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Glacial Influence from Clast Features in Oligocene and Miocene Strata Cored in CRP-2/2A and CRP-3, Victoria Land Basin, Antarctica

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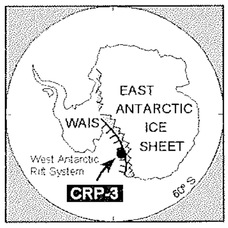
Abstract - Clasts from the Cape Roberts Project cores CRP-2/2A and CRP-3 provide indications of glacially influenced depositional environments in Oligocene and Miocene strata in the western Victoria Land Basin, Antarctica. CRP-2/2A is interpreted to represent strongly glacially influenced, unconformity bound depositional sequences produced by repeated advance and retreat of floating and grounded ice across the shelf. A similar interpretation is extended to the upper 330 meters of the CRP-3 core, but the lower part of the core records shallow marine deposition with significantly less glacial influence. Clast shape analysis from selected coarse-grained facies throughout the cored interval indicates that most clasts are glacially sourced, with little distinction between diamictite and conglomeratic facies. Three dimensional clast fabric analysis from units immediately above sequence boundaries generally display weak or random fabrics and do not suggest that grounded ice actually reached the drillsite at these intervals. Striated and outsized clasts present in fine-grained lithofacies throughout the cores provide further evidence of sub-glacially transported sediment and iceberg rafting. The distribution of these striated and out-sized clasts indicate that a significant glacial influence persisted through most of the time represented by the cores with glaciers actively calving at sea-level introducing ice-berg rafted glacial debris even in the earliest Oligocene.



BACKGROUND

The Cape Roberts Project (CRP) is an international drilling effort, with one of the primary objectives being to obtain a palaeoclimatic history of the Ross Sea region to better understand ice sheet history. The background and details of the project goals are outlined in the Initial report of CRP-2/2A (Cape Roberts Science Team, 1999). Almost 1500 m of strata was recovered on the western margin of the Victoria Land Basin from three drill holes. This paper reports on the features of clasts from two of these, CRP-2/2A and CRP-3, representing strata deposited in the Oligocene and Early Miocene (34-19 Ma). CRP-3 cored 820 metres (m) of the oldest Cenozoic strata in this part of the basin (34-31 Ma). The core records mostly shallow marine deposition with only minor indications of glacially influenced sediment in the lower 300 m, but a repeated glacial advance and retreat signal becoming increasingly clear in the upper part indicating the onset of direct glacial deposition. The glacial fluctuations are evident throughout the 600 m of overlying strata of CRP-2/2A recording the period for 31-19 Ma (Cape Roberts Science Team, 1999). The strata in CRP-2/2 and CRP-3 are divided into lithostratigraphic units and sub-units on the basis of lithological changes. Facies analysis of the sequence identified a number of recurrent lithofacies on the basis of lithology, bed contacts and thickness, sedimentary structures and colour. Twelve such lithofacies are recognised in CRP-2/2A and ten in CRP-3. From these, process and palaeo-environmental interpretations of the sediments were made and preliminary depositional models developed. This lithostratigraphic and facies analysis provided the basis for recognising depositional cyclicity and was used to construct a sequence stratigraphic interpretation of each drillcore. This followed the approach adopted by Fielding et al., (1998) and divides the drillcores into unconformity-bound depositional sequences. CRP-2/2A was divided into 25 sequences, and CRP-3 was divided into 23 sequences down to 480.27 metres below sea floor (mbsf) (Cape Roberts Science Team, 1999). These are thought to represent the accumulation of sediment during cycles of glacier advance and retreat and may also occur in concert with relative sea-level changes. These sequences are typically bounded by sharp erosion surfaces that mark abrupt facies dislocations and represent glacial surfaces of erosion either by movement of grounded ice across the sea floor or more distal effects of glacier advance. These are usually overlain by coarse-grained units such as diamictite (Facies 6 or 7) or conglomerate (Facies 9 or 10), reflecting ice contact or glacier proximal deposition (or possibly more distal fluvial deposition in the lower part of CRP-3) during sea level lowstand/ early transgression and glacial advance and early retreat. These are overlain by generally fining upward successions of various finer grained facies, representing marine and glaciomarine deposition during sea level transgression/ highstand and glacial retreat. Study of clast shape and three dimensional clast fabric assists in the interpretation of the coarse-grained lithofacies and sequence boundaries by investigating transport and erosion histories of the clasts and estimating glacier proximity to the drillsite. This combined with analysis of out-sized clast and striated clast distribution documents the initiation of glacial conditions in the Ross sea region. The lithofacies scheme presented in the Initial Reports of CRP-2/2A (Cape Roberts Science Team, 1999) and CRP-3 (Cape Roberts Science Team, 2000) is used in this paper and summarised in table 1.

METHODS

Twenty two whole round cylinders of core ranging from 19 to 34 cm in length were removed from the cores. All of the CRP-2/2A and some of the CRP-3 samples were taken from clast-rich units immediately above sequence boundary unconformities as these intervals are most likely to record direct glacial deposition and any evidence of grounded ice. Samples are listed in table 2, showing depth below sea floor and facies number. Several samples were taken at lower stratigraphic levels in CRP-3, but cementation prevented extraction of clasts. The cores were secured in an upright position in a simple supporting apparatus with a horizontal stage that was lowered over the core. The core was systematically

Tab. 1 - Summary table of facies characteristics and interpretation for CRP-2/2A and CRP-3 (after Cape Roberts Science Team, 2000).

