DEPOSITIONAL MECHANICS OF

ATYPICAL TURBIDITES

DEPOSITIONAL MECHANICS OF ATYPICAL TURBIDITES, CLORIDORME FORMATION, GASPÉ, QUEBEC

By

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SCOPE AND CONTENTS: This study describes the lateral correlation for 7-1/2 miles of a turbidite sequence in the Cloridorme Formation, Gaspé, Quebec.

Certain unusually thick turbidites display a sequence of internal sedimentary structures different from the typical "Bouma sequence". The depositional mechanics of these beds have been deduced from an analysis of field observations in the light of recent observations from experimental turbidity currents.

Antidune cross-stratification, occurring in the basal divisions of some beds, is described, along with unusual internal structures interpreted as arrested macroturbulent eddies formed in dense grain dispersions.

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ABSTRACT

Thick turbidite beds, belonging to the β_1 member, Cloridorme Formation (Ordovician), are exposed on the wavecut platform between St. Hélier and Fame Point, Gaspé, Quebec. The local paleocurrent direction (to the west) is approximately parallel to the east-west strike of the vertical beds.

These thick turbidite beds display a sequence of sedimentary structures which differs from the sequence defined by Bouma. Three broad divisions are recognised: a basal division consists of either limestone or quartz granule to pebble conglomerate (0-4 cms thick) or coarse sand greywacke or calcareous wacke (0-15 cms thick). Basal divisions of calcareous wacke frequently display ripple-lamination, parallel lamination, or upstream inclined laminae. Where the upstream inclined laminae form a single set, they occur below a sinuous profile (wavelength 40-80 cms, and amplitude 2-5 cms).

A second division (0-330 cms thick) consists in most places of spindle or globular shaped calcareous nodules scattered in an argillaceous matrix. In some beds streaking and lobing of light coloured carbonate bearing material is associated with these nodules. The upper

division consists of fine grained siltstone and shale.

Thick broken blocks which have fallen from the cliffs, display the internal characteristics of the second division. Hemi-ellipsoid structures, arranged en echelon and convex towards the base of the bed, are displayed by one block.

The upstream inclined laminae in the basal divisions of calcareous wacke beds are interpreted as the result of the upstream migration of antidunes. The nodules within the second division developed as 'pseudonodules'. The hemi-ellipsoid structures resemble damped large scale (macroturbulent) eddies associated with the flow of dense grain dispersions. The directions of the internal motions are shown by the orientation of grains and graptolite stipes.

Correlation of these beds has been achieved over a distance of 7-1/2 miles. Over this distance the beds show little change in their characteristics. Basal divisions of granule and pebble conglomerate persist over this distance and show that coarse particles may be transported by turbidity currents over long distances. The sedimentary structures of the basal divisions of several calcareous wacke beds give the appearance (probably misleading) of an increase in flow regime downcurrent.

The beds were probably deposited from initially low concentration but high density turbidity currents accompanied by a period of coarse grain traction and suspension near to the bed. In the case of calcareous wacke beds this period of traction formed rippled, flat or antidune bed forms. Stratification has been preserved by the rapid deposition of sediment *en masse* from the subsequent high concentration body of the current. The formation of a succession of 'quick' beds led to the sedimentation of the second division.

Calculations suggest that the currents moved over slopes of much less than 1^{o}.

CHAPTER ONE

OUTLINING THE PROBLEM

1.1 Introduction

Geologists have shown great interest in beds considered to have been deposited from turbidity currents (suspension effect density currents consisting of turbulent, turbid mixtures of sediment and water). Many features associated with these rocks (turbidites) have been described (for example, Dzulynski and Walton, 1965; Potter and Pettijohn, 1963). Of particular interest have been descriptions of marks originally present on the underlying sediments, but now commonly preserved on the lower bedding plane of the overlying turbidite as sole marks, and the internal structures of graded beds (Bouma, 1962; Walker, 1965).

Turbidites associated with 'flysch' sequences have been the subject of exhaustive descriptions (sole structures, paleocurrent analysis, internal structures and facies variation - see Potter and Pettijohn, 1963; Dzulynski and Walton, 1965). Advances in turbidite studies have been made by relating field observations to theoretical (Bagnold, 1962; Sanders, 1963, 1965; Walker, 1965; Scheidegger and Potter, 1965; Walton, 1967) and experimental studies (Kuenen and

Migliorini, 1950; Kuenen, 1951, 1965b, 1966, 1967; Middleton, 1966b, c, 1967a, b). Insight, particularly into the generation of sole marks, has been gained from the experiments of Dzulynski and Walton (1963), Dzulynski (1965, 1966), Dzulynski and Simpson (1966a, b) and Allen (1969).

Probably the most influential results have been those of Kuenen (the production of graded bedding from experimental turbidity currents) and the recognition by Bouma (1962), and subsequent interpretation by Walker (1965) and Harms and Fahnstock (1965) in terms of flow regime, of an ordered sequence of internal structures in some turbidites. This sequence consists of five divisions: a lower massive graded division A attributed to formation in the antidune phase of bed transport, followed by an overlying laminated division B formed in the plane-bed phase of transport; a division C, attributable to deposition on a rippled bed; a laminated division D deposited from suspension with little bed-load movement, and an upper division E formed by normal pelagic deposition. In nature, not all of these divisions are always present and several may be missing (see Walker, 1967). Hubert (1966) has argued that a dune division should be included below the ripple division in the ideal sequence.

However, the sequence of structures described by Bouma (1962) has tended to divert and monopolise our thinking about the possible nature of natural turbidity currents and this has, no doubt, led to a limited understanding of the importance of sediment properties in controlling the sedimentary structures produced by flows of this type (see Walker, in press). Recent experiments by Middleton (1967a) and Riddell (1969) hint at the possible effects of grain size distribution and grain concentration on the hydraulic behaviour of the turbidity current and its different modes of deposition. Since sedimentary structures produced by the migration of bed forms under unidirectional flow conditions are, to some extent, controlled by the grain size of the bed material and the rate of deposition, we should expect to find in nature a wide spectrum of turbidite internal structures. It is known (for example, Enos, 1969a) that not all turbidites display the typical (Bouma) sequence of internal structures either completely or in part and these 'unusual' types have largely been neglected by sedimentologists, probably either because they were not aware of their existence or because they could not interpret their characteristics satisfactorily.

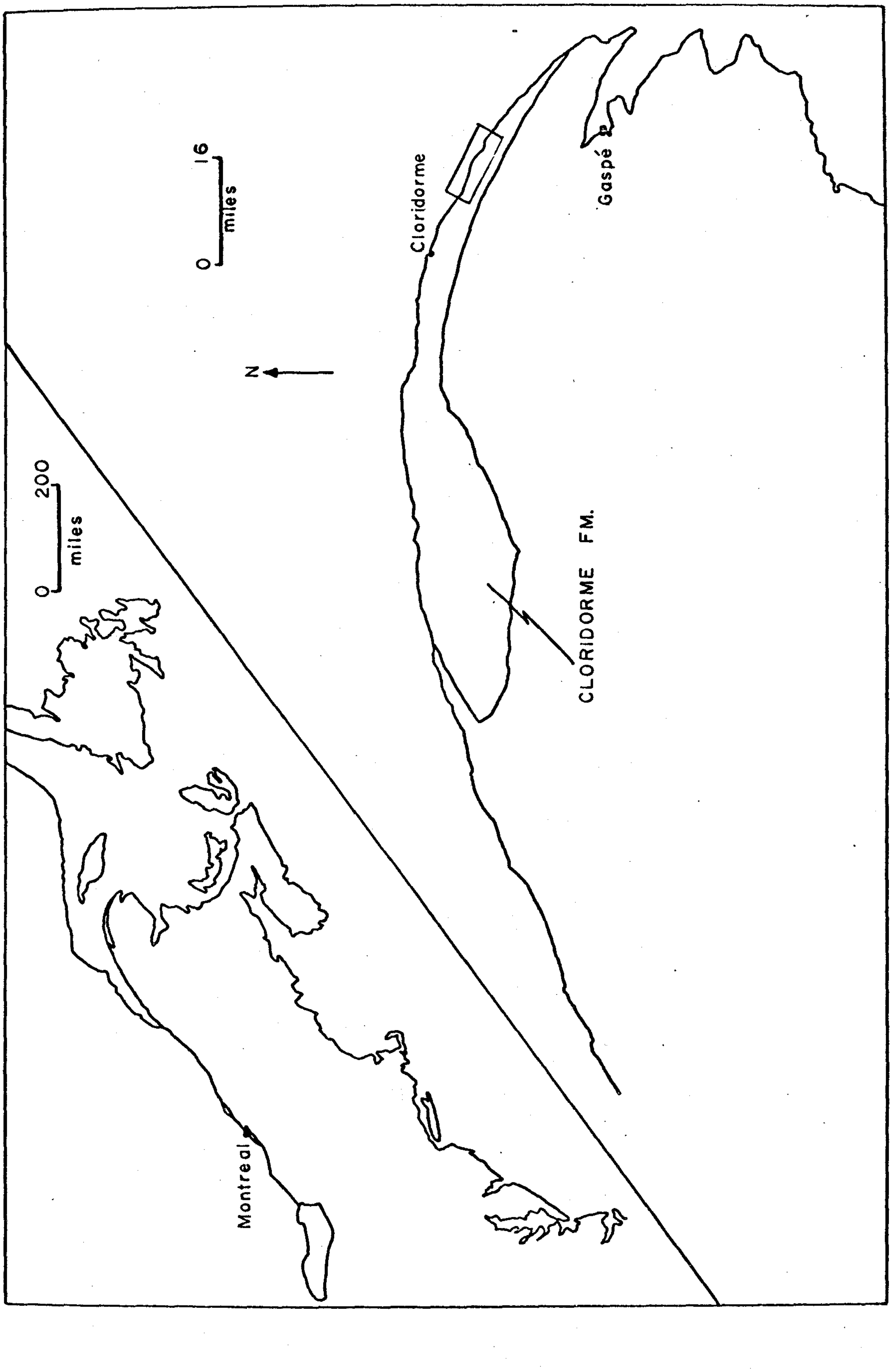
A purpose of this study was to re-examine unusually thick, very argillaceous beds displaying a sequence of internal structures different from the Bouma sequence of internal structures, in the β_1 member of the Cloridorme Formation, Gaspé Nord, Quebec (Enos, 1969a, b). These beds are distinctive because they contain divisions with 'irregular or spindle-shaped light brown calcareous nodules scattered through an argillaceous matrix' (Enos, 1969a, p. 27), structures which themselves required further explanation. Similar beds were also examined elsewhere along the Gaspé coast, particularly at St. Maurice (L'Échourie)in the α_3 member.

In this thesis an attempt has been made to define the mechanics of deposition of these unusual beds from an analysis of their field characteristics, by applying various hypothesis derived from experimental and theoretical studies. Laboratory work has been undertaken to check the visual grain size estimates made in the field and to describe bed petrography.

