Coring for Antarctic
Tectonic and Climatic History

Cape Roberts Project

CORE LOGGING MANUAL

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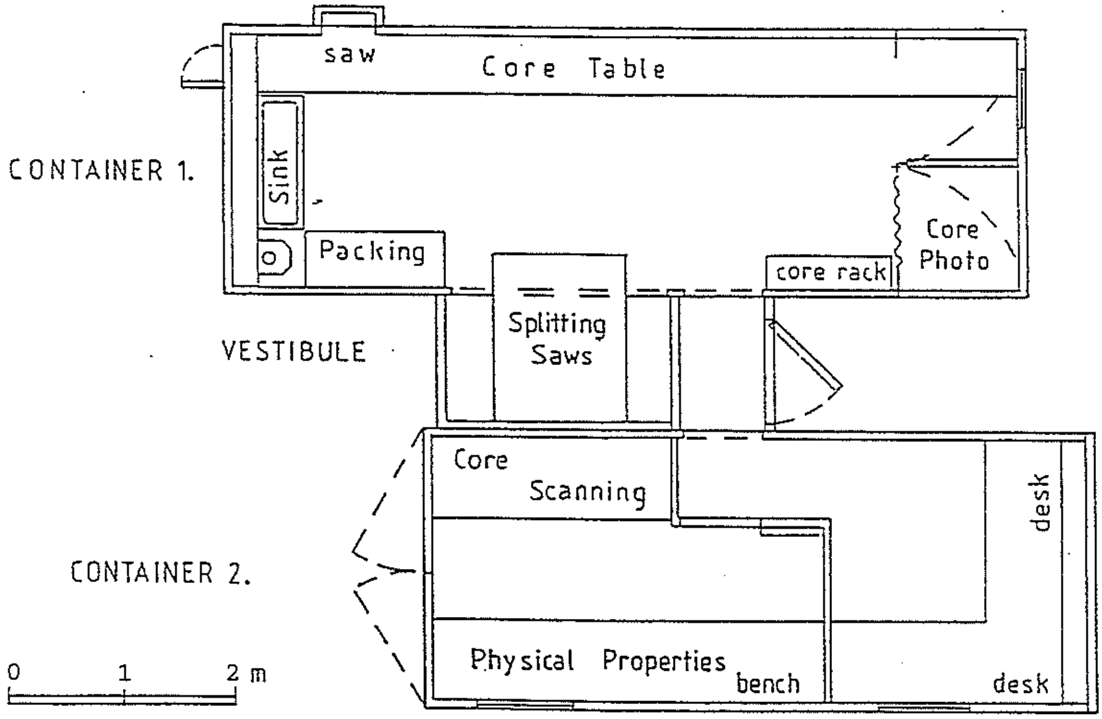
Cover: Part of comparison chart for sorting and sorting classes (S. Rowe after Pettijohn et al. 1972).

CONTENTS

PART 1: CORE DESCRIPTION

PART 2. INTERPRETATION OF SEDIMENTARY ENVIRONMENTS

PART 1: CORE DESCRIPTION



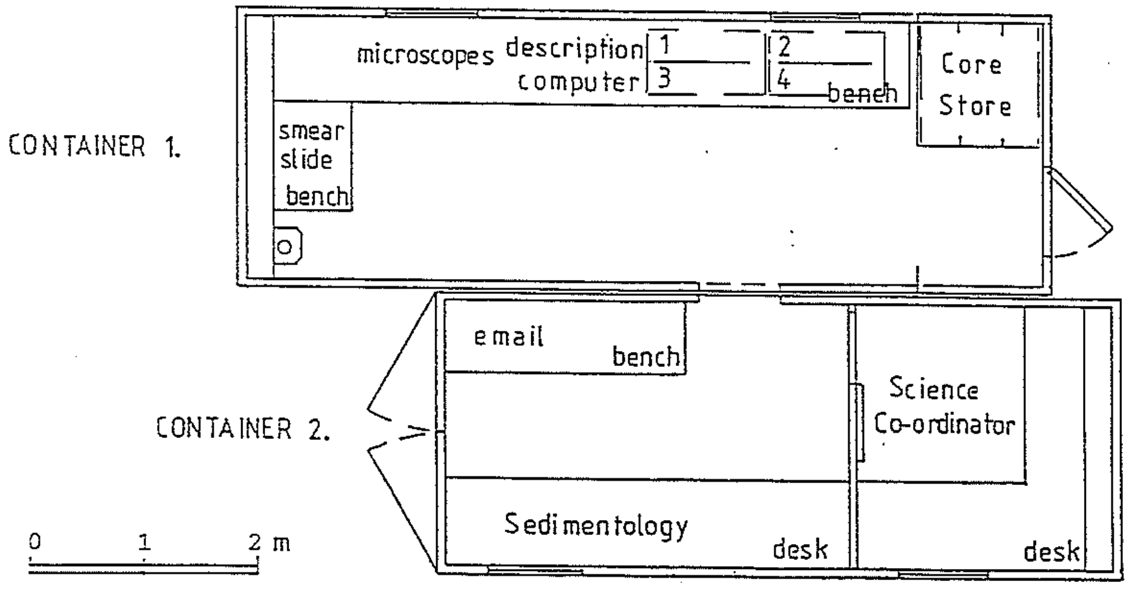


Figure 1. Floor plans of Drill Site Laboratory (upper) and the Cape Roberts Laboratory (lower).

1. RATIONALE

The purpose of this manual is to define procedures and establish conventions to be employed by the sedimentology/lithostratigraphy team at Cape Roberts. In order to provide data that are compatible with previous drilling on the Antarctic continental shelf, this manual draws heavily on the methods employed by ODP Leg 119 to Prydz Bay, East Antarctica in 1987/88 and subsequent Legs (Shipboard Scientist's Handbook 1987; Mazzullo 1988; Barron, Larsen *et al.* 1989), and by CIROS–1 in McMurdo Sound in 1986 (Barrett 1989).

The Cape Roberts core will be processed, described and sampled at three different sites: the Drill Site and Cape Roberts Camp laboratories (Fig. 1), and the Crary Laboratory at McMurdo Station (Fig. 2). This arrangement has been largely dictated by the need to split, package and label the core soon after drilling, and the need for a wide range of expertise, little of which can be accommodated at a drilling camp, to study the core for a comprehensive initial report.

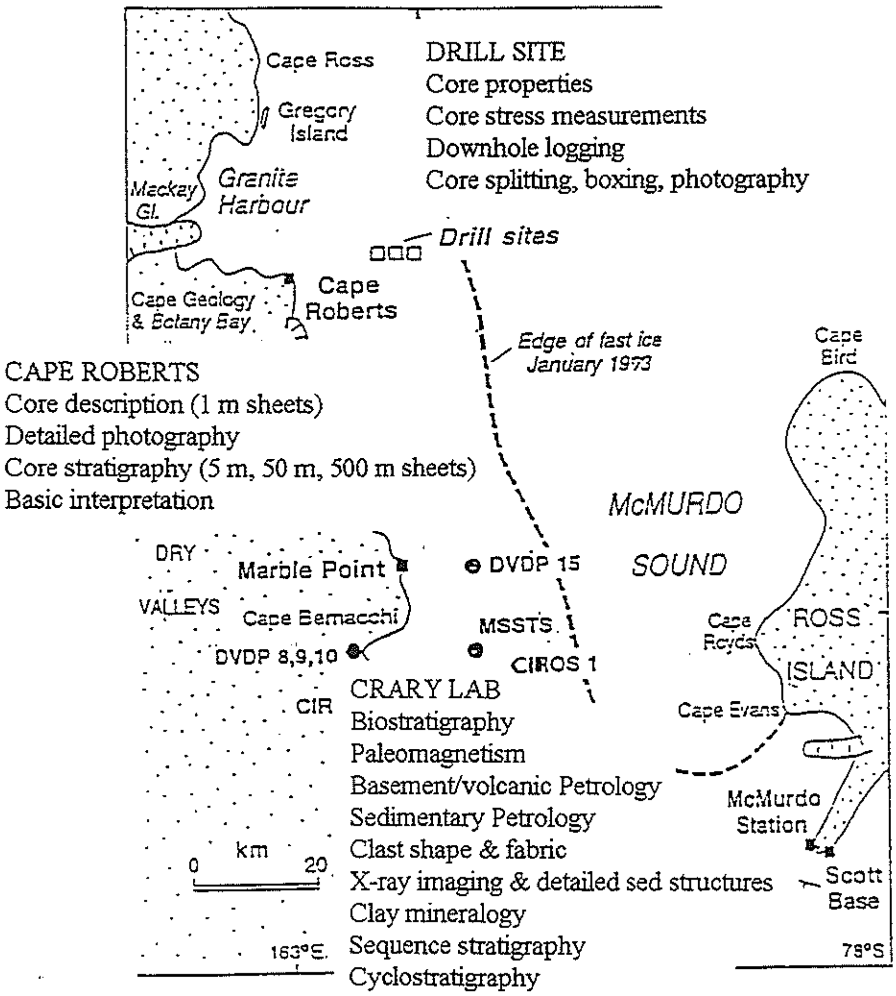


Figure 2. Outline map of McMurdo Sound, showing the locations of Cape Roberts, the drill-sites (up to 20 km offshore), McMurdo Station and Scott Base.

This manual summarises the procedures leading up to the delivery of core material to the Cape Roberts Camp Laboratory, outlines procedures for core-labelling and core-handling, before describing in detail the Cape Roberts Camp Laboratory procedures, which forms the bulk of this document.

2. DRILL-SITE PROCEDURES

2.1. Drill site processing

The core is processed and photographed at the drill site to record core features in pristine condition. The diameter of the core will be 61.1 mm (termed HQ size) in the upper part of each hole and 45.0 mm (termed NQ) in the lower part of each hole. The core will be recovered in either 3 m or 6 m lengths on the rig floor from a core barrel with a split tube insert (known as "splits"), and carried as a single length to the bench in the science laboratory. Here a visual recovery log is made with depths to each core segment identified from the driller's log.

If core orientation (magnetic azimuth) data are determined, the core will be aligned and scribed with north and south lines along the continuous length. Orientation data will be recorded on the recovery log.

The core is then transferred onto "carriers" and sectioned into 1 m lengths. It is then video-scanned and physically examined for fracture studies, and passed through a set of sensors for measuring physical properties, such as porosity, magnetic susceptibility and sonic velocity.

Every few tens of metres, representative cylinders of core about 100 mm long will be removed for other studies, such as stress relaxation and other destructive tests. The absence of the core cylinders will be noted on the recovery log and in the core boxes, because these cylinders will not be replaced.

The 1 m core sections are next transferred and aligned in holders and split along the length into two halves with diamond saws.

The core is boxed into a sample half (BOX ***S) and an archive half (BOX ***A), and the working half is photographed in both black and white, and colour transparency film.

The sampling and archive core boxes, with a copy of the recovery log, are separately transported at each 12-hour change of shift to the Cape Roberts Camp Science Laboratory.

2.2. Site, hole and sample numbering

Drill-sites are numbered consecutively CRP-1, CRP-2, CRP-3, CRP-4, with suffixes A, B etc., if more than one hole is drilled at a site.

For each hole, the drillers and core processors will take care to ensure that depths of the beginning and end of each coring run are accurate and consistent throughout. Once established, these depths will be the only means of identifying parts of the core or samples taken from the core for the remainder of the project. Core boxes will be labelled sequentially from the top of the hole. All other core references will be in terms of depth below the sea floor.

3. CAPE ROBERTS CAMP SCIENCE LABORATORY PROCEDURES

3.1. Introduction

The main activity of the Cape Roberts Camp Science Laboratory is to carry out the sedimentary description of the core and related activities. These procedures form the bulk of this report. The Cape Roberts Laboratory and the Drill Site Laboratory, although physically separated, will need to have continuous communication and interaction.

The following work will be carried out at the Cape Roberts Camp Science Laboratory:

- Description of the "sample" core half with the core log recorded as computerised graphics and incorporating appropriate recovery log data.
- Close-up photography of interesting features in the core as appropriate (noted on the log).
- Microscopic examination of smear slides from core material at about 1 m intervals, with data incorporated in the description.
- Identify fossils, and samples for thin-section preparation and other studies.

Both archive and sample core boxes must be stored in a "warm" area to minimise core-fracturing that may occur on freezing; mudstones are especially susceptible.

Archive and sample core boxes, with accompanying descriptions, will be carried to the Crary Laboratory at McMurdo Station by helicopter every two or three days.

3.2. Core Description

3.2.1 Core description forms

A variety of data are obtained from each core, ranging from mandatory to optional, the latter depending on whether features that require more detailed investigation are present.

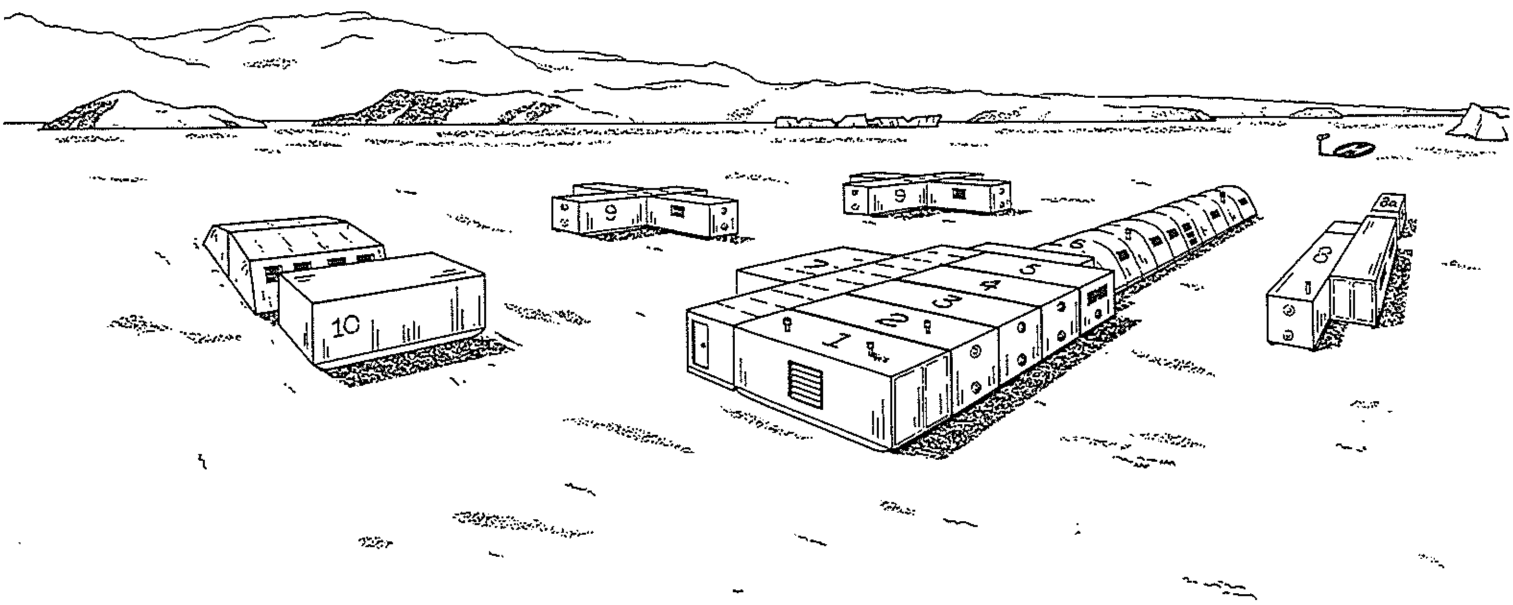
• *Visual core description form (VCD).* These are used by the logging team for the primary documentation of the core at a scale of 1:5 (Fig. 3). A single sheet is used for each 1 m section of core.

Figure 3. Specimen Visual Core Description Form (opposite).

Cape Roberts ____ Scale 1:5 Visual Description	Sheet Interval ____ to ____ Core Type ______ BOX ______	Sheet No. Logged by: ______ on ______

Depth (mbsf)	Drilling Disturbance	Core Face	Clay Silt Sand Gravel	number of clasts	% clasts	structure	bioturbation intensity	colour	consolidation	Description

CAPE ROBERTS CAMP



1 Generators
2 R/O Plant
3 Water Storage/Laundry
4 Ablutions
5 Kitchen
6 Mess and Rec.
7 Toilets/Drying Room
8 Science Laboratory
8a Project Office
9 Sleeping Accommodation
10 Workshop

Drawing : A.R. Pyne, S. Rowe

Figure 3a. Sketch of the Cape Roberts camp layout. The camp provides accommodation for 35 drillers, scientists and camp support staff as well as laboratory facilities for detailed core examination.

Cape Roberts

Sheet Number 1
Scale 1:20
Logged by: KJW 12-11-97

Box #	Core	Depth (mbsf)	Clay Silt Sand Gravel Graphic Log	Description

Record of Alterations:

Figure 4. Specimen core summary form.

Cape Roberts

Sheet Number 1
Scale 1:20
Logged by: KJW 12-11-97

Box #	Core	Depth (mbsf)	Clay Silt Sand Gravel Graphic Log	Description

Sub-unit **.**
***.** m - ***.** m

Degree of interbedding and general lithologies. Lithification, stratification, General lithogy, coulour in words and code. Stratification, bedding, grading. Bioturbation and trace fossils. Macro and micro fossils. Sedimentary structures. Other structure. Secondary minerals. Abundance, lithology, size, and shape of clasts. Lower Contact of Unit.

Other features of note:

Sharp contact or what ever

UNIT 23:

This page is generated in CorelDraw, which will be available at CRP camp. The proceedure for log preparation will be as follows.

1) Core logs (4m/page) will be hand drafted on a blank copy of this template.

2) These hand drafted logs will be scanned on an A4 flat-bed scanner and saves as .TIF Files.

3) The resulting file will be imported into CorelDraw and merged with a clean template.

4) A final camera ready copy will then be produced using Corel.

5) A selection of predefined fills and symbols will be available. A number of which are shown on the following page.

It is anticipated that each shift will see the completeion of the hand drafted logs and the near final copy. This will be dispatched to Crary Lab both as hard copy and on zip disk.

The sedimentology group at Crary Lab will maintain a master which they may edit as new information comes to hand or features of the orginal description are found to be in error. ALL modifications thus made will be recorded at the base of the form.

Record of Alterations: CRF 20-11-97 - shell at 21.98 m, added.
CRF 21-11-97 - description of unit 2 modified for style only.

Figure 4a. Specimen core summary form with notes.

CAPE ROBERTS PROJECT
SMEAR SLIDE DESCRIPTION

Site_________ Hole_________ Core________ Subbottom depth_______
Observer_______________ Date___________

Sediment name____
Lithology_______________ (dominant) _________________ (minor)

TEXTURE:	% Sand	% Silt	% Clay	
Overall	______	______	______	(= 100%)
Terrigenous	______	______	______	(= 100%)
Biogenic	______	______	______	(= 100%)

COMPOSITION: % Terrigenous________ % Biogenic_________ (= 100%)

Terrigenous (% total grains):
- Quartz ______
- Feldspar ______
- Rock fragments ______
- Volcanic glass ______
- Clay ______
- Mica ______
- Accessory Minerals ______
- Others ______

% Biogenic (% total grains):
- Total siliceous ______
  - Diatoms ______
  - Radiolarians ______
  - Spicules ______
  - Silicoflagellates____
- Total calcareous ______
  - Foraminifera ______
  - Nannofossils ______
- Plant debris ______
- Accessory components ______
- Others ______

COMMENTS:

Figure 5. Specimen smear slide composition form.

	**Core	**Interval (mbsf)	**Face (Vertical/Horizontal)	Colour/B&W	**Reason for Photo	**Requestor
1						
2						
3						
4						

Figure 6. Part of form for requesting photographs of core.

• *Graphic illustration of the core.* This allows the recorder to sketch the general appearance of the core, such as fractures, large-scale features, clasts.
• *Lithology.* This is represented by conventional symbols where appropriate, although new ones may need to be created on-site. Figure 4b is a list of the graphic symbols to be used. The characterisation of the sediments indicated is explained in Section 3.3. Critical intervals, such as the location of important lithological boundaries should be recorded.
• *Grain size.* This is indicated by a sideways extension of the graphic lithology column, using the primary grain size divisions (clay, silt, sand, gravel). Poorly sorted sediments are indicated by their coarsest components.
• *Number of clasts*, i.e. of material in the granule and gravel size range, counted per 10 cm of core.
• *Percent gravel.* Visual estimates of the gravel content are made over 10 cm intervals. The data are entered in the relevant column, using Table 1, in order to fully characterise the particle-size distribution along with smear-slide data of the sand and finer fraction.
• *Sorting* is documented according to Pettijohn *et al.* 1972 (Fig. 9), and forms part of the core description.
• *Physical structures.* On the scale of the core, recognising sedimentary structures may be difficult but small-scale structures should be readily visible. They are divided into structures related to sedimentation (primary structures); structures formed after deposition, e.g. by diagenesis (secondary structures); and those of biogenic origin including shells, wood etc. (Fig. 4b).
• *Bioturbation intensity* (see § 3.6).
• *Colour.* Munsell colour charts are to be used to determine colour of *wet* core.

CAPE ROBERTS PROJECT
THIN SECTION DESCRIPTION

Site__________ Hole__________ Core_________ Subbottom depth________
Observer________________ Date____________

Sediment name____
Lithology________________ (dominant) __________________ (minor)

TEXTURE: Grain size (µm): Roundness_________
Max. ________ Sphericity _________
Min. ________ Sorting _________
Mode(s)_________

DETRITAL COMPOSITION (% of total rock)

Quartz	______	(mono) __________: poly __________)
K-Feldspar	______	
Plagioclase		
Rock fragments	______	(types __________; ______________)
Muscovite	______	
Biotite	______	
Heavies	______	
Opaques	______	
Carbonates	______	
Matrix	______	(types __________; ______________)
Others	______	

DIAGENETIC COMPONENTS (% of total rock)

Cement	______	(types __________; ______________)
Other authigenic components		________________________________

POROSITY (% of total rock):

Primary	______
Secondary	______

COMMENTS

Figure 7. Specimen form for thin-section description

Figure 8. Drilling disturbance symbols (from ODP Leg 119; Barren, Larsen & Shipboard Scientific Party 1989). (right).

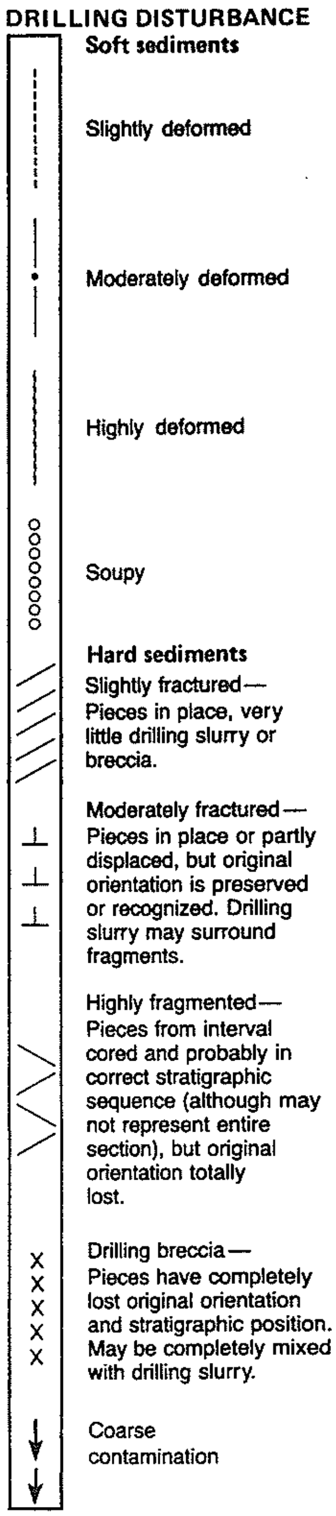
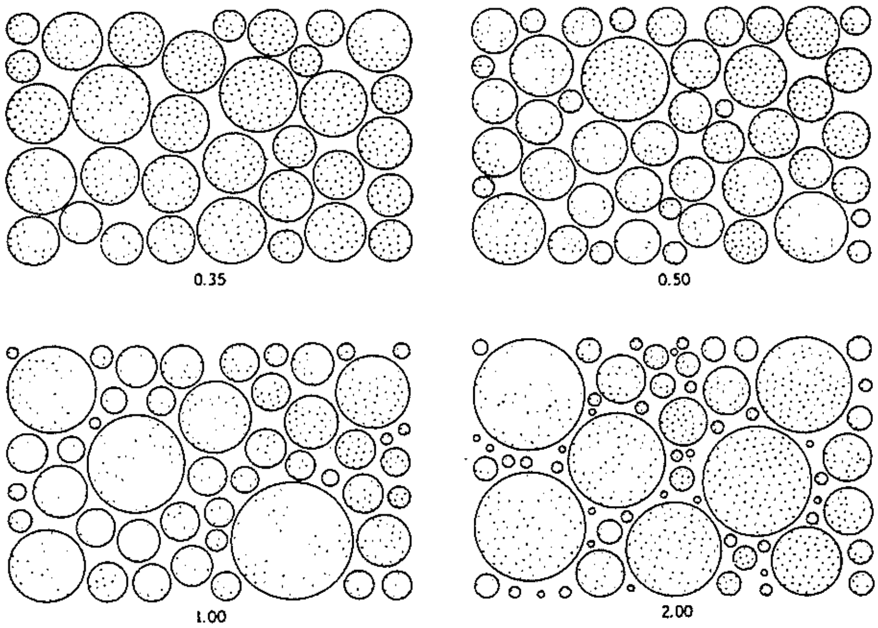


Table 1. Textural classification of poorly sorted sediments containing gravel (modified from Moncrieff 1989) (Below).