Facies	Characteristics	Interpretation
Facies 1 Mudstone	Massive, very fine sandy mudstone and mudstone, common lonestones. Marine fossils.	Hemipelagic sediment in quiet water conditions from fluvially-derived turbid plumes discharging into coastal waters, with minor distal sediment gravity flows and iceberg rafted debris.
Facies 2 Interstratified Sandstone and Mudstone	Ripple or planar laminated sandstones, some bioturbation, common marine fossils, soft sediment deformation and dispersed lonestones.	Marine deposit with features characteristic of a range of current types from low to moderate density sediment gravity flows to combined wave and current action and iceberg rafted debris.
Facies 3 Poorly sorted (muddy) very fine to coarse-grained Sandstone	Varieties of poorly sorted sandstones, locally massive or locally planar or ripple cross laminated. Dispersed clasts grading to conglomerate. Marine fossils.	Medium high-density sediment gravity flows or waning stages of traction flows. Thicker beds may represent rapid sedimentation from fluvial discharges on deltas or grounding line fans and iceberg rafted debris.
Facies 4 Moderately to well sorted, very fine- to coarse Sandstone.	Low-angle cross-bedding and cross-lamination or locally planar lamination, possible hummocky cross stratification. Marine fossils.	Marine deposits at or about storm wave base.
Facies 5 Moderately to well sorted stratified or massive fine-to coarse Sandstone	Planar or cross-stratification but locally massive and amalgamated. Possible hummocky cross stratification. Some clasts, moderate bioturbation and marine fossils.	Marine currents / wave action at shoreface or about storm wave base with influence from icebergs.
Facies 6 Stratified Diamictite	Clast rich to clast poor and sandy or muddy. Stratified with common soft-sediment deformation and rare marine macrofossils.	Debris flow deposits combined with ice-rafting or direct rainout of ice-rafted debris and acted on by currents. Alternatively, these may be subglacial deposits.
Facies 7 Massive Diamictite	Clast rich to clast poor and sandy or muddy. Rare marine macrofossils.	Of all facies, this is most likely to be of sub-glacial origin, but possibly produced by rainout of ice-rafted debris or is a debris flow deposit.
Facies 8 Rhythmically interstratified Sandstone and Siltstone	Very fine and fine sandstone interstratified with mudstone with lonestones and often displays soft-sediment deformation.	Highly turbid overflow plumes originating from fluvial discharges into the sea producing cyclopsam and cyclopel deposits. May include low density turbidity current deposition.
Facies 9 Clast supported Conglomerate	Massive, poorly sorted, locally graded with matrix of poorly sorted, very fine to coarse sand.	Deposition or redeposition from fluvial discharges. Possibly submarine and may have been transported in suspension in turbulent subglacial conduit discharges. Alternatively these could represent high-density, gravity driven, mass flows or redeposited conglomerates.
Facies 10 Matrix supported Conglomerate	Massive and very poorly sorted. Matrix is poorly sorted, very fine to coarse sand.	High density mass flows possibly redeposited from a mixing of fluvial or shallow- marine facies close to source. Alternatively, it may represent waning flow stage of traction currents.
Facies 11 Mudstone Breccia	Massive, clast supported with angular to rounded mudstone intraclasts. Soft sediment deformation.	Mass flow deposits.
Facies 12 Non-welded Lapillistone	Pumiceous, massive or finely laminated.	Air fall through water. Some reworking by marine currents and gravity flows.

disaggregated using chisels to expose individual whole clasts (uncut by coring) in a manner similar to that outlined by Hicock (2000). Three dimensional clast fabric data was collected by recording the trend of the a-axis (long axis) of each clast with a protractor. The plunge was measured with a standard geological compass inclinometer. None of the samples was oriented with respect to north because no azimuth could be determined at the drill site. The lithology of each whole clast greater than 0.5 centimetres in diameter was determined. Lengths of the three orthogonal axes (a, b and c) were measured using standard metric callipers to investigate clast shape. Clast roundness was examined using the visual roundness chart of Krumbein (1941). Krumbein roundness values correspond to Powers (1953) roundness classes as follows: very angular 0.0–0.17; angular 0.17–0.25; subangular 0.25–0.35; subrounded 0.35–0.49; rounded 0.49–0.7; well rounded 0.7–1.0. Clasts were also examined for surface features such as facets and striae. In addition to the whole round core samples, the distribution of striated clasts and out-sized clasts throughout the entire cores were obtained from core examination and core box images. Out-sized clasts are defined as clasts 0.1 m or more in diameter and at least 100 times the diameter of the enclosing sediment. Definitions of siliciclastic sediments in the CRP cores are outlined in Hambrey et al., (1997). Diamictite is defined as a poorly sorted terrigenous sediment with between 10 and 90 percent sand and between 1 and 30 percent clasts. Conglomerate contains greater than 30 percent clasts.

In the study of clast morphology it is useful to view clast shape as the summation of three independent properties: form, roundness and surface texture (Barrett, 1980). These have commonly been regarded as good indicators of transport mechanisms

Tab. 2 - List of whole round core sample numbers and depth in meters below sea floor (mbsf), with facies number for each sample.

Sample No.	Sample depth (mbsf)	Facies number
CRP 2/2A Sample 1	49.60-49.80	7
CRP 2/2A Sample 2	101.67-101.85	7
CRP 2/2A Sample 3	121.59-121.79	5
CRP 2/2A Sample 4	124.92-125.92	9,10
CRP 2/2A Sample 5	233.80-234.04	7
CRP 2/2A Sample 6	351.37-351.67	7
CRP 2/2A Sample 7	372.15-372.46	6
CRP 2/2A Sample 8	387.02-387.32	10
CRP 2/2A Sample 9	406.80-407.09	7
CRP 2/2A Sample 10	441.22-441.52	7
CRP 2/2A Sample 11	490.10-490.39	7
CRP 2/2A Sample 12	518.32-518.62	3
CRP 3 Sample 1	94.96-95.16	7
CRP 3 Sample 2	146.23-146.47	10
CRP 3 Sample 3	152.55-152.80	10
CRP 3 Sample 4	219.25-219.47	10
CRP 3 Sample 5	295.33-295.53	10
CRP 3 Sample 6	350.49-350.83	9
CRP 3 Sample 7	370.28-370.55	10
CRP 3 Sample 8	442.20-442.45	10
CRP 3 Sample 9	479.25-479.45	9
CRP 3 Sample 10	526.03-526.33	10

(Kuhn et al., 1993), and widely used in the analysis of conglomerates and diamictites to help distinguish those of glacial origin from those of non-glacial origin and to differentiate between different glacial facies (Hall, 1989). Form is the gross overall shape of a clast and is displayed on ternary particle-form diagrams following Benn and Ballantyne (1994). This plots the b/a and c/a axial ratios of clasts and divides them into three basic shapes: 1) Blocks (spheres), 2) Slabs (discs) and 3) Elongate (rods). Clast morphology is further explored using covariant plots of clast form and roundness following the method of Benn and Ballantyne (1994). This plots the C_{40} index (percentage of clasts with c/a axial ratio of ≤ 0.4) against the RA index (percentage of angular and very angular clasts) and provides superior data visualisation than the more traditional sphericity and roundness plots (Bennett et al., 1997). Clasts that have experienced "active" glacial transport often have high c/a axial ratios and rounded edges and "passively" transported clasts are more angular and have low c/a axial ratios.