1.2 The Cloridorme Formation

The Middle Ordovician Cloridorme Formation is exposed along the north coast of the Gaspé Peninsula, Quebec (see figure 1). With a total thickness of 7,700 meters (with an uncertainty factor of two, Enos, 1969a, p. 17), the formation consists of dark grey argillite and interbedded greywacke and calcisiltite. It was informally divided into fourteen members grouped into three sequences α, β and γ, each having three, seven and four members designated by subscript figures (for example, α_1, α_2, ..., β_1, β_2, ...) and confined to the eastern, central and western structural blocks respectively (see Enos, 1969a, p. 29-38).

Figure 1. Location maps; exposure of Cloridorme Formation; box to WSW of Cloridorme is area depicted in Figure 2.


0 16 miles
Cloridorme
Gaspé
N
0 200 miles
CLORIDORME FM.
Montreal

The sequences are interpreted as 'flysch', part of a geosyclinal assemblage of clastic rocks and pelagic mud. From a consideration of the characteristics of the clastic rocks, which include some combination of graded beds, scour marks, tool marks, ripple cross-stratification, convoluted laminae, shale clasts etc. and their lateral geometry, it was concluded that these rocks owed their origin to deposition by turbidity currents which periodically invaded a normally pelagic mud and ooze environment. Measurements of paleocurrent indicators (flutes, tool marks, brush marks, cross-stratification) show that, for flutes and cross-stratification, the paleocurrent direction is towards the west. Tool and brush marks yield a current trend in good agreement with the paleocurrent direction obtained from flutes.

The rocks, although often faulted and overturned, are not considered to have suffered extensive metamorphism. Enos (1969a, p. 11) referred them to the lower greenschist facies on the basis of the development of chlorite and sericite on cleavage surfaces and as alteration products of feldspar.

Graptolites, collected by Enos and identified by Berry, assign these rocks to the 'Orthograptus truncatus intermedius zone' of late Wilderness and Trenton age. The Cloridorme Formation may correlate with the youngest Normanskill or overlying Canajoharie

Formation in New York. Later studies by Riva (1968) suggest the presence of two distinct, and in part, coeval sequences. One sequence consists of Enos' β and γ sequences and contains Canajoharie and Lower Utica graptolites. The second sequence, comprising Enos' α has yielded Normanskill, post-Normanskill and lower Utica graptolites.

The lithologies of the Cloridorme Formation are variable and include greywackes, calcareous wackes, calcisiltites, dolostone, limestone, volcanic ash and silty dolomitic argillite (for a complete discussion see Enos, 1969a, p. 18-29).

1.3 The β_1 member

Rocks assigned to the β_1 member are exposed in river and cove sections and on the wave-cut platform along the coast from the vicinity of Grand Étang at St. Hélier (grid reference, 728442; type section of Enos, 1969a) to beyond L'Anse-à-Valleau (872375), Gaspé Nord, Quebec (see figure 2). The strike of the beds (294°) is approximately parallel to the trend of the coastline and the local paleocurrent direction (282°). Their overturned attitude (angle of dip 65-83° southerly) show that they form the steeper limb of an asymmetric anticlinal fold. Vertical sections through these beds are visible particularly on the wave-cut platform and in river and cove sections.

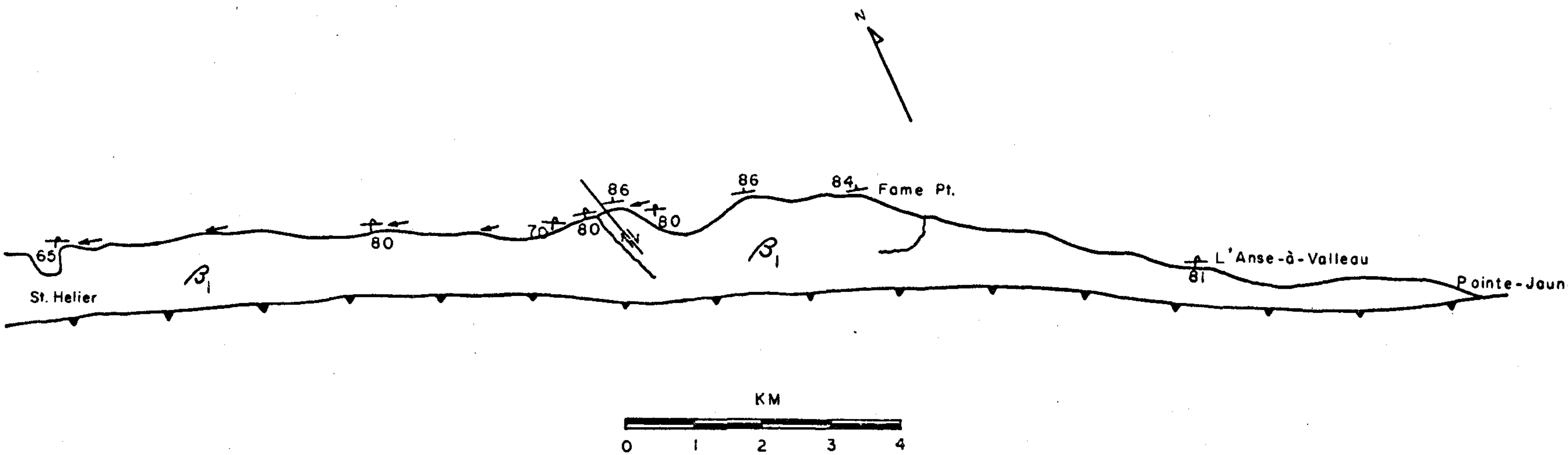


Figure 2. Coastline from St. Hélier to Pointe-Jaune, Gaspé, Quebec to show exposure of the β_1 member. Small arrows are local paleocurrent directions measured from flutes.

The β_1 member is about 1175 meters thick and is characterised by a distinctive suite of lithologies. Argillite makes up 70% of the member, the remainder shared between greywackes (13.5%, type 3 of Enos, 1969a), calcareous wackes (6.7%), calcisiltites (7.2%, type 1 of Enos, 1969a), and dolostone (1.9%). Type 3 greywackes are thick, resistent beds, composed of dolomitic argillite in the upper part of the bed and thin bases with very coarse grains up to pebble size. They may be several meters thick. Calcareous wackes are typically 10 to 30 cms thick and the common sequence of internal structures is small-scale cross-stratification in the basal 0-4 cms produced by the migration of ripples, with convoluted and parallel laminae above. The sequence does not closely resemble that of Bouma (1962, p. 49). Type one calcisiltites are composed of silt-size carbonate grains; many are less than 1 cm thick. Dolostone forms beds from 2 to 75 cms thick and lenses in the form of oblate spheroids with major axes a few meters or less in length and minor axes of 75 cms or less (for discussion see Enos, 1969a, p. 28). They are very persistent laterally.

Type 3 greywackes, and many calcareous wackes, contain divisions with the light brown calcareous nodules and these beds were studied extensively. The chosen areas of study within the β_1 member were the coastal exposures between Grand Étang at St. Hélier and Fame Point. Enos had correlated the type section at Grand Étang (section XVI-2, section 3 of writer) with his section XV3-4 at Ruisseau à l'Échalote (799417; section 10 of writer), a total distance of 4.8 miles. Further more detailed correlations were thought to be possible (Enos, personal communication to G. V. Middleton, 1966). If detailed correlation could be achieved, it would then be possible to study downcurrent changes in beds, particularly those with the calcareous nodules, hereinafter referred to as 'pseudo-noduled' beds.

CHAPTER TWO

FIELD PROCEDURE AND CORRELATION

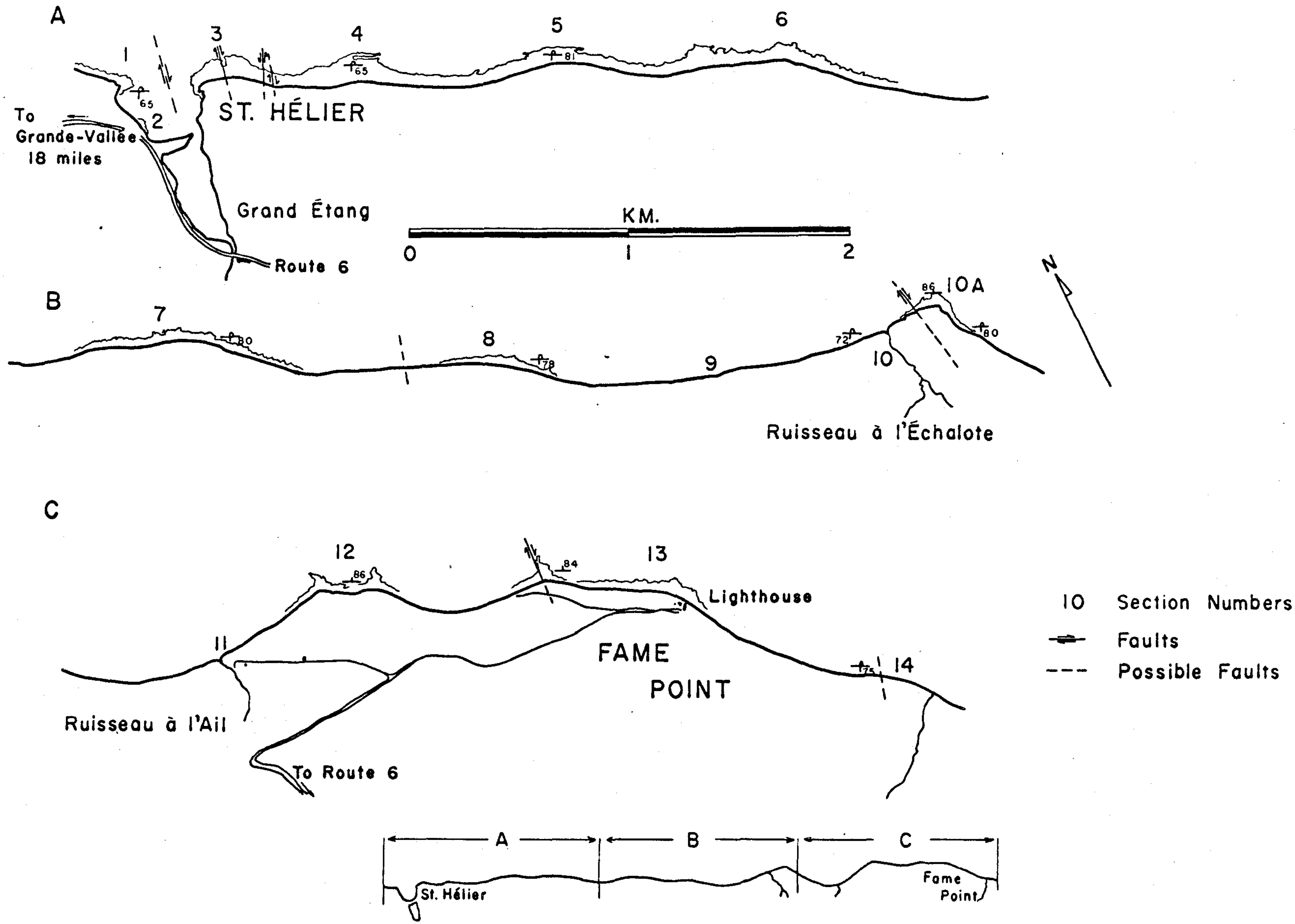
This chapter outlines the field procedure adopted and the correlation of measured stratigraphic sections.