PERCENT SAND IN MATRIX	PERCENT GRAVEL (>2mm) IN WHOLE ROCK ESTIMATED FROM CORE					
		Trace - < 1%	*1 - 5%*	*5 - 30%*	*30 - 80%*	*> 80%*
0–10	FINE-GRAINED SEDIMENTS - See Figure 16	MUDSTONE with dispersed clasts	MUDSTONE with common clasts	MUDSTONE with abundant clasts	Muddy CONGLOMERATE/ BRECCIA	CONGLOMERATE/ BRECCIA
10–50		Sandy MUDSTONE with dispersed clasts	Clast-poor muddy DIAMICTITE	Clast-rich muddy DIAMICTITE	Sandy muddy CONGLOMERATE/ BRECCIA	
50–90		Muddy SANDSTONE with dispersed clasts	Clast-poor sandy DIAMICTITE	Clast-rich sandy DIAMICTITE	Muddy sandy CONGLOMERATE/ BRECCIA	
90–100		SANDSTONE with dispersed clasts	SANDSTONE with common clasts	SANDSTONE with abundant clasts	Sandy CONGLOMERATE/ BRECCIA	

SORTING IMAGES



DIAMETER RATIO (MILLIMETERS)	PHI STANDARD DEVIATION	VERBAL SCALE	
1.0	0.00		
		very well sorted	MATURE
1.6	0.35		
		well sorted	
2.0	0.50		
		moderately sorted	SUBMATURE
4.0	1.00		
		poorly sorted	
16.0	2.00		
		very poorly sorted	

(After Folk, 1965, p. 104–105)

Figure 9. Comparison chart for sorting and sorting classes (from Pettijohn et al. 1972)

• *Consolidation.* To indicate whether core is soft, compact, over-consolidated or lithified.
• *Lithological description.* An informal lithofacies code, based on capital letters for the lithology (maximum of two), together with a small letter modifier following to indicate nature of bedding (Table 2) is given here. A lithological description for each unit or sub-unit on each core log is also given, consisting of (i) a brief summary of the major lithologies in order of importance, followed by a description of sedimentary structures, colour, and other significant features; and (ii) a description of minor lithologies observed with similar information, and a note of their occurrence in the core. Any information about palaeocurrents would also be given here, if the opportunity arises from orientated core.

3.2.3. Microscopic examination

Smear slide examination. Smear slides provide a rough and ready means of identifying the relative proportions of sand silt and clay, and their constituent minerals or biogenic components. The method of preparing smear slides and mineral identification under petrological microscope follows that of Rothwell (1989). Approximately 10 mg of wet sediment on the end of a tooth-pick is placed in the mounting medium on a glass slide, and examined under the binocular petrological microscope. Samples should be taken at intervals of approximately 1 m. Six flow charts are used for mineral identification (Fig. 10, a-f). The final step in the smear slide description, giving a name to the sediment, follows the classification scheme presented below. Abundance is defined as a 'trace' where the estimated content is less than 1%.

LITHOLOGY		PREFIXES	
C	Coal	g	gravelly
B	Breccia/rubble	s	sandy
G	Gravel/conglomerate	m	muddy
D	Diamict(on/ite)	c	calcareous
S	Sand/sandstone	**SUFFIXES**	
M	Mud/mudstone	m	massive
L	Carbonate (limestone/dolostone)	w	weakly bedded
V	Volcanogenic sediments	s	well bedded
O	Siliceous ooze/chert/opal	l	laminated
E	Evaporite	i	inter-stratified
		b	bioturbated

Lamination: < 1 cm *Bedding: > 1 cm*

Table 2. Facies abbreviations for terrigenous sediments.

Smear slide summary. Tables summarising smear-slide data, if available, are to be prepared for each core description form (Fig. 4). The section and interval from which the sample was taken are noted, as well as identification as a dominant (D) or minor (M) lithology in the core. The percentage of all identified components, corrected to include any gravel, is given. These data allow a precise lithological name to be given to the recovered material.

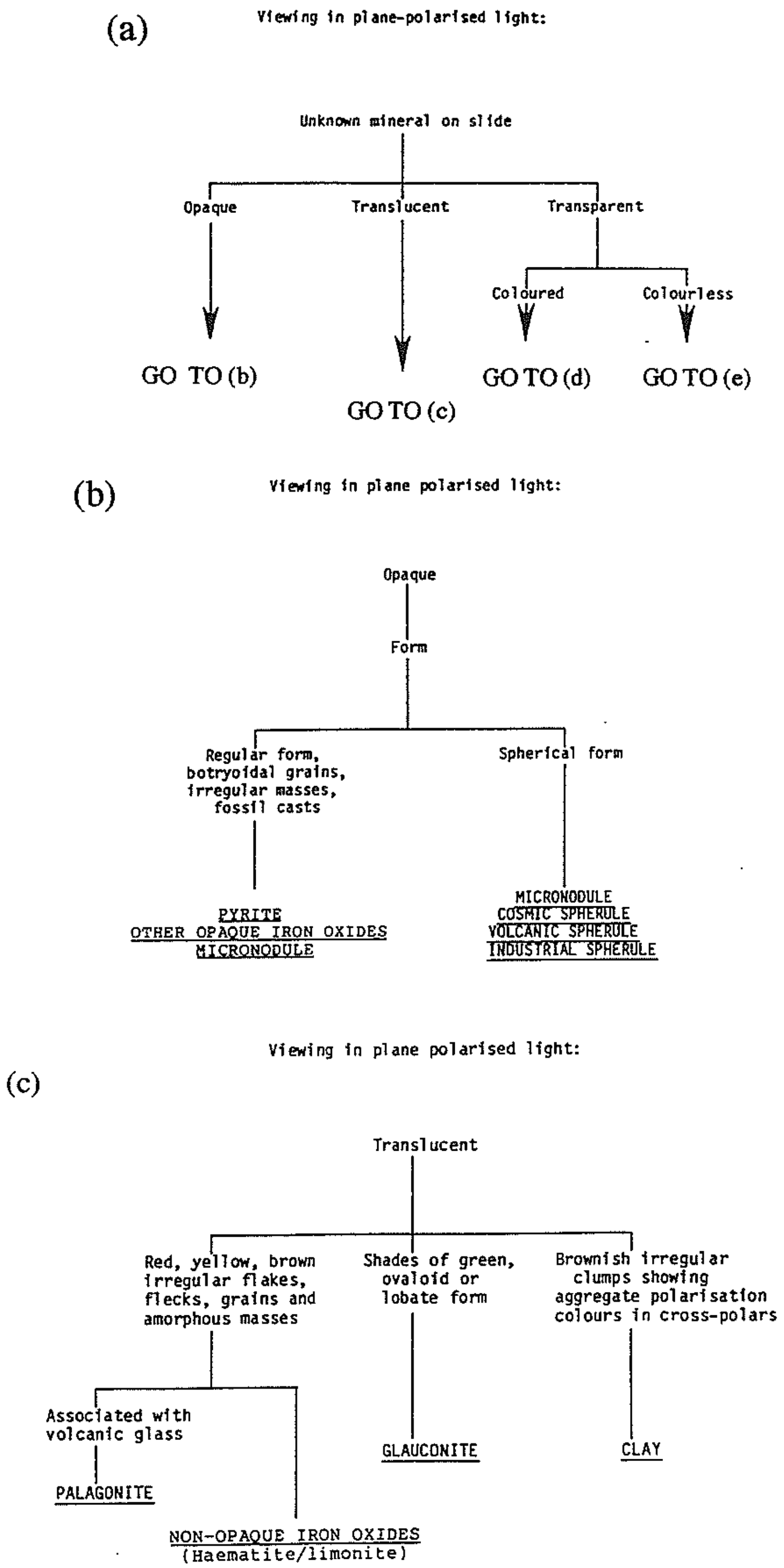
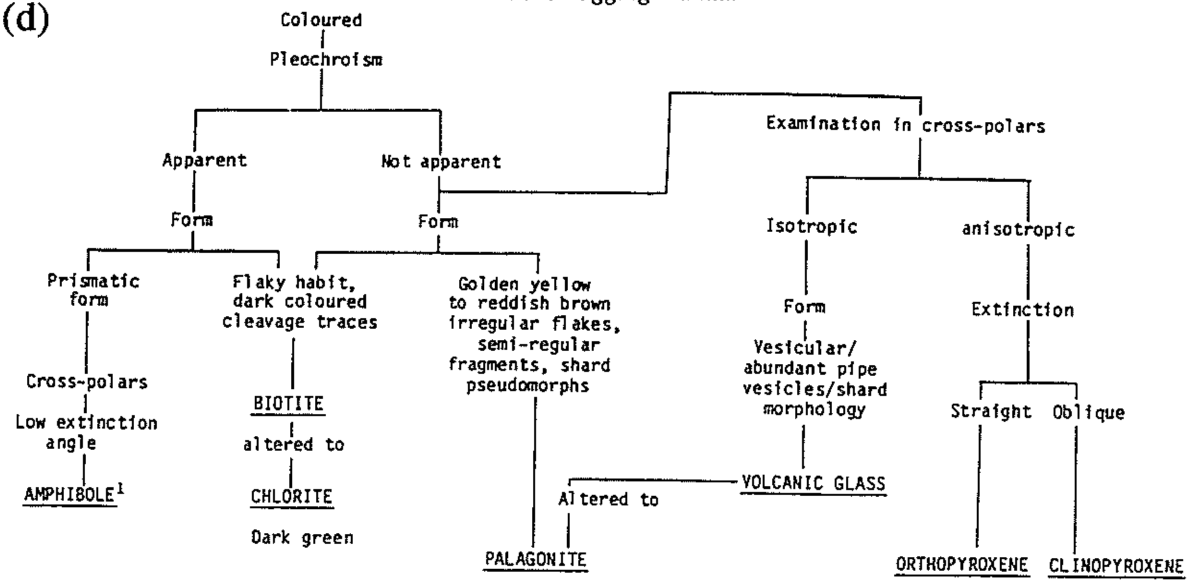


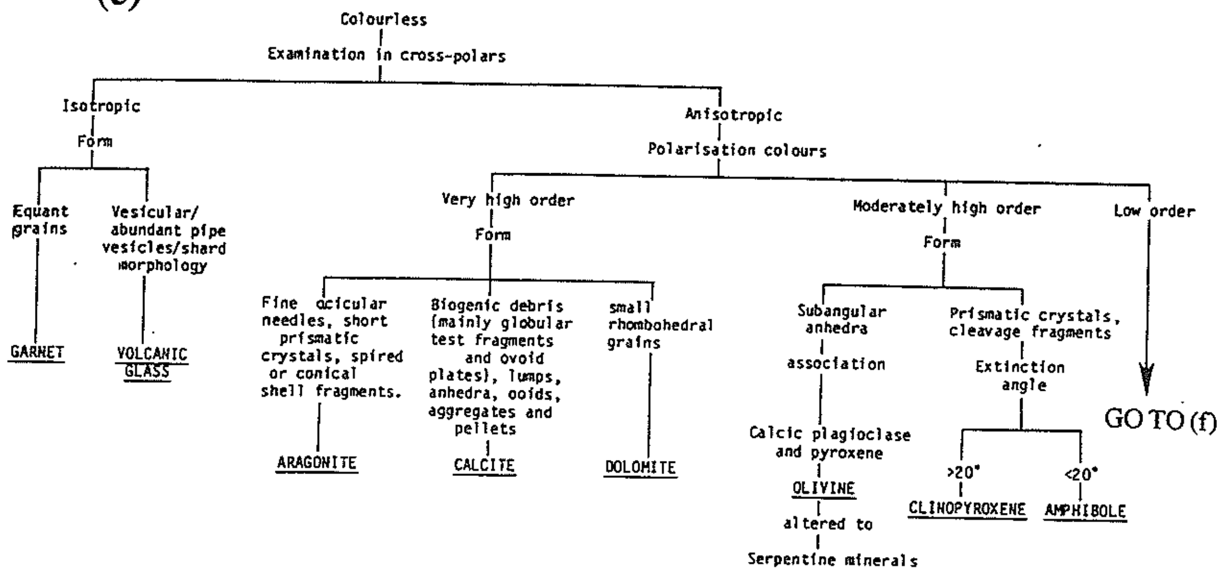
Figure 10. Procedure for the identification of smear-slide constituents (after Rothwell 1989). Continued following page.

(d)



Note: [1] The clinopyroxene aegirine also has a small extinction angle and is coloured and pleochroic.

(e)



(f)

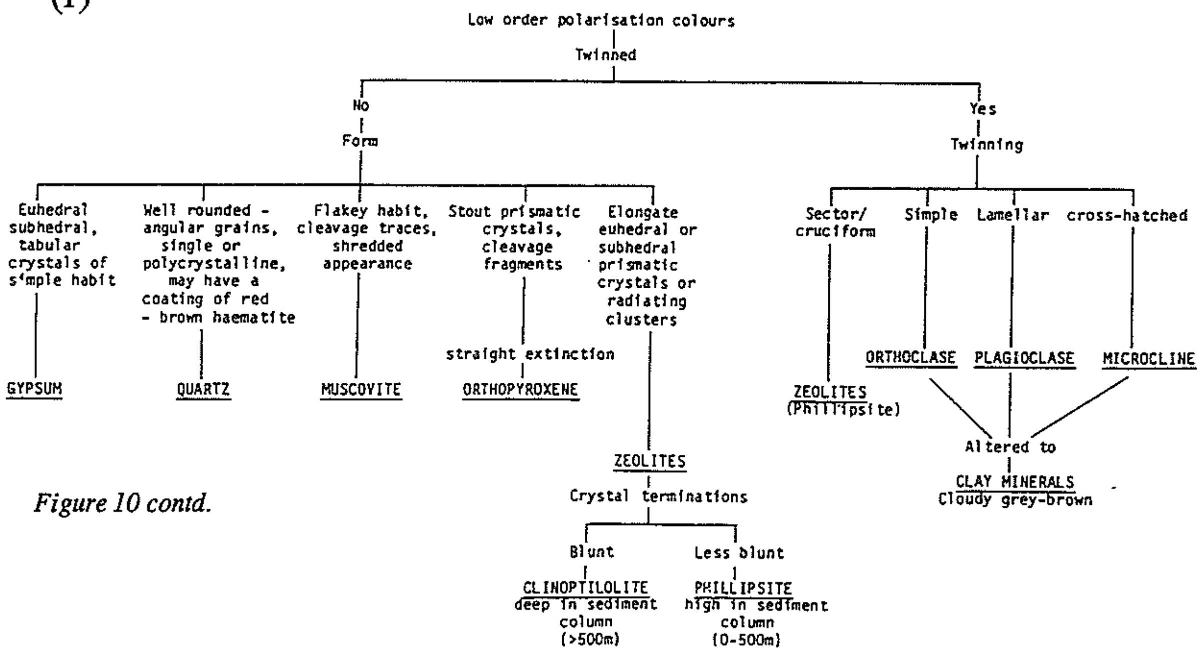


Figure 10 contd.

3.2.4. Definition of units

Units are defined on the basis of common lithologies and lithological associations, each being typically represented by tens of metres of core, although some units may be just a few metres or more than 100 m. A unit is equivalent to a "formation" in terrestrial exposures. Units are best defined on the basis of mutual agreement between the different scientific groups, the initial proposals coming from the sedimentologists. This can only be achieved after the core has been seen in its entirety. Numbering is from top to bottom (as in ODP). Sub-units may be defined where appropriate using ..a, ...b, ...c etc.; these are equivalent to "members".

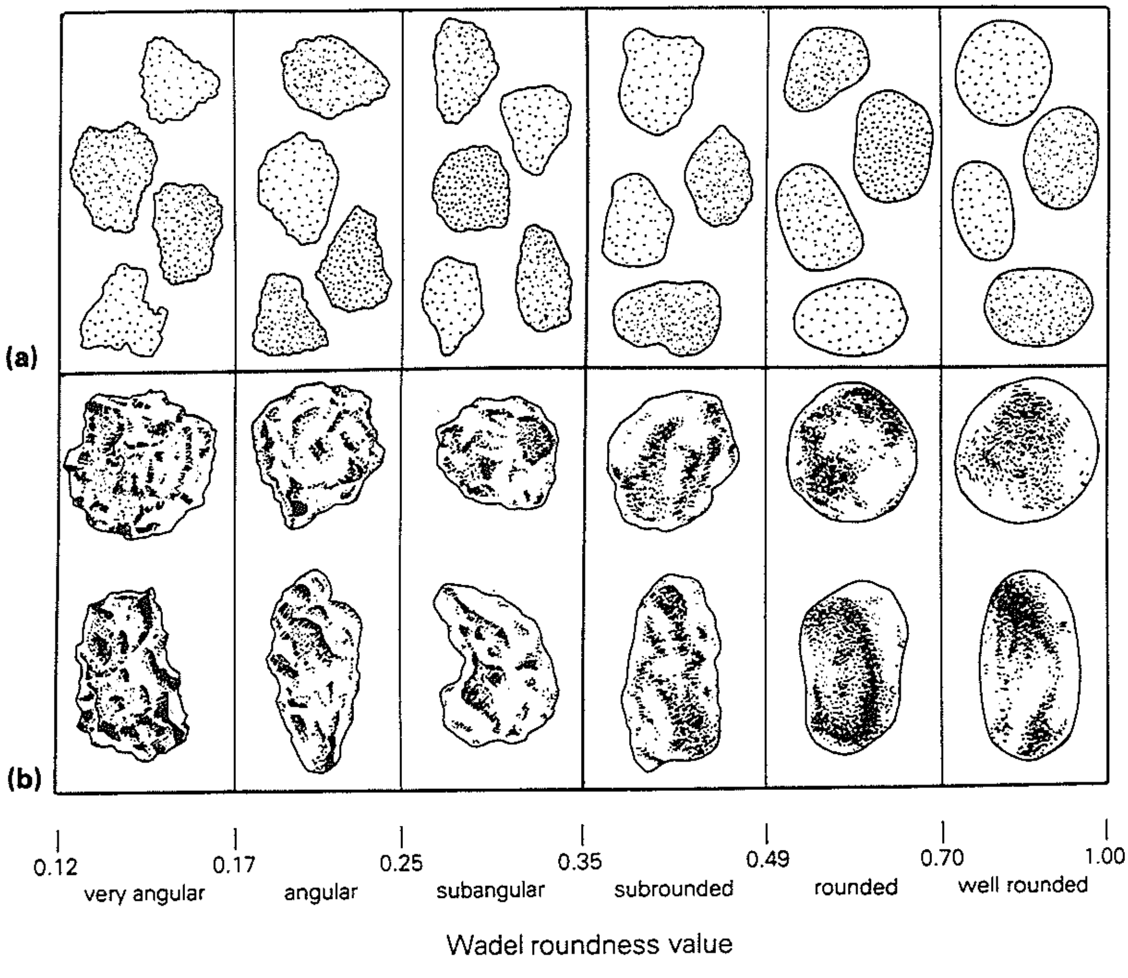


Figure 11. Grain/clast images for visual determination of roundness: (a) two-dimensional grain outlines (based on Krumbein 1941 and Shephard & Young 1961); (b) three-dimensional images (after Powers 1953). Class names and boundaries are based on Powers (1953). (From Lindholm 1987).

3.2.5. Analysis of clasts

Where appropriate for establishing the origin and mode of transport of gravel-bearing sediment, additional observations of the core need to be made, notably clast lithology, shape and fabric.

Clast lithology

Estimate percentages of the main lithological constituents.

Figure 12. Histograms of clast roundness (as depicted in Figure 11) from sediments in a modern, glacially influenced Arctic environment (Svalbard). The "egg gravels" are interpreted as reworked mature interglacial beach deposits (from Bennett et al. 1997).

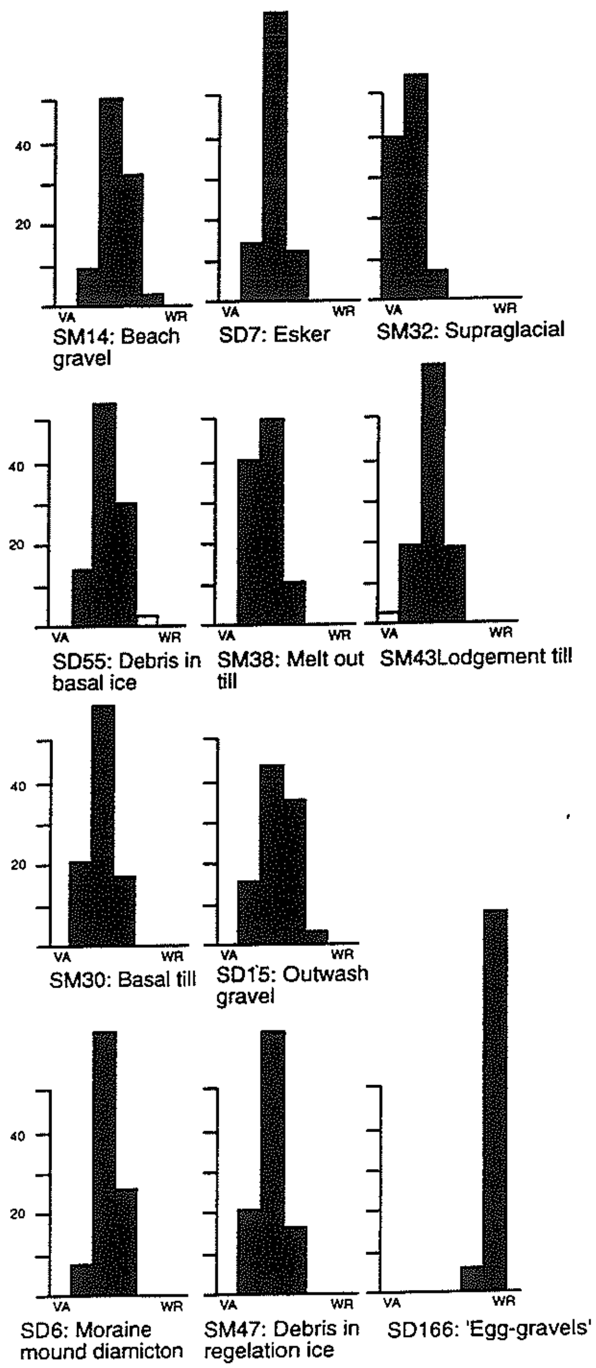
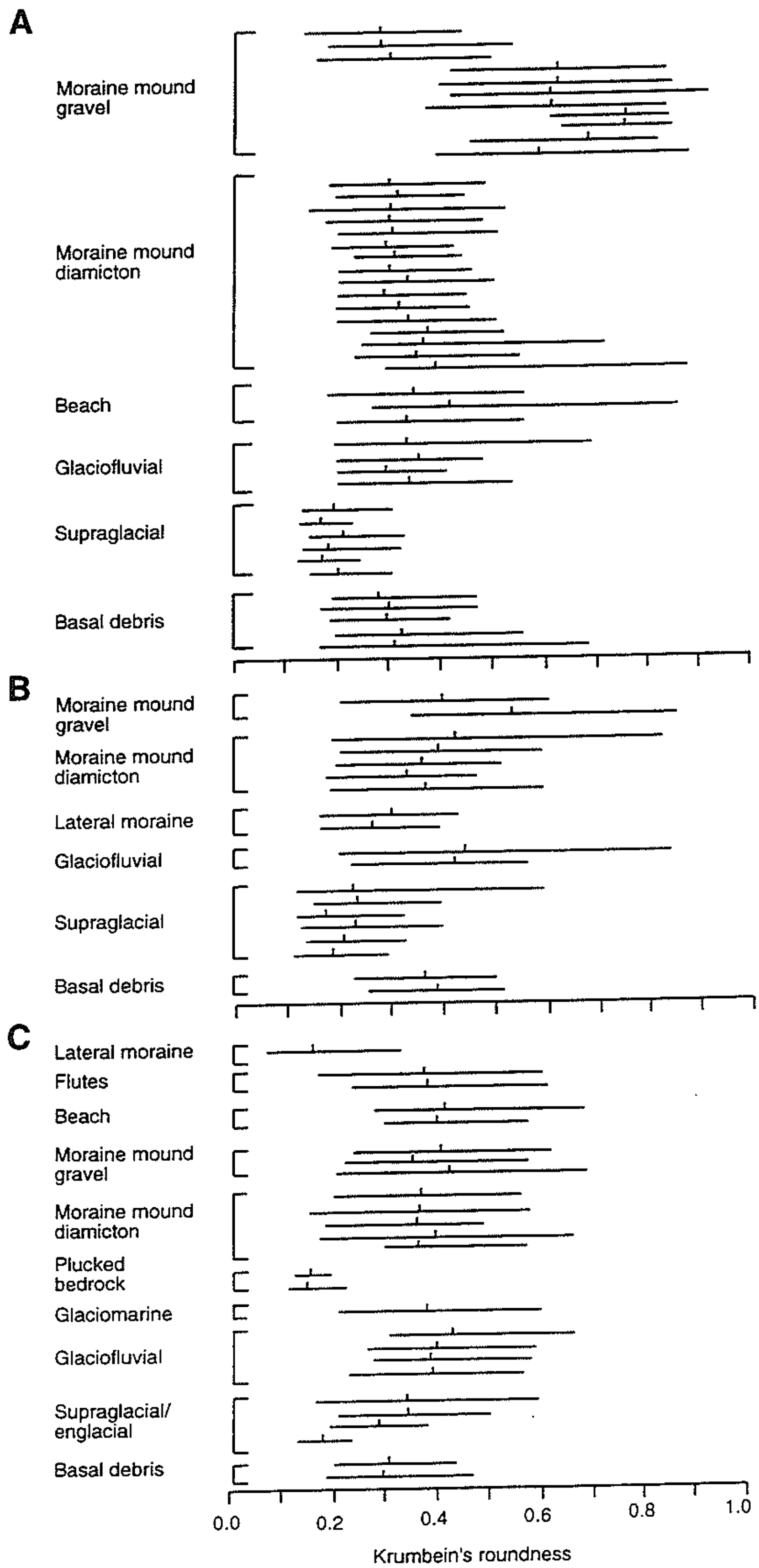


Figure 13. Mean values and ranges of Krumbein roundness for a variety of sediments from a modern, glacially influenced Arctic environment (Svalbard) (from Bennett et al. 1997).



Clast shape

Clast shape represents the summation of particle form, roundness and surface texture (Barrett 1980). It has been widely accepted as a useful diagnostic tool in the analysis of different depositional regimes, and has proved particularly useful in the analysis of glacigenic sediments (Bennett & Glasser 1996). However, in the cut face of the core, it will only be possible to gain a two-dimensional view of clast shape. In this context, Krumbein/Powers roundness should be determined for assemblages of clasts (Fig. 11). The technique has been applied by numerous glacial geologists (e.g. Dowdeswell 1986) since it has sufficient discrimination to assist in discrimination of the mode of transport. Preferably, 50 estimates of shape should be made. For comparison, data from a modern glacial environment (Svalbard) are presented as histograms in Figure 12 and as bar graphs of mean shape and standard deviations in Figure 13. Data from other depositional settings are desirable.

