Dirt pictures reveal the past extent of the grounded Antarctic ice sheet

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5. QUATERNARY SEDIMENTS OF MARGUERITE BAY, ANTARCTIC PENINSULA, FROM A MICROSCOPIC POINT OF VIEW - THE DISTINCTION BETWEEN DIAMICTS IN THE GLACIGENIC SEDIMENTARY RECORD

Abstract - Micromorphological analyses were carried out on a selection of thin-sectioned intervals of Deep Freeze 1985 cores from Marguerite Bay, Antarctic Peninsula, to provide more reliable interpretations with respect to the local Quaternary glacial history. Results show that both pristine glaciomarine and deformed glaciomarine deposits are preserved in the sedimentary record. Deformation was determined to be either the result of gravity-driven movements of sediment, subglacial shearing, or coring imperfections. Subglacially deformed sediments were found in the southwest part of the bay, which indicates the former presence of a grounded ice sheet, at least in this region of the Marguerite Bay continental shelf.

In review with Arctic, Antarctic and Alpine Research.

INTRODUCTION

Since Mercer (1978) postulated that the deterioration of ice shelves in the Antarctic might be related to a CO$_2$-induced atmospheric warming, glaciological research focused on monitoring the ongoing disintegration of floating ice around the Antarctic Peninsula. Mercer's 'prophecy' that the loss of ice shelves might eventually affect the stability of the West Antarctic Ice Sheet focussed interest on this problem over the last two decades.

Marguerite Bay plays a key role in investigations of growth and decay of ice shelves as it is situated at the transition between the temperate/sub-polar glacial regime of the northern Antarctic Peninsula and the true polar regimes of the southern Peninsula and West Antarctica (Fig. 5.1). With a Mean Annual Air Temperature between -5$^\circ$C and -8$^\circ$C, the area is right at the present-day ice shelf limit (Scambos and Vaughan, 1999). Therefore, local glacier dynamics may be regarded as being extremely sensitive to climatic fluctuations (cf. Doake, 1982; Doake and Vaughan, 1991). Marguerite Bay currently contains two ice shelves: the George VI Ice Shelf, which occupies the trench separating Alexander Island from Palmer Land, and the Wordie Ice Shelf, which drains several Palmer Land glaciers.

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FIGURE 5.1. Map of the Marguerite Bay area with core locations (after Kennedy and Anderson, 1989); DF 1985 station numbers.

To predict future developments of the ice sheet it is useful to consider former glacier dynamics in the area as well. Forecasts tend to become more accurate with the implementation of ‘historical information’ simply because long-term records provide better insight in the behaviour of the ice sheet in time. Two relevant studies that addressed the Quaternary glacial history of the area are those of Clapperton and Sugden (1982) and Kennedy and Anderson (1989). Clapperton and Sugden proposed a reconstruction of Late Quaternary glacier fluctuations in George VI Sound on basis of onshore geomorphological and sedimentological data, whereas Kennedy and Anderson
analysed seismic profiles and short sediment-cores from the Marguerite Bay continental shelf and arrived at a reconstruction of the glacial history for the bay. Because reconstructions from sedimentological and geomorphological 'end products' necessarily involve assumptions regarding processes that have taken place in the past, there will always be questions in terms of the validity of such reconstructions. One of the most persistent problems that emerge when analysing a glacigenic record from sediment-cores, is that of the possible ambiguity in interpretation of diamicts. Several studies have shown that glacimarine diamicts deposited close to an Antarctic grounding line macroscopically may be indistinguishable from basal tills and, furthermore, that distinguishing gravity-driven deformation from subglacial deformation in diamicts may not always be straightforward (e.g., Kurtz and Anderson, 1979; Anderson et al., 1980; Licht et al., 1999). Kennedy and Anderson (1989) also encountered such problems in their analyses of the cores from Marguerite Bay.

This ambiguity in the interpretation of diamicts in the Marguerite Bay sedimentary record is the main reason for carrying out the present study. Eight representative thin sections of Deep Freeze 1985 cores - the same that were investigated by Kennedy and Anderson (1989) - were analysed micromorphologically to provide more conclusive evidence regarding the origin of the glacigenic sediments. Micromorphology was applied because earlier publications had shown that the technique has the potential of delivering essential, independent information where conventional techniques are inconclusive (e.g., Carr, 1999; Hiemstra, 1999; Hiemstra and Van der Meer, 1997; Kluiving et al., 1999; Menzies, 1998; Menzies and Maltman, 1992; Van der Meer, 1987; 1993; 1997; Van der Meer and Hiemstra, 1998).