2.1 Field Procedure

Good exposures of turbidite beds assigned to the β_1 stratigraphic member, occur in river and cove sections and on the wave-cut platform at low tide, along the coastline between St. Hélier and Fame Point. Stratigraphic sections were measured wherever exposure was favorable between these two locations. The sections were numbered 1 to 14, including a section 10A; the lowest section number being to the west, and the highest to the east except in the case of section 2 which occurs below section 1 on the west side of St. Hélier (see figure 3). In all, 15 sections were measured; their total thickness being 1,740 meters.

The section data were recorded on the standard Sedimentology Data Sheet 2 (McMaster University Geology Department) constructed by R. G. Walker for turbidite analysis. Since the beds of interest in this study lacked the typical turbidite succession, short notes were added and the specific columns ignored when occasion

Figure 3. Coastline between St. Hélier and Fame Point, Gaspé, Quebec. The members 1 to 14 are the measured section numbers.



A
1
2
3
4
5
6
ST. HÉLIER
To
Grande-Vallée
18 miles
Grand Étang
Route 6
KM.
0
1
2
B
7
8
9
10
10A
Ruisseau à l'Échalote
C
11
12
13
14
Lighthouse
FAME
POINT
Ruisseau à l'Ail
To Route 6
10 Section Numbers
Faults
Possible Faults
A
B
C
St. Hélier
Fame
Point

warranted it. For this reason and for detail, section 3 was graphically logged on an arithmetic scale (1/2 inch representing 10 cms) with all features shown as in the field. This log was valuable in recognizing specific stratigraphic intervals for correlation. The beds in each section were numbered from the bottom upwards. For recording notes and diagrams in the field notebook, the section number was hyphenated to the bed number (for example, 3-342; section 3, bed 342).

Vertical sampling was undertaken at St. Hélier at regular intervals within beds. The distance of the sampling interval depended on the bed thickness and the rate of change within beds. Some beds were sampled at intervals of 10 cms (beds 228, 352), at 30 cms (bed 381) or as much as 100 cms (bed 91). Extra samples were collected within beds where it seemed neccessary outside the sampling scheme. Nine beds which correlated laterally were chosen for detailed study and were also sampled vertically at sections east of St. Hélier (beds 302, 311, 314, 316, 324, 343, 352, 363, 368 and 381). The vertical sampling interval at these other locations was the same as at St. Hélier for respective beds.

All samples were labelled with their appropriate section number (e.g. 3), bed number (e.g. 311), and sample number and given a hyphenated number of the form 3-311-2 (section 3, bed 311, sample 2). Details of the specimen were recorded in the field notebook.

Photographs of various features shown by individual beds were also appropriately numbered as, for example, 1-352-11-15 (section 1, bed 352, reel 11, photo 15).

2.2 Correlation between sections

After completion of the preliminary logging of individual sections, the data sheets were carefully scrutinised to pick out any similarities in the number and sequence of beds. Dolostones and Type 3 greywackes appeared in every section and sequences of them were plotted on graph paper at a scale of 1/2 inch to 10 cms for every measured section. Although thickness changes were apparent, it was a relatively simple matter to correlate sections from the occurrence of dolostone beds and the thick Type 3 greywackes. Sections 1 to 11 were correlated in this way.

Sections 9 and 13 were later abandoned because bed by bed correlation could not be achieved, probably because of the lack of a recognizable sequence of dolostone and greywacke beds and/or their displacement by faulting from expected points of correlation. The inferences made were checked in the field and as more details of bed properties, particularly those with the 'pseudo-noduled' division, and bed sequence were collected, the correlations were very convincing, although some dolostone beds do disappear and others appear in neighboring sections.

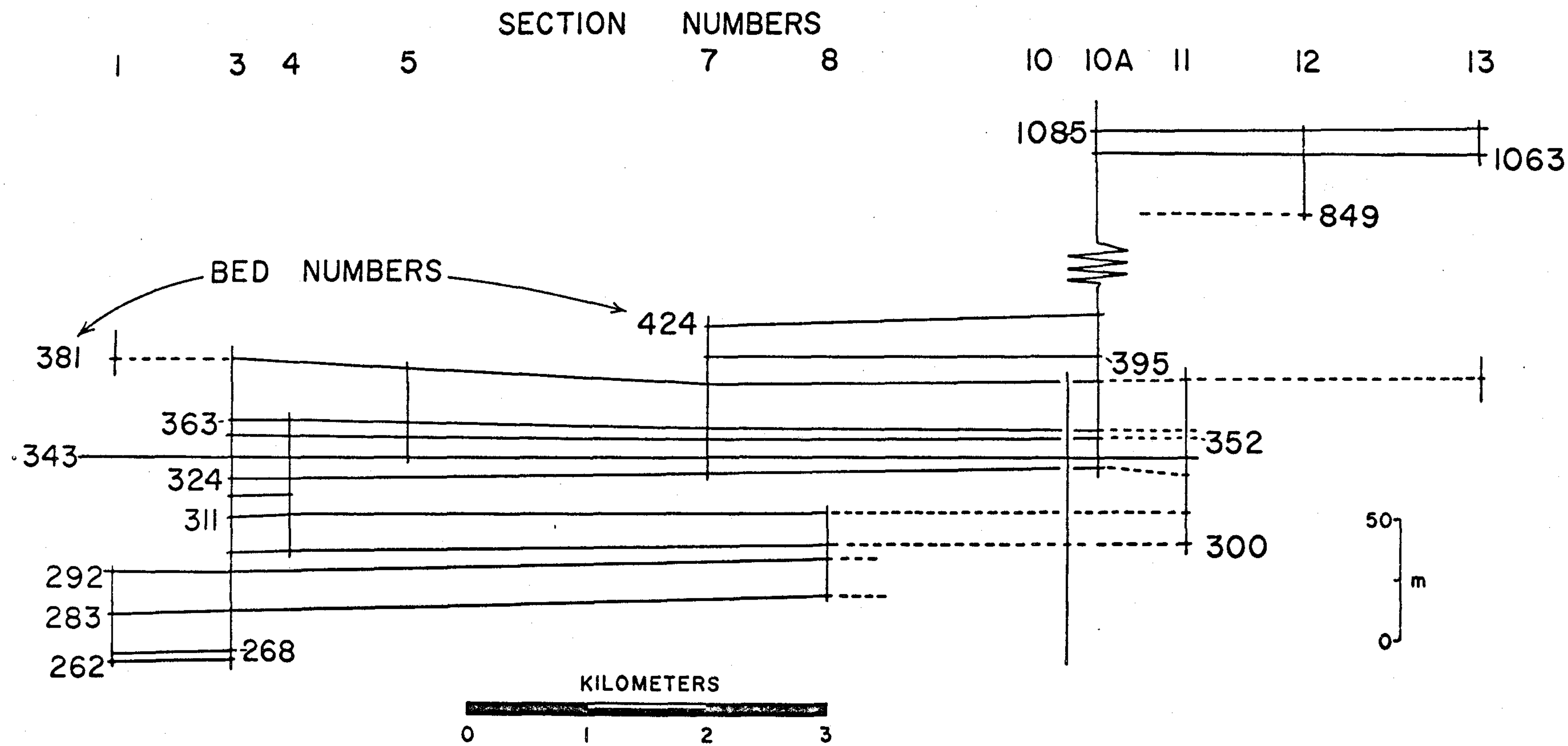
The sequence of beds 368-381 was particularly recognizable at sections 1, 3, 5, 6, 7, 10 and 10A and below the lighthouse at Fame Point, just east of section 13. Polaroid photographs, bed thickness measurements and the logging of local sections convinced the writer of the accuracy of correlation for a total distance of 7 1/2 miles. The tops of sections 10A, 12 and 13 were correlated on the occurrence of similar thick, graded, very coarse grained massive beds.

The natural outcome of the correlation enabled bed numbers designated at section 3 (type section at St. Hélier) to be applied to other sections. Hence it is possible, for example, to refer to bed 342 at section 10A. Where extra beds appeared in the sections they were designated by letters attached to the older bed occurring below them; for example, 1-206a means a bed in section 1 which occurs immediately above bed 206 which was not assigned a number in section 3, the type section. This may have arisen because it was less than one centimeter thick at section 3. Beds thinner than this were excluded in the logging procedure.

The lateral correlation achieved is shown in figure 4.

2.3 Variations between sections

Figure 4. Correlation of measured sections 1 to 13. Bed 343 used as reference bed. Vertical bars below section numbers show the limit of measured exposures. Thickness data at sections 10 and 11 ignored although beds were exposed as indicated by dashed lines.


SECTION NUMBERS
1
3
4
5
7
8
10
10A
11
12
13
1085
1063
849
BED NUMBERS
424
381
395
363
352
343
324
311
300
292
283
268
262
KILOMETERS
0
1
2
3
50
m
0

Total thicknesses between given bed numbers (base to base) were computed for several small intervals of the stratigraphic sections. The intervals chosen were common to several measured sections. For instance, beds 300-311 were chosen as an interval because they were the limit of the measured exposure at section 8. The beds marking the upper and lower limits of the intervals were beds containing the 'pseudo-noduled' division. This was because of their lateral persistency and ease of recognition and correlation; thinner beds would be more likely to thin out and disappear completely between sections.

The results of the thickness changes between sections are also shown in figure 4. There is a consistent thickening of intervals in a westward direction below bed 395 except between sections 10A and 7 for the interval 363-381. Interval 395-424 between sections 10A and 7 shows a decrease in thickness westwards. Data from sections 10 (Enos, 1969a, section XV3) and 11 were neglected in the analysis because both sections show a thickening of intervals which is contradicted by section 10A which occurs between them. This is probably a result of the opening up of cleavage in response to downslope movements in the two river sections.

Data for the total thickness, total thickness of shale (interturbidite), percent shale, total thickness of clastic material and number of beds within intervals is given in Table I. Examination of the data shows that, in general, there is an increase in the thickness of shale towards the west. The data indicates that the increase in thickness of the intervals towards the west is, in general a result of the increase in shale thickness, and possibly an increase in the thickness of the 'pseudo-noduled' beds (note that 'pseudo-noduled' beds are excluded from the data, Table I, b). The variation in the total thickness of beds other than dolostones and beds with the 'pseudo-noduled' division is negligible (Table I, d).

TABLE 1

Data from measured intervals.

(a) total thickness (excluding dolostones).

(b) total thickness of shale (excludes 'pseudo-noduled' divisions and dolostones).

(c) percent shale.

(d) total thickness of beds (excludes dolostones, 'pseudo-noduled' beds and shale). Number of beds in each interval for respective sections shown in brackets.

Interval	Section number 3	4	5	7	8	10A
300-311	1447	1454			1210	
311-316	874	884				
316-324	660	627				
324-343	945	852		684		390
343-352	859	817	820	741		750
352-363	627	596	601	456		344
363-381	2626		2286	1772		2133
381-395				1057		971
395-424				1283		1833

Table 1(a): total thickness (excluding dolostones) in cms.