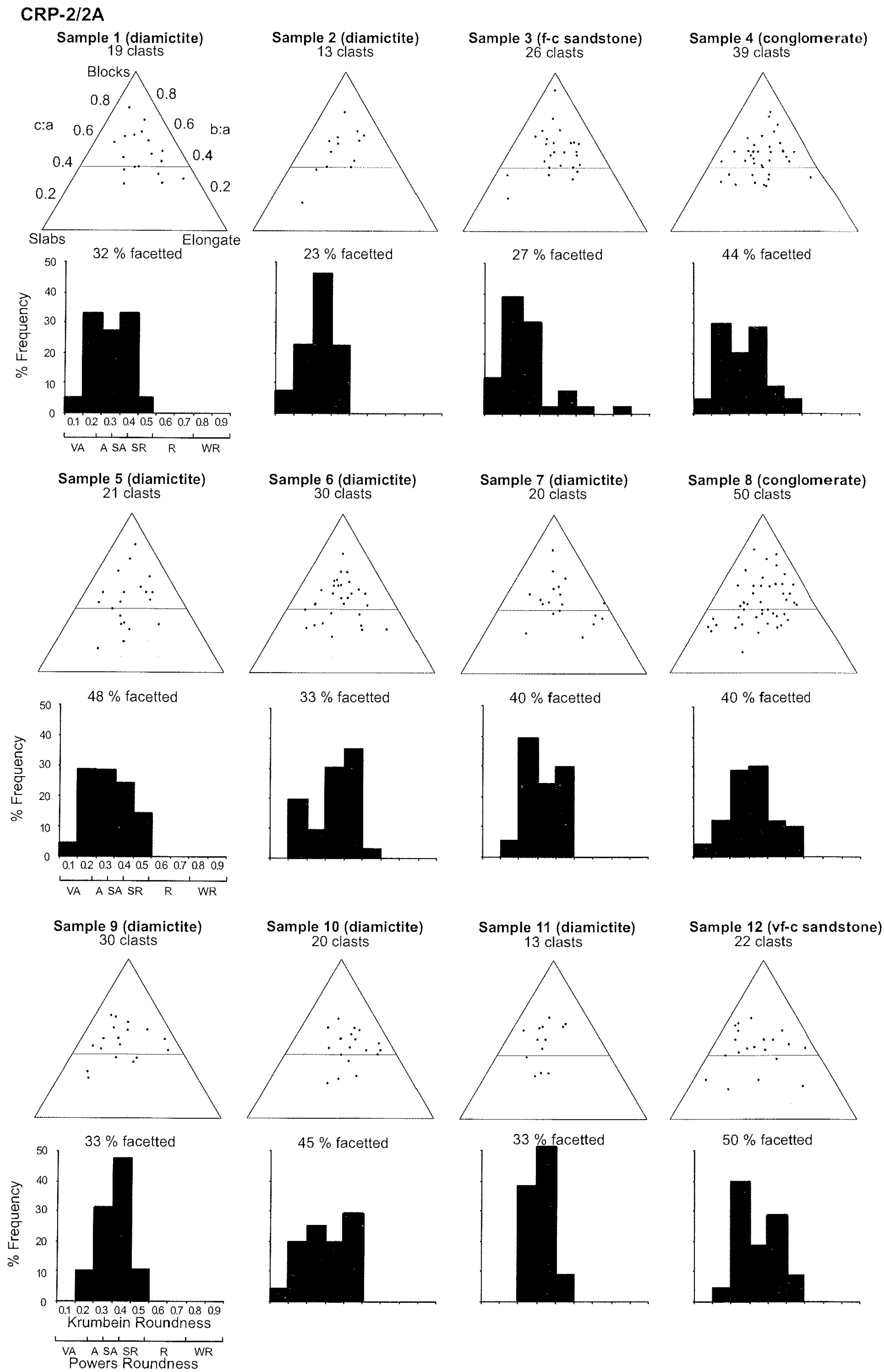
Clast fabric has been used by many workers to assist in the interpretation of clast-rich sediments, particularly those of glacial origin, specifically to infer the mode of deposition and to define glacial flow directions (*e.g.* Domack & Lawson, 1985; Dowdeswell et al., 1985; Dowdeswell & Sharp, 1986). Fabric data are normally displayed on lower hemisphere, equal area (Schmidt) stereonet plot that allows a visual analysis of data clustering or modality. In addition, the orientation tensor or eigenvalue method is widely used to analyse fabric data and essentially summarise fabric strength. Benn (1994b) introduced the powerful "eigenvalue ratios" ternary diagram for analysing fabric data and is superior to other types of eigenvalue plot because it focuses attention on fabric shape, thereby facilitating interpretation (Bennett et al., 1999). This method is employed here.

RESULTS

Several lithologies are represented by the clasts. Granitoid and dolerite clasts are dominant in all samples with minor sedimentary, volcanic and metamorphic clasts present also. Lithologies of the types in the CRP cores have little influence on clast shape or roundness (Bennett et al., 1997; Dowdeswell et al., 1985; Kuhn et al., 1993) and therefore results from different lithologies are not treated separately here. However, surface features are strongly influenced by lithology and given particular attention below.

Form

Form is displayed on ternary particle diagrams in figure 1. The results show that all samples contain a


CRP-2/2A
Sample 1 (diamictite)
19 clasts
Blocks
0.8
0.6
0.4
0.2
c:a
b:a
Slabs
Elongate
32 % facetted
% Frequency
0 10 20 30 40 50
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
VA A SA SR R WR
Sample 2 (diamictite)
13 clasts
23 % facetted
Sample 3 (f-c sandstone)
26 clasts
27 % facetted
Sample 4 (conglomerate)
39 clasts
44 % facetted
Sample 5 (diamictite)
21 clasts
48 % facetted
Sample 6 (diamictite)
30 clasts
33 % facetted
Sample 7 (diamictite)
20 clasts
40 % facetted
Sample 8 (conglomerate)
50 clasts
40 % facetted
Sample 9 (diamictite)
30 clasts
33 % facetted
Sample 10 (diamictite)
20 clasts
45 % facetted
Sample 11 (diamictite)
13 clasts
33 % facetted
Sample 12 (vf-c sandstone)
22 clasts
50 % facetted
Krumbein Roundness
Powers Roundness