PREVIOUS QUATERNARY GLACIAL STUDIES IN THE GREATER MARGUERITE BAY AREA

The reconstruction of glacier movements in Marguerite Bay by Clapperton and Sugden (1982) was based on interpretations of data from Alexander Island (Fig. 5.1). A diamict on the southernmost part of the island was interpreted as a till derived from Palmer Land. Shell fragments occurring in this diamict led Clapperton and Sugden to infer that George VI Sound must have been ice-free prior to an occupation by grounded ice. They suggested that 'Palmer Land ice', while flowing across the sound, must have incorporated shells in its basal debris, which was subsequently deposited on the island. Though dating of the shell fragments proved to be difficult, the glacial expansion was
assumed to correspond to the LGM.

‘Ice shelf moraines’ (Clapperton and Sugden, 1982) in the central shore-region of Alexander Island account for the idea that the stage of grounded ice was followed by an ice shelf period, cautiously dated at 12-10 ka BP (Clapperton and Sugden, 1982). This ice shelf was probably not the same as the current because shell fragments from a younger ice shelf moraine were dated at 6.5 ka BP. George VI Sound must consequently have been ice free approximately 6500 years ago (Sugden and Clapperton, 1981; Clapperton and Sugden, 1982).

Kennedy and Anderson (1989) focussed on the Marguerite Bay area itself (Fig. 5.1). Their reconstruction starts with ‘circumstantial’ evidence for grounded ice in the bay. They argued that the general lack of sediment cover over acoustic basement in seismic profiles represents a major erosional event. They propose a temperate ice sheet that removed most previously deposited sediments and that deposited these re-mobilised sediments beyond the shelf break.

Thin remnants of these sediments were sampled from the continental shelf during the Deep Freeze 1985 cruise. Diamictic sediments in three of the cores recovered from the south-western region of Marguerite Bay (DF 85-115, 116, 118) would according to Kennedy and Anderson (1989) qualify as basal tills, which seems to directly support their grounded ice idea. Constituents in these diamicts point to a ‘derivation’ from lithologies occurring in the north of Alexander Island.

Kennedy and Anderson interpreted sediments directly overlying the ‘basal tills’ as being transitional glacimarine in origin, that is, they envisage deposition proximal to a grounding line (cf. Anderson et al., 1980; Bryan, 1993). Fine-grained terrigenous and biogenic deposits that top the transitional facies were interpreted as distal glacimarine facies. The succession as a whole would represent a retreat from grounded ice to a slowly disappearing ice shelf, to a stage of permanent pack ice and, finally to modern ‘seasonal ice cover sedimentation’ (Kennedy and Anderson, 1989; also see Anderson et al., 1991).
FOCUS ON PREVIOUS STUDIES

In spite of the fact that the results of the studies by Kennedy and Anderson (1989) and Clapperton and Sugden (1982) are largely compatible, I would argue that particularly the interpretations of the Marguerite Bay diamicts require testing using micromorphological analysis.

Kennedy and Anderson (1989) made use of the diamict classification method in Bryan (1993). In this scheme basal tills are suggested to have random pebble fabrics, rounded pebble shapes, textural and mineralogical homogeneity, and no sorting or stratification. Combined with specific geotechnical characteristics and the absence of intact marine fossils, these criteria were applied to differentiate between glacimarine and subglacial sediments.

No matter how elaborate this list may seem I would argue that in macroscopic practice the two types are often very similar (also see Licht et al., 1999). Glacimarine deposition in close proximity to a grounding line may produce diamicts that possess most, if not all of the discriminating basal-till-characteristics of the Bryan (1993) classification scheme. Perhaps more importantly, sediments that were deposited in a glacimarine environment may subsequently have been modified by overriding ice (Van der Meer and Hiemstra, 1998; Hiemstra, 1999). Dependent on how and to what degree primary sedimentary characteristics are retained in this process, the often deformed, overridden sediments macroscopically may still look like glacimarine deposits, whereas they should be classified as basal tills (cf. Dreimanis, 1988; Van der Meer et al., 1994).

Kennedy and Anderson (1989) obviously encountered such problems in Marguerite Bay. However, they made rather ‘definitive’ inferences regarding the origin of diamicts. Evaluating their arguments, it appears that because other criteria were not diagnostic, the geotechnical properties of sediments were often the decisive criterion in their interpretations. Kennedy and Anderson followed the principle that due to the weight of the overlying ice mass, basal tills are likely to be ‘overconsolidated’, which in turn is likely to be ‘reflected’ in high cohesive and high compressive strengths (Anderson et al., 1980; Domack, 1982).