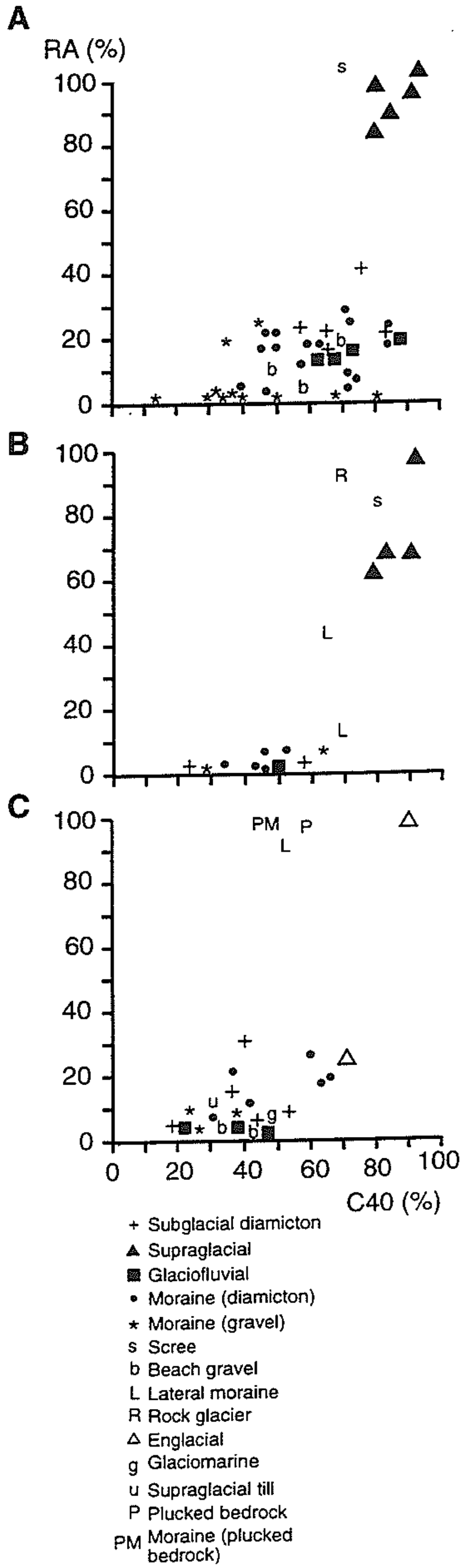
Quantification of clast shape requires disaggregation of tens of centimetres of core so that clasts can be measured in three-dimensions. Form is calculated from the lengths of the three orthogonal axes, and roundness derived from the Wadell roundness scale (Krumbein 1941) (Fig. 11b). Surface features such as striae, individually or in sets, and facets are also recorded, along with clast lithology. Although numbers are likely to be small for individual samples, grouping will provide average values for the various stratigarphic units and for particular lithologies.

Plots of roundness *versus* sphericity have been used to discriminate between different transport paths in glaciers (Boulton 1978), but recent work (Bennett *et al.* 1997) has shown that sphericity has no discrimination capacity. In contrast, Benn & Ballantyne (1994) have advocated the use of ternary diagrams, and demonstrated that co-variant plots of a roundness index known as the RA index (percent of angular and very angular clasts), and of the C40 index (percent of clasts with a c/a axial ratio of < 0.4), gives excellent discrimination between different glacial facies. RA-C40 plots from a range of different facies in the modern high-Arctic environment of Svalbard are illustrated in Figure 14.

Clast fabric

This technique is relevant for discriminating different types of glacigenic facies: terrestrial, marine or reworked. Three-dimensional studies are not feasible because a large amount of core would need to be destroyed. However, if cross-cut surfaces are available, it should be possible to determine the relative (but not absolute) orientation of coarse sand-sized and larger grains in two-dimensions, allowing discrimination between preferred and non-preferred orientation fabrics. X-ray analyses of gravelly muds and muddy diamicts may help to elucidate fabric. *NB* This work is ear-marked for the Crary Laboratory.

Figure 14. Discrimination of a variety of sedimentary facies in Svalbard using a plot of the RA index (percent of angular and very angular clasts) against the C40 index (percent of clasts with mean c/a axial ratio of < 0.4) (from Bennett et al. 1997).



Surface features on clasts

Debris transported at the base of a glacier acquires certain distinguishing characteristics. The development of facets (flat surfaces with rounded edges) is widespread, often with as many as 80% of clasts being affected. Occasionally two parallel sets of facets give rise to "flat-iron" shapes. Other clasts may develop pentagonal or bullet shapes. Facets tend to develop on all rock types if basally transported, and they do not necessarily form preferentially along bedding, foliation or joint surfaces.

Striae and associated features, such as crescentic gouges and chattermarks, develop on basally transported stones; they are especially common on subrounded and faceted clasts. Whether or not striations develop very much depends on lithology. Hard crystalline rocks, such as quartzite, granite, gneiss and schist, rarely display striations, whereas fine-grained igneous rock, carbonates and mudstones, commonly do. For example, in glacigenic sediment from the Antarctic continental shelf Kuhn *et al.* (1993) found that, out of populations of several hundred, only 4% of gneisses had striations, in comparison with 43% of basic igneous rocks. (from Hambrey 1994).

3.2.6. Composition of fines

Smear-slide and thin-section data on core composition should be incorporated, the latter following preparation at the Crary Laboratory, or when XRD data are available, i.e. at the end of the season.

3.3. Classification of Granular Sediments

Classification of granular sediments of sand and finer grain size broadly follows the ODP "Handbook for Shipboard Sedimentologists" (Mazzullo & Graham 1988). Poorly sorted sediments, comprising material in the clay to gravel range, are dealt with separately.

3.3.1. Types of granular sediment

The following types of grain are defined: (1) siliciclastic, (2) pelagic, (3) neritic and (4) volcaniclastic, (Fig. 15). Siliciclastic grains are composed of mineral and rock fragments derived from igneous, sedimentary and metamorphic rocks. Pelagic grains are composed of the debris of open-marine, siliceous, and calcareous microfauna and microflora (e.g. radiolaria and nannofossils) and associated organisms. Neritic grains are composed of coarse-grained calcareous debris and fine-grained calcareous grains of non-pelagic origin (e.g. micrite). Volcaniclastic grains are composed of rock fragments and minerals derived from volcanic sources. These make up four major classes of sediment to which may be added a fifth, "mixed sediments" (Fig. 15).

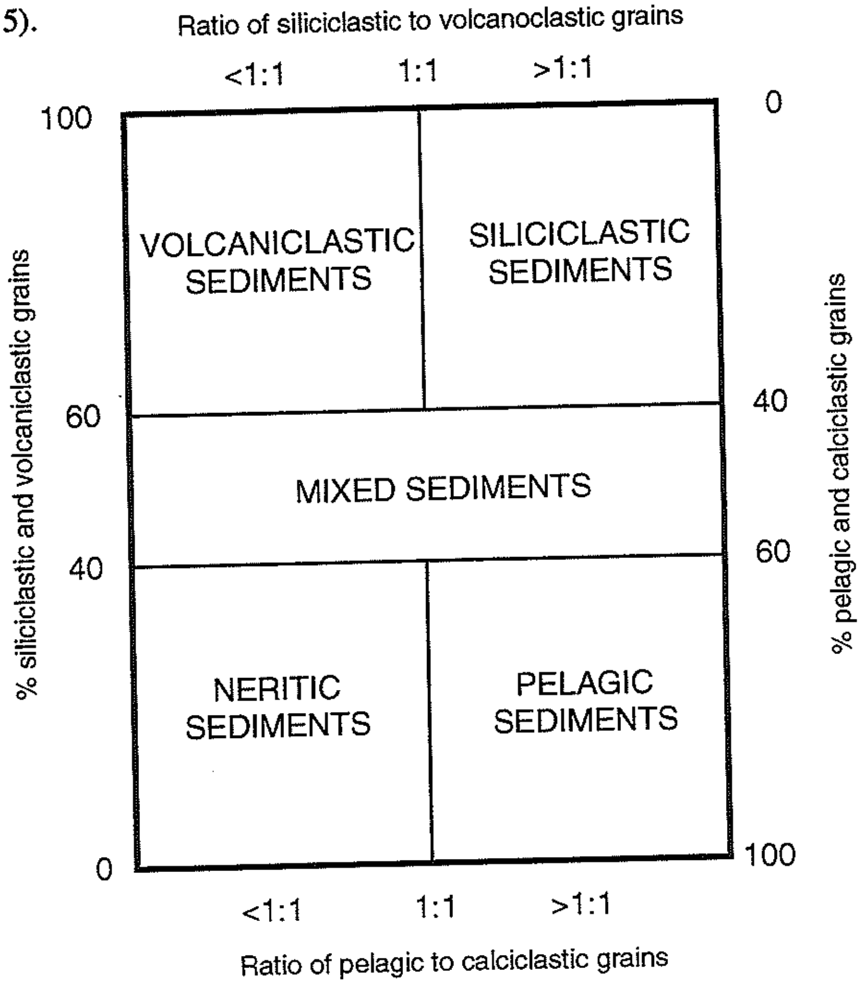


Figure 15. Diagram showing the ODP classification scheme for granula sediments (after Mazzullo & Graham 1988).

(1) Siliciclastic sediments are composed of >60% siliciclastic and volcanic grains and <40% pelagic and neritic grains. The proportion of siliciclastic exceeds that of volcaniclastic material.

(2) Pelagic sediments are composed of >60% pelagic and neritic grains and <40% of siliciclastic and volcaniclastic grains. Pelagic > neritic grains.

(3) Neritic sediments are composed of >60% neritic and pelagic grains and <40% siliciclastic and volcaniclastic grains. Neritic > pelagic grains.

(4) Volcaniclastic sediments are composed of >60% of volcaniclastic and siliciclastic grains. Volcaniclastic > siliciclastic grains.

(5) Mixed sediments are composed of 40–60% siliciclastic and volcaniclastic grains and 40–60% pelagic and neritic grains.

Modifiers may be used to increase the detail of the sediment classification. The description of composition and textures of grain types that are present in proportions > 25 % form 'major modifiers' and precede the 'principal name'. 'Minor modifiers' describe components and texture present in proportion between 25 and 10% and follow, preceded by a suffix, the principal name.

Major modifiers describe the composition of pelagic grains (e.g. foraminiferal, radiolarian, ...), the composition of neritic grains (ooids, intraclast, ...), the texture of siliciclastic grains (very fine, fine, medium, coarse, and very coarse according to Table 3), the composition of siliciclastic and volcanic grains (quartz, feldspatic, glauconitic, pyritic, volcanic, basaltic...), the fabric (grain-supported, matrix-supported.....), the shape (well rounded....), and the colour (Munsell Soil Colour Chart) of the sediment.

Minor modifiers, preceded by the suffix 'with', principally describe the composition of a minor component of the sediment (e.g. .... with diatoms, ...with coarse sand, etc...).

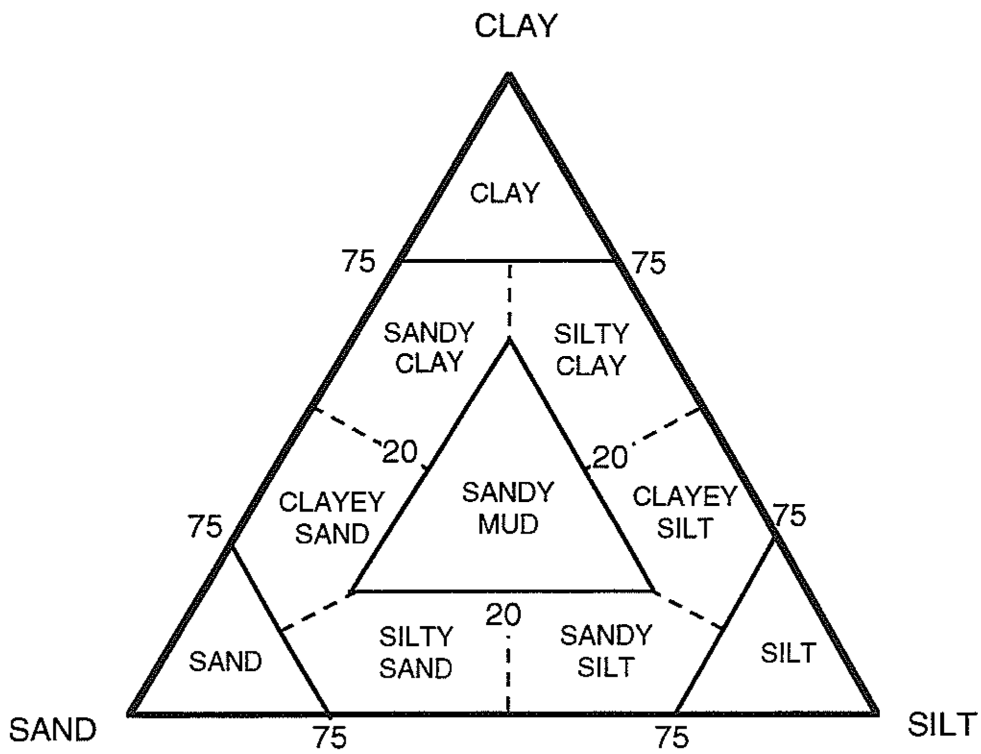


Figure 16. Slightly modified classification scheme for siliciclastic sediments, based on grain size of clastic components (after Mazzullo & Graham 1988).

3.3.2. Classification of siliciclastic sediments by sub-gravel particle size

Siliciclastic sediments are expected to be the dominant type at Cape Roberts. The composition of a sediment in the sand/silt/clay range enables it to be classified according to a ternary diagram (Fig. 16), modified after Shepard (1954). The diagram indicates the possible 'principal names' of granular siliciclastic sediments; it should only be used where the gravel content is <1%. For sediments with >1% gravel, see §3.3.3.

Grain size						
	(mm)	(µm)	(ϕ)	Wentworth size class	
			−0.20		
	4096		−0.12		
	1024		−0.10	Boulder (−0.8 to −0.12 ϕ)	
	256		−0.8	—Cobble (−0.6 to −0.8 ϕ)—	
	64		−0.6		
	16		−4	Pebble (−0.2 to −0.6 ϕ)	gravel
	4		−2		
	3.36		−1.75		
	2.83		−1.5	Granule	
	2.38		−1.25		
	2.00		−1.0		
	1.68		−0.75		
	1.41		−0.5	Very coarse sand	
	1.19		−0.25		
	1.00		0.0		
	0.84		0.25		
	0.71		0.5	Coarse sand	
	0.59		0.75		
1/2	0.50	500	1.0		
	0.42	420	1.25		
	0.35	350	1.5	Medium sand	
	0.30	300	1.75		
1/4	0.25	250	2.0		
	0.210	210	2.25		
	0.177	177	2.5	Fine sand	
	0.149	149	2.75		
1/8	0.125	125	3.0		
	0.105	105	3.25		
	0.088	88	3.5	Very fine sand	
	0.074	74	3.75		
1/16	0.0625	63	4.0		
	0.053	53	4.25		
	0.044	44	4.5	Coarse silt	
	0.037	37	4.75		
1/32	0.031	31	5.0		
1/64	0.0156	15.6	6.0	Medium silt	
1/128	0.0078	7.8	7.0	Fine silt	
				Very fine silt	
1/256	0.0039	3.9	8.0		
	0.0020	2.0	9.0		mud
	0.00098	0.98	10.0		
	0.00049	0.49	11.0	Clay	
	0.00024	0.24	12.0		
	0.00012	0.12	13.0		
	0.00006	0.06	14.0		

Table 3. Grain-size categories used for classification of terrigenous sediment (from Wentworth 1922).

The size limits for these constituents are those defined by Wentworth (1922) (Table 3). Ten major textural groups are recognised, defined on the basis of the abundance of clay, silt, and sand. The term 'mud' is introduced only to define the sediments containing a mixture of sand, silt and clay in proportions between 20 and 60% each. The resulting sediment is classified as 'sandy mud'. Note that the modified Shepard (1954) scheme of Figure 16 must be adopted in the classification of poorly sorted sediments where the gravel content is less than 1%.

The 'principal names' indicated in Figure 16 apply to unlithified sediments only. The suffix -stone is used in case of lithified equivalents (in general, only those that can be cut by a saw).

A few examples of classification of siliciclastic sediments (after the ODP Handbook of Shipboard Sedimentologists) are given in Table 4.

Example 1 - Sediment with 100% sand, composed of well-rounded quartz grains.

Principal name: sand

Major modifier: rounded quartz:

Minor modifier: none

ROUNDED QUARTZ SAND

Example 2 - Lithified sediment with 70% medium and 30% fine sand, composed of quartz (60%), feldspar (30%) and mica (10%).

Principal name: sandstone

Major modifier: feldspar quartz fine-medium

Minor modifier: with mica

FELDSPAR QUARTZ FINE-MEDIUM SANDSTONE WITH MICA

Example 3 - Lithified sediment with 50% clay, 35% quartz-silt, and 15% forams, red in colour.

Principal name: claystone

Major modifier: red silty

Minor modifier: with forams

RED SILTY CLAYSTONE WITH FORAMS

Example 4 - Sediment with 60% quartz-silt and 40% ash.

Principal name: silt

Major modifier: ashy quartz

Minor modifier: none

ASHY QUARTZ SILT

Table 4. Examples of siliciclastic sediment classification (after the ODP Handbook of Shipboard Sedimentologists, 1988)

3.3.3. Classification of siliciclastic sediments containing gravel

Poorly sorted sediments containing varying proportions of gravel are likely to be a common feature of the Cape Roberts core. The non-genetic terms diamicton/diamictite have generally been applied to unlithified/lithified sediments in a glacial context, though equally they can apply in a non-glacial setting. Diamicton/diamictite is defined as "a non-sorted or poorly sorted terrigenous sediment that contains a wide range of particle sizes" (Flint 1960). The term diamict embraces both (Harland *et al.* 1966). For the purposes of laboratory and field investigation, a textural classification of diamictite was devised by Moncrieff (1989). A modified version of this is used here (Table 1). It is based on the proportions of sand and mud (as matrix), discernible using a hand lens, or with the naked eye or in smear slides, against the proportion of gravel clasts. The lower limit of gravel for the name diamicton/diamictite to apply is as low as 1%, reflecting previous but much less constrained usage of the term. The upper limit of gravel for these names to apply is 30% (compared with 80% in Moncrieff, 1989), which is the upper limit at which clasts are commonly matrix-supported (Folk 1984). Above this limit of 30%, the terms gravel (unconsolidated), breccia, conglomerate and breccio-conglomerate (consolidated) are used.

The biogenic component may make up a considerable proportion of the sediment. Prefixes such as shelly, diatomaceous and calcareous shall be used where such components make up 10–40% of the sediment.

Estimation of the gravel content of core can be made with reference to Figure 17. The estimates can be checked using X-radiography at the Crary Laboratory.

3.3.4 Volcaniclastic sediments

It is not known whether such sediments will be found at Cape Roberts, but given the proximity to Cenozoic volcanoes this is a possibility. Pyroclastic rocks are described according to the textural and compositional scheme of Fischer & Schminke (1984), which subdivides volcaniclastic material into:

(i) Blocks and bombs (ø > 64 mm)

(ii) Lapilli (ø 2-64 mm)

(iii) Ash (ø < 2mm);

In terms of sediment equivalents, the respective end-members are breccia, lapillistone and tuff, with intermediate types being tuff-breccia and lapilli-tuff. Compositionally, these pyroclastic rocks may also be described as vitric (glassy), crystalline or lithic.

Clastic sediments of volcanic provenance are described in the same manner as siliciclastic sediments, noting the dominant composition of the volcanic grains where possible. The petrologists at the Crary Laboratory may assist in describing such sediments.

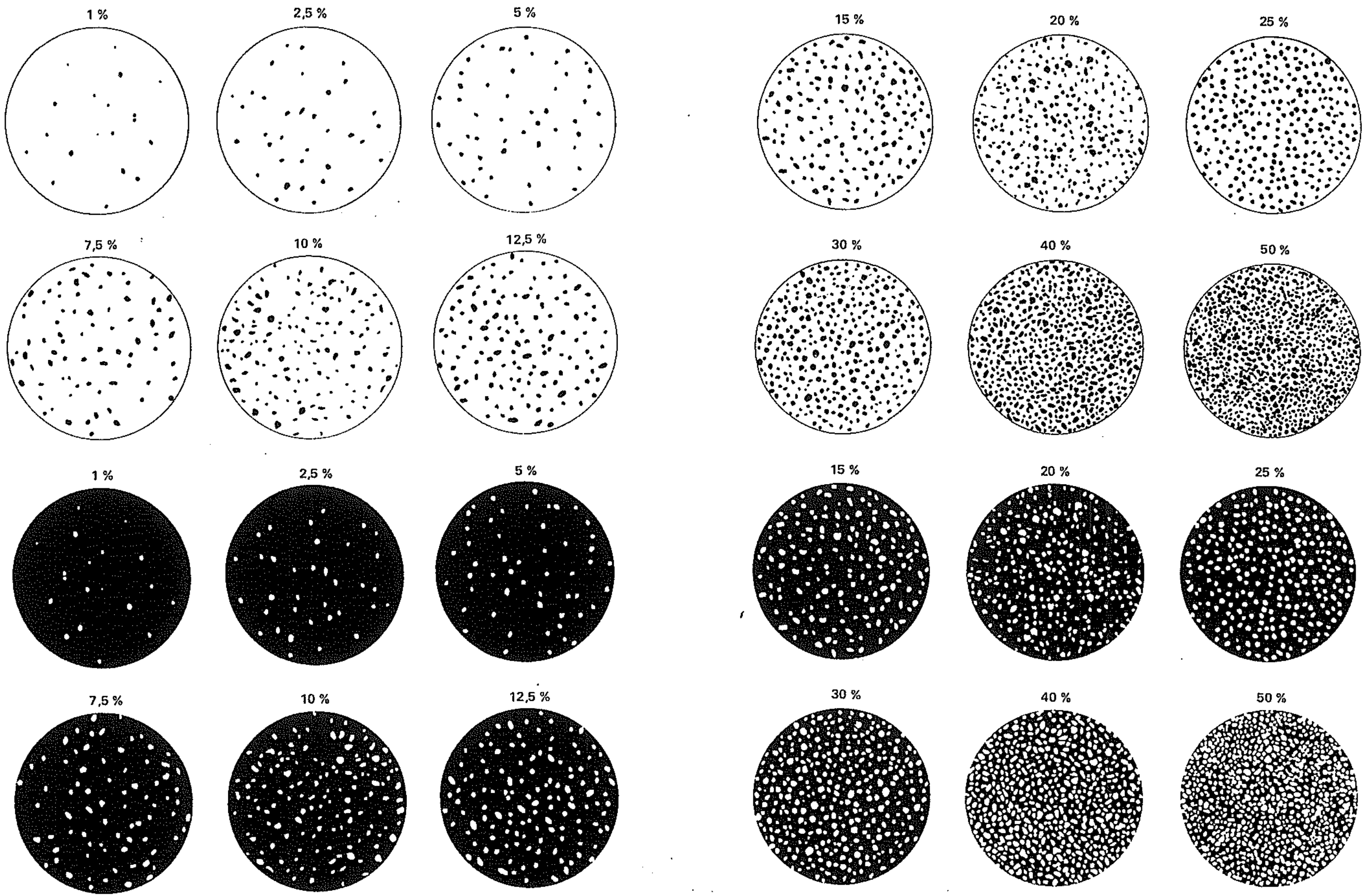


Figure 17. Charts for the visual estimation of clast percentage in cross-section of core (from Flügel 1978, after Bacelle & Bosellini 1988).

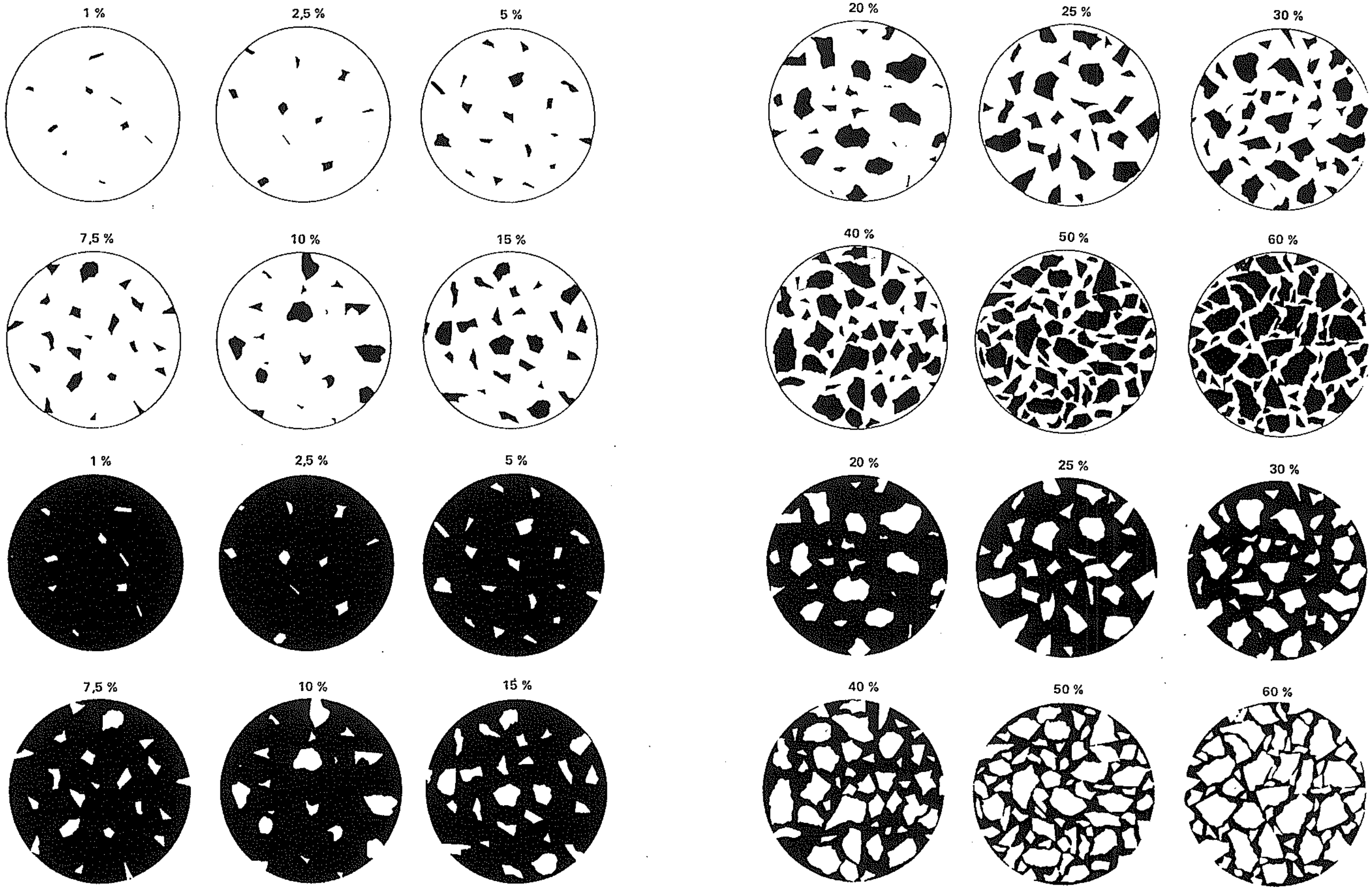


Figure 17 continued.