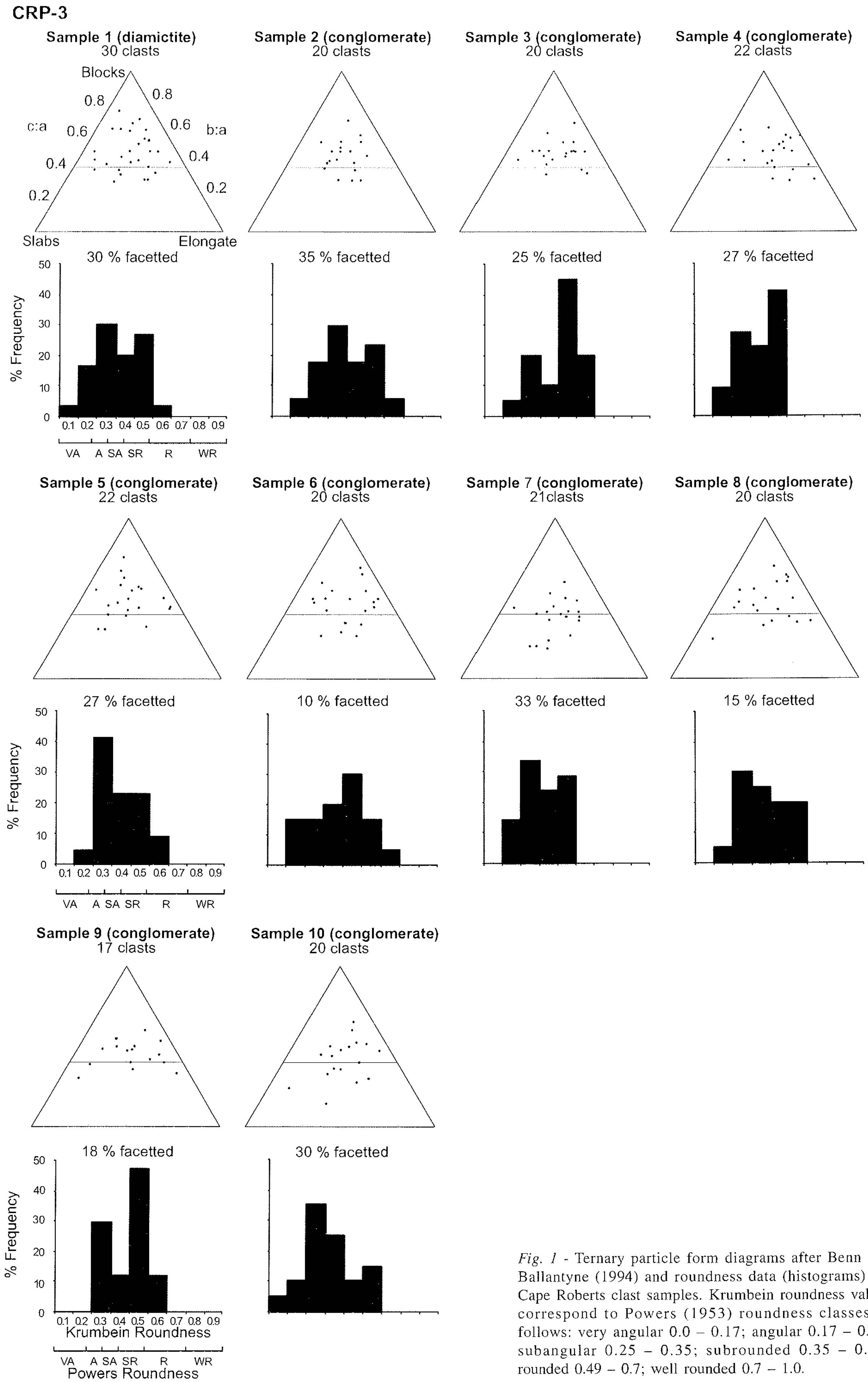


Fig. 1 - Ternary particle form diagrams after Benn and Ballantyne (1994) and roundness data (histograms) for Cape Roberts clast samples. Krumbein roundness values correspond to Powers (1953) roundness classes as follows: very angular 0.0 – 0.17; angular 0.17 – 0.25; subangular 0.25 – 0.35; subrounded 0.35 – 0.49; rounded 0.49 – 0.7; well rounded 0.7 – 1.0.

high proportion of blocky clasts (high c/a axial ratios). There are few clasts with unmodified slabby or elongate forms (c/a axial ratios less than 0.4). There is no apparent distinction between samples from diamictites (facies 6 and 7), sandstones (facies 3 and 5) and conglomerates (facies 9 and 10). No significant change in clast form is apparent throughout the sequence.

Roundness and facetting

The roundness results are plotted as frequency percent histograms in figure 1. CRP-2/2A samples show broad roundness distributions, often displaying a mix of very angular and angular with rounded clasts. Average roundness values are sub-angular or sub-rounded. All contain a significant percentage of facetted clasts, 23% in CRP-2/2A Sample 2, but at least 30% for all others. Interestingly, clast roundness from conglomerate facies 9 and 10 show similar roundness characteristics to the diamictites. The percentage of facetted clasts remains high in these samples. CRP-2/2A Sample 3 (Facies 5) shows the most unusual distribution with both very angular and well rounded clasts present. All CRP-3 samples show broad roundness distributions similar to those in CRP-2/2A, although average roundness is generally slightly higher in CRP-3 with all being classed as sub-rounded. The percentage of facetted clasts is generally slightly lower than CRP-2/2A, but there is no progressive trend down the sequence. There is no distinction in clast roundness between the only diamictite sample (CRP-3 Sample 1) and the conglomerate samples (all others) in CRP-3.

Covariant plots of clast form and roundness

Figure 2 displays covariant plots of clast form and roundness. Overall, the data show that most samples have relatively low percentage of clasts with c/a axial ratios below 0.4, (low C_{40} index) and low to moderate percentage of very angular and angular clasts (low to moderate RA index). Samples higher in the sequence (CRP-2/2A Samples 1,2 3,4 and 5) have slightly higher RA values (greater than 30 %) than samples lower in the sequence with all CRP-3 samples having less than 20 % angular and very angular clasts. There is no apparent distinction between samples from different lithofacies.