To indicate that the spread between the multivariate groups (parameterised by both cohesive and compressive strengths) may not be sufficient to guarantee a ‘reliable’ subdivision into glacimarine and subglacial sediments, it is noted that the ranges of individual parameters show absolute overlaps of the order of 50 % (p.268 in Kennedy and Anderson, 1989). Although this overlap is obviously not a good statistical measure...
of the discriminative power because values are not normally distributed, misclassifications cannot be ruled out. When taking into account too that basal tills are not necessarily overcompacted (Alley et al., 1989; Kluiving et al., 1999), the actual number of occasions where glaciomarine sediments have wrongly been qualified as basal tills, or vice versa, may be considerable.

MICROMORPHOLOGICAL ANALYSES

As described in the introduction, micromorphological studies may be very useful in cases where standard sedimentological techniques do not provide definitive interpretations of sediment genesis.

Kennedy and Anderson (1989) postulated that sediments from the east, central and southwest regions of Marguerite Bay have different ‘glacial signatures’, i.e. that the sediments represent varying depositional environments. Using their reconstruction as a guide, eight samples of predominantly diamictic composition were selected to represent these regions (Table 5.1; Fig. 5.1). The lengths of the samples range from 12 to 18 cm and the width of each is about 5 cm (the width of the core). Structural analyses were carried out using a Leica™ microscope at magnifications up to 35 times. Terminology used in descriptions of the thin sections follows that proposed by Brewer (1976). In an outline of the technique of micromorphology, Van der Meer (1996) showed that this terminology, which was originally formulated for soils, is also applicable in describing sediment thin sections.

TABLE 5.1. List of thin sections

<table>
<thead>
<tr>
<th>Sample</th>
<th>Core</th>
<th>Interval</th>
<th>Depth</th>
<th>Region</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.348</td>
<td>DF 85-76</td>
<td>52-67 cmbsf</td>
<td>594 m</td>
<td>East</td>
<td>68°05.4' S</td>
<td>68°07.5' W</td>
</tr>
<tr>
<td>C.349</td>
<td>DF 85-77</td>
<td>19-31 cmbsf</td>
<td>316 m</td>
<td>East</td>
<td>68°05.1' S</td>
<td>67°52.5' W</td>
</tr>
<tr>
<td>C.350</td>
<td>DF 85-82</td>
<td>35-47 cmbsf</td>
<td>275 m</td>
<td>East</td>
<td>68°14.4' S</td>
<td>67°30.2' W</td>
</tr>
<tr>
<td>C.568</td>
<td>DF 85-125</td>
<td>70-85 cmbsf</td>
<td>558 m</td>
<td>Central</td>
<td>68°13.9' S</td>
<td>69°40.7' W</td>
</tr>
<tr>
<td>C.569</td>
<td>DF 85-126</td>
<td>58-70 cmbsf</td>
<td>860 m</td>
<td>Central</td>
<td>68°10.3' S</td>
<td>69°41.0' W</td>
</tr>
<tr>
<td>C.351</td>
<td>DF 85-117</td>
<td>87-105 cmbsf</td>
<td>503 m</td>
<td>Southwest</td>
<td>68°29.7' S</td>
<td>70°12.5' W</td>
</tr>
<tr>
<td>C.566</td>
<td>DF 85-116</td>
<td>93-108 cmbsf</td>
<td>650 m</td>
<td>Southwest</td>
<td>68°29.0' S</td>
<td>70°36.0' W</td>
</tr>
<tr>
<td>C.567</td>
<td>DF 85-119</td>
<td>220-232 cmbsf</td>
<td>787 m</td>
<td>Southwest</td>
<td>68°20.6' S</td>
<td>70°22.8' W</td>
</tr>
</tbody>
</table>
DESCRIPTIONS OF THE THIN SECTIONS

The East region

Thin section C.348 covers the contact between laminated silty mud and a fine-grained diamict in core DF 85-76. Distribution of the coarse fraction in the diamict is faintly stratified. Its matrix, including the plasma (particles finer than 30 μm, the thickness of a thin section), is isotropic except for a few subtle indications of drapes over pebbles. A series of inclined, curvilinear microfaults (Fig. 5.2a) occur at two levels at about 55 cmbsf and about 60 cmbsf (centimetres below seafloor). The silty mud underlaying the diamict is irregularly intercalated with distinct, up to 3-mm thick, clayey laminae and stringers. The laminae are often graded and fine up as is shown by gradual darkening trends from bottom to top (Fig. 5.2b). Small-scale silty lumps that protrude down into underlying mud provide evidence of loading.