Section number

Interval	3	4	5	7	8	10A
300-311	982				926	
311-316	638	671				
316-324	505	467				
324-343	677	703		584		249
343-352	643	633	568	412		538
352-363	536	515	515	396		239
363-381	1944		1750	1324		1818
381-395						
395-424						

Table 1(b): total thickness of shale (excludes 'pseudo-noduled' divisions and dolostones)

Interval	Section number 3	4	5	7	8	10A
300-311	67				76.5	
311-316	73	76				
316-324	79.6	74.4				
324-343	71.7	82.5		85		64
343-352	77.4	77.4	69.2	55		71
352-363	85.4	86.4	85.6	84		66
363-381	74		72	74		84
381-395						
395-424						

Table 1(c): percent shale

Interval	Section number 3	4	5	7	8	10A
300-311	(8) 43	(13) 50			(11) 55	
311-316	(3) ?6	(11) 30				
316-324	(4) 38	(13) 60				
324-343	(17) 105	(12) 98		(17) 74		(15) 84
343-352	(7) 47	(7) 50	(6) 52	(10) 69		(7) 74
352-363	(9) 38	(9) 43	(13) 53	(11) 38		(8) 37
363-381	(10) >237		(38) 364	(40) 291		(32) 287
381-395						
395-424						

Table 1(d): total thickness of beds (excludes dolostones 'pseudo-noduled' beds and shale). Number of beds in each interval for respective sections shown in brackets.

CHAPTER THREE

CHARACTERISTICS OF BEDS

This chapter describes the vertical sequence of structures in beds containing divisions with 'pseudo-nodules', the internal characteristics of these beds, and their downcurrent changes and describes briefly their maximum grain size characteristics.

3.1 Vertical characteristics of beds in the β_1 stratigraphic member

The vertical characteristics of the beds containing 'pseudo-nodules' were variable but for the purpose of brevity they were considered to have three distinct divisions; division 1, called basal; division 2, loosely termed the 'pseudo-noduled' division; and division 3, the shale (logged as interturbidite) (see figure 5). Division thickness data for some bed examples in section 3 is given in Table II.

The base of the basal division commonly displayed flutes. Some beds (for example, bed 3-234) had counterparts of grooves and skip marks, whilst others (3-343) exhibited smooth soles. Most of the beds studied had basal divisions characterised by a well cemented layer of greywacke or calcareous wacke (seldom more than 5 cms thick; for example, beds 3-186, 3-192, 3-247, 316, 324) or pebble to granule conglomerate (beds 3-81, 3-91, 3-283, 300, 381) com-

Table II

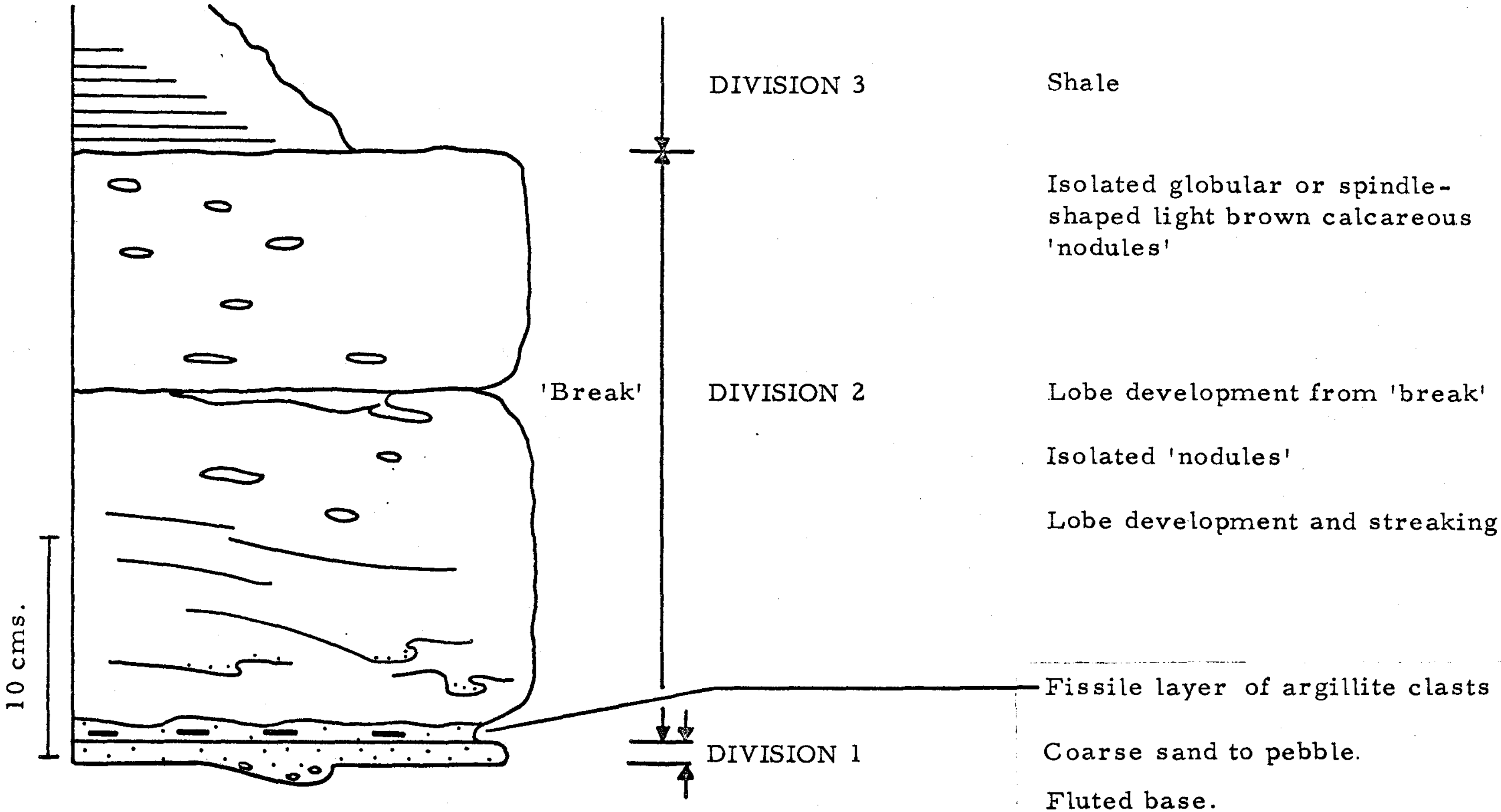
Division thickness data of some beds with a 'pseudo-noduled' division at St. Hélier

Bed Number	Division 1	Division 2	Division 3
368	1	60	218
363	4	32	104
352	3	21	170
343*?	< 1	140	300
324	3	68	97
316	4	30	72
314	5	90	196
311*?	1	95	132
309	4	70	105
300*	< 1	250	288
297	10	22?	86
292*	3	49	79
290*	1	70	250
283*	< 2	333	522
280	6	18	46
268	3	56	77
257	15	21	65
255*	1	93	150
247*?	7	28	109
245*?	1	136	80
192*	2	50	114
179*	1	91	148
176*	2	60	75
172*	2	58	173
161*	2	90	95
158*	1	73	81
148*	2	185	312
145*	3	83	150
109*	1	50	121
107*	2	28	110
104*	2	130	120
91*	≈ 5	310?	200
89*	1	85	105
81*	< 5	180(minimum)	340

* Type 3 greywacke of Enos.

The other beds are calcareous wackes of Enos. Thickness in centimetres.

Figure 5. Vertical characteristics of 'pseudo-noduled' beds. Also see figure 7.


DIVISION 3
Shale
Isolated globular or spindle-shaped light brown calcareous 'nodules'
'Break'
DIVISION 2
Lobe development from 'break'
Isolated 'nodules'
Lobe development and streaking
10 cms.
Fissile layer of argillite clasts
DIVISION 1
Coarse sand to pebble.
Fluted base.

posed of carbonate fragments and terrigenous material in a matrix of argillite. This layer may be continuous or occur as local fillings of scours, particularly flutes. The maximum grain size is from 0 to -3 phi (1-8 mm).

The carbonate fragments constitute a major proportion (more than 60%) of the clasts in the conglomeratic basal divisions. Lime mudstone, packstone and wackestone fragments are the most important although some grainstones and dolostone fragments do occur. The percentages of the major limestone constituents are variable although lime mudstones are the most abundant (cf. Enos, 1969a, p. 27). The non-carbonate terrigenous grains are predominantly of quartz and volcanic rocks with minor amounts of shale clasts and schist fragments. Calcite often girths the grain margins of quartz and feldspar where replacement by calcite has occurred (for example, bed 3-36-1). Fragments or parts of body fossils (orthocones, crinoids, bryozoans, brachiopods and graptolites) may also be present (see plate 1). The grain composition of calcareous wackes is dominated by quartz and quartzite (approximately 65%), with 20% lithic fragments and 15% feldspar (largely sodium-rich plagioclase). The lithic fragments are variable but include volcanic rocks, shale, schist and serpentine.

The basal divisions of calcareous wackes commonly

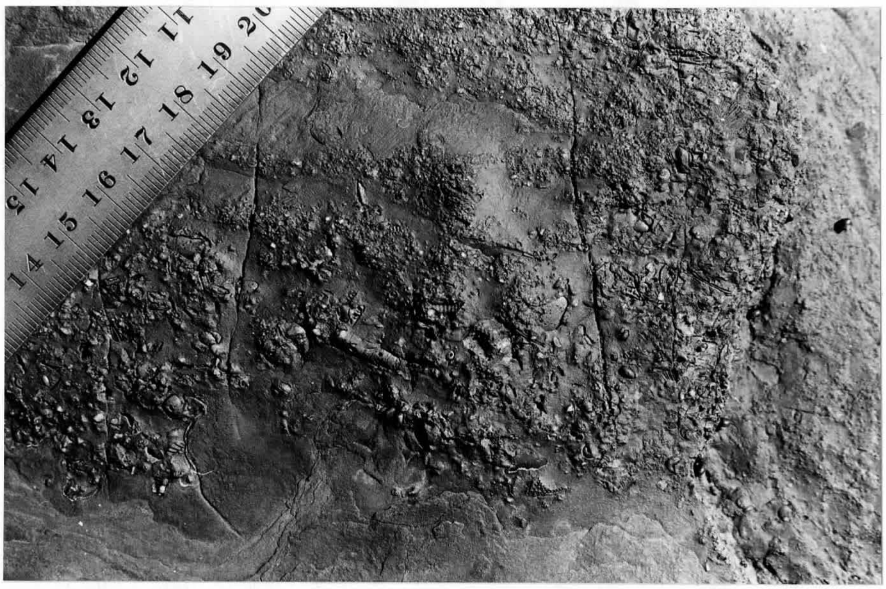


Plate 1. (3-311-7-16A)

Base of bed 3-311. Note the abundance of fossil debris which includes fragments of crinoids, brachiopods and cephalopods.

have small-scale cross-stratification produced by the migration of ripples (for example, bed 3-206), parallel lamination (bed 3-237), or laminae inclined in a direction opposing the local paleocurrent direction to the west given by flutes (e.g. beds 3-352, 3-324). In some beds (for example, 3-270) the direction of the inclined laminae within individual sets was opposed at different levels.