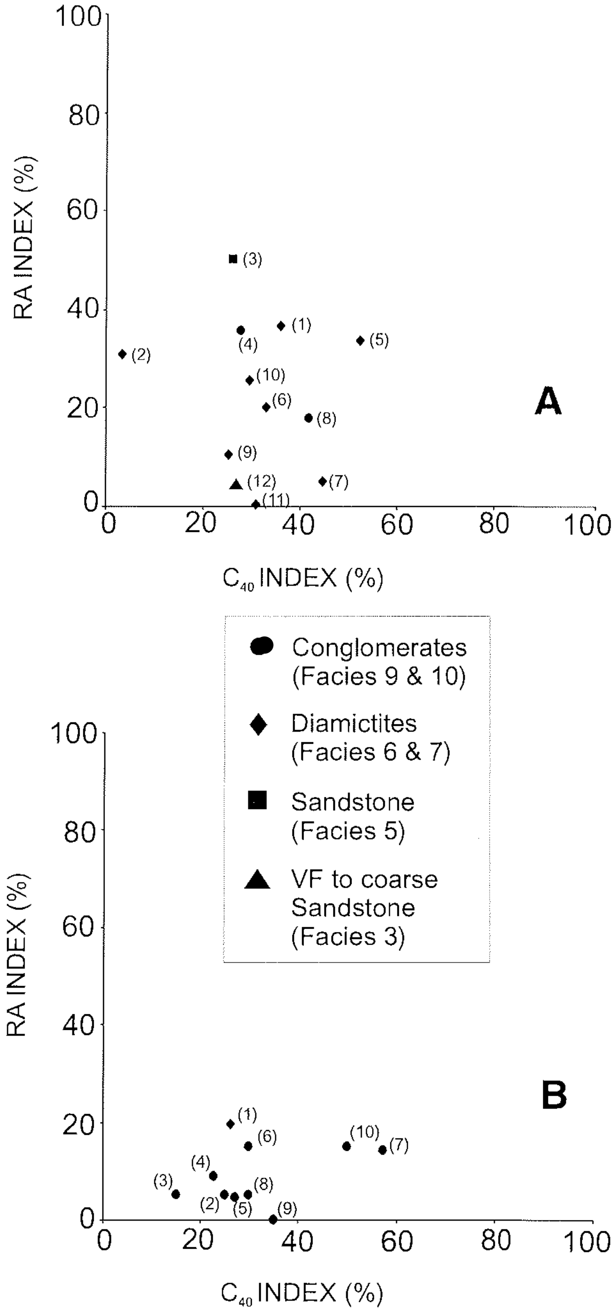


Fig. 2 - Covariant plots of the RA index (% very angular and angular clasts) and C_{40} index (% of clasts with c/a axial ratio ≤ 0.4) for Cape Roberts clast samples. A) CRP-2/2A samples and B) CRP-3 samples. Numbers in brackets refer to sample number.

Surface Features

Only 32 striated clasts were recovered from the cores. Most of these are fine-grained, indurated mudstone, but this lithology is rare. A few other sedimentary clasts and occasional dolerite clasts also carry striae. Figures 3 and 4 clearly show the distribution of striated clasts in the Cape Roberts cores is sparse and sporadic, but persistent down to 778.80 mbsf in CRP-3. In CRP-2/2A, striated clasts occur in all lithofacies except facies 1 and 8. Most (five) were present in separate diamictite units (Facies 6 and 7), although three were found in separate conglomerate units (facies 9 and 10). In CRP-3, striated clasts occur in all lithofacies except facies 2 and 8, with most present in conglomerate units and only one in a diamictite.

Out-sized clasts

Figure 3 displays the distribution of out-sized clasts in CRP-2/2A and CRP-3. The distribution shows that out-sized clasts occur sporadically but are persistent throughout most of both cores. In CRP-2/2A,

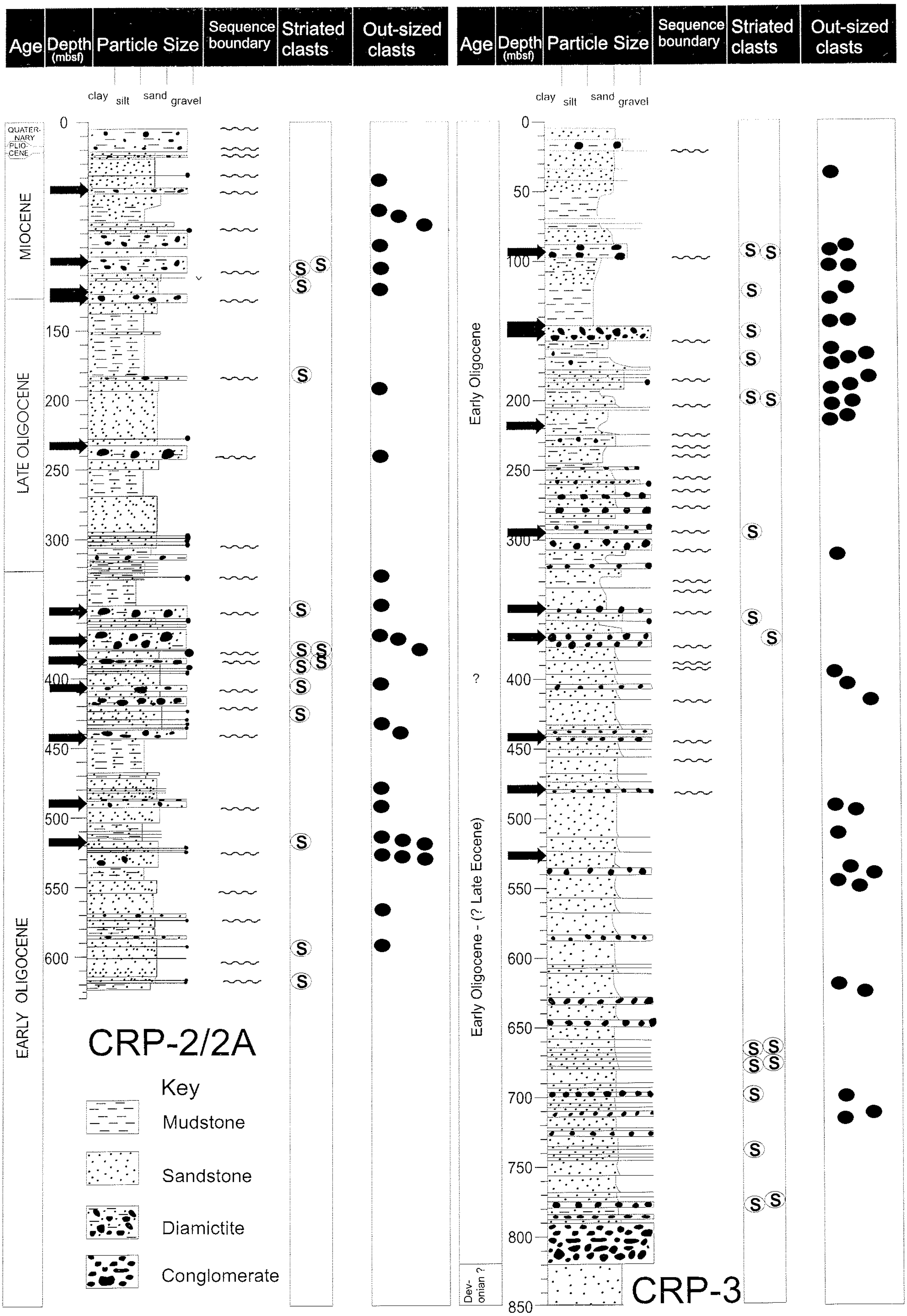


Fig. 3 - Stratigraphic columns for CRP-2/2A and CRP-3, with distribution of out-sized clasts (diameter greater than 0.1m) and striated clasts. Out-sized clasts are not plotted in conglomeratic facies 9 or 10. Dark arrows indicate whole-round core sample locations.

