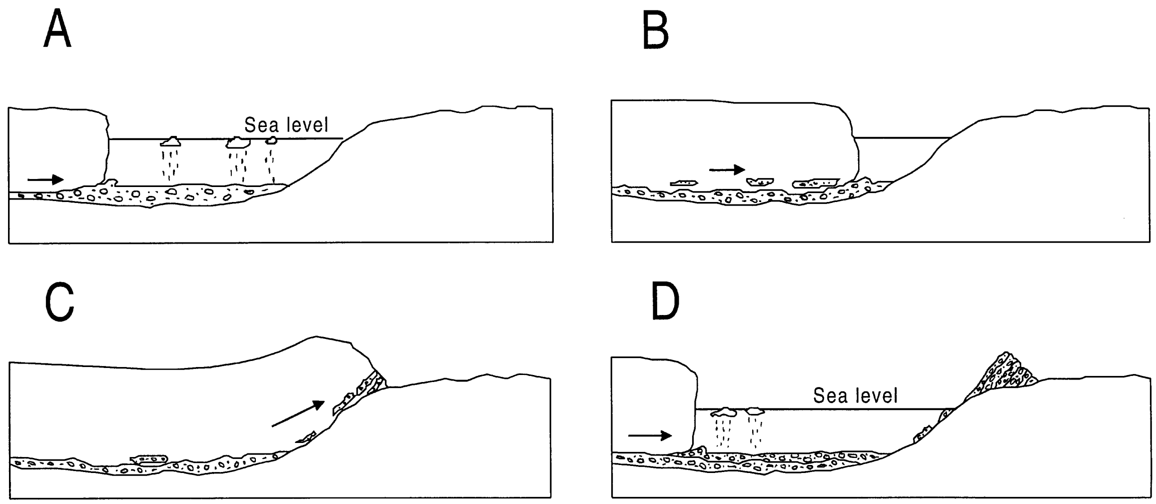

Figure 10. Depositional model for the formation of thrust-block moraines at the margins of outlet glaciers: (A) open-water glaciomarine deposition prior to ice advance; (B) ice advance, localized freezing of unconsolidated substrate and detachment of frozen slices of glaciomarine sediment; (C) transportation of the frozen thrust block away from the site of entrainment; (D) deposition of the thrust blocks by imbricate stacking on the shore of a marine inlet.

1986). Boulton (1972) suggests that debris can be entrained in this situation if the 0°C isotherm does not lie far beneath the glacier bed, particularly if lithologic planes of weakness coincide with the 0°C isotherm or if frictional resistance is reduced by high water pressures. Both could explain the failure of the sediments described in this study. Unconsolidated, mud-rich, glaciolacustrine sediment has very low shear strength, which could permit the formation of thrust blocks (Moran *et al.*, 1980). In addition, elevated pore-water pressures could be generated in the glaciomarine sediment as the 0°C isotherm penetrates the saturated sediment and drives pore water against underlying rock or permafrost. However, these suggestions cannot be substantiated from the field evidence.

Although the field evidence provides no indication of how quickly the material is likely to be entrained, observations over a number of years show that annual moraines do not form. The principal moraines adjacent to the Sørsdal Glacier date to ice-margin fluctuations within the last thousand years.

Depositional model

The depositional setting, in which the sediments described in this study formed, is the margin of an outlet glacier that flows across a fjord or valley. Figure 10 is a model of the processes associated with the formation of thrust-block moraines closest to the Sørsdal Glacier. The first part of the model shows the margin of an outlet glacier adjacent to a marine inlet prior to advance, when sediments accumulate in the marine inlet from marginal melting of basal debris and ice rafting (Figure 10A). As the ice advances, glaciomarine sediments are deformed and the thermal mass of the cold-based marginal ice causes freezing in the surface layers of the glaciomarine sediment (Figure 10B). Although the mechanism of detachment of the blocks cannot be clearly established from the field evidence, it is likely to involve failure at the 0°C isotherm or along a lithological discontinuity, or both. The entrained frozen blocks are transported from the site of erosion towards the distal shore of the marine inlet (Figure 10C). As the blocks reach the ice edge they are deposited in *en echelon* arrangement on the distal shore. This forms a discontinuous ridge that consists of a series of stacked thrust plates (Figure 10D). When the ice retreats, sea water reoccupies the inlet and glaciomarine sedimentation resumes.

CONCLUSIONS

1. The principal moraines in the Vestfold Hills are thrust-block moraines produced by the outlet glacier, which is the most responsive part of the glacial system.

2. The thrust-block moraines consist of an *en echelon* arrangement of thrust plates which are up to 0·5 m thick. They have formed as glaciomarine sediment is entrained by basal freezing and thrusting.
3. Well-preserved sedimentary structures, and lack of deformation of the glaciomarine debris except at the upper and lower surfaces of the thrust blocks, shows that the material was frozen during entrainment, transportation and deposition and that the blocks have probably travelled less than 2 km.
4. The sedimentology, structure, thickness of the thrust plates, and inferred entrainment processes are consistent with Weertman's (1961) hypothesis of large-scale basal freezing.
5. Radiocarbon dates from intact shells and worm tubes record sedimentation in the fjord, rather than the age of moraine formation, and show that morainic materials within 2 km of the ice margin have been entrained and deposited within the last thousand years. The pattern of radiocarbon dates suggests progressive erosion of sediments beneath the ice and the existence of discrete thrust blocks suggests episodic entrainment.
6. The model developed from this study of thrust-block ice-shelf moraines provides a framework for the investigation of similar moraines in coastal Antarctic oases and other high-latitude areas.

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