It was observed in many beds, in particular in bed 3-352, that where the upstream inclined laminae were preserved as a single set, they occurred below a sinuous profile which marked the upper boundary of the basal division (see plate 2). The characteristics of these laminae are shown in plate 3. They may be asymptotic with truncated foresets or sigmoid in shape. Where the laminae are truncated, continuous sinuous laminae mark the upper boundary of the basal division. The wavelength of the sinuous profile (crest to crest) varied locally from 40 to 80 cms, with an amplitude of from 2-5 cms. The bases of these beds commonly displayed flutes, coarse grains being concentrated towards the nose of the maximum depth of the flute.

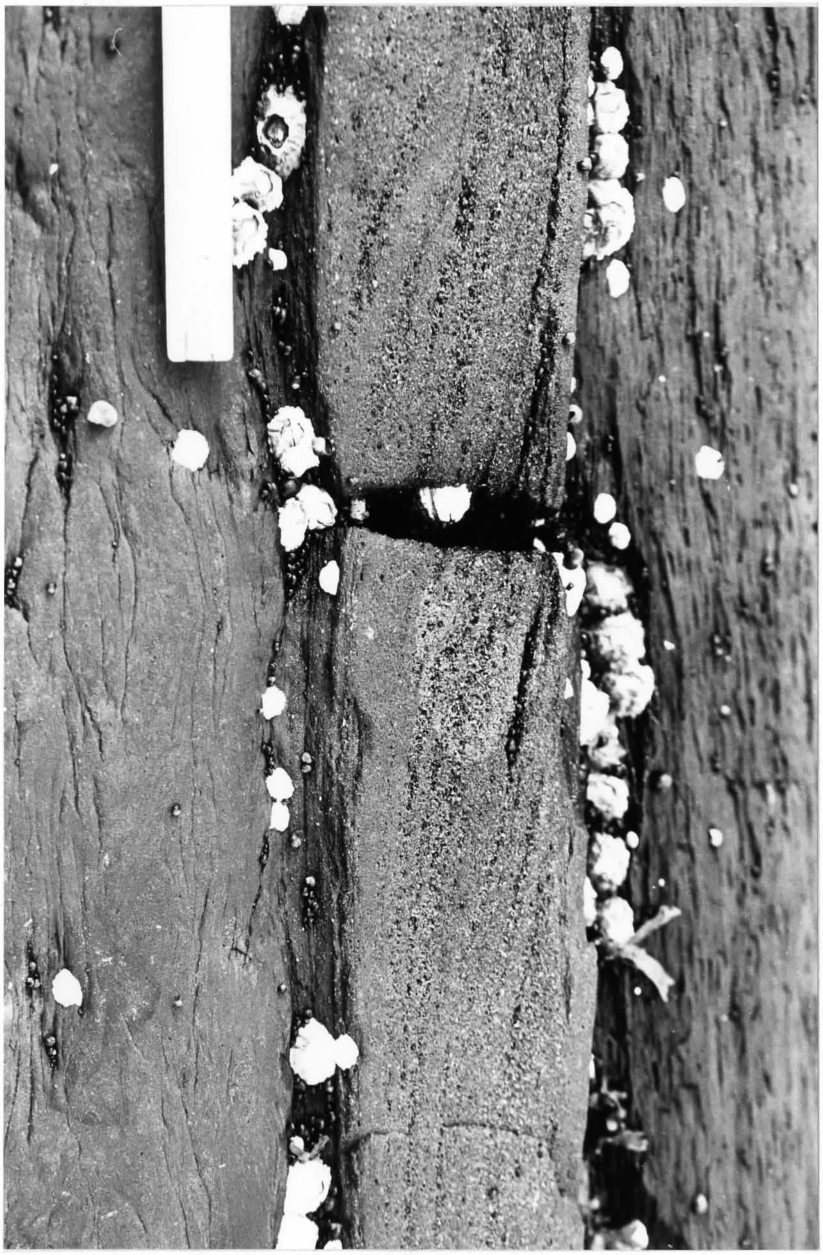
The boundary between the basal division and division 2 is marked by a distinct break in the weathering profile where argillite fragments, of various sizes, produce a fissile layer separating the coarser grained basal division from the finer grained di-

Plate 2. (3-352-11-15)

Bed 352 at Grand Étang. Upstream inclined laminae (single set large-scale cross-stratification) occurring in the basal division below a sinuous profile which marks the junction between divisions 1 and 2. Note the occurrence of flutes, thin carbonate bearing laminae, and the nature of division 2. Paleocurrent from right to left.

Plate 3. (3-352-11-10A)

Characteristics of the upstream inclined laminae. Note their sigmoid shape, their apparent grain size distribution and their scale. Paleocurrent from right to left.

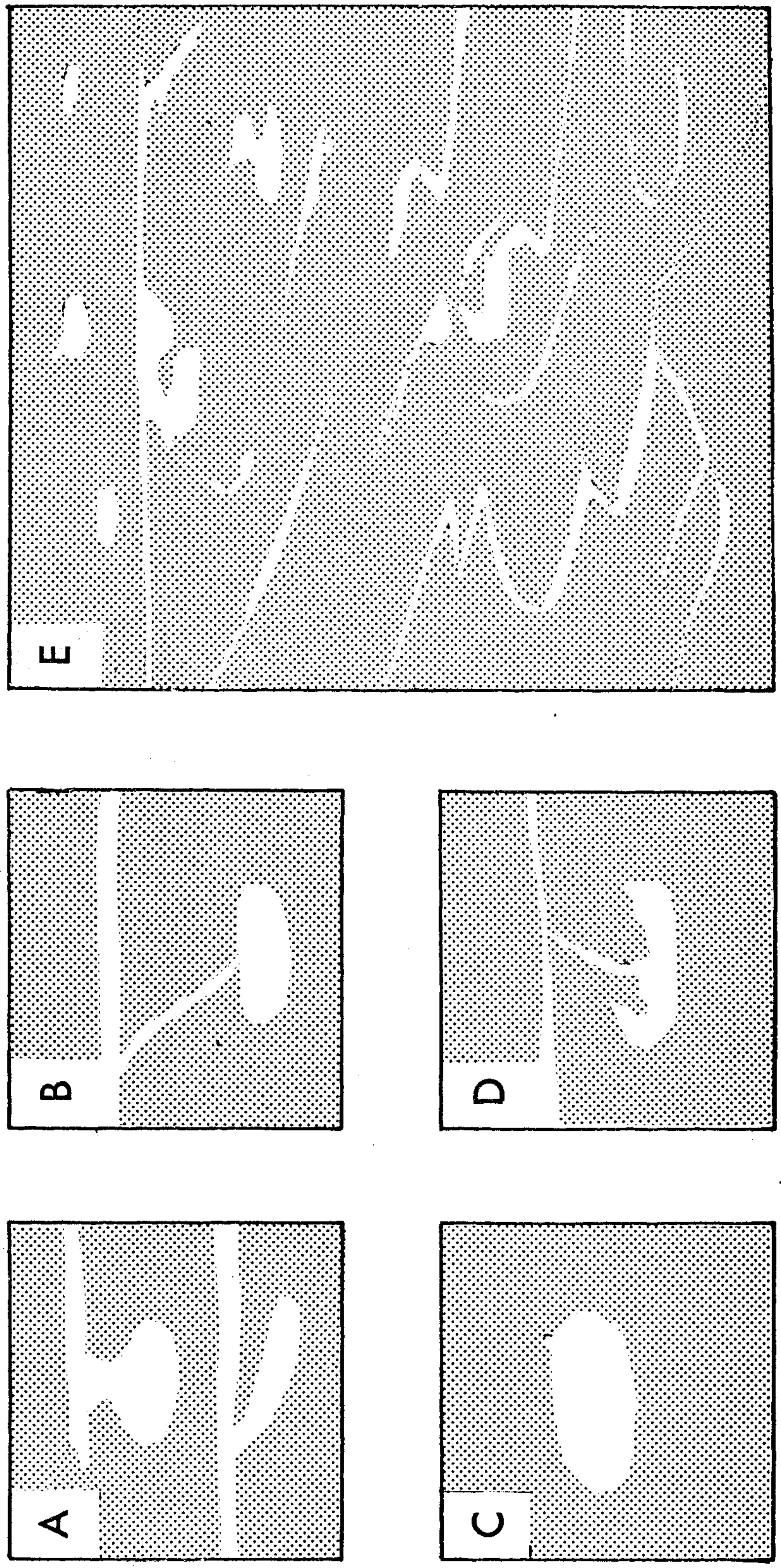


vision 2. In some beds, the junction is marked by thin (less than 0.5 cm thick) carbonate laminae alternating with thin shale laminae. The carbonate has frequently produced minute load structures where the denser carbonate has moved into the less dense underlying material.

The second division, in some beds of the order of meters thick, was composed of silt to fine sand sized grains. Scattered through this division, in varying quantities, were buff colored globular to spindle shaped nodules whose origin had been attributed to erosion of pre-existing calcisiltite into fragments which became dispersed within the depositing current (Enos, 1969a, p. 27). They vary in size from minute blebs to large nodules over 5 cms in diameter. They do not show vertical or lateral grading in any bed. These were not the only features seen in this division. Many of the structures are difficult to describe and are best shown by reference to sketches and photographs. For this purpose, see figure 6.

Figure 6 illustrates schematically the various types of structures seen in division 2. The structures show varying amounts of lobe development below carbonate bearing laminae, in many cases leading to the development of elliptical blobs or 'nodules' of sediment connected by a thin thread to the laminae above them. These are portrayed in subfigures A, B and D of figure 6. A similar form of the

Figure 6. Sketches of structures seen in the 'pseudo-noduled' division. Subfigures A to D drawn at half-scale; subfigure E at scale of 1:7.


E
B
D
A
C

'nodule' in subfigure B and shown in subfigure C is the major diagnostic structure of the second division in all beds. These are the buff colored nodules referred to by Enos.

Other structures of immense variability similar to subfigure E in figure 6, are visible because light colored material forming them contrasts with the dark grey host material. Light colored laminae streak the second division. As an example, consider plates 4 and 5. Large globular shaped objects (up to 9 cms in diameter) occur about 40 cms above the base of the bed. These resemble structures of subfigure C in figure 6. Examination of plates 4, 5 and 6 will also verify that structures, similar to that shown in subfigure E, are very prominent in this bed example (bed 1-255). The streaked-out laminae appear to have originated from areas within the bed which show the development of various lobe structures (see plate 6). Lobe development, apparently concomitant with the process of streaking, is seen to have occurred into the argillaceous layer which separates the basal division from division 2 in plate 5. Downwarping of thin light colored stringers of coarse grains is clearly visible. Frequently, the streaked laminae were inclined at shallow angles to the east (upcurrent: see plate 6).