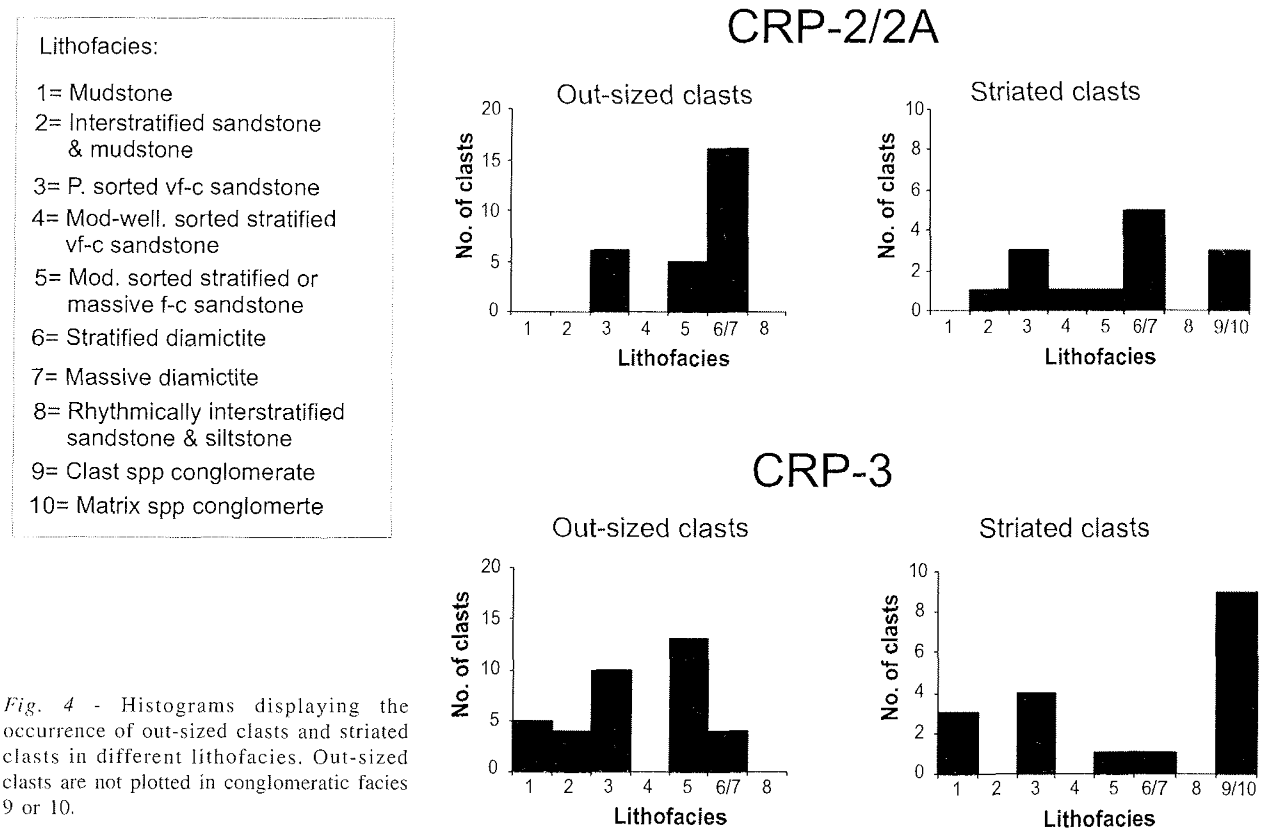


Fig. 4 - Histograms displaying the occurrence of out-sized clasts and striated clasts in different lithofacies. Out-sized clasts are not plotted in conglomeratic facies 9 or 10.

out-sized clasts occur most commonly in diamictites (facies 6 and 7) but are also present in fine-grained facies 3 and 5 and conglomerates (facies 9 and 10). For CRP-3, out-sized clasts occur in all lithofacies except facies 4 and 8 and are most common in facies 3 and 5 (see Fig. 4). In the case of conglomerates (facies 9 and 10), it is possible that out-sized clasts may have been transported by traction currents or sediment gravity flows. Therefore, out-sized clasts in these facies have not been plotted.

Fabric

Clast fabric is displayed as scatterplots on lower hemisphere, equal area Schmidt stereonet projections (Fig. 5). The data show broad scatter for most samples, none have strong or even spread unimodal clusters, with most samples best described as polymodal or random. Eigenvalues show low S_1 values of between 0.422 and 0.617 and S_3 values of between 0.079 and 0.238. On the "eigenvalue ratios" diagram of Benn (1994), shown in figure 6, the Cape Roberts data show a wide distribution, but most have moderate to high isotropy and moderate elongation (clustering). Obvious outliers are CRP-2/2A Sample 5 that appears to have a slightly girdled distribution and CRP-2/2A Sample 10 is highly isotropic. CRP-2/2A Sample 11 (diamictite) and CRP-3 Sample 3 (conglomerate) show the lowest isotropy but neither show significant clustering. There appears to be no distinction between clast fabrics from different facies.

INTERPRETATION AND DISCUSSION

The overall dominance of blocky clast form with high c/a axial ratios (low C_{40} index), combined with the broad roundness distributions showing sub-angular to sub-rounded averages, but lacking high percentages of angular and very angular clasts (low RA index), suggests that most clasts in coarse-grained facies are glacially derived and have experienced subglacial transport. On the covariant plots of clast form and roundness (Fig. 2), the CRP samples plot in the same field as subglacial, till and moraine samples from Jotunheimen, Norway (Benn and Ballantyne, 1994) and subglacial diamicton, moraine and glaciofluvial samples from Svalbard (Bennett et al., 1997). No sample from the Cape Roberts cores indicates unmodified slabby or elongate forms such as scree or "passively" transported clasts. The slight irregular increase in average roundness and decrease in percentages of facetted clasts between the upper 250 m (Miocene/Late Oligocene) of CRP-2/2A and samples lower in the sequence may indicate an increase in fluvial influence, consistent with the inference of increased meltwater and more temperate glacial conditions in the Early Oligocene (lower) interval of CRP-2/2A (Powell et al., 2000). Despite this subtle trend, overall clast shape observations actually highlight the similarity of clasts in different facies rather than discriminate between them suggesting that most clasts have actually experienced