FIGURE 5.2. East region sediments. a. Detail of thin section C.348 in plane light. The longer side of the image represents 18.0 mm. Top of the thin section is to the left. The image shows a microfaults dissecting a clayey lamina, which is highlighted by a crack at approximately 60° from the vertical. b. Detail of thin section C.348 in plane light (correctly positioned: top to top). The longer side of the image represents 13.8 mm. It shows a series of laminae fining up from silt to
clayey mud. Note the conjugate faults dissecting the laminae. c. Detail of thin section C.350 in plane light (correct position). The longer side of the image represents 18.0 mm. The image shows a gradational, subvertical contact between fine silty mud on the left-hand side and diamict on the right. d. Thin section C.350 in plane light. Top of the thin section is to the left. The longer side of the image represents 11.2 mm. Detail of the fine-grained diamict containing intraclasts of the described casing-type. Note that fine silt grains in some of the casing are oriented with their long axes parallel to the surface of the core grain.

Plasmic fabrics, which have been defined as patterns of preferred orientations in plasma as exhibited in cross-polarised light due to birefringent properties of domains of clay minerals (see Brewer, 1976), are either absent or very poorly developed in thin section C.348. Only one clay-lamina at 66 cmbsf shows moderately to well-developed, unidirectional birefringence. A dominant, pervasive massepic fabric is parallel, and a subordinate array of discrete, unistrial linings (cf. Brewer, 1976) is subparallel with the lamination.

Thin section C. 349 (core DF 85-77) represents a diamict with a broad textural spectrum and scattered pebbles up to 3 cm in size. Grains and clasts coarser than 5 mm are arranged in two vaguely defined 4-cm-thick strata of relatively high skeleton density (particles coarser than 30 μm). The sample is devoid of microstructures, even in the plasma, which is isotropic and of even density throughout. It provides no directional information in terms of plasmic fabrics, although the clay percentage is as high as 25% (Bryan, 1992).

Thin section C.350 is from a sandy mud with abundant pebbles in core DF 85-82, in which two outsized, elongate clasts were noticed between 35 and 47 cmbsf (Bryan, 1992). One of these clasts must have intersected the plane of the thin section. Although the pebble itself was apparently removed during preparation, it left a large, irregular void.

From a microscopic point of view, this characterisation can be refined. A remarkable subvertical contact (Fig. 5.2c) was observed to separate an unstratified, relatively coarse-grained diamict and a finer-grained, better-sorted sandy mud. The latter has a peculiar wedge shape with a base of about 30 mm wide at 47 cmbsf, and its upper end - at 35 cmbsf - pinching out to one side. Plasma is slightly grainy but uniform throughout the whole sample, even across the identified contact. No plasmic fabrics occur but, particularly in the fine-grained wedge, sharply bounded vesicles, either circular or elongate, are common.

Intraclasts are common to abundant with generally circular forms. They consist of up to 400 μm thick 'casings', which either encompass one single particle or a cluster of particles (Fig. 5.2d). The casings are clayey, compact and have concentric laminae. The laminae are constituted by microfabrics of silt and by plasmic fabrics. Their appearance
suggests a layer-by-layer accumulation. The number of intraclasts and the intraclast-density are higher in the diamict.

**The Central region**

The two samples from the central part of Marguerite Bay are very similar. Both are diamicts, macroscopically massive and homogeneous, but microscopically heterogeneous. Thin section C.569 (core DF 85-126) is in fact very heterogeneous: it is composed of poorly defined, muddy intraclasts within a slightly silty matrix (Fig. 5.3a). The intraclasts are mainly rounded, vaguely bounded and randomly dispersed throughout the sediment. Thin section C.568 (core DF 85-125) also shows this chaotic arrangement within the plasma but overall it is not as poorly sorted because intraclasts are not as common.

Both samples contain intact microfossils and show local differences in skeleton density. Sample C.569 has local grain concentrations, whereas in C.568 very fine, curvilinear desiccation cracks outline areas that differ texture-wise from the ambient matrix. In both samples, plasmic fabrics – if present at all - are weakly developed.