3.3.5. Siliceous biogenic sediments (pelagic)

Siliceous biogenic sediments are composed of <50% siliciclastic grains and >50% biogenic grains, with a greater proportion of siliceous biogenic grains tha calcareous biogenic grains. The major and minor modifiers describe the composition and concentration of the siliceous biogenic grains:

- 10-25% diatoms, e.g. diatom-bearing sand
- 25-50% diatoms, e.g. diatomaceous sand
- > 50% diatoms, diatom ooze

The occurrence of terrigenous or calcareous biogenic matter may also find its expression in modifiers. For example, if a sediment contains 8% siliciclastic sediment, 20% calcareous nannofossils, 35% radiolaria and 37% diatoms, it would be called *nannofossil-bearing radiolarian diatom ooze.*

Hard varieties of siliceous biogenic sediments are called diatomite, radiolarite, porcellanite and chert.

3.3.6. Calcareous biogenic sediment

Calcareous biogenic sediments are distinguished by a biogenic $CaCO_3$ content of >30%, and are treated in the same way as siliceous biogenic sediments (§ 3.3.5). They fall into two categories:

(i) *Pelagic calcareous biogenic sediment.* Contains >30% biogenic $CaCO_3$ and <30% silt + clay:

- Soft : calcareous ooze
- Firm : chalk
- Hard : indurated chalk
- Cemented : limestone

The principal components are nannofossils and foraminifera. One or two qualifers may be used, e.g.:

<10% forams : nannofossil ooze/chalk/limestone

10–25% forams : foraminiferal–nannofossil ooze etc.

25–50% forams : nannofossil–foraminiferal ooze etc.

>50% forams : foraminiferal ooze.

(ii) *Transitional calcareous biogenic sediment.* Contains 30–60% $CaCO_3$ and >30% silt + clay.

- Soft : marly calcareous (or nannofossil/foraminiferal etc.) ooze
- Firm : marly chalk
- Hard : marly limestone

Sediments containing 10–30% $CaCO_3$ fall into other classes where they are denoted by the qualifier "calcareous" (*cf.* § 3.3.2). Where the $CaCO_3$ content is <10%, it is ignored.

3.4. Classification of Chemical Sediments

3.4.1. Introduction

It is unlikely that chemical sediments will be recovered in the Cape Roberts cores. However, in case such a possibility does arise, the following section is intended to provide some criteria for describing and interpreting these sediments.

3.4.2. Evaporites

Chemical sediments precipitated directly from water which has been concentrated by evaporation, are 'evaporites'. The main evaporite minerals are gypsum, anhydrite and halite. Two main categories of evaporitic depositional environments are recognized:

(i) shallow to deep water bodies, of variable extent, e.g. shelf lagoons, and deep, barred basins of intracratonic or rift origin (the product of subaqueous precipitation),

(ii) arid sabkhas or shallow, desiccated saline pans (the product of subaerial precipitation).

Distinctive crystal habit, texture and bedding are key features that can help to identify the evaporitic environment (Fig. 18):

• Discoidal, rosette, selenitic and twinned gypsum crystals, at a centimetre-scale, are characteristic of sabkha environments, occuring as the common nodular and enterolithic structures of anhydrite. Often, dolomite, intertidal and supratidal structures are associated with these environments.

• Large selenitic crystals of gypsum and anhydrite (both twinned and split crystals) may form continuous beds with a peculiar palmate texture, or they may build up as domal and cabbage-like structures on the floors of lakes, lagoons and shelf areas. Clay or fine-grained muddy carbonates may be intercalated with these facies.

• Thin millimetre-scale laminae of gypsum, anhydrite and halite, alternating with calcareous or organic-rich laminae, are the result of precipitation from concentrated sea water in relatively deep basins. Bodies of gypsum and anhydrite, similar to the palmate texture, developed on the sea-floor, may be associated with laminated evaporites, as a consequence of the final shallowing of a brine-filled basin.

Waves and currents may fragment, transport and resediment the evaporite crystals and bodies to produce clastic deposits. These might occur in the Cape Roberts basinal sequences, as a result of debris flowage and turbidity currents reworking the deep evaporitic deposits, while it is quite unlikly that resedimented shallow-water evaporites will be found.

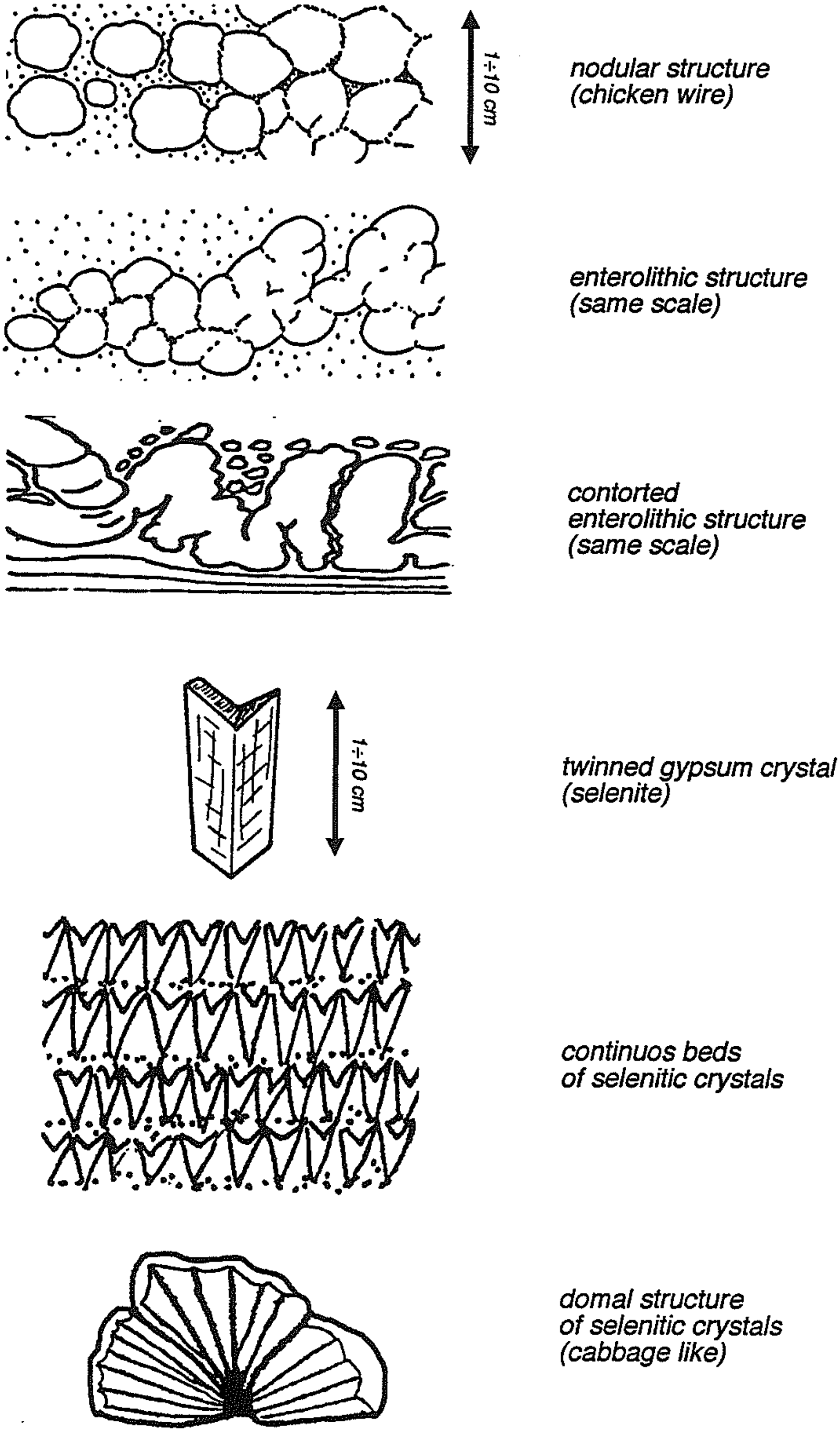


Figure 18. Crystal habit, texture and bedding characteristics of evaporites (modified from Dean & Schreiber 1978).

3.4.3. Ironstones

Ferromanganese nodules and crusts are widely distributed on today's sea floor, especially in areas of slow sedimentation or where bottom currents are strong. Ironstones may be related to hydrothermal or volcanic processes, which are able to modify the water chemistry and lead to direct precipitation of these minerals. Other ironstones that may be found in the Cape Roberts cores may be the result of reworked older deposits, e.g. oolitic ironstone formations or iron-rich mudrocks. They are commonly composed of iron oxides (haematite, limonite and göethite) and siderite. Both these types of sediment may be the primary deposit if the necessary chemical conditions exist in the environment, typically in lagoons, deltas and estuaries.

3.4.4. Siliceous rocks

Cherts are commonly differentiated into bedded and nodular types. For both types, the origin of the silica can be ascribed to biogenic or volcanic enrichment of the sea water chemistry.
The siliceous oozes are produced in near-surface waters and are controlled by upwelling and nutrient supply; the oozes are concentrated in deep basins, where the depth exceeds the carbonate compensation depth (CCD). In some cases bedded chert are associated with lavas or volcaniclastic deposits. Siliceous sediments may be diagenetically transformed and chemical reprecipitation may occur, forming nodular structures (from subspherical to irregular shapes) which are frequently concentrated along bedding planes. Despite diagenesis, original grains, organic shells and primary sedimentary structures may be preserved within the nodules.

3.5. Clastic Carbonates

3.5.1. Introduction

Although terrigenous sediments are made up basically of disintegration products from other types of rock, and by the transportation of the resulting sediment to the depositional basin, carbonates are mainly formed within, or close to, the site of production, with little or no transport. Thus, some limestones consist of grains deposited under the action of currents or waves, and from this point of view they can be labelled clastic. Other limestone are formed *in situ* by the simple accretion of biologically accumulated or chemically precipitated material.

Limestones formed *in situ* are characterised by the absence of current-transport and redeposition structures. Examples include massive and wave-resistant bodies of coral or bryozoan reefs at the margin of carbonate platforms, or well-stratified stromatolites in the peritidal belt of a carbonate platform. These carbonates are termed autochthonous. Other examples of autochthonous limestones are rather minor deposits of a chemical nature, such as caliche and travertine.

Like their non-carbonate counterparts, the mechanically deposited limestones are classified as intraformational (often intrabasinal) rocks, and the carbonate material, transported and redeposited to a limited extent, is defined as allochthonous. The bulk of this detrital material (allochems) is characterized by skeletal and non-skeletal grains, fragments of reefs, clasts made up of early-stage lithified sediments or other fine-grained aggregates.

Non-skeletal grains are: ooids and pisoids, peloids, intraclasts, oncoids, aggregates (grapestone and lumps) and intraclasts. Skeletal grains are fragments of carbonate-secreting invertebrates and are commonly called bioclasts, but a variety of types of bioclasts exists, based on the different kinds of organisms with a carbonate skeleton. Many limestones have a fine-grained, often dark-coloured, calcareous matrix, which is represented by micrite (microcrystalline calcite, the size of which is generally less than 4 μm). In some cases, the rocks are composed entirely of this lithified lime-mud.

It must be born in mind that the distinction between these two types of limestone is not straightforward, and in many cases a single limestone formation may represent a combination of both types. For example, large fragments of autochthonous reef-rocks may be resedimented in the slope system, and found as boulders in calcareous breccias and megabreccias.

3.5.2. Classifications

The most common classification schemes for limestones are based on different basic properties of the sediments and rocks. Each one of these provides useful information since, once a rock has been classified, it becomes necessary to infer the depositional environment.

(A) The most simple classification divides limestones on the basis of grain size:

- calcirudites: size of the majority of the grains > 2 mm,
- calcarenites: 2 mm > size of the majority of the grains > 62 μm,
- calcilutites: size of the majority of the grains < 62 μm.

This classification is useful when the carbonate rocks studied exhibit textural relationships similar to those found in sandstones. Grain-size analysis will provide important information about the transport energy-level, and the depositional environment.

(B) *Classification of Folk (1962)* (Fig. 18) is based on the distinction between the various components which make up the carbonate rock: allochems, micrite and cement (mainly drusy sparite). Allochems may be differentiated in skeletal grains (bioclasts) and non-skeletal grains (ooids, peloids, and intraclasts) and are abbreviated and used as a prefix (bio-, oo-, pel-, intra-, or sometimes a combination of them) to micrite or sparite, depending upon which one is dominant. In the same scheme, two additional categories are present: biolithite, which describes carbonates rocks formed *in situ* (such as in stromatolites or reefs) and dismicrite, an obsolete term referring to a micrite with fenestral cavities. In this classification the interpretation of limestone depends upon the relative proportions of the dominant type of grains, which gives information concerning the depth, chemistry and energy of the water from which the allochems originated.

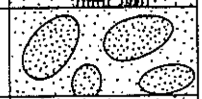
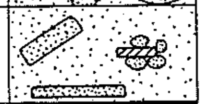
Principal allochems in limestone	Limestone types			
	cemented by sparite		with a micritic matrix	
skeletal grains (bioclasts)	biosparite		biomicrite	
ooids	oosparite		oomicrite	
peloids	pelsparite		pelmicrite	
intraclasts	intrasparite		intramicrite	
limestone formed in situ	biolithite		fenestral limestone -dismicrite	

Figure 19. Folk's classification scheme for limestone (from Tucker 1991).

(C) *Classification of Dunham (1962)* (Table 5). Limestones are subdivided on the basis of their original depositional texture: mud-supported *versus* grain-supported carbonate rocks. Four main classes are distinguished for limestones where the components are not bound together during deposition, in the sense that they can act as grains.

- mudstone: micrite is dominant and grains < 10%,
- wackestone: grains are floating in a micritic matrix (grains > 10%),
- packstone: grains are in contact and micrite is disperse in pore space.
- grainstone: grains are in contact and micrite is lacking.

When the amount of grains is relevant, it is also useful to use modifiers which can specify the dominant type of carbonate grains present (i. e. oolitic grainstone, peloidal wackestone, etc.). If the original components were already bound during deposition (i.e. in stromatolites or reefs), the general term "boundstone" is used. Lastly, if the original depositional texture is not recognizable due to dolomitization or intense diagenesis, the classification scheme refers to crystalline carbonate.

<table>
<tr><td colspan="5">Depositional texture recognizable</td><td>Depositional texture not recognizable</td></tr>
<tr><td colspan="4">Original components not bound together during deposition</td><td>Original components were bound together during deposition</td><td rowspan="4">Crystalline carbonate</td></tr>
<tr><td colspan="3">Contains mud
(particles of clay and fine silt size)</td><td rowspan="2">Lacks mud and is grain-supported</td><td rowspan="2">as shown by intergrown skeletal matter or lamination contrary to gravity</td></tr>
<tr><td colspan="2">Mud-supported</td><td>Grain-supported</td></tr>
<tr><td>Less than 10 percent grains
Mudstone</td><td>More than 10 percent grains
Wackestone</td><td>Packstone</td><td>Grainstone</td><td>Boundstone</td></tr>
</table>

Table 5. Dunham's classification scheme for limestone (from Scoffin 1987).

The principles underlying the Dunham classification are: (i) the presence or absence of binding during deposition, (ii) the presence or absence of carbonate mud, and (iii) the abundance of grains. It is evident that each of these three characteristics refers to the original texture in the depositional environment, without any implication of late diagenesis.

Generally speaking, the amount of carbonate mud (micrite) reflects the average energy of the depositional environments. Mudstone and wackestone imply calm water, as in inner tidal flat areas, quiet lagoons, outer ramps and deep basins. Grain-supported limestone (as packstone and grainstone) are normally identified with conditions of agitated water, which determine the absence or paucity of mud. Turbidites in the basins, storm deposits in lagoons, ramps, tidal environments and sandy platform margins may be characterized by mud-free carbonate rocks. Nevertheless, particular care must be used when the interpretations are made.

3.5.3. Discussion

Limestones occur in a variety of different marine environments, from shallow shelf areas to deep basins. The formation of carbonate depends mainly upon biological or chemical precipitation, and for this reason most of the carbonate production occurs in shallow marine environments, or in the upper part of the water column in deep environments. In a simplistic view, three main zones of accumulation may be distinguished:

(i) subtidal areas (normally a lagoon, a shelf or a shelf margin) where carbonate sediment is produced and accumulated *in situ*;

(ii) tidal-flat systems and beaches, where the carbonate is transported from the subtidal site of production; and

(iii) slopes and basins, where fine-grained carbonate is exported seawards from the shelves, and where deposits with a variable degree of lithification are resedimented by mass-transport; in the same areas zoo- and phytoplanktons with calcareous shells can contribute significantly to the carbonate accumulation.

The only types of limestone which are likely to be encountered in the Cape Roberts cores belong to this third group, and are pelagic and resedimented deep-sea limestones.

• *Pelagic limestones.* At water depths of a few hundred metres, carbonates are composed of the shells of pelagic organisms (such as planktonic and nannoplanktonic organisms), micrite exported from adjacent areas and variable amounts of terrigenous material. Accumulation is controlled by the carbonate dissolution rate, which is a function of the depth (ACD, lysocline, CCD) and by the calcareous productivity in the oceans. Pelagic deposits commonly display a characteristic alternations of calcareous-rich and calcareous-poor beds, which are arranged in couplets and bundles of complex hierarchy. Peculiar features of pelagic limestones are condensed and nodular structures, hardgrounds, stylolites, lithoclasts, neptunian dykes, sheet cracks, and some resedimentation structures of pelagic and hemipelagic sediments (slumps, turbidites and debrites).

• *Resedimented deep-sea limestones.* Carbonate sediments, which are produced and accumulate in subtidal areas and in shelf margins, can be exported on slopes and basins by turbidity currents and grain flows, and as debris flows. This material is deposited and interbedded with pelagic and hemipelagic calcareous ooze or micrite. Characteristic features are turbidites (both coarse and dilute, with Bouma sequences), breccias and megabreccias, with planar- and cross-lamination. The same attributes as discussed above for pelagic limestones, are also present.

3.6. Recognition of Trace Fossils and Ichnofacies

Trace fossils are an *in situ* record of epi/infaunal behaviour, or in the case of plant-related structures of plant colonisation of a surface. Because trace fossils record behaviour, and because behaviour has been subject to convergent evolution, so similar types (geometries) of trace fossil can be interpreted as a record of similar behaviour.

Trace fossils are of considerable use in palaeoenvironmental analysis, since behaviour is related to environment and hence certain types of trace fossils will be concentrated in different environments. This is the basis for the "ichnofacies" concept of Seilacher, whereby assemblages of trace fossils can be used (with care) to help reconstruct the environment of deposition of a given unit (see paper by Pemberton *et al.* 1992a).

Grade	Percent Bioturbation	Classification
0	0	Unbioturbated
1	1-5	Very slightly bioturbated
2	5-30	Slightly bioturbated
3	30-60	Moderately bioturbated
4	60-90	Highly bioturbated
5	90-99	Intensely bioturbated (vestiges of some physical structures still discernable
6	100	Completely bioturbated

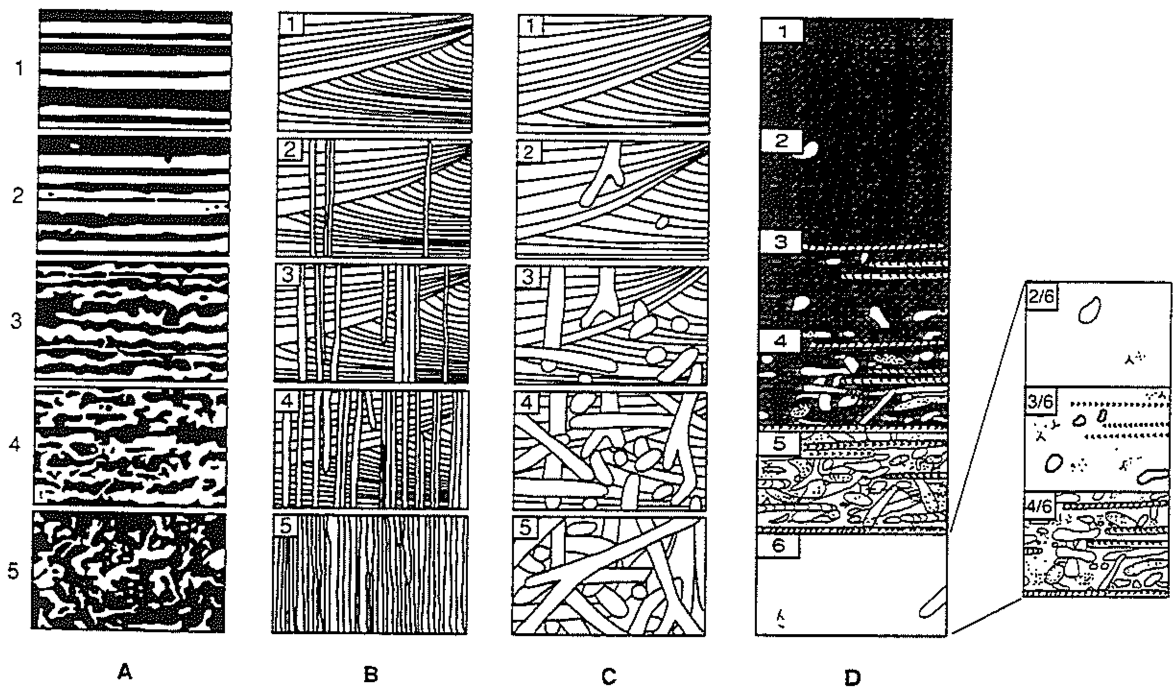


Figure 20. Schematic diagrams of estimates of the degree of bioturbation (ichnofabric index). (A) For thin-bedded strata. (B) for thick-bedded strata dominated by Skolithos. (C) For fine-grained deep-water environments. (From Pemberton 1992b).

Recognition of trace fossils in core is considerably more difficult than in outcrop, because of the three-dimensional nature of most traces, and the fact that they are often larger than the core diameter. The paper by Pemberton and the illustrations in the Chapter by Chamberlain

(1978) will assist in the identification of trace fossil genera. To assist in the facies analysis of the Cape Roberts core, it is suggested that sketches be made, and photographs taken, of all discrete traces recognised.

Another useful aid in the study of bioturbated sediments is a semi-quantitative index of bioturbation intensity (see paper by Droser & Bottjer 1986, and diagram of Pemberton *et al.* 1992b) (Fig. 20). This index is particularly useful in circumstances where overprinting of traces by further animal activity renders identification of individual traces impossible.

3.7. Identification of Palaeosols

Palaeosols are ancient soil profiles, and are very useful in diagnosing continental environments in the rock record. Furthermore, because soils develop in response to the prevailing environmental conditions, palaeosols can provide useful information concerning the nature of the palaeo-environment.

Various schemes of soil classification have been proposed, the most widely used being the U.S. Department of Agriculture system (see summaries by Retallack 1990). This classification (and most others) relies on the recognition of distinct zones or horizons within the soil profile, which are defined on a chemical basis. In practice, it is often difficult to apply this scheme to ancient rocks which have undergone significant diagenetic change. Nonetheless, horizons within palaeosols are often clearly recognisable through changes in colour and fabric.

A related classification of soils, which one of us (Fielding) has found more applicable to geological situations, is that proposed by Duchaufour (1982). The principal soil groups recognised within Duchaufour's classification are:

- Immature soils
- Calcimagnesian soils
- Soils with matured humus: isohumic soils and vertisols
- Brunified soils
- Podzolised soils
- Hydromorphic soils
- Sesquioxide-rich soils
- Ferruginous soils
- Salsodic soils.

care must be taken in interpreting palaeosols, particularly stratigraphic changes in palaeosol character. A vertical succession from drab, hydromorphic soil-bearing strata upwards into more strongly coloured, iron-oxide bearing soils would conventionally be interpreted as reflecting a change to a more arid climate. Such a pattern could equally be interpreted in terms of progressive change in elevation of a depositional surface in response to a change in the balance between subsidence and sediment supply, however (see Besly & Fielding 1989, for a case study involving such a succession).

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PART II

CORE INTERPRETATION

1. ALLUVIAL FACIES AND ENVIRONMENTS

C. Fielding

1.1. Introduction

Alluvial systems can be conveniently divided into channel and non-channel environments. River channels are the major pathways of water and sediment transport across continental landscapes. Floodplains are areas adjacent to alluvial channels which are inundated by water only during high flow stage events. Such areas in subsiding basins may be permanently waterlogged floodbasins where shallow lakes and wetlands predominate.

Alluvial channels are commonly classified according to planform, the major variants being meandering, anastomosing/anabranching, braided and straight (Fig. 1). In reality, however, there is a continuous spectrum of channel planform. Furthermore, a single fluvial system may change its planform style downstream in response to changes in gradient, sediment and water supply, may change through time in response to environmental changes of regional extent, or may even change during short-term variations in discharge. Diagnosing channel planform from surface exposures of ancient strata is often a difficult exercise, and from core often impossible.