None of these structures show features formed by the migration and partial preservation of bed forms. From bed observations

Plate 4. (1-255-10-15)

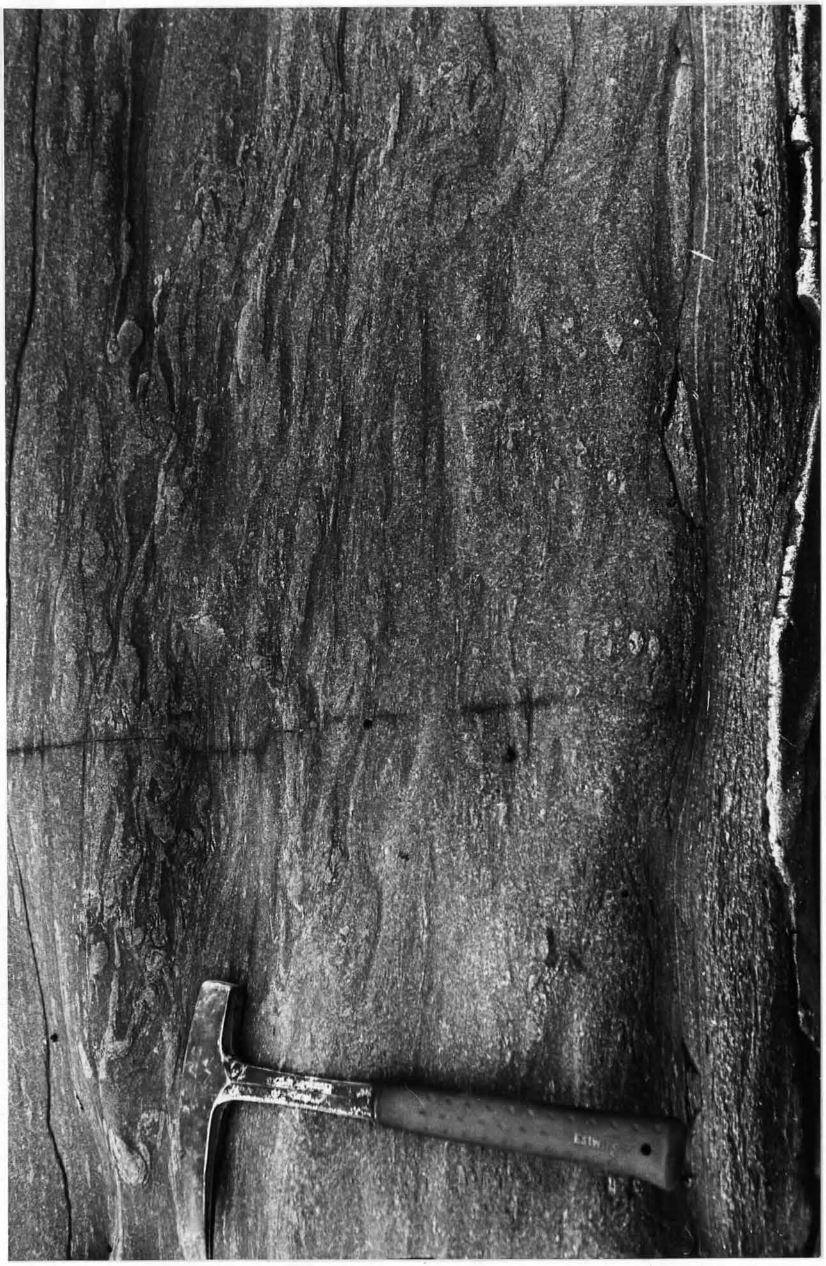
Characteristics of bed 255, west side of Grand Étang. Note the large nodules to the left (west) of hammer and the long persistent laminae which lobe into the underlying shale. The thin basal division is separated from the second division by an argillaceous zone which also contains several thin carbonate bearing laminae.

Plate 5. (1-255-10-14)

Vertical characteristics of division 2, bed 255 on the western side of cove at St. Hélier (Grand Étang).

Plate 6. (1-255-11-20A)

Structures within the second division of bed 255, west side of cove at St. Hélier.



it was apparent that many of these structures were genetically related. Structures shown in subfigures A to D are load structures and the mechanism of their formation is described in Chapter five. The structures shown in subfigures B and C are 'pseudo-nodules' sensu stricto (Macar, 1948) and justify the use of the term 'pseudo-noduled' division. Structures of subfigure E suggest that in the process of development of structures of subfigures A to D, there has been horizontal displacement of sediment. These are flow structures in the sense of Dzulynski and Walton (1965, p. 142). Their 'pattern' is similar to that of the flow structures described from the Athabasca oil sands and illustrated by Carrigy (1967, plate 1B, p. 342).

A 'parting' is developed in the second division of some beds and may show various amounts of curvature and bifurcation. In plates 3 and 7 note the contrast between the 'parting' development in the second division and the cleavage in the underlying argillite. The argillite displays parallel planar cleavage surfaces. Clearly, the development of the 'parting' is controlled by inhomogeneities in the rock and it is possible that it picks out some facet of the internal structure of this division.

Not all beds visibly displayed all these characteristics. This was a function of their location and the manner in which they were being weathered. The best examples were seen where beds had

Plate 7. (3-311-7-15)

Note the 'pocket' of coarse grains and the nature of the 'parting'.

been smoothed by the sea on the wave-cut platform.

Although the second division appeared resistant and fairly massive, several breaks occurred in the profile. The significance of these breaks could not always be appreciated. They were not normally associated with visible grain size differences but in many beds there were thin layers of carbonate rich material, resembling that which constitutes the 'pseudo-nodules' within the argillaceous matrix (see plate 5). These layers may be very discontinuous, and often they occur just as local 'blobs', their upper surface, commonly straight, marking the position of the break, their lower surfaces lobing into the argillite below. They resemble structures attributed to subfigure A in figure 6.

There may exist several breaks in any one profile, not all of them showing the same features. From observations made on one bed, their presence is clearly connected to the origin of the 'pseudo-nodules' and the mode of deposition of this division. In bed 1-255 and 3-255 (see plates 4, 5 and 6) thin laminae within the bed could be seen to have given rise to 'pseudo-nodules'. The wakes produced by the passage of the present 'pseudo-nodule' through the original mud were clearly visible (see plate 5). Where several breaks do occur in any one bed, it was not unusual to find that the lower parts of division 2 was characterised by structures of all types in figure 6. The higher parts contained only 'pseudo-nodules' at best.

The grain size of the 'nodules' is from coarse silt to very fine sand (bed 3-255). Mineralogically, they are composed predominantly of quartz and plagioclase feldspar with a matrix rich in carbonate. A small quantity of dolomite may be present in the form of ankerite, the oxidation of the iron giving the 'nodules' their buff color.

Terrigenous material (up to coarse sand size) and argillite clasts (up to 10 cms longest diameter) may be scattered in the lower portion of division 2, particularly in beds with very thin basal divisions (for example, 3-245, 3-81, 3-91 and 3-300). In a few beds, for example bed 300 at sections 3 and 8, thin laminae of coarse sand occurred several centimeters above and parallel to the base of the beds. Some beds (see plate 7) also displayed pockets of coarse grains. The shapes of the pockets resembled the shape of the buff colored nodules but the buff coloring was absent.

Argillite clasts and discs were a predominant feature within division 2; few hand specimens did not show visible clasts. In general, the clasts became smaller up through the bed although they were more plentiful, i.e., the clasts showed grading. They lay flat with their longest dimensions parallel to the base of beds.

The upper boundary of division 2 was difficult to define precisely. It was taken at the point where there was an abrupt recession in the weathering profile. Usually this corresponded to the upper presence of 'pseudo-nodules'. Frequently however, there were small 'pseudo-nodules' occurring in the lower few centimeters of division 3, the shale.

3.2 Downcurrent changes in particular beds

It is desirable that any attempt to trace turbidites laterally should be based on good paleocurrent control and correlation. Soles of individual turbidites between sections 3 and 10 are poorly exposed and there is little paleocurrent data (see Table III). Bed 343 always exhibited a smooth sole and no flutes or any current trend features (e.g. grooves) were seen. Flute control on other beds has been established at some sections showing that the paleocurrent direction was towards the west. Beds exhibiting upstream inclined laminae were very carefully scrutinised and beds 324, 352 and 363, which have this characteristic, do show flutes on their soles at several localities, the best exposure being at Grand Étang. However, in all the sections examined which contain beds correlated with the sequence at Grand Étang, no evidence of any significant changes in paleocurrent direction were seen for beds below 381, with which this study is mainly concerned.

Because of accessibility and exposure, six beds which exhibited the 'pseudo-noduled' characteristic, i.e. beds 324, 343, 352,

Table III

Paleocurrent Data

Section	3	4	5	7	8	10A
Strike	294°	294°	292°	292°	288°	290°
Mean paleo-current direction	280°	292°	291°	292°	281°	280° *
Number of measurements(n)	n=134	n=9	n=4	n=8	n=6	**
Standard Deviation	±15°	± 7°	±4.5°	±5.2°	±4.2°	

* Flutes and ripple cross-stratification

** Many beds below 10A-1000 show the development of ripple-drift cross lamination which yields a paleocurrent direction to the west. Two beds, 10A-1095 and 10A-1164, show, by flutes on their soles, a paleocurrent direction directly <u>opposed</u> to this direction.

363, 368 and 381, were studied at and between sections 10A and 3 (a distance of approximately 8 kilometers). Other observations were made on other beds over shorter distances, i.e. bed 316 between sections 4 and 3. The characteristics of five beds are shown in figure 7.