![Figure 5.3. Central region sediments. a. Detail of thin section C.569 in plane light. Top of the thin section is to the left. The longer side of the image represents 7.0 mm. The photomicrograph shows a 'chaotic' composition of sediment. The lower left quadrant shows some rounded, clayey intraclasts within a silty mud matrix. The right half of the picture shows a more homogenised matrix, in which silt and clay 'agglomerations' are visible. b. Detail of thin section C.568 in plane light (correct position). The longer side of the image represents 13.8 mm. It shows ice rafted grains in a silty mud matrix. Note that the coarsest grain, in the lower center has parabolic 'impact trails' that indicate that it protruded in the mud from above. The right arm of the parabola is best visible as a slightly lighter streak in the dark mud.](image-url)
Stratification in C.569 is poorly preserved. Apart from one wavy, discontinuous silt stringer at 65 cmbsf, there is only the vague stratification in the 3 to 6 mm size fraction that may be from primary depositional processes. The mud overlying the diamict shows 'laminae' of dispersed sand-sized grains; most other grains are isolated. In one case, at about 74 cmbsf, a grain shows an oblique trail of 6 mm long (exhibited in the arrangement of silt grains in the matrix), which suggests an intrusion from above (Fig. 5.3b).

The Southwest region

The three sediments from the southwestern part of the bay are all macroscopically massive diamiccts. They have been described as sandy muds (muddy sands) containing common to abundant scattered pebbles (Bryan, 1992). The unstratified sediment in thin section C.351 (core DF 85-117) shows a broad spectrum of particle sizes without distinctive modes. The plasma has a compact, isotropic but grainy (fine silty) character. Plasmic fabrics are rarely developed, probably due to the low clay percentage (6 %, cf. Bryan, 1992). Only diffuse, chiefly subhorizontal striae formed by discontinuous plasmic fabrics occur at discrete horizons. A 'suggestion' of a planar structure is visible at about 93 cmbsf. The 'phantom feature' is about 4 mm thick and inclined at about 65° from the vertical (Fig. 5.4a).

FIGURE 5.4. Southwest region sediments. a. Detail of thin section C.351 in plane light (correct position). The longer side of the image represents 18.0 mm. The image shows a narrow, subhorizontal zone in which the fine-grained diamict is relatively grain-poor. It runs subhorizontal from the upper right to the lower left. The planar surfaces of the opposing pebbles on the right 'mark out' the feature. In cross-polarised light this planar zone shows poor to moderately developed birefringence, which might be an expression of shear. b. Detail of thin
section C.351 in plane light (correct position). The longer side of the image represents 18.0 mm. The center of the image shows a circular arrangement of grains (a turbate structure). Note that the long axes of the particles forming the circle are mainly subtangential with the circular form.

A 2-dimensional microfabric analysis carried out to identify preferential skeleton grain alignments, showed significant intra-sample variations. About half of the measurements made within areas where faint, planar plasmic fabrics and other suggestions of planar features occur (the lower half), proved to be (sub)horizontally aligned. More random orientations occur through the rest of the sample. Turbates, which are circular constellations of grains with preferred long-axis orientations subtangential with the circular form (cf. Van der Meer, 1993; 1997), occur predominantly in the upper regions of the sample (Fig. 5.4b).

Thin section C.566 from core DF 85-116, shows a faintly stratified mud overlying a fine-grained, massive diamict. In the mud, the predominantly sand-sized skeleton is distributed in vague, distorted laminae, but isolated grains also occur. The contact between the two sediment units is sharp but disturbed: smoothly shaped lobes of diamict protrude up into the mud (Fig. 5.5a). The features resemble reversed loadcasts with occasional necking.
FIGURE 5.5. (a-d previous page) Southwest region sediments. a. Detail of thin section C.566 in plane light. Top of the thin section is to the left. The longer side of the image represents 11.2 mm. The contact between fine-grained diamic and overlying mud is ‘contorted’. The symmetrical perturbations resemble reversed loadcasts. b. Detail of thin section C.566 in plane light. Top of the thin section is to the left. The longer side of the image represents 11.2 mm. Textural differentiation within a diagonal, slightly wavy clayey mud feature that runs from upper left to lower right in the image. Note the preferred long axes orientation of elongated grains within and along the sides of the feature. c. Detail of thin section C.566. See caption Fig. 5.5b. Now cross-polarised view of the same area to show unidirectional (essentially plane-parallel) plasmic fabrics. d. Detail of thin section C.566 in plane light (correct position). The longer side of the image represents 11.2 mm. Turbate structure around the large grain in the center of the image. Circular halo of grains is associated with a clayey, contorted streak directly to the right of it. e. Detail of thin section C.567 in plane light (correct position). The longer side of the image represents 7.0 mm. Local anomalies in plasma density and silt content. Note curvilinear (discontinuous) micro-cracks that ‘highlight’ and delineate intraclasts and clayey elements in the silt matrix. f. Detail of thin section C.567 in cross-polarised light. Top of thin section is to the right. The longer side of the image represents 5.6 mm. A moderately to well-developed plasmic fabric is related to the presence of pebbles.