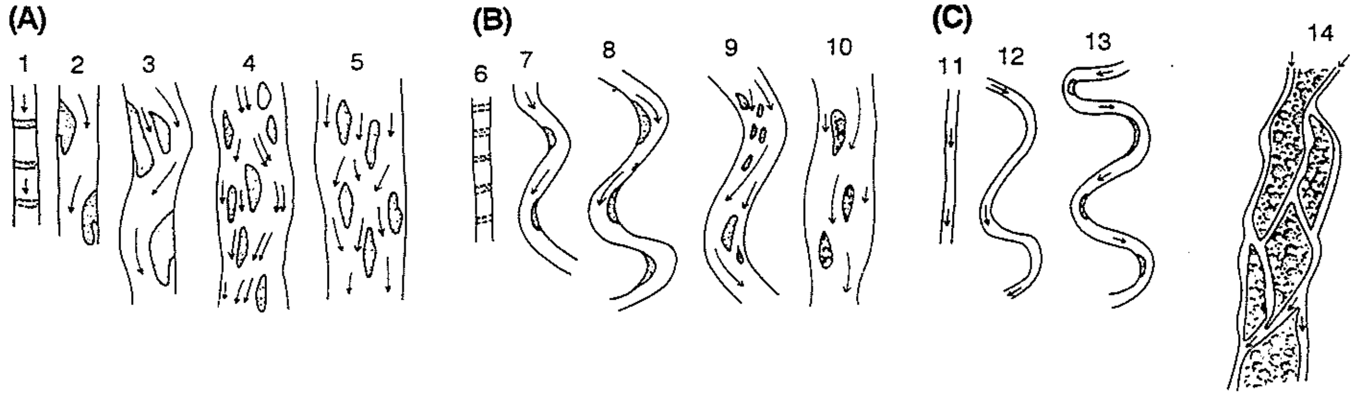


Figure 1. The range of alluvial-channel patterns: (A) bedload channels, (B) mixed-load channels, (C) suspended-load channels. The four major chnnel styles are meandering (7, 8, 12, 13), braided (3-5, 9, 10), anastomosed (14) and straight (2). Straight channels (1, 6, 11) are rare in nature. (From Miall).

1.2. Alluvial Facies

1.2.1. Channel deposits

Alluvial channel deposits are typically sharply-based units of varying grain-size, some of which show a fining-upward tendency over several metres section (Fig. 2). Many such bodies show a basal gravelly lag which may contain extraformational debris and/or intraformational clasts of locally derived material. Presence of abundant, large mudrock clasts that display soft-sediment deformation within such basal lags may indicate collapse of nearby channel banks or erosion of an underlying substrate during excavation of the channel. The main body of the channel fill may be gravel, sand or finer-grained: some channel fills are composed of thinly interbedded sandstone and mudrocks (termed heterolithic fills). Typical sedimentary structures are cross-bedding of various types, flat lamination and ripple cross-lamination. Organic sedimentary structures include common plant debris, and rare, simple bioturbation. Scour surfaces are also common within channel fill sequences, indicating a multi-storey character to the lithosome.

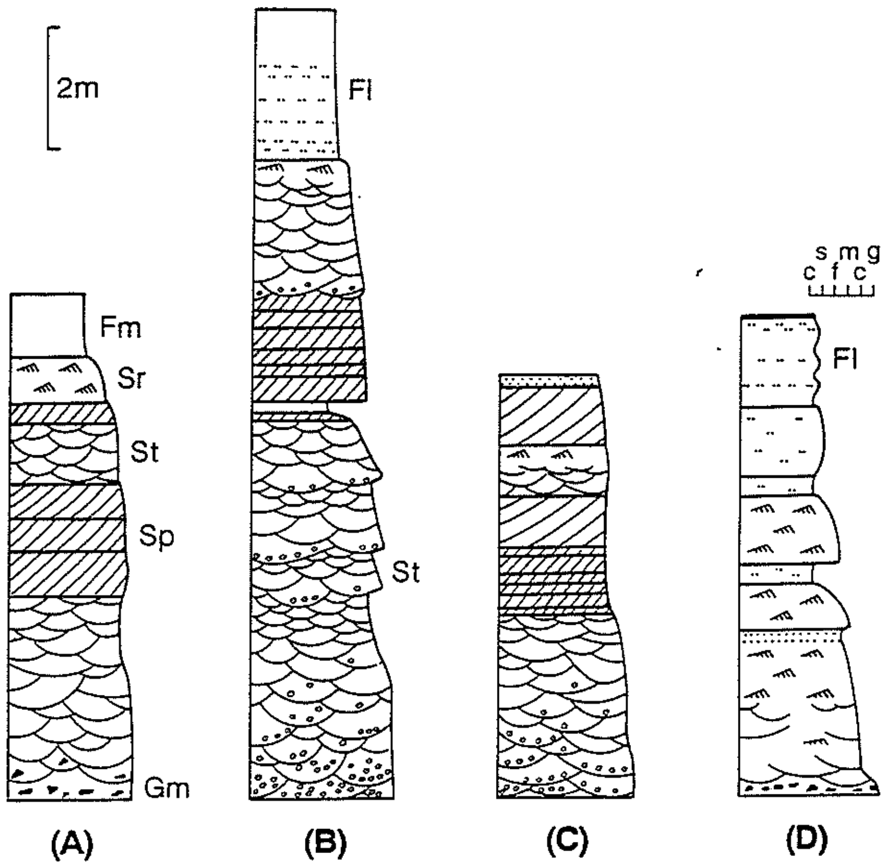


Figure 2. Comparison of four vertical profile showing how similar fining-upwards scycles may be produced in several different ways. (A) Model cyclic sequence, Battery Point Formation (Devonian), Quebec, probably formed by vertical bar aggradation in a low-sinuousity (braided river). (B0 Sequence formed by lateral accretion of a point bar, Castisent Sandstone (Eocene), Spain. (C) Sequence formed by lateral accretion of a point bar, modern Amite River, Louisiana. (D) Sequence formed by vertical aggradation and progressive channel abandonment on an alluvial fan, under conditions of tectonic quiescence, Upper Carboniferous coal measures, northern Spain. Columns A, B and D include fine-grained overbank deposits at the top formed by vertical accretion on the floodplain following the abandonment of the bar (From Miall).

1.2.2. Non-channel facies

Floodplain and floodbasin facies are typically finer-grained than those of associated channels. Thinly bedded sandstone and siltstone sequences are commonly associated with such environments, and may either display primary reddening and evidence of desiccation if exposed persistently to the atmosphere, or a predominance of grey colours and preservation of humic plant debris if permanently water-saturated. Since peat can accumulate readily in alluvial floodbasins, it is common to find coal associated with such floodbasin deposits. Clastic sediment is introduced into floodbasins by two main processes: (i) breaching (crevassing) of channel banks, which gives rise to sharply-based beds of coarse sediment termed splays, and (ii) overbank sheet flows, which give rise to thinner, sheet-like layers of sand and silt-grade sediment. Facies representative of levées (elevated natural ridges adjacent to channel banks) are often thinly and rhythmically interbedded sandstone-siltstone.

2. DELTAIC FACIES AND ENVIRONMENTS

C. Fielding

Deltas form where a river terminates in a standing water basin and more sediment is supplied to the river mouth than can be reworked by basinal processes (Fig. 3). Deltas can form on marine or lacustrine coasts. The planform of any delta is controlled by the relative strength of various physical processes that act on the coast, principally: fluvial outflow, wave action, and tidal flux. Fluvially dominated deltas tend to show a digitate to lobate plan morphology, wave-dominated deltas are typically arcuate or cuspate, and tide-dominated deltas show a highly complex coastline.

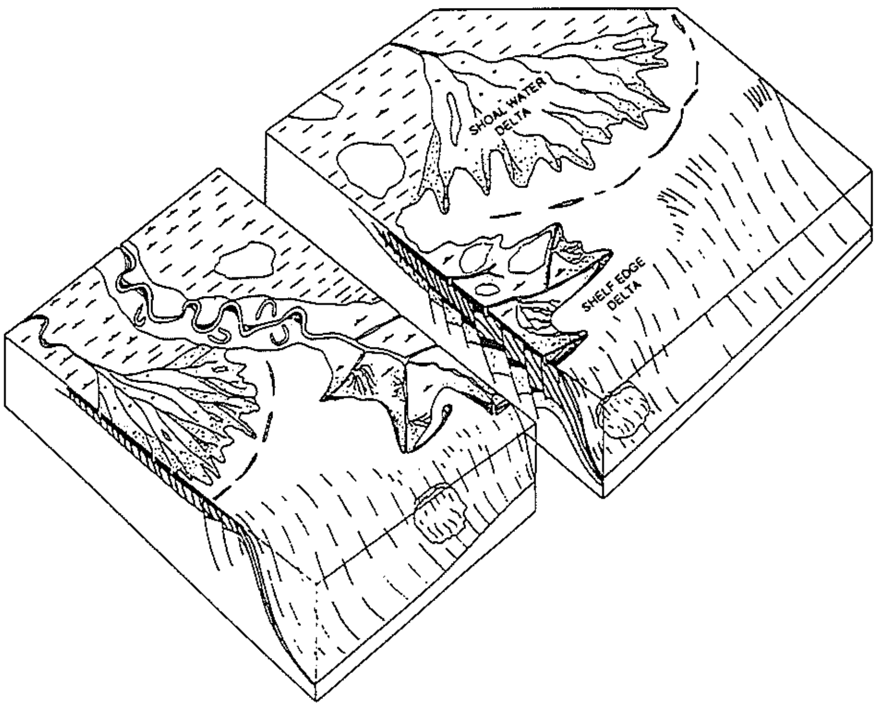


Figure 3. Block diagram contrasting lobate shoal-water (or shelf phase) deltas and shelf-edge deltas. Note thickening of facies across growth faults in the shelf-edge delta. (From Bhattacharya & Walker).

Deltas may be subdivided into three principal zones: the delta plain (or platform: that area at or above water level, generally a complex of distributary channels and interdistributary lakes and bays), the delta front (the zone immediately offshore from the river mouth, generally a sloping submarine surface), and the prodelta (the distal fringe of the system, in deeper water). As coarsest sediments are generally deposited close to the river mouth and progressively finer sediments deposited further offshore, so the stratigraphic record of a prograding delta is generally a coarsening-upward sequence, the thickness of which may give a first approximation of formative water depth.

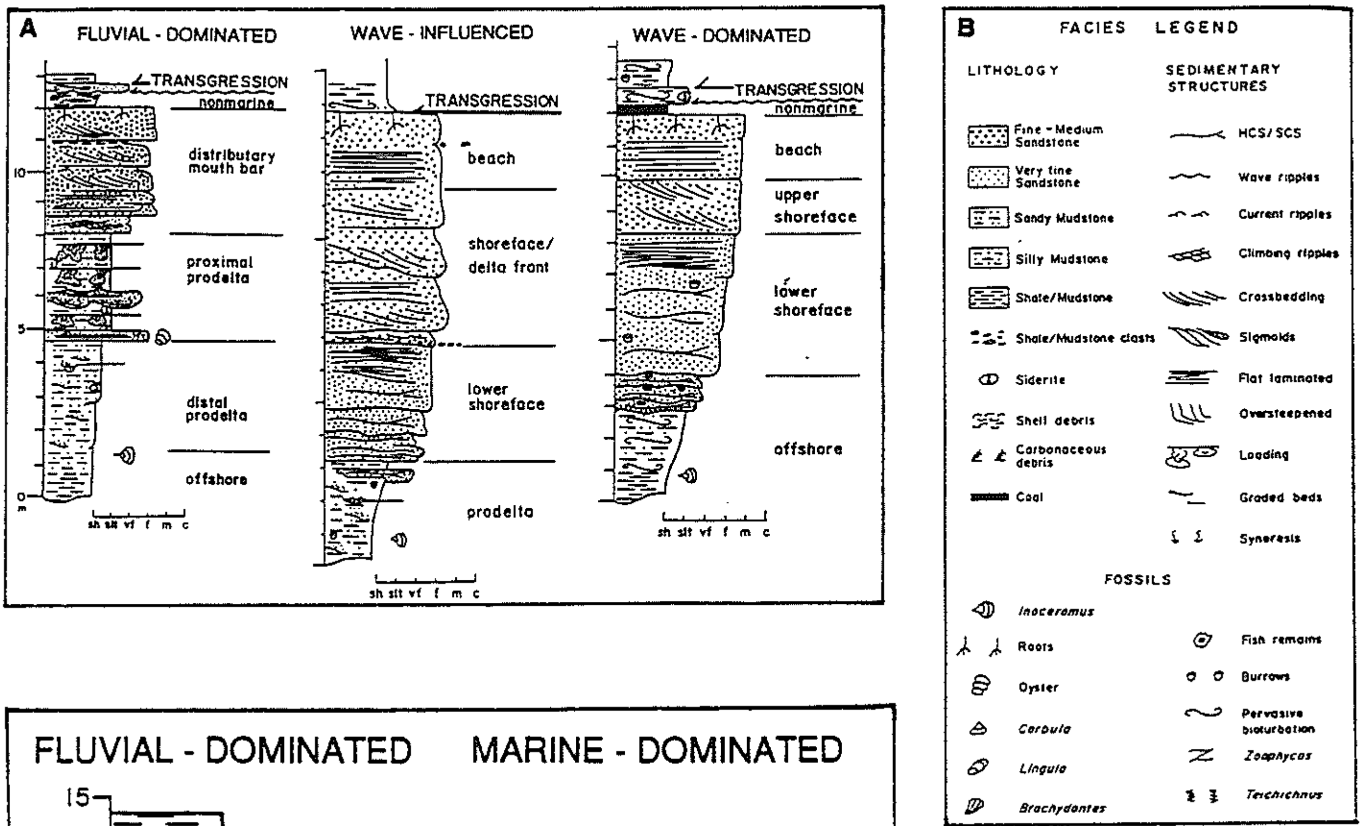


Figure 4 (top). Comparison of delta front successions in river-dominated, wave-influenced, and wave-dominated deltas in the Upper Cretaceous Dunvegan Formation, Alberta. The river-dominated succession is the most irregular. Basal mudstones are increasingly bioturbated with decreasing fluvial influence. (From Bhattacharya & Walker).

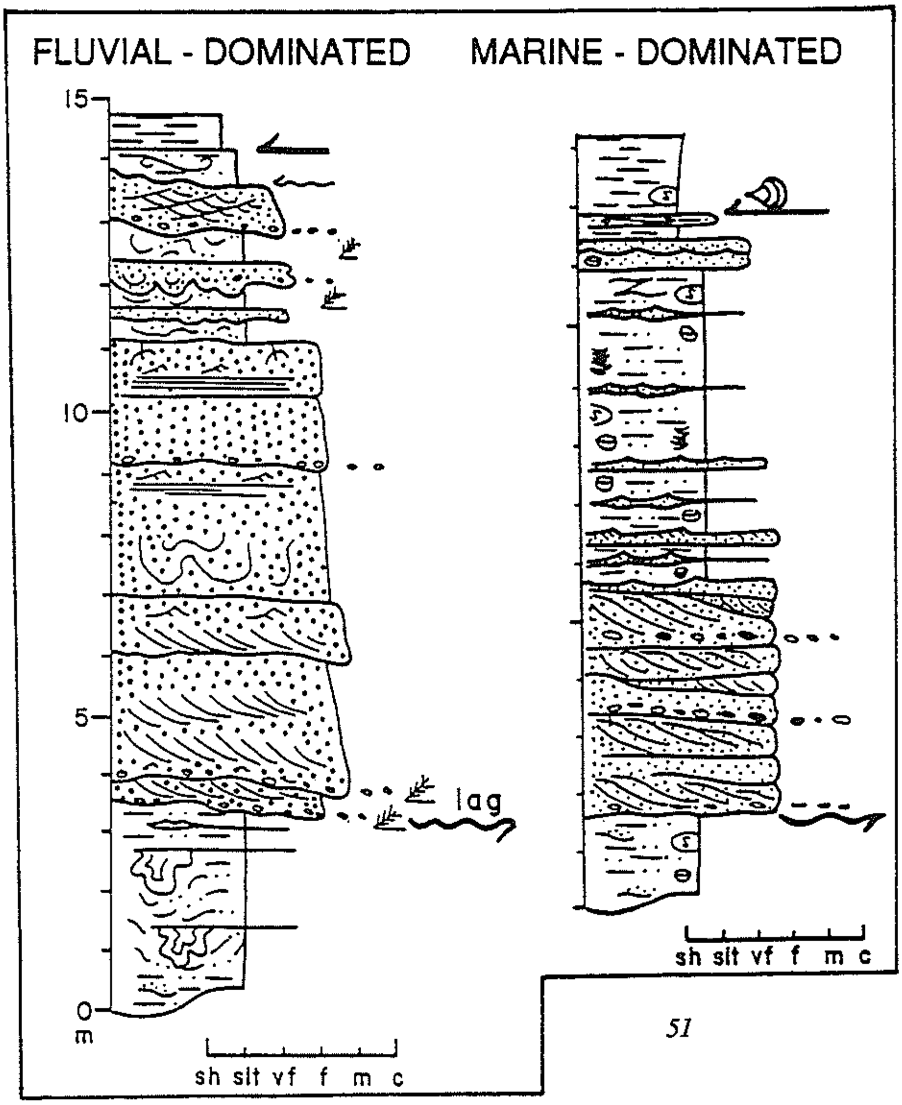


Figure 5 (left). Comparison of distributary channel-fill successions in fluvial- and marine-dominated deltas of the Dunvegan Formation (Creataceous, Alberta). In the marine-dominated system, the distributary fill reflects transformation of the distributary into an estuary. Arrow indicates transgression. Key as in Figure 5. (From Bhattacharya & Walker).

The facies that form within delta systems to a considerable extent also reflect the dominant physical processes in that system (Figs. 4, 5). Prodelta facies are typically fine-grained, bioturbated offshore marine or lacustrine deposits. It is in the delta front that the record of basinal processes is best preserved: deposits of fluvially-dominated and tide-dominated deltas show current-generated sedimentary structures, whereas those of wave-dominated deltas are typified by well-sorted, flat-laminated and hummocky cross-stratified sands. Deposits of tide-dominated systems show an abundance of mud, often in discrete layers interbedded with coarser sediment. Shallow subtidal and intertidal deposits often display cyclical arrangements of thin mud layers (termed tidal 'bundles'). Delta plain facies are similar to those of alluvial plains, containing erosively-based, distributary channel fills and the finer-grained deposits of interdistributary areas. In humid climate settings delta plain environments are often sites of extensive peat accumulation, and ancient delta plain successions host significant coal resources.

One major difference between the facies of alluvial and delta plain floodbasins is the abundance of small-scale, coarsening-upward sequences formed by crevasse-derived minor (or sub-) deltas in delta plains and their scarcity in alluvial systems.

3. CONTINENTAL SHELF FACIES AND ENVIRONMENTS

Lawrence A. Krissek

3.1. Introduction

Continental shelves are valuable recorders of the interplay between local environmental conditions, sediment supply rate, and relative sea-level changes. Because the tectonic history of an area can affect the rate of sediment supply and the position of sea-level, shelf sediments that may be recovered during the Cape Roberts Project can contribute to interpretations both of paleoenvironments and of tectonic events in the western Ross Sea and the adjacent Transantarctic Mountains. Recent useful summaries of the environments and deposits of non-glaciated continental shelves have been provided by Walker (1992), Dalrymple (1992), and Johnson and Baldwin (1996).

This chapter considers the characteristics of non-glaciated continental shelves below fairweather wave base (i.e., below the shoreface), and summarizes:

(1) important physical processes and depositional patterns on modern shelves,

(2) important large-scale (allocyclic) controls that affect the longer-term depositional record on a continental shelf, and

(3) important lithologic characteristics for recognizing and interpreting a continental shelf sequence.

3.2. Physical processes and depositional patterns on modern shelves

Studies of modern continental shelves have recognized two primary types of hydraulic regime: wave-dominated, with associated storm influence, and tide-dominated. A few modern continental shelves are dominated by energy supplied by intruding oceanic currents, but ancient analogues are not well known.

3.2.1. Wave-dominated shelves

On a wave-dominated shelf, direct wave influence below the shoreface extends down only to the level of storm wave base, although other relatively high energy processes, which also develop during storms, can act below storm wave base. These "deeper water" processes include (i) subsurface flows that are driven offshore by storm set-up along the coast (Fig. 6), and (ii) density currents that are generated by wave loading, the ebb of the storm set-up, storm-related fluvial discharge, or other factors.

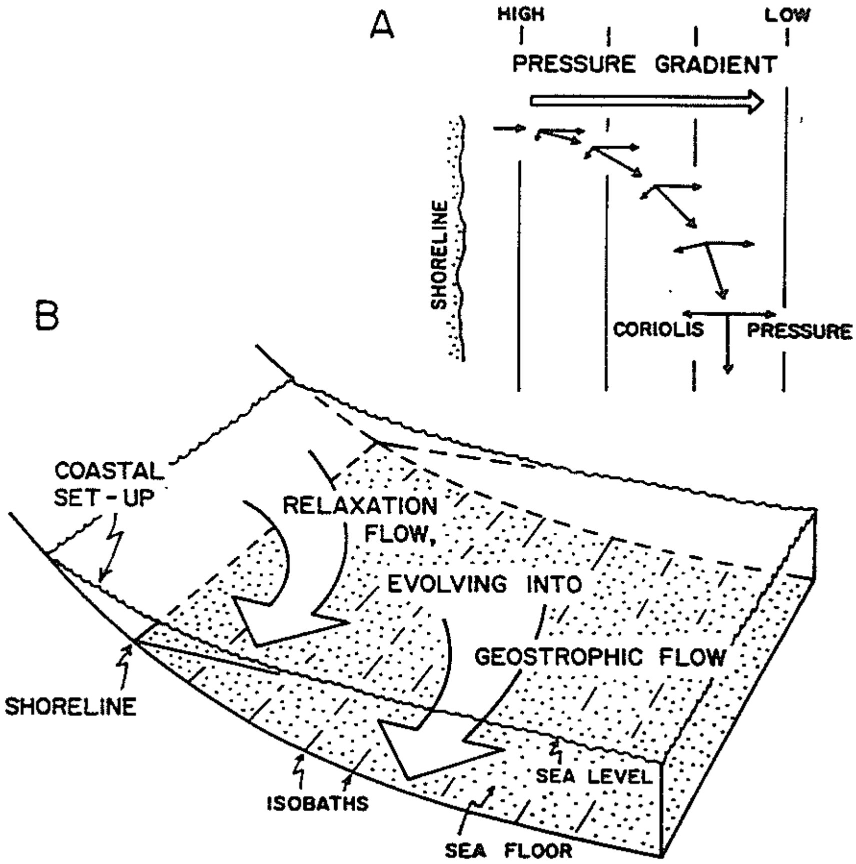


Figure 6. Coastal set-up raises sea-level along the shoreline, which produces a subsurface pressure gradient offshore (A). Water driven offshore by the pressure gradient is turned by the Coriolis force (to the right in the Northern Hemisphere, as shown here; to the left in the Southern Hemisphere) to form a geostrophic flow parallel to the isobaths (B). From Walker and Plint (1992).

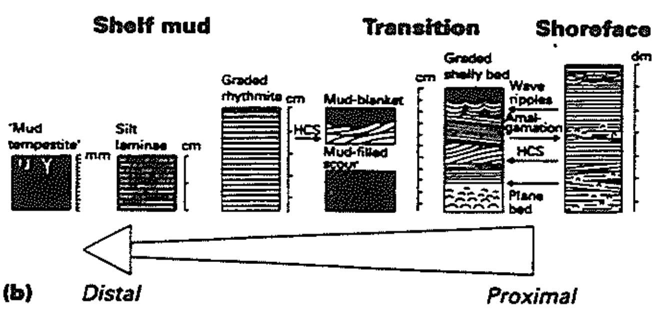


Figure 7. Proximal-distal changes in the characteristics of a single storm bed, based on observations of modern shelf storm deposits in the German Bight (southeast North Sea). From Johnson and Baldwin (1996).

The classic model for deposition on a wave-dominated shelf calls for sediment grain size to decrease offshore, in response to decreasing wave energy. This gives rise to an "equilibrium" or "graded" shelf. Modern continental shelves that exhibit such a textural profile tend to occur in settings with a high rate of sediment input and/or abundant wave energy, so that evidence of shallower water depths during the late Pleistocene sea-level lowstands are not reflected in the surficial sediments. On other wave-dominated shelves, with less wave energy or slower sediment supply, "relict" Pleistocene sands are still exposed at the surface in offshore settings.

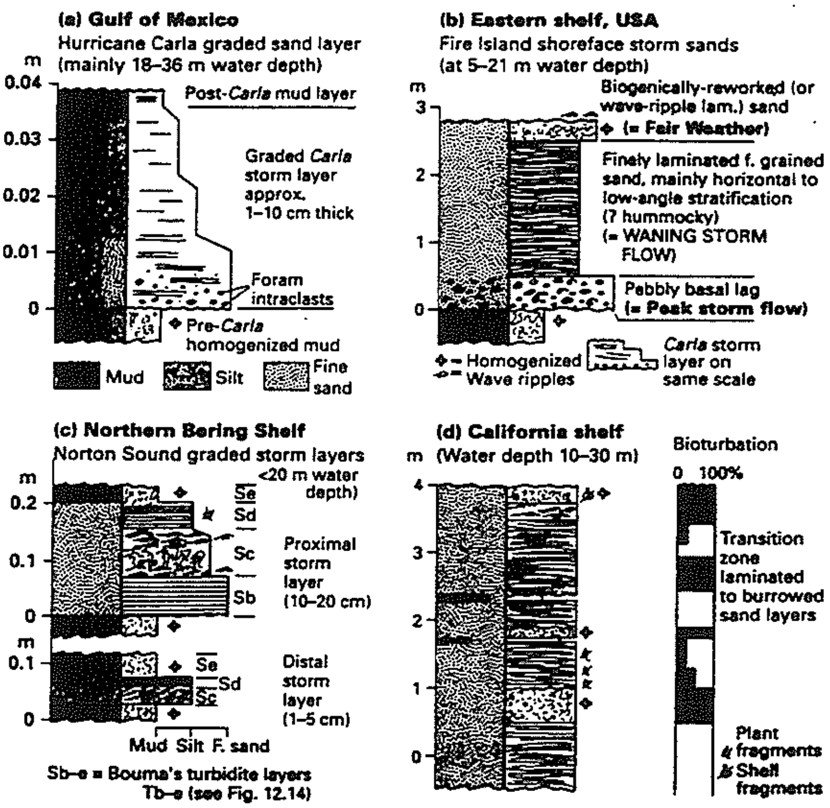


Figure 8. Four examples of modern offshore storm deposits from contrasting shelf settings (note difference in vertical scales). (a) Graded sand layer resulting from Hurricane Carla, offshore Texas. (b) Three-part subdivision of storm sands from Fire Island shoreface. Note the slightly coarser, winnowed fairweather sand layer on top. (c) Proximal and distal graded storm sand/silt layers from the epicontinental Bering Shelf. Note terminology equivalent to that used for turbidites. (d) Sequence of amalgamated storm sand layers from the Transition Zone of the California shelf. From Johnson and Baldwin (1996).