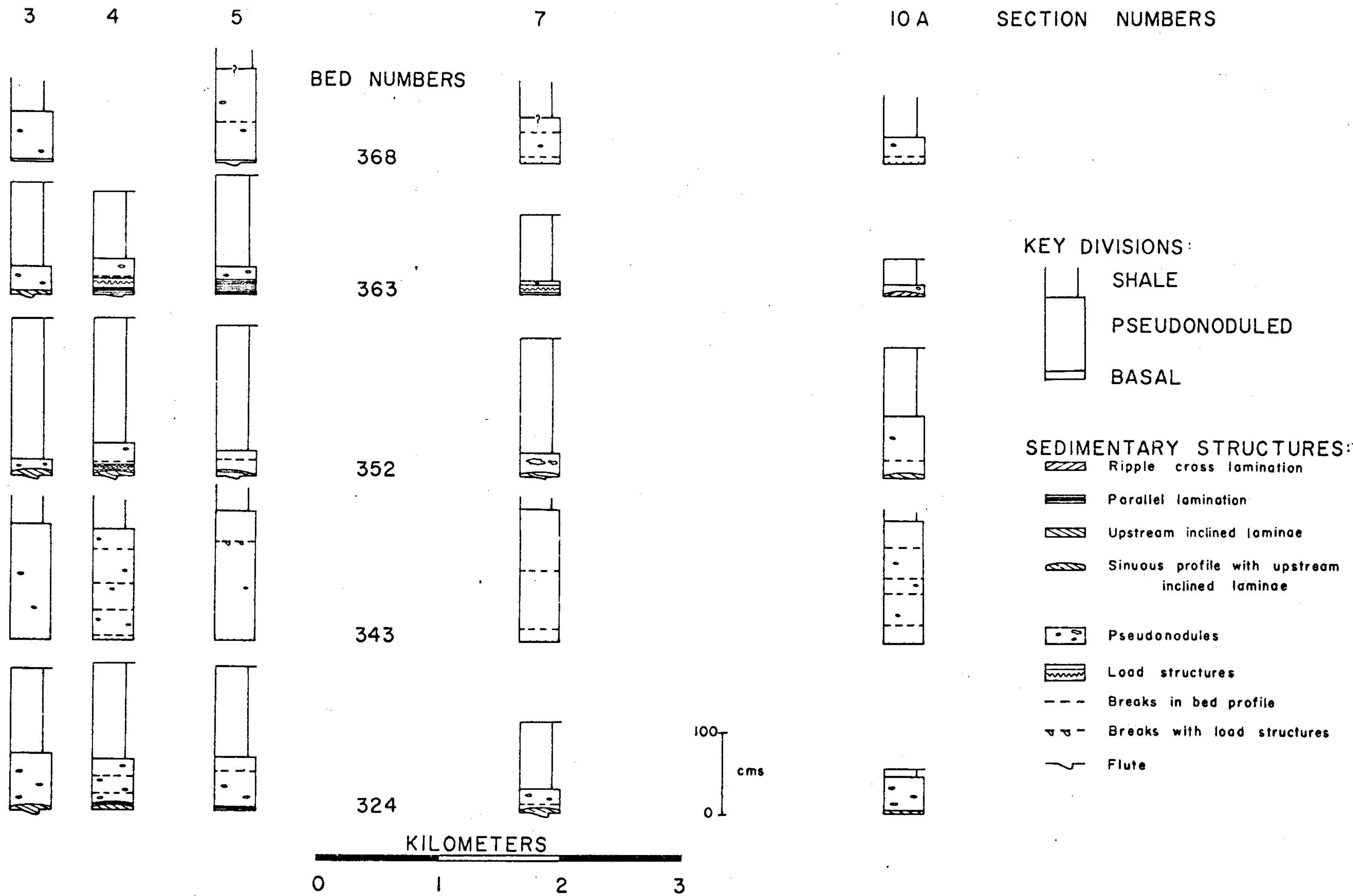
At section 10A, bed 324 displayed laminae inclined at less than 5° to the east within a basal division less than 5 cms thick. A similar occurrence was noted at sections 3 and 4. At section 3 the cross-laminae occurred beneath a sinuous profile. At section 5, the basal division consisted of parallel lamination. The 'pseudo-noduled' division had no unusual characteristics. Flutes occurred on the base at sections 3 and 7 indicating a paleocurrent to the west.

Bed 363 had ripple cross-lamination occurring below a shallow ripple profile at section 10A; towards the west this gave way to parallel lamination (sections 7, 5 and 4) and upstream inclined laminae at section 3. Flute control was established at section 3.

All occurrences of bed 352 showed that the basal division was composed of upstream inclined laminae beneath a sinuous profile, with good flute control at sections 7, 5, 4 and 3.

Bed 343 exhibited a smooth sole at all localities and had a poorly developed basal division, seldom more than a few grain diameters thick.

Figure 7. Vertical characteristics of beds 368, 363, 352, 343, and 324 at different sections. Note the downcurrent changes (paleocurrent from right to left).


3
4
5
7
10 A
SECTION NUMBERS
BED NUMBERS
368
363
352
343
324
?
100
cms
0
KILOMETERS
0
1
2
3
KEY DIVISIONS:
SHALE
PSEUDONODULED
BASAL
SEDIMENTARY STRUCTURES:
Ripple cross lamination
Parallel lamination
Upstream inclined laminae
Sinuous profile with upstream inclined laminae
Pseudonodules
Load structures
Breaks in bed profile
Breaks with load structures
Flute

In general, it can be seen that the 'pseudo-noduled' division increased in thickness westwards (bed 324, 343, 363 and 368). This however was not always the case as bed 352 showed a general decrease in thickness towards the west.

The basal divisions were likewise variable and no consistent relationship is apparent. Nevertheless, bed 368 between sections 10A and 3 and bed 363 between sections 10A and 5 showed an increase in thickness downcurrent. Bed 363 between sections 5 and 3 showed a decrease in the thickness of the basal division downcurrent.

Comparison of neighboring profiles for individual beds showed that there was no consistent relationship between the number and height of occurrence of breaks within the profile of the second division.

Other beds, not shown in figure 7, had similar characteristics. For example, bed 302 (calcareous wacke) showed the same features at sections 3 and 4 as at section 8. Its basal division of coarse sand (about 13-18 cms thick) had single-set small-scale cross-stratification occurring below parallel lamination. The thicknesses of the second division (approximately 16 cms) and the succeeding shale (approximately 75 cms) were the same at all three sections. The basal division of bed 316 at section 4 exhibited 1-2 cms of parallel lamination immediately above the base, followed by 1-4 cms of upstream inclined laminae below a sinuous profile formed of sinuous laminae (wavelength 47-65 cms and amplitude 3 cms). At section 3, the basal division (5 cms thick) was composed of small-scale "herringbone" cross-stratification, laminae being inclined in opposing directions.

3.3 Internal structures of some beds

At several localities along the coast, both to the west and to the east of St. Hélier, fallen broken blocks of division 2 provided an opportunity for study of the internal characteristics of some of these beds in the third dimension. Unusual structures, never before reported in the literature, were seen just west of section 7 at grid reference 765428 and are shown in plate 8. Poorer examples were seen elsewhere (plate 9).

The blocks were all composed of silt to fine sand with mud flakes and graptolites in abundance. In plan view the structures seen in plate 8 are hemi-ellipsoids. They are convex towards the sky and resemble upturned boats arranged en echelon. The scaling characteristics of the convex surfaces is similar to that observed in some examples of primary current lineation and suggests grain orientation in one direction (see figure 8).

In plate 9, the structures are essentially linear with graptolite orientations of one usually opposed to that of its neighbor (see

Plate 8. Hemi-ellipsoid structures seen in fallen block located just west of section 7. (photograph 8-17A)

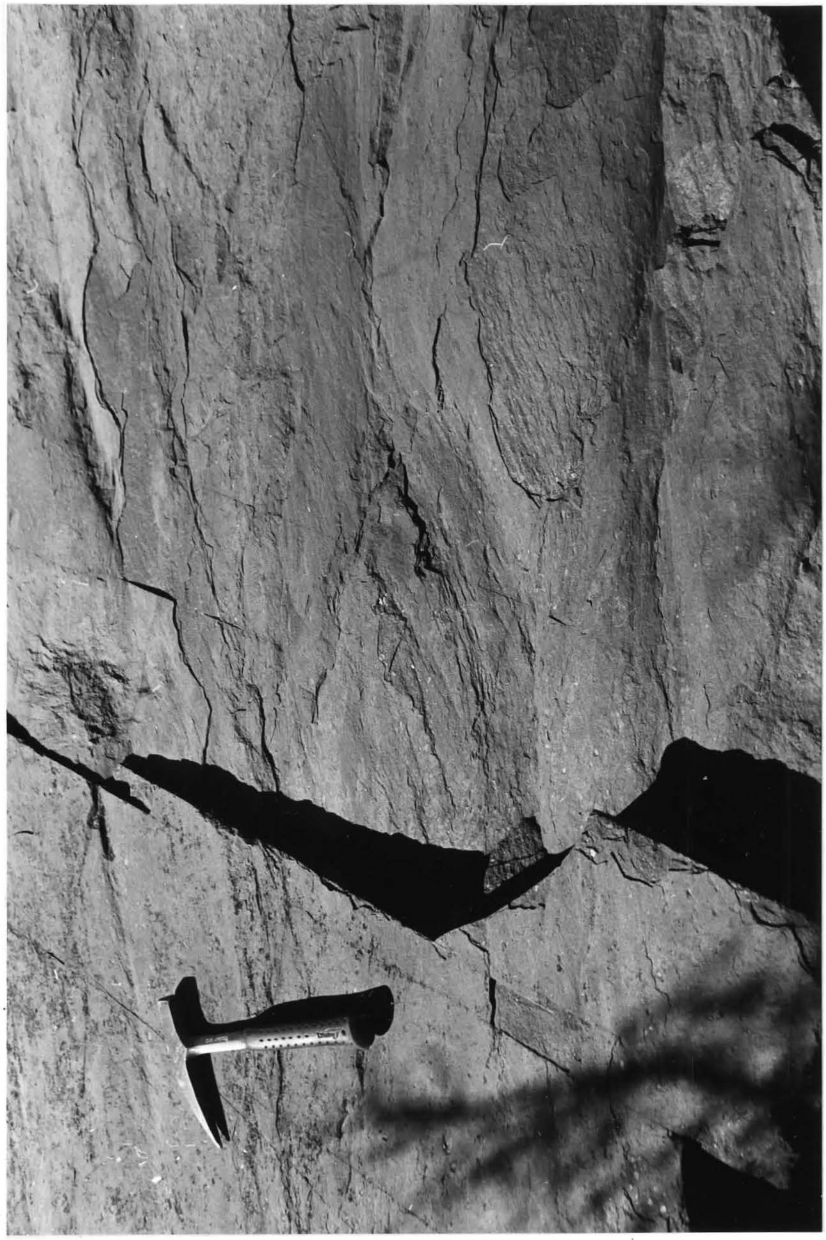


Plate 9. Internal structures of fallen block located west of St. Hélier. (photograph 10-17)

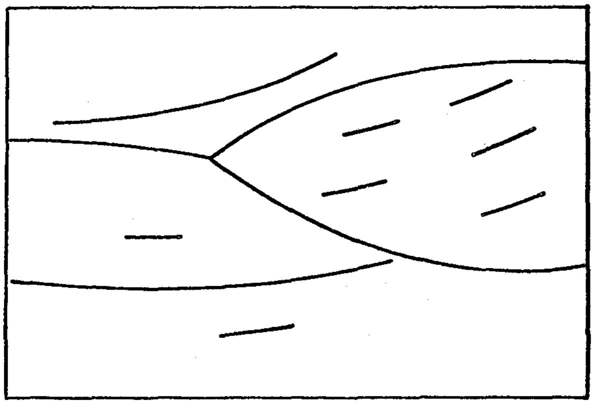


Figure 8. Sketch to show graptolite orientation and grain orientation inferred from scaling on structures shown in plate 8. Bars denote orientation.