Grain density in the diamic is high and the skeleton size distribution has size modes at 200-500 µm and at about 1 mm. Coarser grains are concentrated in zones, for example near the bottom of the thin section at 107 cmbsf. Moderately developed masepic plasmic fabrics occur in relatively clay-rich areas in the diamic (Figs. 5.5b and 5.5c). Turbate structures occur directly adjacent to the plasmic fabric features (Fig. 5.5d), whereas intraclasts consisting of core grains with casings occur more dispersed. The upper part of thin section C.567 from core DF 85-119 is moderately sorted and shows minor, thin laminations. The lower part is a slightly coarser-grained diamic that structurally resembles the ‘chaotic’ diamic of the central region. The diamic has local plasma and skeleton concentrations, which are often highlighted by curvilinear desiccation cracks (Fig. 5.5e). Plasmic fabrics in the sample are restricted to areas along the sides of medium pebbles (Fig. 5.5f).
INTERPRETATION OF THIN-SECTIONED SEDIMENTS

In the following discussion microstructure associations are compiled for each thin section. Most associations are representative of certain processes and may be used to infer the origin of the sediments. Microstructures described in the previous section are synthesised in Table 5.2.

TABLE 5.2. Selection of microscopic characteristics of the samples. Key to the symbols used: - = absent; • = rare/poorly developed; ● = common/moderately developed; ●● = abundant/well developed.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Plasmic Fabrics</th>
<th>Lineaments</th>
<th>Turbates</th>
<th>Intraclasts</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.348</td>
<td>●, locally ●•</td>
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<td>C.568</td>
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<tr>
<td>C.567</td>
<td>●</td>
<td>-</td>
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<td>●</td>
</tr>
</tbody>
</table>

Glacimarine deposition

Many samples exhibit characteristics of glacimarine sedimentation. One example of a proximal glacimarine diamict is that of thin section C.349 (DF 85-77) from the eastern region. The vague lamination caused by banded concentrations of skeleton grains indicates periodically intensified deposition of coarser sediment, which can be interpreted as a reflection of derivation or rafting from floating ice. The fact that the sample is devoid of any micro-tectonic structures suggests that the sediment was not physically altered in any way during or after deposition. Hence, deformation as a result of mass movement or glacial action may be excluded (see also Kluiving et al., 1999).

Thin section C.348 from DF 85-76, also from the eastern part of the bay, is the only of the investigated sediments that is distinctly laminated. The sediment consists of a quite homogeneous, silty mud, intercalated with isolated, discontinuous clayey stringers and sets of recurrent micro-laminae (Fig. 5.2b). The latter commonly exhibit normal grading. Most probable source for the silty mud is a meltwater plume that issued its load of fine-
grained sediment in a glacimarine environment, which in turn accounted for the identified sorting.

Syn-sedimentary micro-faulting (Fig. 5.2a) and discrete plasmic fabrics in a clay lamina near the bottom of the sample indicates that this deposit was prone to gravity-driven movement. These features suggest sliding of relatively coherent plugs of glacimarine sediment along slip planes along which stress was concentrated (cf. Hiemstra et al., in prep.).

**Gravity-driven deformation**

Diamicts of thin sections C.568 (DF 85-125) and C.569 (DF 85-126) from central Marguerite Bay have a chaotic matrix of silty mud with rounded, clayey mud intraclasts (Fig. 5.3a), which suggests that sediments of different composition were mixed. The poor definition of the muddy intraclasts within the ambient silty mass points to a water-saturated medium, in which originally sharp intraclast-boundaries 'faded'. The clustered, anisotropic distribution of skeleton grains in these diamicts indicates rearranging of primary sediment constituents (cf. Hiemstra and Rijstrijik, in prep.). The grain clusters (occasionally turbates) and the rounded clayey mud intraclasts (occasionally the casing-type intraclasts with their inferred 'layer-by-layer accretionary' origin) are considered proof of internal modification by rotational movements (see Van der Meer, 1997). These features lead to the interpretation that the deposits in C.568 and C.569 are the products of gravity-driven mass movement in a subaqueous, (glaci)marine, environment. Reorientations in the plasm are poor and random, which is to be expected in gravity-driven flows (see Bertran, 1993; Bertran and Texier, 1999). The two samples only have circular deformation features, which suggests that rotational movements, not planar shear, were prominent during a re-depositional process. Again this is to be expected in situations of unconfined deformation where the sediment is not impeded by glacial loading and as such is free to 'expand' in all directions (see Hiemstra, 1999).