Below the shoreface on modern wave-dominated continental shelves, the major lithofacies types are muds and coarser-grained storm layers (Fig. 7). The muds are input primarily as fine-grained suspended fluvial load, either as sediment plumes (with relatively high concentrations of suspended particles) or as lower-concentration near-bed or near-surface nepheloid layers. Assorted marine processes (oceanic currents, tidal action, storm-induced currents, and mass movements) can subsequently redistribute this material. The coarser-grained storm layers are deposited as more identifiable "event" beds, usually with some or all of the following characteristics (Fig. 8):

- an erosional base;
- a coarse-grained basal lag, perhaps composed of mud rip-ups, shells, or plant debris;
- an interior dominated by horizontal to low-angle lamination; the low-angle laminations may occur as hummocky cross stratification;
- wave-ripple cross-lamination, particularly in the upper portion of the storm layer (Fig. 9);
- bioturbation that extends downward into the storm layer from its upper surface (Fig. 10).

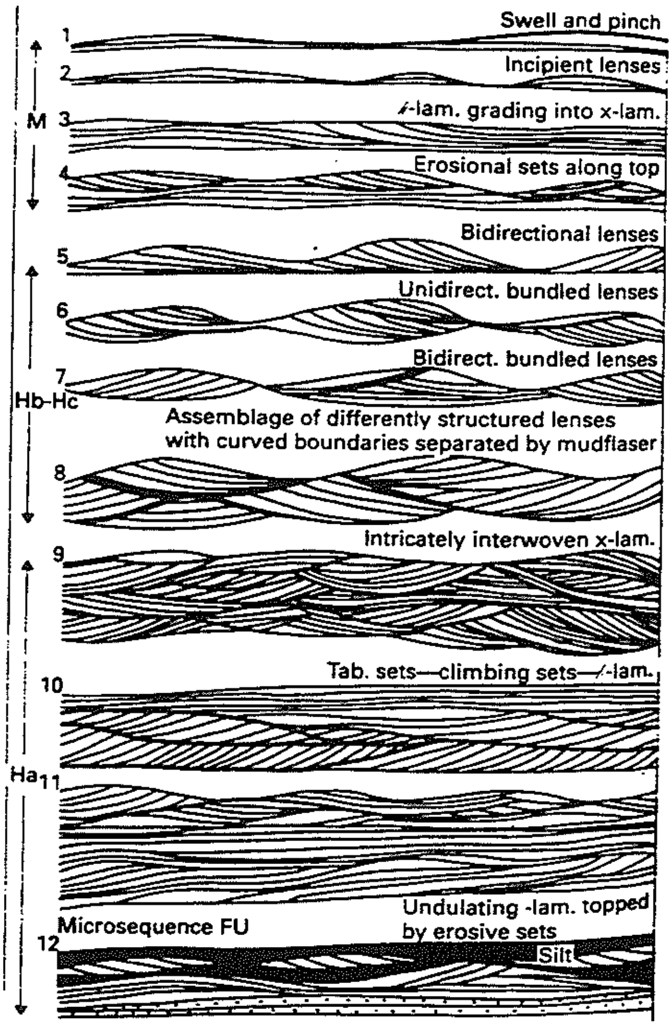


Figure 9. Some characteristic types of ripple cross stratification formed by waves. From Johnson and Baldwin (1996).

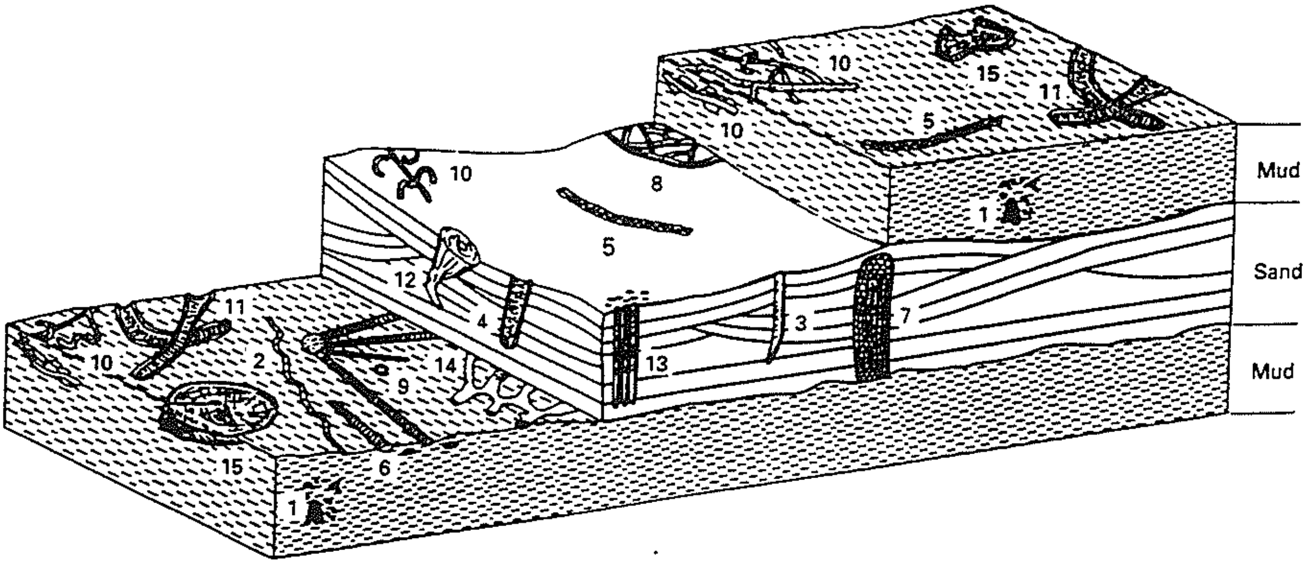


Figure 10. Typical trace fossil assemblages within offshore storm (hummocky cross-stratified) sand layers and their bounding mud units. 1, Chondrites; 2, Cochlichnus; 3, Cylindrichnus; 4, Diplocraterion; 5, Gyrochorte; 6, Muensteria; 7, Ophiomorpha; 8, Palaeophycus; 9, Phoebichnus; 10, Planolites; 11, Rhizocorallium; 12, Rosselia; 13, Skolithos; 14, Thalassinoides; 15, Zoophycus. From Johnson and Baldwin (1996).

Important characteristics for distinguishing these storm layers from classical turbidites include:

- the presence of wave ripple cross-lamination,
- wave rippling on the top of the storm layer,
- the presence of *in situ* shelf faunas within the encasing muds,
- lateral or vertical association with other "shallow-water" facies.

3.2.2. Tide-dominated shelves

On a tide-dominated continental shelf, the currents at a single location change direction and strength during a tidal cycle, and those changes may not be symmetric. As a result, the currents generated at a site over one tidal cycle are often summarized graphically as a "tidal current ellipse", and the degree of elongation of the ellipse indicates the asymmetry of the currents at that location (Fig. 11).

The classic examples of modern tide-dominated shelves (e.g. the areas around the British Isles) are areas where the present rate of sediment supply is low, so that pre-existing sediment is undergoing extensive reworking. In these areas, sands are deposited in, and may subsequently be reworked from, large bedforms. Such bedforms include tidal sand waves and tidal sand ridges, both of which can exhibit extremely complex internal depositional geometries

(Fig. 12). Diagnostic internal characteristics of these large bedforms include mud drapes (Fig. 13), which are deposited during periods of relatively quiet water, major low-angle internal bedding planes, and smaller-scale high-angle cross-stratification. Over a larger area of a tide-dominated shelf, sediment may be transported away from one region (a "bedload parting") and deposited as a lateral sequence of sand ribbons, sand waves, and sand sheets, respectively. Modern examples of tide-dominated shelves with abundant sediment supply are not well known.

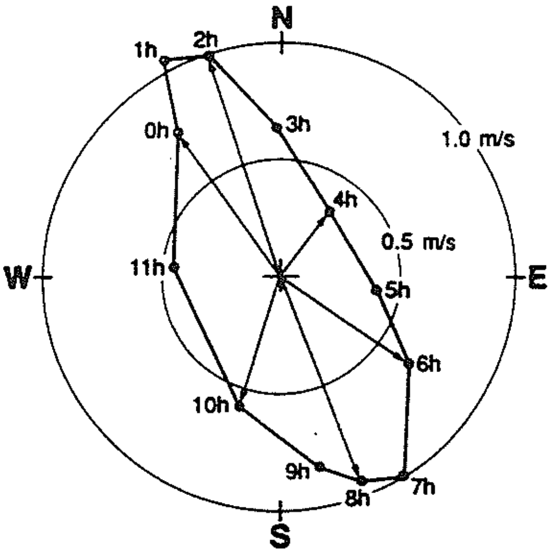


Figure 11. Rotary tidal currents and the tidal ellipse for a site on Georges Bank. The tidal ellipse is constructed by joining the tips of successive current-velocity vectors, which have length scaled to the speed of the current. The tidal ellipse becomes more elongate as the currents during a tidal cycle become more asymmetric. From Dalrymple (1992).

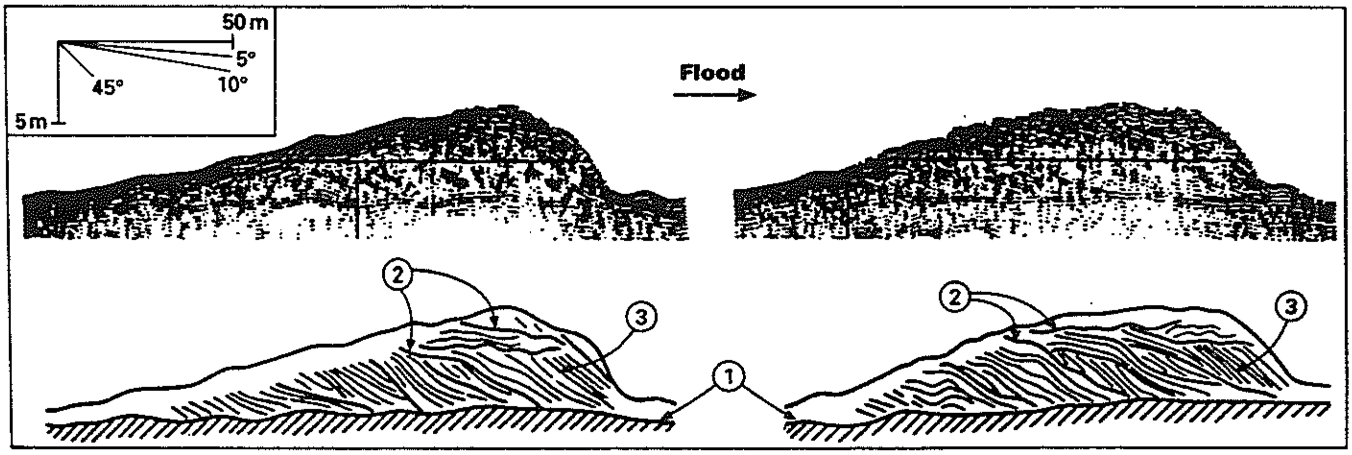


Figure 12. High-resolution seismic reflection profiles and line drawing interpretations through asymmetric sandwaves from offshore Brittany, France. Interpreted sections highlight: (1) major, subhorizontal lower bounding surface (sea bed); (2) low-angle second-order internal bounding surfaces; and (3) packages with angle-of-repose foresets. (Note exaggerated angles due to differences in vertical and horizontal scales.) From Johnson and Baldwin (1996).

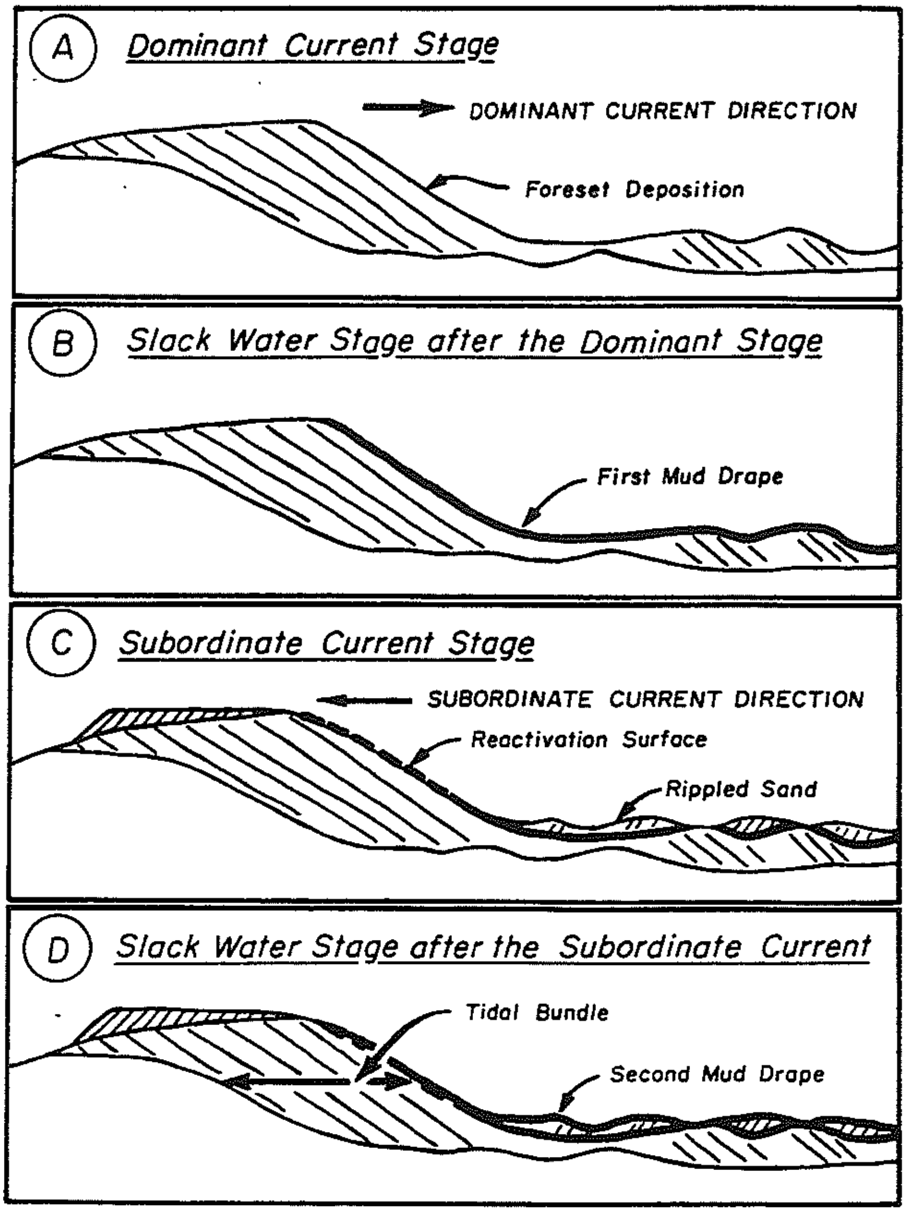


Figure 13. Structures produced in a sandy bedform during one tidal cycle. In this example, the currents exhibit pronounced asymmetry, and suspended sediment concentrations are moderately high. A tidal bundle is the deposit of the dominant portion of the tidal cycle. From Dalrymple (1992).

3.3. Large-scale controls on shelf sedimentation

The preserved stratigraphic record of deposition on a continental shelf depends on both: (i) the local hydraulic regime, and (ii) the relative rates at which sediment is supplied and accommodation space is created. The rate of sediment supply, in turn, responds to such factors as relief, climate, and bedrock of the sediment source, whereas the rate of creation of accommodation space depends on local tectonics and changes in eustatic sea level. In general, a supply-dominated shelf experiences a regression, whereas an accommodation-dominated shelf experiences a transgression.

3.3.1. Characteristics of supply-dominated shelves

The development of a supply-dominated shelf requires the input of a significant amount of sediment, and that sediment must be of a type that can be distributed widely across the shelf. Because rivers are the primary suppliers of large volumes of sediment, and because fine sediments are the type most likely to be widely distributed, supply-dominated shelves tend to contain large volumes of fine-grained, fluvially supplied sediment. These sediments may appear to be relatively homogeneous during visual examination, but detailed inspection using x-radiography can provide evidence of variations in grain size, bioturbation type and intensity, and sedimentary structures. Mineralogic and geochemical data can provide evidence of source rock type, weathering conditions, dispersal patterns, and depositional conditions (such as bottom-water oxygenation). The rapid deposition on a supply-dominated shelf enhances preservation of individual storm beds, which may be either the sandy storm beds described above or finer-grained storm beds that can only be identified by x-radiography.

3.3.2. Characteristics of accommodation-dominated shelves

An accomodation-dominated shelf develops when the rate of sediment supply is low relative to the rates at which accommodation space is created and/or sediment is dispersed off the shelf. As a result, such a shelf generally experiences a transgression, with erosional retreat of the shoreface and significant reworking across the shelf. Erosional surfaces and condensed sections are important components of the stratigraphic record, and the lithofacies present are generally thin, laterally variable, and coarse-grained (including winnowed lags). Extensive bioturbation records the long exposure times experienced by stratigraphic surfaces.

3.3.3. Indicators of continental shelf deposits

Recent studies and summaries of continental shelf sediments (especially Johnson and Baldwin, 1996) have recognized that no single sedimentological or stratigraphic criterion is diagnostic of shelf environments. Muds form the majority of most shelf sequences, but the subordinate sands have been the primary focus of most studies. When examining the sands, it is necessary to use multivariate data sets, including grain size, sedimentary structures, sandbody geometries, paleocurrent patterns, paleontological evidence, and vertical and lateral stratigraphic relationships. As described above, equivalent data may be gained from the muds by applying x-radiographic techniques. In addition, recent experiences on the Cretaceous strata of western North America (e.g. Walker and Plint, 1992) have demonstrated the importance of understanding the nature of marine erosion surfaces and their relationships to sand bodies when interpreting the "shelf" *versus* "shoreface" origin of the sands.

Unfortunately, many of the criteria that are most helpful for identifying a shelf deposit and interpreting the detailed depositional history of that deposit (e.g., sandbody geometries, paleocurrent patterns, lateral stratigraphic relationships) are unavailable in a study based on limited core and seismic data. As a result, interpretation of a "continental shelf" sequence during initial description of the Cape Roberts cores must be based on those features that: (i) can be observed within a core, and (ii) are considered most likely to be diagnostic of shelf sediments. Such an interpretation, however, should be considered preliminary until all applicable sedimentological, palaeontological and geophysical data can be synthesized.

3.3.4. "Diagnostic" features of wave-dominated shelf deposits

At the scale of individual beds (centimetres to several decimetres), the following sedimentary structures are considered relatively diagnostic of a wave-dominated shelf setting:

(1) wave ripples and wave-ripple cross-stratification (Fig. 9)
(2) hummocky cross-stratification
(3) graded beds,
(4) limited amounts of tabular or trough cross-stratification

As described above, storm influence is especially recorded by "storm beds", which ideally grade upward from a basal erosion surface (perhaps with a lag of intraclasts) through an interval with low-angle cross-stratification (hummocky cross-stratification), overlain by wave ripples or wave-ripple cross-lamination, and capped by bioturbated muds (Fig. 14). These four intervals reflect erosion at the onset of the storm, deposition during the main portion of the storm, deposition as the storm wanes, and deposition in fairweather following the storm, respectively.

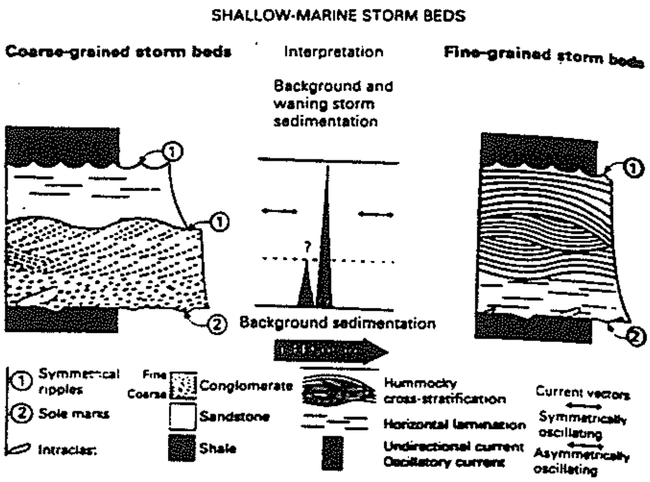


Figure 14. Comparison of sedimentary structures and vertical profiles in coarse- and fine-grained storm beds. From Johnson and Baldwin (1996).

At a larger stratigraphic scale (10s of metres or more), regression on a continental shelf can be recorded by:

(1) an increase in either average grain size or maximum grain size, and/or

(2) an increase in the thickness and/or frequency of storm beds (Fig. 15).

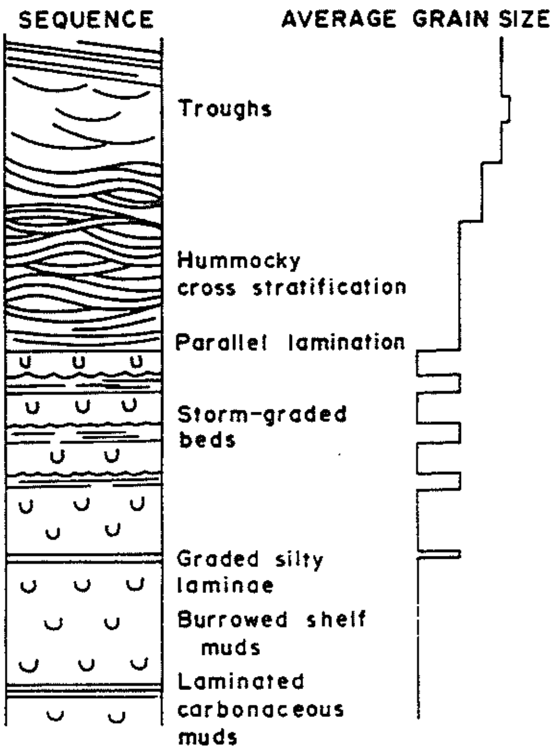


Figure 15. Idealized coarsening-upward succession deposited during regression on a storm-dominated continental shelf. From Boggs (1995).

Transgressions may be accompanied by limited sediment supply, so that a gradational decrease in grain size or storm bed importance is not developed. Instead, the transgression may be recorded by condensed sections and intervals showing extensive reworking.

Both body fossil and trace fossil data can also be useful for interpreting: (i) the marine origin of a potential shelf deposit, and (ii) palaeobathymetric trends within the shelf sequence (Fig. 16).

3.3.5. "Diagnostic" features of tide-dominated shelf deposits

At the small scale (centimetres to decimetres), the following sedimentary structures have traditionally have been considered as diagnostic of tidal influence (Fig. 17):

(1) bidirectional ("herringbone") cross-stratification,

(2) flaser/lenticular bedding,

(3) clay drapes, and

(4) tidal bundles.

These structures have generally been observed in areas on the inner to middle continental shelf, however, so their validity as tidal indicators in more offshore settings is open to debate.

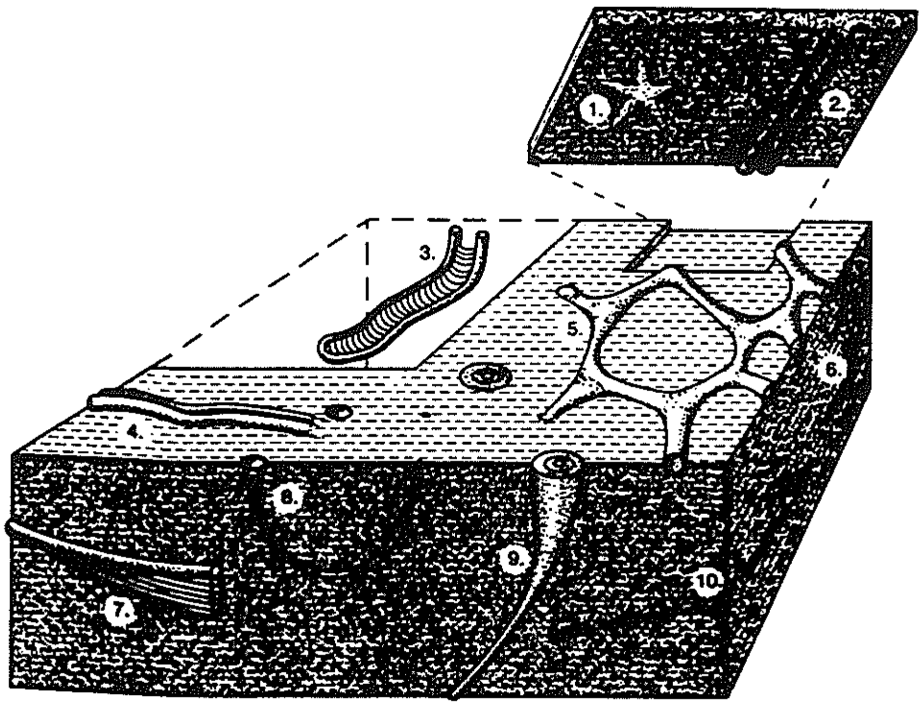


Figure 16. Trace fossil association characteristic of the Cruziana ichnofacies. 1) Asteriacites, 2) Cruziana, 3) Rhizocorallium, 4) Aulichnites, 5) Thalassinoides, 6) Chondrites, 7) Teichichnus, 8) Arenicolites, 9) Rosselia, 10) Planolites. From Pemberton, MacEachern, and Frey (1992).