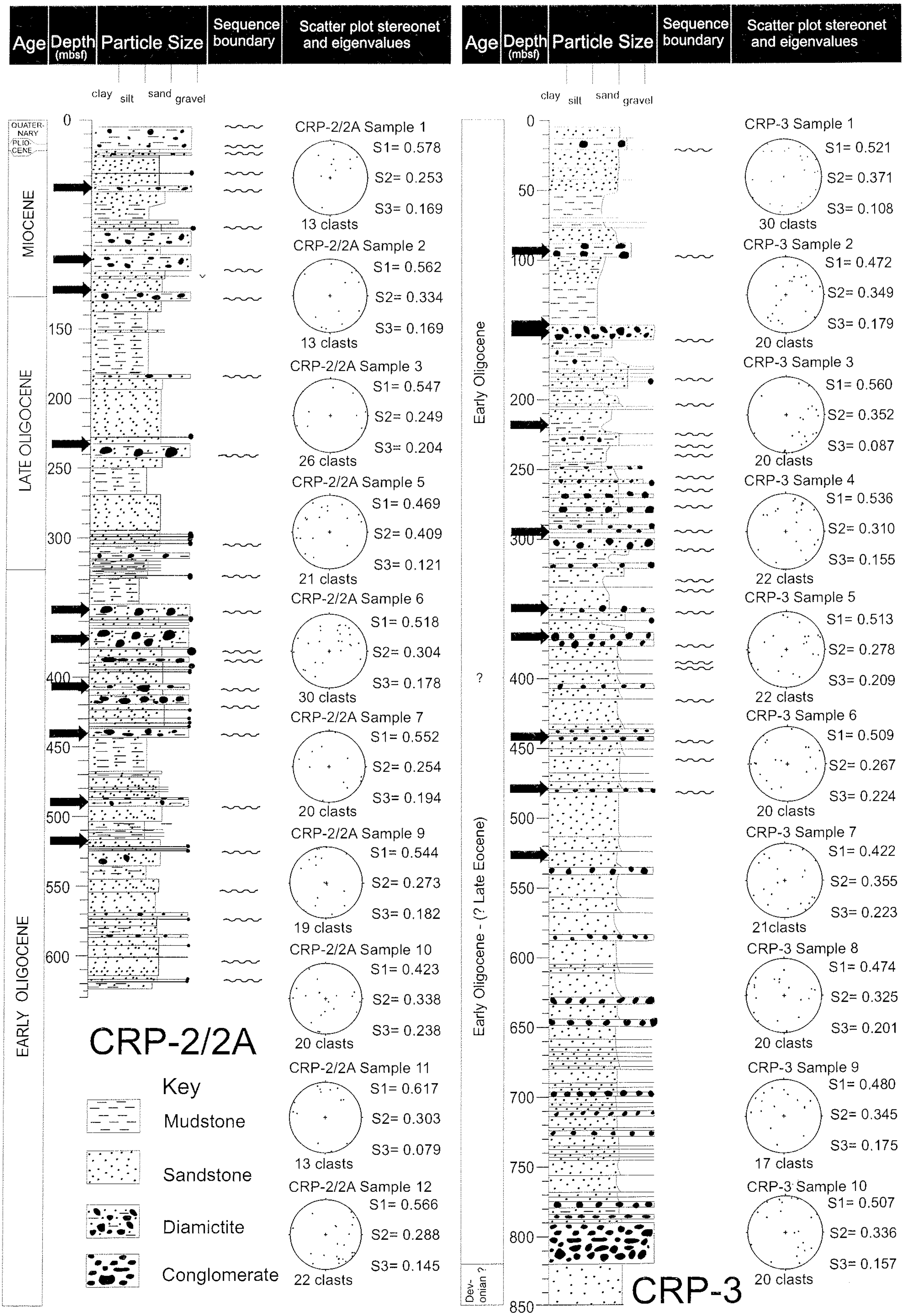


Fig. 5 - Stratigraphic columns for CRP-2/2A and CRP-3, with fabric data displayed as lower hemisphere, equal area Schmidt stereoplots. Principle eigenvalues are presented also. Dark arrows indicate whole-round core sample locations.

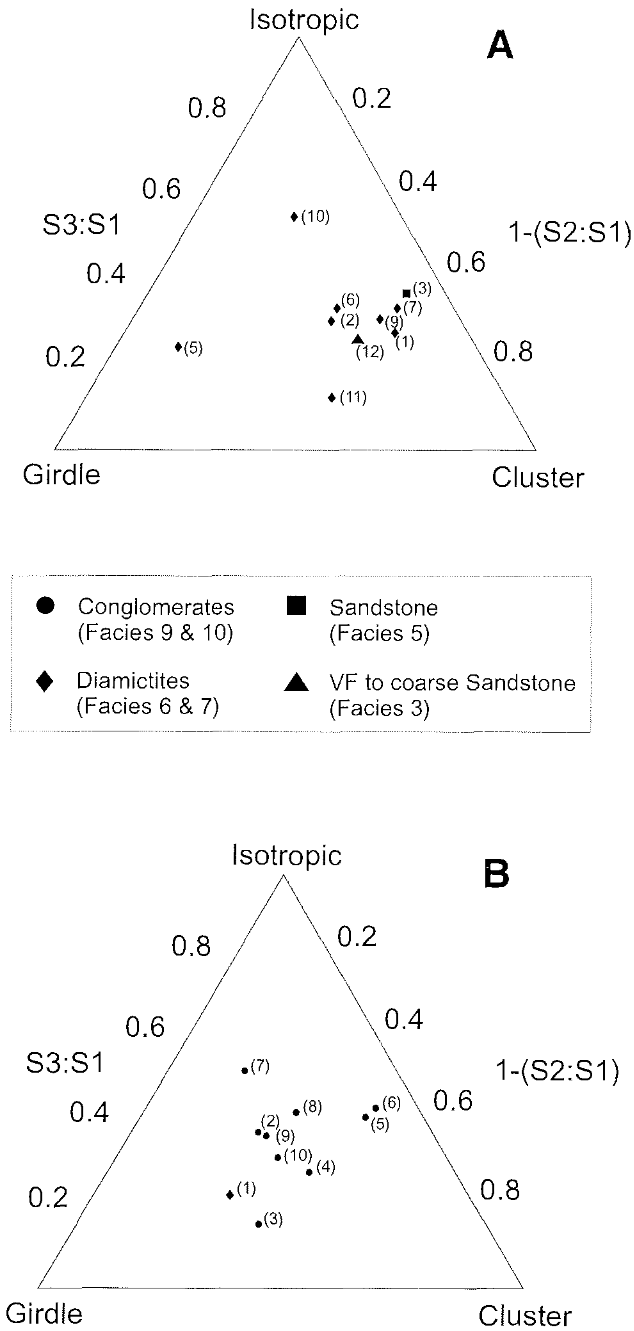


Fig. 6 - Fabric shape diagrams of Benn (1994b) with eigenvalues of Cape Roberts clast samples plotted. **A**) CRP-2/2A, **B**) CRP-3.

similar transport and erosion histories regardless of the facies. This indicates that any fluvial reworking that might be expected in the conglomerates is very limited.