Similar mass movement deposits occur in the eastern region (C.350 - DF 85-82) and in the southwestern region (C.567 - DF 85-119). The diamict in thin section C.350 has many intraclasts of the casing-type. Their generally smooth, circular outlines, as well as the fringe-like internal arrangement of both clays and silts suggest that rotational movements of grains accounted for 'circum-grain' adhesion of fines (Fig. 5.2d).

The disorganized character of the matrix and the occurrence of intraclasts suggest a mass movement origin of C.567 (Fig. 5.5e). Plasmic fabrics in the upper part of the
sample are poorly developed and in the lowermost part of the sample, some very faint, discontinuous, subhorizontal planar features occur among more ‘patchy’ plasmic fabric patterns. Other than in C.350, C.568 and C.569, these features indicate that during re-distribution the sediment was not completely water-saturated and can therefore not have been deposited from a turbulent slurry flow. A slightly more coherent mass movement is envisaged for C.567, more comparable with the ‘intermediate’ flow-slide form in Bertran and Texier (1999). The chaotic, patchy plasmic fabrics in the lower half of C.567 are associated with clasts, occurring mostly along the edge of, or between outsized pebbles (Fig. 5.5f).

Coring deformation

This brings us to the topic of piston core deformation. In C.567 and in C.350, outsized clasts accounted for sediment deformation during core barrel penetration. Clasts in the lower half of C.567 locally reinforced the pure shear forces exerted by the piston, which is reflected in the patchy plasmic fabrics (Fig. 5.5f). The relative inertia of the clasts apparently accounted for ‘moulding’ of adjacent fine sediments during the coring. More intense coring deformation occurred in C.350. The subvertical separation between diamict and mud is artificial (Fig. 5.2c): it is envisaged that clasts from the diamict caused a partial obstruction of the core cutter. This obstruction would create a low-pressure zone within the core barrel, which effectively sucked in the weak, water-saturated finer-grained matrix, whereas more cohesive sediment entered the core in relatively unaltered diamict ‘blocks’. The occurrence of vesicles in the fine-grained unit shows the dilated character of the sediment, whereas a subvertical microfabric signal also suggests that this unit flowed into the core barrel.

Subglacial deformation

Two of the three samples from the southwest region exhibit associations of microstructures that may be attributed to a grounded glacier. The diamict in sample C.566 (DF 85-116) has several features strongly indicative of either direct subglacial deposition or of post-depositional modification during glacial overriding. Distinctive, subhorizontal, linear features such as unidirectional plasmic fabric signals and systematic, parallel microfabrics each indicate that the sediment was deformed through discrete, parallel shear-displacements, and that the responsible stress regime must have
been deviatoric (Figs. 5.5b and 5.5c). Although not as widespread as in the mass flow deposits, turbates do occur in the subglacially deformed sediment of C.566. However, instead of occurring scattered throughout the sediment, the turbates identified in C.566 occur mostly near shear planes: the discrete horizontal movements taking place along the planes apparently generated rotational movements that led to circular features (Fig. 5.5d). The close relation between planar displacement features and circular, rotational features is considered evidence of subglacial shearing.

The nature of the contact between the diamic t and the overlying mud in C.566 is unique in that irregular lumps of diamic t form upward protuberances into the mud (Fig. 5.5a). The drop-like protuberances cannot be explained in terms of subglacial shearing or by reversed density gradients (e.g., Anketell et al., 1970). For an explanation of the features it is tempting to assume that the sediment at some point was 'fluidised' during the coring operation. The contorted stratification in the mud and the flow-like appearance and the 'symmetry' of the contact suggest that this deformation aspect may be artificial.

A subglacial imprint is also proposed for thin section C.351 from DF 85-117. Although the low clay percentage is not ideal for the formation of plasmic fabrics, i.e. for the identification of deformation structures in the diamic t, planar features in the lower part of the sample were 'suggested' by faint birefringence signals and subtle textural differentiation (Fig. 5.4a).

These suggestions were 'confirmed' by microfabrics, because they were found to be subparallel to the suggested structures. The turbates present in the sample only occur in its upper part (Fig. 5.4b), which means that they are not directly associated with the planar signals. For this reason, the inferences regarding C.351 being a subglacial deposit are tentative.