Larger sandy bedforms, which are important on modern accomodation-dominated tide-dominated shelves, are too large to recognize in detail in the subsurface without closely spaced cores or detailed geophysical data. However, these features often contain: (1) crossbed sets ranging in thickness from 0.1 to *c.* 10 m, and (2) complex internal depositional architecture, with low angle accretion or reactivation surfaces (Fig. 18). Mud drapes may also be present within these bedforms.

Areally extensive, low-relief erosion surfaces also appear to be an important component of tide-dominated continental shelves, because such shelves are accommodation-dominated. These surfaces can be overlain by thin, sheet-like pebble or granule lag layers, and then buried by thin offshore muds and silts. Recognizing such surfaces in a single core may be difficult.

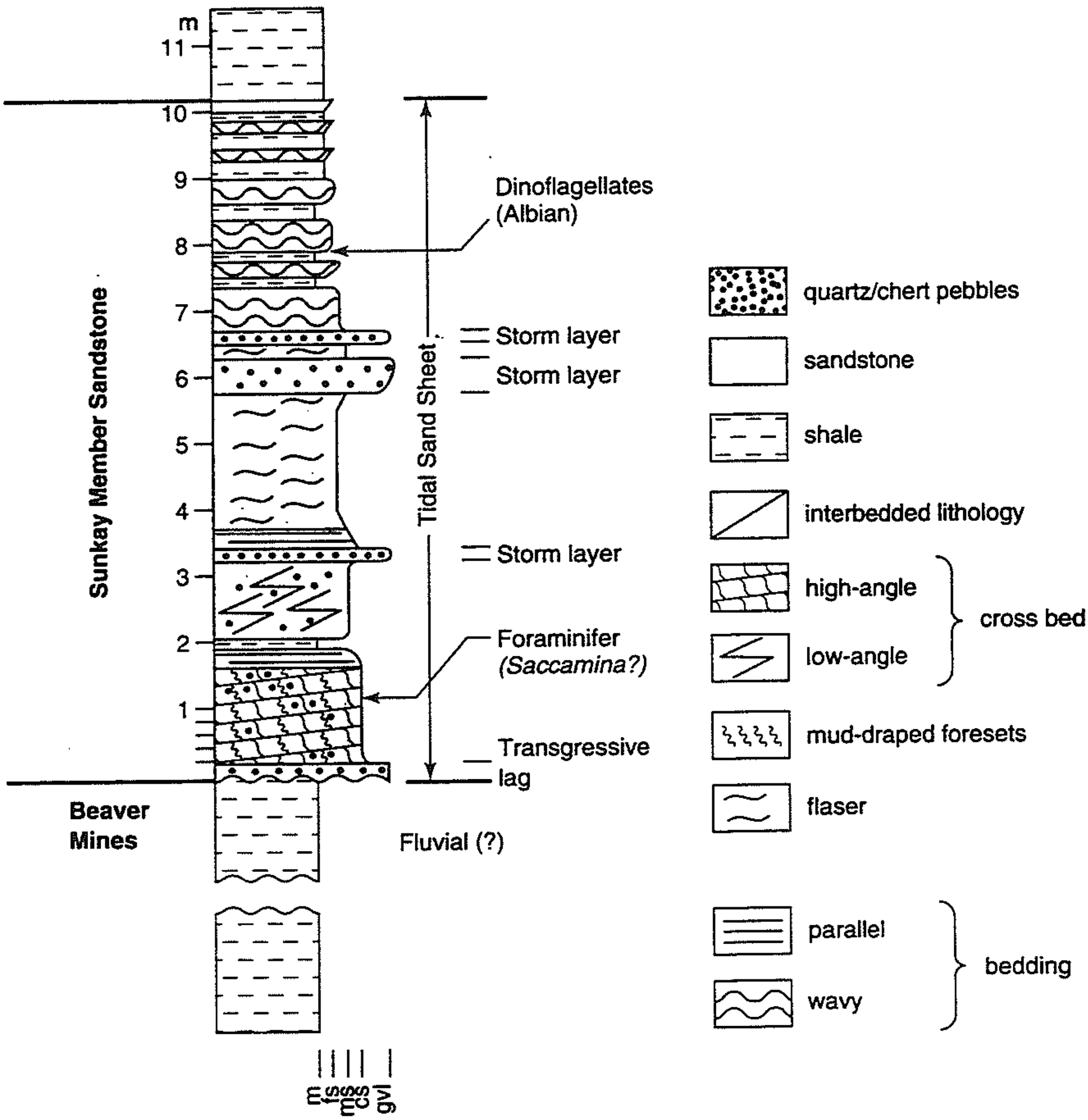


Figure 17. Vertical succession of sandy tidal shelf deposits in the Sunkay Sandstone Member of the Lower Cretaceous Alberta Group, southern Alberta, Canada. Symbols in the grain-size scale are gvl = gravel, cs = coarse sand, ms = medium sand, fs = fine sand, and m = mud (silt-clay). From Boggs (1995).

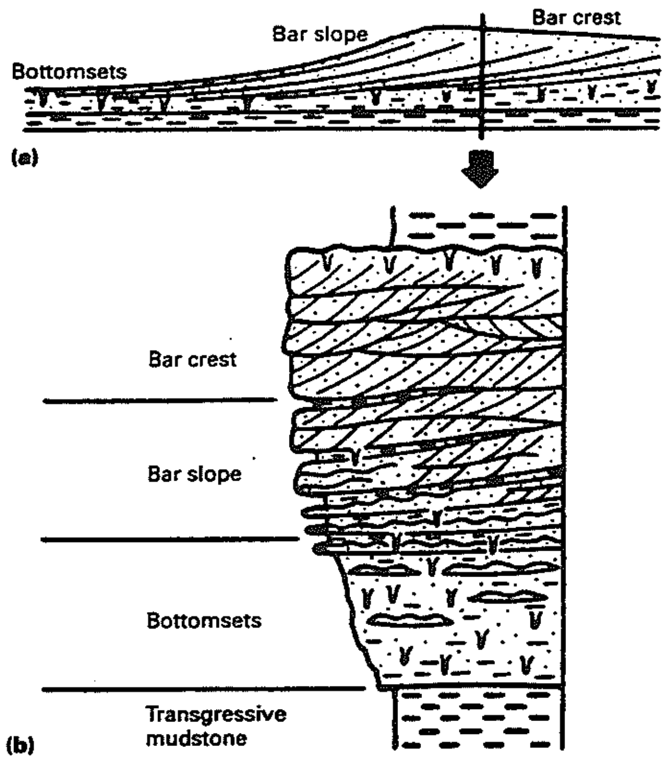


Figure 18. (a) Model of a prograding, linear tidal sand ridge, and (b) schematic coarsening/thickening-upward facies succession. From Johnson and Baldwin (1996).

4. CONTINENTAL SLOPE AND RISE FACIES AND ENVIRONMENTS

John A. Howe & Angelo Camerlenghi

4.1. Processes

A number of classification schemes of deep-water slope / rise sediments are available, from the complex, detailed work of Pickering *et al.* (1989), to the broader process-oriented of Stow (1994).

In the broadest sense, there are three main groups of processes capable of eroding, transporting and resedimenting sediments on the continental slope and rise (from Stow 1994) :

(1) Resedimentation processes

(2) Bottom currents

(3) Hemipelagic settling.

Added to this are authigenic processes, the in situ formation of minerals in the deep-sea.

Process	*Transport*	*Slope*	*Dimensions*	*Velocity*	*Duration*	*Distance*	*Average sedimentation Rate*	*Environment*
Slump	Shear failure	>1°	<500m thick	?	?hours	0.001-100km	High	Slope (high Sediment deposition)
Debris Flow	Shear+ slow plastic flow	>1°	tens of metres	1-20cm/sec	?hours	<350km	Moderate-High	Slope/Rise (High sediment deposition)
Turbidity current	Low viscosity flow supported by fluid turbulance	>0.5°	Length 10's of km X 100's metres thick	10-250cms/sec	?hours-days	<1000kms	<5cm->5m per 1000yrs	Mid-Lower Slope/Rise/ Basin
Canyon Current	'clear water flows' with tidal periodicity.	Up and down slope <few°	10's metres thick	0-30cms/sec	Semi-continuous	100'skms	Low	Slope
Bottom current	Deep, slow thermohaline flows	>few°	width of 10's kms X 100's metres thick	<200cms/sec	Semi-continuous	1000kms	<10cm per 1000yrs	Slope/Rise
Hemipelagic Settling	Vertical settling of grains and flocs.	Ubiquitous	settling through 100's-1000's metres of water.	0.002-0.005cms/sec (settling rate)	Semi-continuous	No horizontal transport	<1cm/1000yrs	Slope/Rise/ Basin

Table 1. Deep-Water processes and their depositional characteristics (adapted from Stow 1994; after Nardin et al., 1979).

From this simple threefold classification a table can be drawn, summarising the depositional processes and the physical characteristics of their deposition (Table 1, from Stow 1994, adapted from Nardin *et al.* 1979). Whilst not all these are expected in the Cape Roberts core, it is worth examining this table, noting, in particular the differences in scale of certain processes. Also worth noting is that whilst the thickness of certain units is easily identified, the lateral extent of any deposit and its geometry will be uncertain in the core record. Caution is advised before assigning a depositional process to a certain unit especially with respect to the discrimination between alongslope and downslope deposition.

4.1.1. Resedimentation.

This broad group covers any sediment that has been moved downslope from shallower water. This includes; Debrites, turbidites, and slump deposits. Described below are short summaries of each process and brief descriptions of the kind of unit that may be encountered in the core.

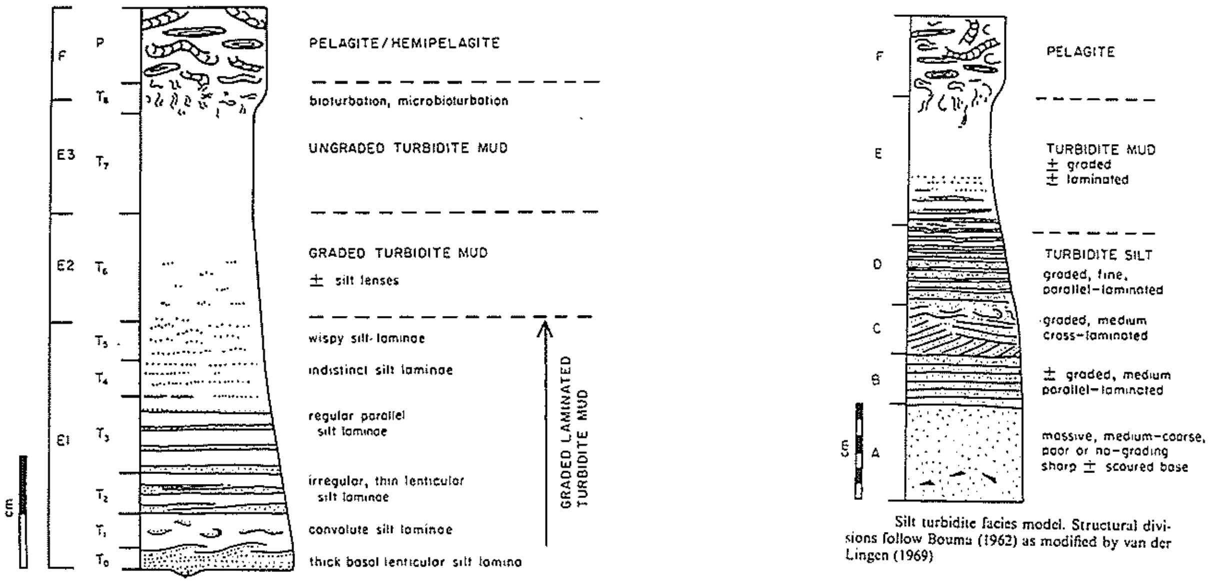
(i) *Debris flows (debrite).* Debris flows are highly concentrated downslope movements of sediment on a slope. They can be muddy slurries on the cm scale or tens of metre thick clast supported units. Commonly, when seen in core section debrites range from 0.5cm to >200m thick. Disorganised poorly sorted gravels and sands with a flat or deeply scoured base to disorganised muds with only scattered clasts are common. Clast sizes range from fine pebbles and boulders in a matrix of muds. Grading is very rarely present. Debrites may be structureless or contain some evidence of lamination, slumping and convolute bedding and clast rich horizons. Of note is the continuum between ice-rafted debris from overturning bergs and thin, slurry debris flows on the slope, (Pickering *et al.* 1989, Howe 1995, Mulder & Cochonat 1996).

(ii) *Turbidity currents (turbidite).* Turbidites can be generated from debris flows, spillover in canyon heads, storm derived build-up of nepheloid layers and from rivers and glacial meltwaters. Seen in core section they can be <5cm thick to tens of metres thick for very high concentration flows. Typically normally (+ve) graded, with a sharp/erosive base, there can be some evidence for reverse (-ve) grading near the base of coarser-grained flows. Occasional silt or sand laminae, cross bedding leading to more massive, finer units with increasing evidence of bioturbation. Its is rare to find complete turbidite sequences with top-absent, or mid-absent and base-absent types commonly described. Compositionally they can be very varied depending on the source material from volcaniclastic to fine-grained mud turbidites. Examples of a variety of turbidites are shown in Figures 19 and 20 (from Stow & Piper 1984, Howe 1994).

Figure 19 (overleaf). Example of a silt turbidite, from the Barra Fan, Rockall Trough, North Atlantic. On the right is the core surface photograph, on the left an X-radiograph of the same.


2.00m
C
C1 turbidite
C
2.35m
Bouma (1962)
F
E
D
B
A
Stow and Piper (1984)
T6
T4/5
T3
T2
To

(iii) *Slumping and sliding (slump deposit).* Slides and slumps are the downslope movement of semi-consolidated sediment along a shear plane. In sliding the internal structure of the unit is maintained. With slumping the unit is folded and disturbed. Seen in core section, slides can be difficult to identify other than an exotic or apparently not *in situ* units, with an erosive lower contact. Slumps are easier to identify with overturned or contorted horizons bounded at both contacts by more 'normal' horizontally bedded sediment. Other common slump structures are folds, thrusts, balls and overfolds. Both slumps and slides range in thicknesses from anything up to hundreds of metres thick (Simm *et al.* 1991).



Mud turbidite facies model. Structural divisions after Piper (1978) and Stow (1977)

Silt turbidite facies model. Structural divisions follow Bouma (1962) as modified by van der Lingen (1969)

Figure 20. Interpretive facies models of silt and mud turbidites (from Stow & Piper, 1984).

4.1.2. Bottom Currents

Whilst it is doubtful if we will be able to see much evidence for contour current activity in the core, it may be useful to include a brief summary of this powerful process of sediment transport and deposition along the continental margin. Contour currents and their resultant deposits, contourites, are the result of deep-water (>200m), thermohaline or geostrophic flow, following the bathymetric contours along topographic highs and margins of ocean basins. Contourites encompass a variety of types depending upon the source material and the depositional environment. The basic division of Stow & Lovell (1979), Lovell & Stow (1981) and Stow and Piper (1984) still holds true of sandy and muddy contourite types. Basically, the greater the velocity of the alongslope current the greater the grain-size of the resulting winnowed unit. A fluctuating or irregular current will produce, over time, silt and clay laminations whereby the coarsening upward (-ve) grading represents increasing current activity and the fining upward (+ve) grading therefore indicates a waning or decreasing current. Contourites can be very enigmatic with wholesale bioturbation of the units, typically tens of centimetres thick. The contourite facies model (Fig.21, from Stow & Piper 1984) describes the continuum from muddy-sandy contourites.

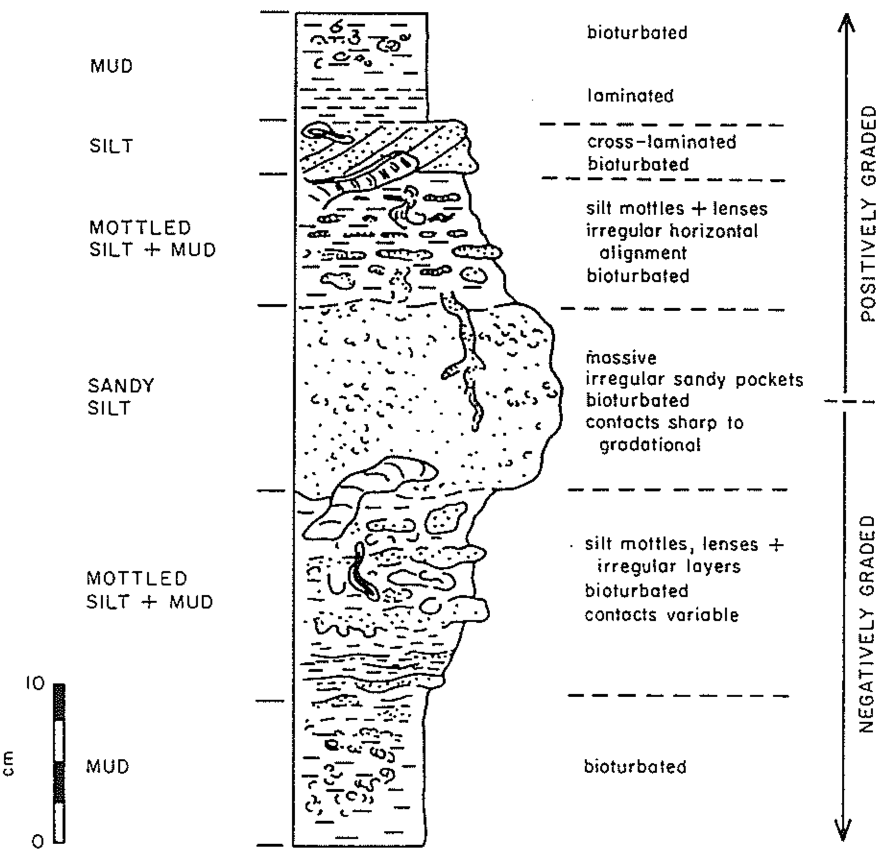


Figure 21. The contourite facies model (from Stow & Piper 1984).

4.1.3. Hemipelagic Settling

Hemipelagites are the result of slow settling of fine-grained particles in continental margin settings. Hemipelagites, as opposed to pelagites, contain a greater proportion of terrigenous material. Typically the sediments are fine-grained, poorly sorted with very low rates of sedimentation and continuous bioturbation. They contain 1-15% sand and could broadly be described as 'silty clays'. No primary structures remain, the entire unit being homogenised by bioturbation. Difficulties can arise over the recognition of hemipelagites in slope-rise environments due to, inevitably, confusion over what is, say, a very low concentration fine-grained turbidites or a muddy contourite. Stow and Wetzel (1990) defined the term 'hemiturbidite' to define the deposit resulting from the settling out of a dilute, stationary cloud above a dying turbidite. In a glacimarine environment, hemipelagites contain dropstones and in deeper water units, monosulpidic knots and mycelia threads are common. A typical facies model for a hemipelagite is shown in Figure 22.

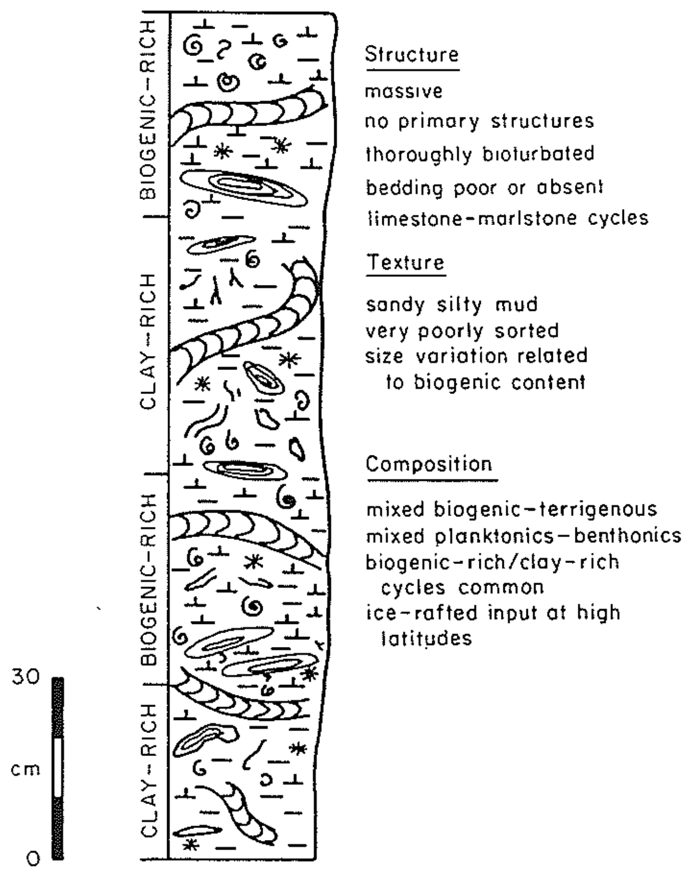


Figure 22. The hemipelagite facies model (from Stow & Piper 1984).

4.2. Facies Associations

Within the Cape Roberts core it is hoped that by assigning a series of vertical sequence or facies associations to the deposits a deep-water palaeoenvironmental reconstruction can be attempted. For example, turbidite, contourite and and interbedded hemipelagite sequences may be indicative of an open slope with channels, interchannels swept by a persistent slope-current. Total contourite and hemipelagite sequences could be an indication of contourite drifts at the base of the slope, or even smaller 'plastered' drifts on the mid-lower slope. Hemipelagites and contourites together sometimes indicate a fluctuating and irregular current, in this environment any downslope, low concentration turbidites become laterally diverted and redeposited as contourites. Farther up the slope associations of turbidites and debris flows suggest a downslope depostional area, with large volumes of material being fed onto the upper slope leading to slope instability. Slumps, debrites and muddy and sandy turbidites are sometimes associated with canyons and channels.

Because the facies association and the definition of paleoenvironment of deposition belong to the strictly speaking interpretative work, we do not propose any particular model and leave the method open to decision of the investigators, depending on the type of material that will be encountered in the cores.

5. GLACIGENIC FACIES AND ENVIRONMENTS

M. J. Hambrey & R. D. Powell

5.1. Introduction

Identification of glacigenic sediments is likely to be crucial to this investigation. This topic is not adequately treated in sedimentology textbooks, but a number of specialised texts have recently been published (Hambrey 1994; Menzies 1995, 1996; Bennett & Glasser 1996). Hence particular attention is paid here to the classification and interpretation of glacigenic sediments.

The non-genetic classification of poorly sorted sedimentary rocks has been given in Part I, Section 3.3.3. Here, we focus on the classification of glacigenic sediments and their interpretation in terrestrial and marine contexts. This discussion represents an attempt to marry ideas arising from different standpoints, a sedimentological/stratigraphic standpoint (Hambrey 1994), and a process-based view (Powell 1984).

5.2.Terminology of glacigenic sediments

The question of terminology of till and till-like deposits has received a thorough airing repeatedly over the past three decades (e.g. Hambrey & Harland 1981, with reference to pre-Pleistocene sediments; Dreimanis 1989, for Quaternary sediments). However, despite an INQUA Commission on the "Genesis and Lithology of Quaternary Deposits", there remains much disagreement concerning how terminology should reflect processes, especially those operating in the marine environment.

For an unsorted deposit with a wide range of grain sizes released directly from glacier ice, whether on land or beneath a floating glacier, and not subsequently modified, the term till is applied. The term for a lithified glacial deposit, tillite, historically has evolved separately and is not strictly equivalent to the term "till". Many authors have used the term "tillite" to embrace sediments containing a significant proportion of iceberg-rafted debris. Other authors have been more restrictive, although few would restrict it solely to debris known to have been deposited on land, but would include lithified till-like sediment deposited beneath a floating glacier. Here, the terms "till" and "tillite" are used to include sediments released directly from a glacier, whether on land or through a water column, that have not been subject to reworking, such as by currents or gravity flowage resulting in disaggregation. Such sediments are therefore normally massive. Till which is apparently stratified may have been sheared by overriding ice during deposition.

Sediments released by ice into the sea, whether by continuous rain-out beneath a floating mass of glacier ice, or sporadically from icebergs, even if the proportion is small, are collectively referred to as glacimarine sediments (also referred to in the literature as glacial-marine, glaci(-)marine). Thus, the broad inclusive definition proposed by Andrews & Matsch (1983:2 and Borns & Matsch (1989: 263) is adopted in modified form here:

"Glacimarine sediment includes a mixture of glacial detritus and marine sediment deposited more or less contemporaneously. The glacier component may be released directly from glaciers and ice shelves or delivered to the marine depositional site from those sources by gravity, moving fluids, or iceberg rafting. The marine component comprises mainly terrigenous and biogenic ('biogenous' in North America) sediments".

This classification draws attention to the wide range of ice-margin types and depositional processes, but does not define them or discuss how genetically different sediments may be distinguished.

5.3. Genetic classification of terrestrial tills

Tills (and tillites) are said to be more variable than any other sediment known by a single name (Flint 1971: 154; Goldthwait 1971: 5). A comprehensive classification of terrestrial tills emerged that in the 1980s satisfied the majority of INQUA correspondents at the time (Dreimanis 1989). The INQUA classification represents the broadest consensus concerning glacial sediments at the present time and the terrestrial elements are adapted here (Table 2). The factors considered in the INQUA classification are primarily the formational and depositional processes, the general environment of deposition, and the position in relation to glacier ice. However, discrimination of some different types of till is still premature, as the processes of deposition are not properly understood. Thus, a simplified classification is used here.

Supraglacial till is sediment let down from the surface of the glacier onto the substrate without significant disaggregation or flow. Texturally, this can be extremely varied as the sources of supraglacial debris include: (i) rockfalls, (ii) ice that has been subject to thrusting, rasing basal and subglacial debris to the surface, and (iii) debris associated with ice-foliation development, resulting from the melt-out of folded englacial and subglacial debris (Hambrey *et al.* in review).

Subglacial till is deposited from debris-rich basal ice as a result of melt-out or lodgement (plastering-on) processes, although the detailed mechanisms are poorly known. Texturally, this facies reflects abrasion and fracturing of debris at the ice/bedrock interface, and comprises mainly subangular and subrounded clasts, and has a broad grain-size distribution (from clay to boulder).