Striated clasts have been widely reported from contemporary glacial sediments, although their abundance varies greatly (Hambrey, 1994). It is also noted that striae can form by non-glacial mechanisms (*e.g.* Jensen and Wulf-pederson, 1996; Winterer and von der Borsch, 1968; Dionne, 1985; McLennan, 1971). However, the presence of striae on clasts from the Cape Roberts cores, in the context of high latitude deposition are here considered to provide good evidence of basal glacial transport. The fact that striae are most common on rare fine-grained sedimentary clasts combined with the few opportunities to see uncut clast faces in the core is significant as it represents the "tip of the ice-berg" in terms of recording the contribution of sub-glacially derived clasts. For diamictite facies, the presence of striated clasts supports the inference from shape data that clasts in diamictite units are glacially derived but does not help resolve the question of the depositional mechanism. Striated clasts could be sourced from ice contact deposition by grounded ice or by ice-rafting. The occurrence of striated clasts in the conglomeratic units (facies 9 and 10) is more interesting because the conglomerates have been interpreted in the Cape Roberts facies scheme as representing fluvial discharges or high density mass flows. Delicate surface features such as striae do not survive significant fluvial reworking, confirming the inference from clast shape data that fluvial transport was very limited. This reinforces the interpretation of conglomerates as glacier proximal deposits sourced from subglacial debris and probably representing very short transport subglacial discharges or high-density mass flows. Striated clasts in the finer grained Facies 1, 2, 3, 4 and 5, are interpreted as rainout of ice-berg rafted subglacial debris. The sporadic but persistent distribution of these throughout both cores indicates significant glacial activity on land producing calving ice-bergs in the region since the earliest Oligocene.

Out-sized clasts in the fine-grained lithofacies (1, 2, 3, 4, 5), are 100 times larger than the mean diameter of the enclosing sediment. This defines a hydrodynamic paradox, or a contrast between the low energy environment of the host sediment and the high energy levels necessary to transport the out-sized clast laterally (Bennett et al., 1994). These clasts are therefore interpreted to be dropstones rafted to the site and deposited vertically through the water column. Bennett et al., (1994) reviewed various agents responsible for the introduction of dropstones into marine environments. Of these, the only possibilities for the emplacement of the out-sized clasts in the fine-grained facies in the Cape Roberts sequence include biological agents such as rafting in tree roots and kelp or climatological agents such as ice-bergs, ice shelves or sea ice. Terrestrial palynology from the core indicates low diversity, scrubby or closed forest vegetation even in the most favourable places in the early Oligocene and shows an overall progressive vegetation and climate deterioration further up the cores (Cape Roberts Science Team, 2000). This sparse vegetation is unlikely to have produced significant biological rafting. Combined with the sporadic but persistent occurrence of subglacially transported striated clasts, out-sized clasts are interpreted to have been introduced into the sediment by rainout of ice-berg rafted debris. In diamictite units (facies 6 and 7) out-sized clasts may represent ice-contact deposition such as subglacial till or by rainout of iceberg rafted debris, particularly in the stratified diamictites (facies 6). As these are glacially related processes, out-sized clasts in these facies have been included in the distribution. The distribution of out-sized clasts indicates that significant ice-rafting occurred throughout most of the time represented by the cores.

Three dimensional clast fabric analysis from coarse grained facies is a useful method of investigating clast orientation that may indicate whether or not grounded ice extended out to the drillsite during eustatic lowstand. However, many researchers have commented on the problems involved with interpreting fabric data (*e.g.* Dowdeswell and Sharp, 1986; Benn, 1994b; Hicock et al., 1996; Bennett et al., 1999). For example, Hicock et al., (1996) advocated the use of Schmidt plots in conjunction with eigenvalue analysis. They stress that multiple criteria must be considered when drawing conclusions on till genesis and that clast fabric alone is not able to discriminate between different glacigenic facies. Problems are compounded when attempting clast fabric analysis in drillcores. Often, very low numbers of whole clasts are availabie and other criteria such as glaciotectonic structures are not visible on core scale. In addition, only split core faces are usually available, prompting some to attempt two dimensional fabric studies (*e.g.* Hambrey, 1989). For the CRP cores, three dimensional clast fabric analysis was possible from the whole round core samples, but many of the other limitations apply, meaning that the fabric data, in particular eigenvalues, must be viewed cautiously. Although the data are simply too limited to infer specific genesis of coarse-grained facies and eigenvalues only provide a basic guide to fabric strength, stereoplots and eigenvalues are considered here to provide a indication (or lack of) of ice grounding at any of these intervals. Analysis of stereoplots show that none of the three dimensional clast fabrics have tightly clustered data and eigenvalue ratios highlight the absence of highly elongate, low isotropy fabrics indicative of subglacial tills or grounded ice at the drillsite.

CONCLUSIONS

Clasts from selected coarse-grained intervals in the Miocene/Oligocene strata in the Cape Roberts cores show features indicating subglacial transport histories and confirm that most clast-rich sediments are glacially derived. There is little real difference in clast shape between diamictites and conglomerates and the presence of subglacially derived facetts and striae on some clasts within conglomerates (facies 9 and 10), indicates the clasts have not experienced significant fluvial transport and that conglomerates are glacier proximal high-density mass flows or very short transport subglacial discharges.

Three dimensional clast fabrics from the drillcores must be treated cautiously, but weak to random orientations do not suggest ice grounded at the drillsite, although other evidence (van der Meer, 2000) indicate periods of grounded ice in the Late Oligocene and Early Miocene.

Out-sized clasts and striated clasts in fine-grained lithofacies represent dropstones sourced from icebergs. The distribution of these striated and out-sized clasts indicate that a glacial influence was significant and persistent during most of the time represented by the cores with glaciers actively calving at sea-level introducing ice-berg rafted glacial debris into the Ross sea region even in the very earliest Oligocene.

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