SYNTHESIS

As the micromorphological analyses in this study were primarily designed to test previous interpretations of Marguerite Bay diamic ts, the outcome of this study will now be compared to the results presented by Kennedy and Anderson (1989). The small number of thin sections that was analysed in this study would obviously not allow for major model revisions or inferences regarding bay-wide trends. Nevertheless, assuming that the thin sections are a representative selection of (diamic tic) sediments in Marguerite Bay, following essential points - indispensable when it comes to reconstructions - are noted.
The conclusion by Kennedy and Anderson (1989) that gravity flows are an important part of the sedimentary record of Marguerite Bay is confirmed, however thin section analyses suggest that the number of mass movement deposits may be much higher than they considered (see Fig. 5.6). Several previously unrecognised mass movement deposits were found. Although the proposed origin as a transitional glacimarine deposit for C.568 from DF 85-125 (Kennedy and Anderson, 1989) may be valid, microscopic characteristics strongly suggest gravity-driven re-distribution as the last process affecting the sediment. The mass flow characteristics of the diamict unit of core DF 85-126 (C.569) are even more evident. Again, it is emphasised that the sediment itself may have melted out from the basal debris zone of an ice shelf near the grounding line, but, contrary to the interpretation of Kennedy and Anderson (1989), the suite of microscopic features unmistakably points to gravity-driven deformation of the sediment.

FIGURE 5.6. Map of the area (after Kennedy and Anderson, 1989) with interpretations of sediments based on micromorphological observations. Key to the symbols: ▲ - basal till; ■ - glacimarine sediment; ● - mass movement deposit.
The continental shelf is intensely dissected throughout Marguerite Bay; therefore it is not surprising that apart from the central part (cores DF 85-125 and 126), mass movement deposits also occur in the other regions. Sediments in the east region (C.350; core DF 85-82) and in the southwest region (C.567; core DF 85-119) show indications of gravity-generated flow-deformation, but it is unclear to what extent these movements may be related to the proximity of a (dynamic) grounding line. Kennedy and Anderson (1989) suggested that the laminated deposit in C.348 (DF 85-76) represents sedimentation from pulsating subglacial meltwater. On basis of micromorphological information, this can be substantiated. However, this thin section, from the east region, also shows evidence of more slide-like movements, which can likewise be related to subaqueous slope processes.

The occurrence of basal tills in the southwest regions of the bay suggested by Kennedy and Anderson (1989) can be substantiated (Fig. 5.6). Microscopic characteristics of the diamicct in C.566 (DF 85-116) suggest that it was either directly deposited by a grounded glacier or that it was initially deposited beneath floating ice and subsequently modified by glacial overriding. Kennedy and Anderson (1989) interpreted this sediment as a basal till which is confirmed microstructurally. Thin section C.351 (DF 85-117) also shows features that either individually or in combination indicate subglacial deformation. In a similar way to C.566, this diamicct may have been deposited in a glacimarine setting to be overridden subsequently by a grounded glacier. The microscopic evidence within this sediment is not convincing, particularly when trying to fit observations of individual deformational features into a model of concurrent processes, but I would nevertheless interpret it as a basal till. Kennedy and Anderson (1989) classified this diamicct as a transitional glacimarine sediment.

CONCLUSIONS

Although interpretations of individual thin sections may differ from core interpretations by Kennedy and Anderson (1989), results of the micromorphological analyses do not contradict a grounded-ice-to-recessional-ice-shelf scenario for Marguerite Bay (Kennedy and Anderson, 1989; Anderson et al., 1991). Subglacial deformation was identified in one, and possibly two samples from the southwest region, which supports the hypothesis that grounded ice (presumably LGM) extended across (this part of) the
continental shelf. Thin section analyses also showed that the sediments that stratigraphically overlie the basal tills are both proximal and more distal glacimarine ice shelf zone deposits, which suggests that the proposed ice shelf may indeed have existed. The discrepancy in interpretations does thus not involve the distinction between basal tills and glacimarine sediments so much. Rather it concerns the number of mass movement deposits in Marguerite Bay, which has been underestimated. Out of eight thin sections that were studied, five somehow showed features that should be associated with gravity-driven movements of seafloor sediment. The study also showed that some care is needed regarding recognising piston core deformation. Coring imperfections, which obviously occur quite commonly, are theoretically capable of altering the sediment in such a way that the newly obtained features of coring artefacts might macroscopically be mistaken for primary sedimentary characteristics or natural deformation.

This paper proved that micromorphology is a very useful technique when it comes to distinguishing subglacial, gravity-driven and artificial deformation in cored diamicts. Thin section analyses establish a greater confidence in the interpretation of the glacigenic sedimentary core records, and can as such be recommended to anyone working on Antarctic offshore sediments.

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REFERENCES


Small body and small mind
Big head and big headaches

Mark Everett (E)