Release of glacial debris and its deposition or redeposition			Depositional genetic varieties of till		
I Environment	II Position	III Process	IV By environment	V By position	VI By process
	Ice-marginal	*A. Primary*		Ice-marginal till	*A. Primary till*
	frontal	Melting out			Melt-out till
	lateral	Lodgement			Lodgement till
		Sublimation		Supraglacial till	Sublimation till
Glacio-terrestrial	Supraglacial	Squeeze flow	Terrestrial		Deformation till
		Subsole drag	non-aquatic till		Squeeze flow till
				Subglacial till	
	Subglacial	*B. Secondary*			*B. Secondary till*
		Gravity flow			Flow till
		Slumping			
	Substratum	Sliding and rolling			

Table 2. Genetic classification of till in terrestrial settings (adapted from the INQUA classification; Dreimanis 1989). The verical columns are independant of each other and no correlation horizontally is implied. Not all combinations are feasible. (From Hambrey 1994).

Flow till (glacigenic sediment flow) may be derived from any glacial debris upon its release from glacier ice or from a freshly deposited till in direct association with glacier ice, normally on land. Redeposition is accomplished by gravitational slope processes, mainly by gravity-flow, and it may take place ice-marginally, supraglacially or subglacially, and subaerially.

These process terms may conveniently be used in combination with the terms for position, e.g. "supraglacial melt-out till". Many other terms for till and combinations have been used (Table 2), of which Dreimanis (1989) has provided a comprehensive review.

Recognition of lodgement till, melt-out till and flow till has long been a matter for debate, and the most useful criteria are tabulated in detail by Dreimanis (1989). Genetic terms for lithified sediments may have the suffix "-ite".

5.4. Distinguishing glacigenic sediments from other poorly sorted sediments

There are few individual criteria which can be used to unequivocally to demonstrate whether a poorly sorted sediment is glacigenic or not, unless the depositional setting can be determined (as for modern environments). This is particularly true of diamictons which are commonly the product of mass-flow processes. Nevertheless, if several criteria typical of glacigenic sediments can be identified, then the weight of evidence may be sufficient to favour the involvement of glacial processes. Often investigations going beyond the purely visual must be undertaken, including clast shape and fabric analyses. A large body of comparative data for establishing processes of deposition in glacial environments has been assembled by Menzies (1995, 1996), but a simpler summary of criteria (from Hambrey 1994), which can be used as a check list of key characteristics is given in Table 3.

(a) Evidence for terrestrial glaciation	
Abraded surfaces	striated and/or polished surfaces
	crescentic gouges; chattermarks
	striated boulder pavements
Clast-rich beds with:	irregular thickness (usually *c.* 50 m)
	lenses of sand/gravel (glaciofluvial)
	depositional shear structures in massive diamict; otherwise structureless diamict
	preferred clast orientation
Depositional fossil landforms, e.g. moraines, eskers	
(b) Evidence of glaciomarine/glaciolacustrine deposition	
Massive to stratified beds, often tens or hundreds of metres thick, with gradational boundaries	
Dropstones in stratified units	
Random clast fabric	
Slight sorting or winnowing at top of beds	
Association with fossils	
Association with rhythmites of varve or turbidite origin	
Association with resedimented deposits (debris flows)	
(c) Evidence common to both environments	
Variable clast lithologies	
Poorly or non-sorted with wide range of clast sizes	
Exotic (far-travelled) varieties of clasts	
Fresh minerals	
Constant mix of clasts over wide area common	
Clast characteristics	shape variable from angular to rounded
	some striated and faceted surfaces
	flat-iron/bullet-nosed shapes
	calcareous crusts
	fragile clasts
	quartz grain textures; chattermarks on garnet grains
(d) Other evidence of cold climate	
Ice wedge clasts	
Fossil sorted stone circles, polygons and stripes	
Fossil solifluction lobes	
Association with lithified loess (loessite)	

Table 3. Principal criteria for establishing a glacial origin of diamict successions.

5.5. Genetic classification of glacimarine (and glacilacustrine) sediments

In terms of preservation potential and volume, glacimarine sediments are vastly more important than terrestrial glacial sediments, yet before the late 1970s little was known about this contemporary environment, and sediment classifications were not based on direct observations of processes in this environment (e.g. Harland *et al.* 1966). Since then, however, glacimarine environments have received considerable attention, notably those in Svalbard and Alaska, and several simple classifications have been adopted.

Waterlain till is sediment that is released steadily from floating basal glacier ice and accumulates on the sea (or lake) bottom without being affected by winnowing processes, and so is a massive diamict. In character it resembles basal till, from which it may be difficult to distinguish without clast orientation measurements. Francis (1975) introduced the term "waterlain till" in preference to the semantically incorrect waterlaid till of Dreimanis (see Dreimanis 1979). The term "waterlain till" has been adopted for Antarctic sediments (Hambrey *et al.* 1989, 1991). The INQUA perception of waterlain till is, nevertheless, vague, and the term is used here with reservations, pending the development of a broader consensus concerning the classification of glacimarine processes. Alternative terms could be "rain-out diamict" or "waterlain diamict".

Mud/mudstone with clasts, also termed gravelly (or pebbly) mud/mudstone is the standard non-genetic term for fine sediments that include coarser ice-rafted debris. Ice-rafting occurs in three ways, by ice shelves and floating glacier tongues, icebergs and sea ice. If these environments are determined by sedimentological analysis, then a genetic terminology may be used for these deposits. *Ice shelf zone* (or *shelfstone*) *mud/mudstone* is used for gravelly mud accumulating under an ice shelf. *Iceberg zone* (or *bergstone*) *mud/mudstone* is used for mud/mudstone with clasts rafted by icebergs. If clasts occur in higher proportions with sand (see Table 4), and a diamict is produced, then similar terminology is used, such that *ice shelf zone* (or *shelfstone*) *diamict* and *iceberg zone* (or *bergstone*) *diamict* are used for diamicts formed under ice shelves and floating glacier tongues, and by icebergs, respectively.

Other distinctive facies produced in the glacimarine environment are *cyclopels* and *cyclopsams* (Mackiewicz *et al.* 1984, Cowan & Powell 1990). These are finely laminated sediments, described from Alaskan fjords, that are produced within 15-20 km of grounding lines when particles in suspension fall from turbid overflow plumes moving barotropically away from a glacier terminus. Laminae are cyclically produced by interactions of subglacial stream discharges and tidal currents. The laminites produced occur as couplet cycles of mud with either silt (*-pel*) or sand (*-psam*) laminae. The coarser laminae in a couplet can be just one grain thick or may be several centimetres thick, depending on the sediment load of the plume. Coarser laminae have sharp basal contacts, the thicler ones grading normally with top contacts that may be sharp or gradational. Coarser grained, thicker laminae are generally produced closer to source, but there is radial dissipation of grain size around the point-source, i.e. the subglacial stream discharge. Problems exist in distinguishing some of the layers with fine grained turbidites, but the one-grain-thick laminae are quite distinctive.

TERRESTRIAL GLACIERS				
LITHOFACIES	**STRUCTURES & GEOMETRY**	**INTERPRETIVE FACIES**	**FACIES ASSOC-IATIONS**	**DEPOSITIONAL SYSTEM**
				GLACIO-TERRESTRIAL
Sandy gravel	Structureless; VA and A clasts; clasts lack striations; irregular spreads or lines of debris	Meltout from supraglacial (rockfall-derived) debris cover	Supra-glacial	
Diamict	Massive to sheared; SA and SR clasts normally dominant within broad range of shapes; striated and faceted clasts; preferred orientation fabric parallel to flow; typically a few to several m thick, filling hollows in underlying substrate; sediment overconsolidated; sharp contacts; occasional boulder clusters and pavements.	Subglacial till	Sub-glacial	
Sandy muddy gravel	As above, but clast concentration in range 30-80%	Lodgement till	Sub-glacial	
Diamict	As diamict above, but weak stratification inherited from ice foliation, stronger fabric and not overconsolidated	Subglacial melt-out till	Sub-glacial	
Diamict	Massive; clasts as diamicts above; occasional crude grading (normal and reversed); diffuse clusters of clasts or uneven sorting; clast fabric variable (girdle, multimodal, rarely preferred); poorly consolidated; sorted sand/silt stringers; folds (overturned); sharp bottom (erosive) and top to bed; individual beds a few m thick	Flow till (glacigenic sediment flow)	Pro-glacial, supra-glacial (remobil-ised)	
Sand/gravel	Sheets, lenses up to several m thick, trough cross-bedding, ripples, imbrication, (syn-sedimentary faults and down-sagging)	Proglacial glaciofluvial (with ice contact collapse structures)	Pro-glacial	

Table 4. Lithofacies in glacial terrestrial and glacimarine environments, their interpretation, typical associations and their grouping into depositional systems.

LITHOFACIES	STRUCTURE & GEOMETRY	INTERPRETIVE FACIES	FACIES ASSOC-IATIONS	DEPOSITIONAL SYSTEM
				GLACIO-LACUSTRINE
Sand and gravel	Weakly bedded, laterally extensive beds; cross-bedded, local current riplles; gravel lags	Deposition from subaquatically discharging streams and deposition on top of prograding wedge	Topset	
Sand and gravel	Trough cross-bedded prograding units; climbing ripples in sand; channels with levees and lobes	Prograding wedge with channel formation and switching from fast-flowing bottom currents	Foreset	
Diamict	Sharply-defined beds up to a few m thick; structureless except for occasional coarse-tail grading (normal and reverse); variable concentration of clasts; load structures	Subaquatic debris-flow (proximal)	Foreset	
Sand and mud	Laminated, cross-laminated, climbing ripples, draped lamination, dropstones; laminae laterally continuous; graded laminae and/or couplets of coarse/fine sediment (varves, varvites); lamination may be bioturbated	Sedimentation from suspension-settling, gravity flow (turbidity currents) and by iceberg rafting	Bottom-set	
Diamict	As diamict above, but units cm/dm thick	As diamict above (distal)	Rain-out deposits	
Evaporites	Continuous beds or stromatolite mounds, often laminated	Polar-arid ice-contact lake deposits	Shallow water/ emergent	

Table 4 contd.

TEMPERATE GLACIER TIDEWATER TERMINI				
LITHOFACIES	**STRUCTURES & GEOMETRY**	**INTERPRETIVE FACIES**	**FACIES ASSOCIATIONS**	**DEPOSITIONAL ENVIRONMENT & SYSTEM**
				GROUNDING-LINE SYSTEM
	bank geometry			MORAINAL BANK
gravel - beds & lenses	push structures	nests of iceberg-rafted clasts	chaotic mixture	
sand	no bioturbation			
mud				
diamict				
	fan geometry			GROUNDING-LINE FAN
massive scour-fill sand	angular clasts	marine outwash		
massive open-work gravel	push structures	nests of iceberg-rafted clasts		
graded sands-muds	sediment failure structures	sediment gravity flow deposits	submarine fan associations	
massive sands	no bioturbation			
diamicts				
	fan geometry			DELTA
standard fan-delta facies	no bioturbation	nests of icebrg-rafted clasts	fan delta associations	
gravel lenses				
	sheet geometry			PROXIMAL ICEBERG ZONE
laminites:	very rare bioturbation	cyclopsams & cyclopels	bergstone muds & diamicts	

Table 4 contd.

TEMPERATE GLACIER TIDEWATER TERMINI				
graded sand & silt				
massive sand & silt				
one-grain-thick sand & silt laminae				
gravelly mud				
graded sands-muds				
massive or stratified diamict		diamict varves		
graded sands & silts - muds	no bioturbation	sediment gravity flow deposits	submarine fan associations	
massive sands & silts		mainly turbidites &		
diamicts		debris flow deposits		
	sheet geometry			DISTAL ICEBERG ZONE
stratified gravelly mud	common bioturbation	cyclopels	bergstone mud	
massive gravelly mud		nests of iceberg-rafted clasts		
graded silts - muds		sediment gravity flow deposits	submarine fan associations	
massive silts		mainly: distal turbidites		
bioclastics		various biofacies	hardground associations	
	sheet geometry			HEMIPELAGIC ZONE
standard hemipelagic facies	common bioturbation		standard hemipelagic associations	

Table 4 contd.

POLAR GLACIER FLOATING TERMINI				
LITHOFACIES	**STRUCTURES & GEOMETRY**	**INTERPRETIVE FACIES**	**FACIES ASSOCIATIONS**	**DEPOSITIONAL ENVIRONMENT & SYSTEM**
				GROUNDING LINE
	wedge geometry			GROUNDING-LINE WEDGE
massive diamict	dispersed/ random clast fabric	waterlain till		
stratified diamict		shelfstone diamict		
massive & stratified diamict	multi-modal clast fabrics	sediment gravity flow deposits:	debris flow sheets & lobes	
		mainly debris flow deposits		
	very rare bioturbation			
	bank geometry			MORAINAL BANK
massive & stratified diamict	dispersed/ random clast fabric	waterlain till and shelfstone diamict	chaotic association	
	push structures			
	very rare bioturbation			
	fan geometry			GROUNDING-LINE FAN
same as for tidewater termini	sheared flat top(?)	same as for tidewater termini	same as for tidewater termini	
	very rare bioturbation			

Table 4 contd.

POLAR GLACIER FLOATING TERMINI				
	sheet geometry			PROXIMAL ICE SHELF ZONE
massive diamict	dispersed/ random clast fabric	waterlain till		
stratified diamict		shelfstone diamict		
massive & stratified diamict	multi-modal clast fabric	sediment gravity flow deposits: debris flow deposits	sediment gravity flow sheets and lobes	
massive or graded sand & silt	very rare bioturbation	turbidites		
	sheet geometry			DISTAL ICE SHELF ZONE
gravelly mud	condensed section or hiatus	shelfstone mud		
	very rare bioturbation			
	sheet geometry			ICEBERG ZONE
sandy mud	rare nests of iceberg-rafted clasts	bergstone mud	hemipelgite association	
biogenic ooze	common bioturbation			
	sheet geometry			PELAGIC ZONE
standard pelagite facies	common bioturbation		standard pelagite associations	

Table 4 contd.

Glacimarine varves are being characterised in temperate and polar settings. In temperate settings they are defined by iceberg-rafted debris layers (either gravelly muds or diamicts), produced during the winter, interbedded with bergstone muds with cyclopels and cyclopsams, deposited in summer (Cowan *et al.* 1997). In poalr settings, glacimarine varves are defined by annual phytoplankton blooms (mainly diatoms), formed after the braek-out of sea ice in the summer, interstratified with siliciclastic sediment from glacial sources (Leventer *et al.* 1996).

Of the various glacimarine depositional systems, perhaps the grounding-line system differs the most from other sedimentary systems. Other glacimarine systems, like the ice shelf and iceberg zone systems, have 'normal' marine processes acting that are superposed by ice-rafting processes. Different grounding-line systems are produced by different subglacial processes which are commonly related to glacial regime, and the type of terminus, namely whether it is a grounded tidewater cliff or a floating tongue or ice shelf (Powell & Domack 1995).

Morainal banks are systems that have a bank geometry, and are a chaotic mixture of facies (Table 4). They accumulate where the terminus is cliffed and sediment originates from subglacial streams, subglacial lodgement, subglacial squeezing, pushing and ice-rafting. Systems in the shape of fans are produced at the point sources of subglacial stream-mouths, and include submarine outwash and sediment gravity-flow deposits. These fans may aggrade and prograde up a cliffed terminus to eventually form a delta with characteristics of fan-deltas. Grounding-line wedge systems are less well known. They appear to be made up mainly of diamict, but are commonly seismically stratified along grounding lines, and are suggested to be fed by subglacially deforming till.

5.6. Facies analysis of glacigenic sediments

The concept of facies has been used ever since it was recognized that features found in particular rock units were useful for interpreting the environment of deposition and for predicting the occurrence of mineral resources. (Reading 1978 gives a useful summary).

A sedimentary facies or lithofacies is a body of sediment or rock with specified characteristics, namely colour, bedding, geometry, texture, fossils, sedimentary structures and types of external contacts. The term "facies" has been used in many different senses, for example, in the strictly observational sense, in the genetic sense, and in an environmental sense. However, a facies should ideally be a distinctive rock that forms under certain conditions of sedimentation, reflecting a particular process or environment. Facies may be subdivided into subfacies or grouped into facies associations (Reading 1978), or considered on a regional scale in terms of facies architecture.

Here, glacial facies refers to the different sediment types one finds in a glacial environment, and which are interpreted as till, glacifluvial, glacilacustrine and glacimarine deposits. Grouped together we have terrestrial glacial, glacilacustrine and glacimarine facies associations, and so on.

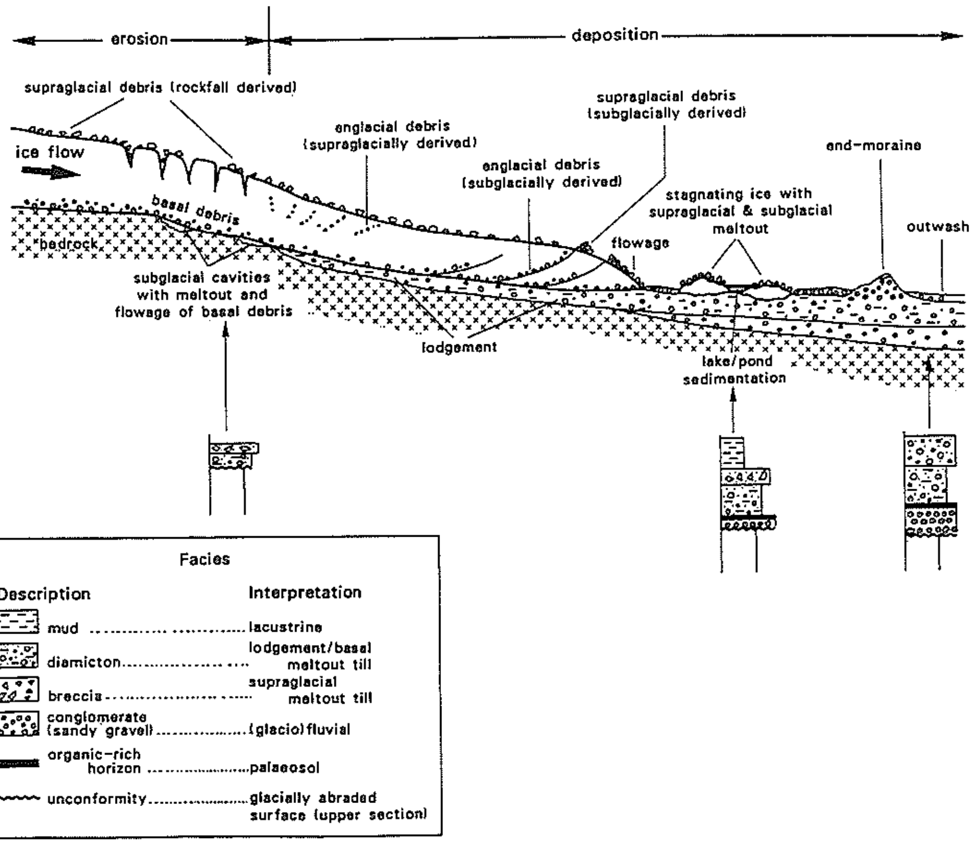


Figure 23. Cross-sectional view of a typical temperate glacier to illustrate the various types of glacigenic sediment deposited as the ice recedes (from Hambrey 1994).

Examination of contemporary glacial environments indicates that sedimentary facies are varied and related in an often complex manner. Identification of these facies in Quaternary sequences is relatively straightforward, but in detail, for example, it may be difficult to distinguish different types of glacigenic sediment. Glacial, fluvial, aeolian, marine, lacustrine mass-flow and sediment gravity flow processes account for the wide variety of facies present. In cores, the limited sampling of strata often makes it difficult to determine the precise depositional environment and the degree of direct glacial influence in a particular facies. It is therefore important to undertake first a descriptive facies analysis, using the criteria listed in Table 3 applying non-genetic terms such as diamict, and only then interpret them. Even then, there is scope for a wide variety of interpretations of a particular facies.

In order to facilitate assessment of depositional environments, lithofacies are grouped into associations, from which it may be possible to determine all-embracing depositional systems (Table 4).

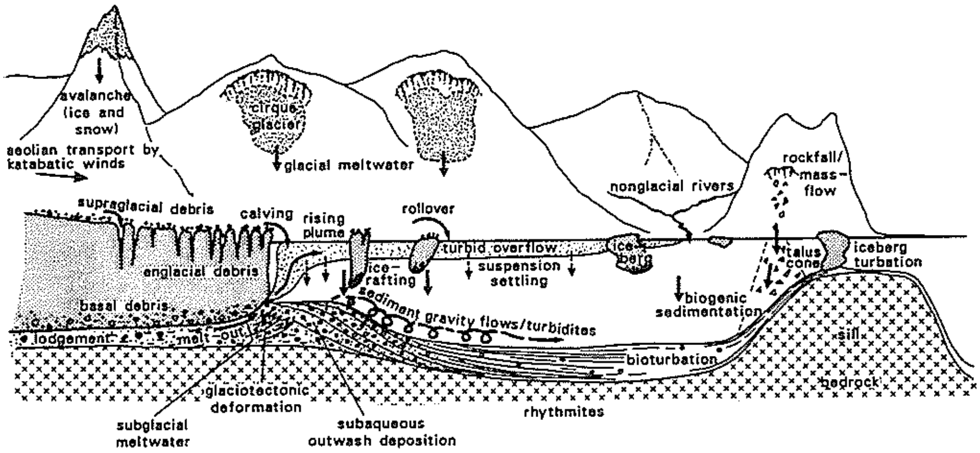


Figure 24. Processes and sedimentary products in a glaciolacustrine setting (from Hambrey 1994).

5.7. Models depicting processes and facies in glacier-influenced environments

A variety of conceptual models have been developed for glacier-influenced settings. A number of these, which are self explanatary, showing processes, lithofacies and their interpretation are illustrated: terrestrial temperate glacial settings (Fig. 23), glacial lake (Fig. 24), temperate glacier-dominated fjord (Fig. 25) and modern Antarctic continental shelf (Fig. 26).

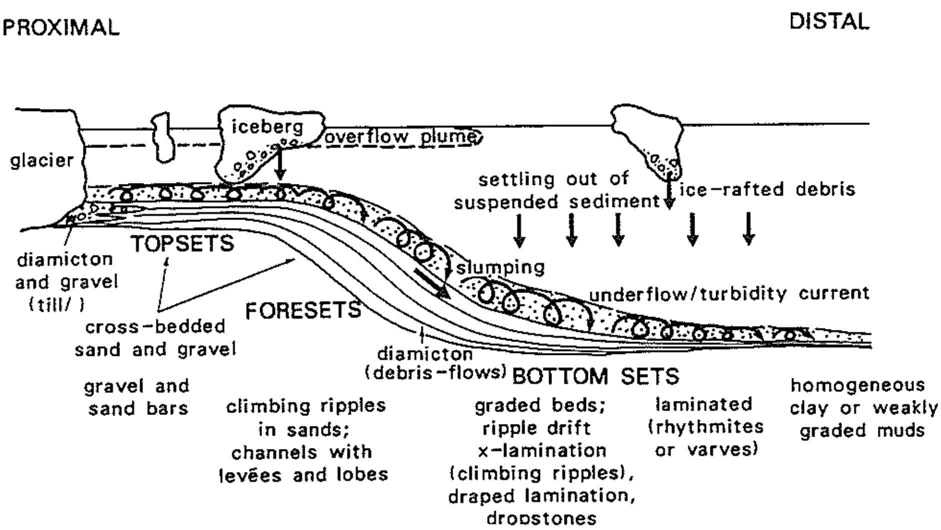


Figure 25. Sediment sources and processes operating in a fjord influenced by a grounded, temperate, tidewater glacier (from Hambrey 1994).

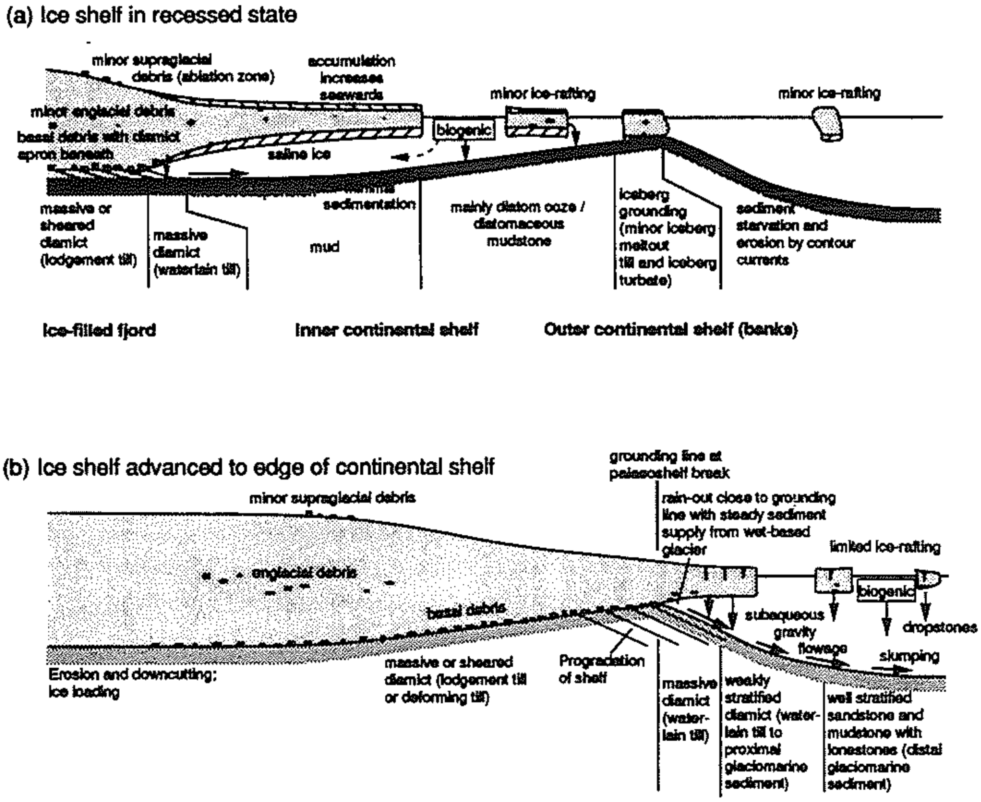


Figure 26. Sediment sources and sedimentary process, products and their interpretation at the margin of the East Antarctic ice sheet. (a) Ice shelf with grounding -line at the inner part of the continental shelf, as at the present day. (b) Ice shelf having grounded on the continental shelf and advanced across it to the continental shelf break, where it becomes decoupled from the bed, as at glacial maxima (from Hambrey 1994).

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