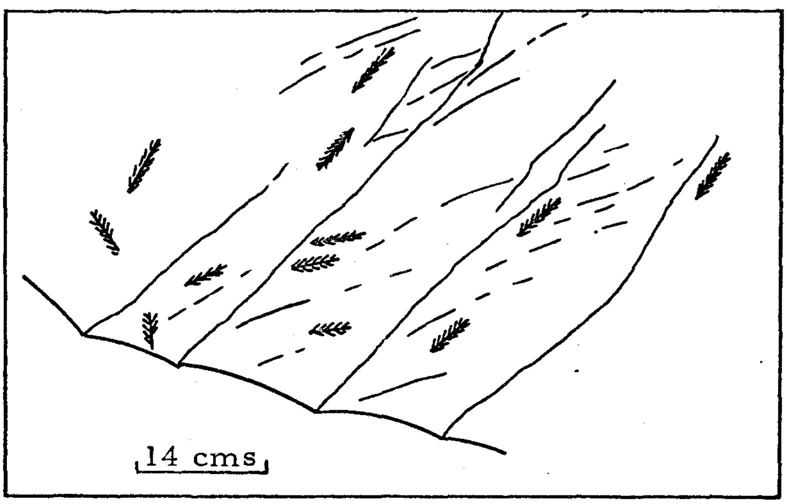


Figure 9. Graptolite orientation on structures shown in plate 9. Drawn from sketch in field notebook.

figure 9).

Examination of the sides of these blocks commonly showed load structures and hence it was possible to determine their correct attitude at the time of deposition. The surfaces exposed to the sky occurred towards the base and hence in nature, the structures were concave or synform upwards. The hammer in plate 8 rests on a smooth surface (probably near to the base of the original bed) suggesting that the hemi-ellipsoid structures did not occur in the original bed until a certain, unknown distance above the base of the bed had been reached.

Some blocks, particularly rich in nodules, had fallen from the cliff and had smashed open and weathered. The three dimensional nature of the nodules could be discerned on the tops of these blocks. They appeared to dot the surface and in many blocks, it could be seen that nodules were composed of several hemispherical layers packed inside one another.

Large scale structures (about 30 cms across) resembling subfigure A in figure 6 were exposed on surfaces near to the base of some beds. Bed 3-91 exhibited the structure seen in plate 10. The lower surface of this tructure displayed linear features. In plate 10, the lineations fan out from a nodal point just right of the hammer handle. This type of feature may be an indication of grain orientation.

Plate 10. (3-91-7-4A)

Large load structure exposed near base of bed 3-91. Note the lineations fan from a nodal point just to the right of the hammer handle.

3.4 Maximum Grain Size Characteristics

The maximum grain size of several beds was determined by measuring the largest intercept of ten largest quartz grains and calculating their means. Only quartz grains were measured so as to maintain hydraulic similarity. The size measurements were made on a Shadowmaster when thin sections were available or by using a binocular microscope or by visual estimate.

Changes in the maximum size with height above the base for several beds are shown in figure 10. The maximum size curves are generally concave up the bed, with a very prominent 'kick' towards the coarser grain sizes in the lower few centimeters, particularly for those beds with a conglomeratic base (for example, 91, 300 and 381). All beds show a wide variation in the maximum grain size of quartz grains between the base and ten centimeters above the base. In many beds, the size decreases by as much as four phi intervals. The higher portions of beds from the specimens studied seldom have maximum grain sizes greater than 3 phi. Certainly the top of the second division is finer than 4 phi. The decline curves show that with respect to maximum size there exists vertical grading.

Downcurrent changes in the maximum grain size curves for beds 324, 343, 352 and 381 are shown in figure 11. With respect to the maximum grain size there is little change downcurrent. Var-

Figure 10. Changes in the maximum grain size for quartz grains with height above the base for several beds.

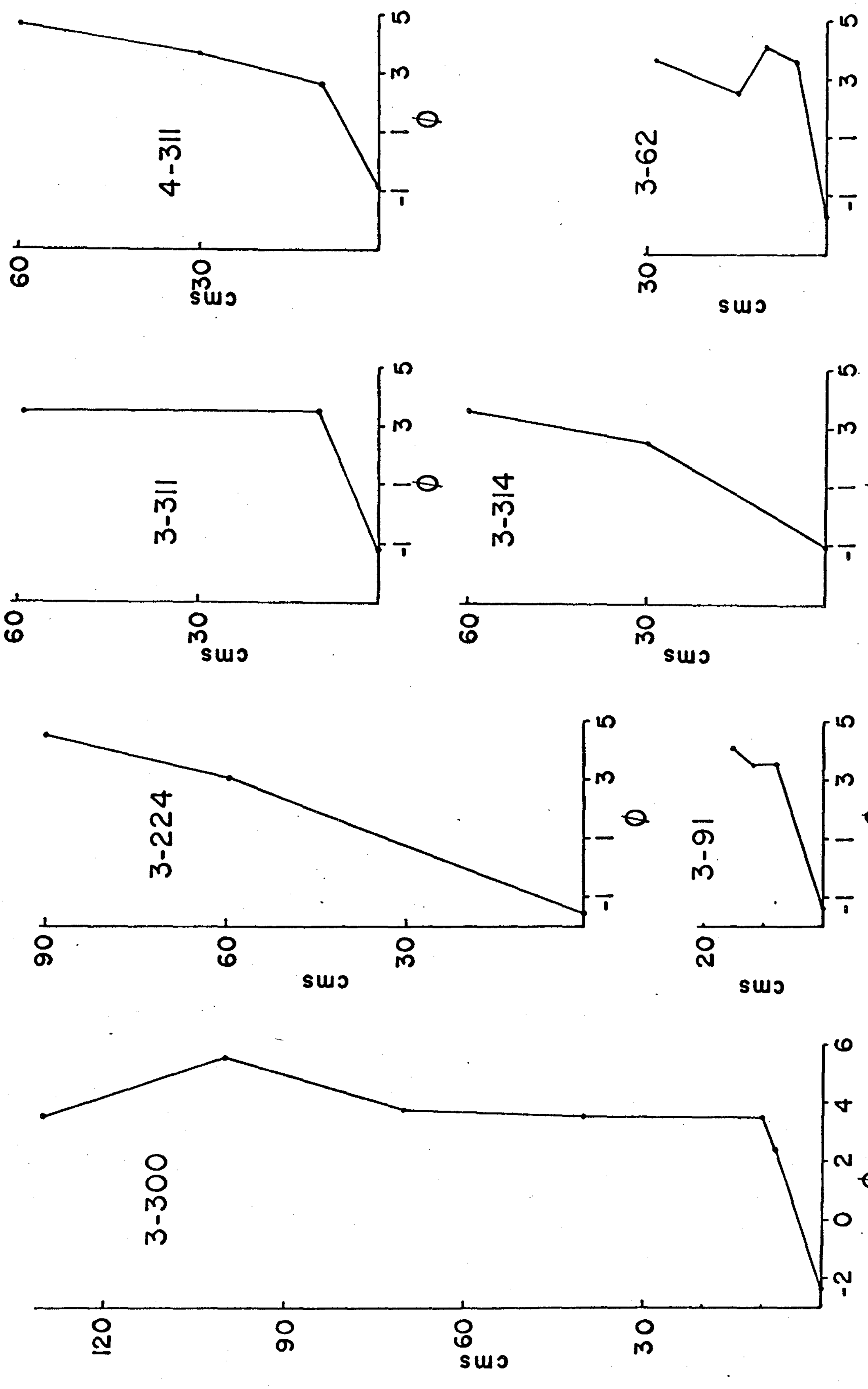
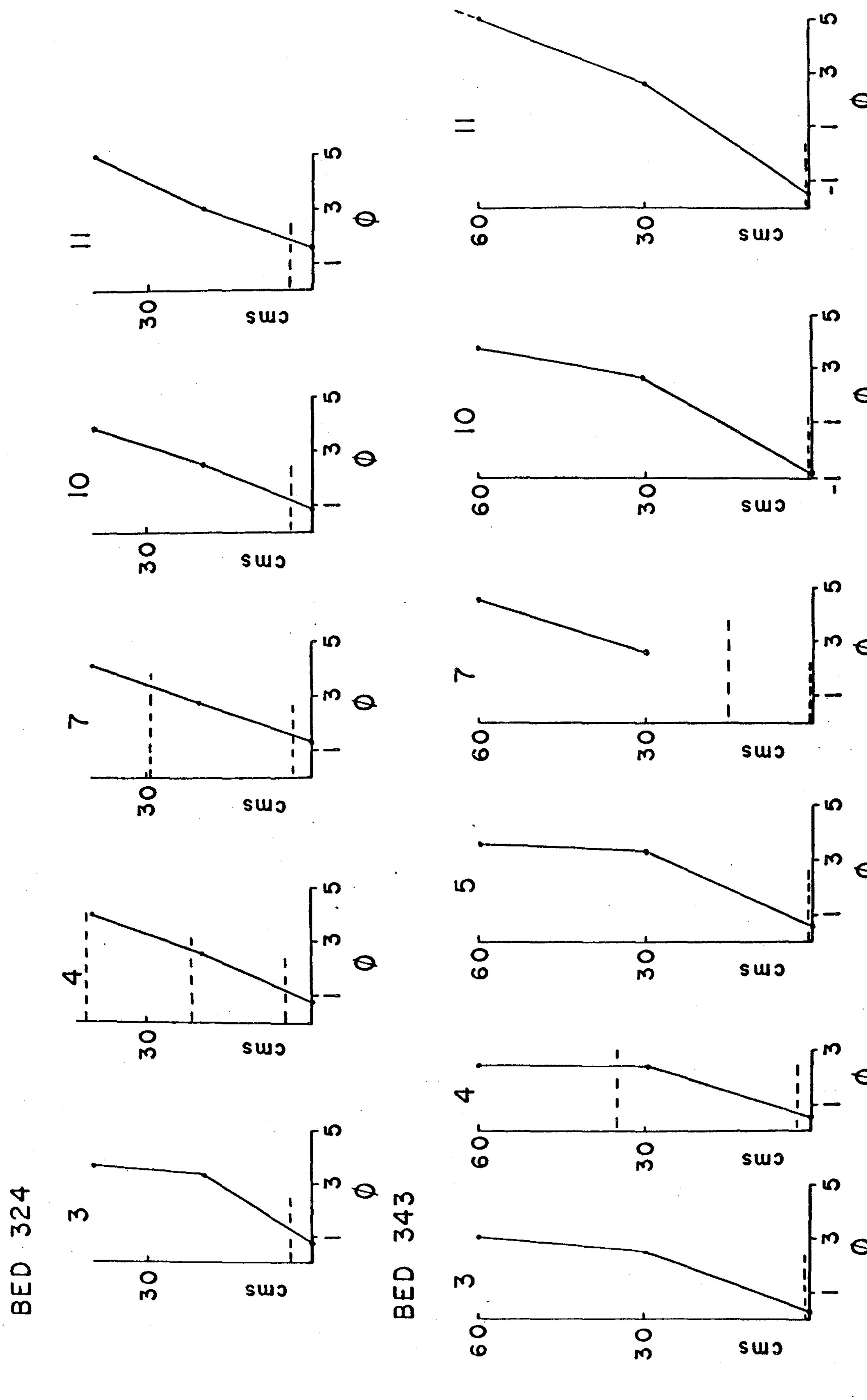

3-300
3-224
3-91
3-311
3-314
4-311
3-62
cms
φ

Figure 11. Maximum grain size of quartz grains with height above the base of bed. Beds Beds 324, 343, 352, 381.


BED 324
3
4
7
10
11
30
cms
φ
1
3
5
BED 343
60
-1

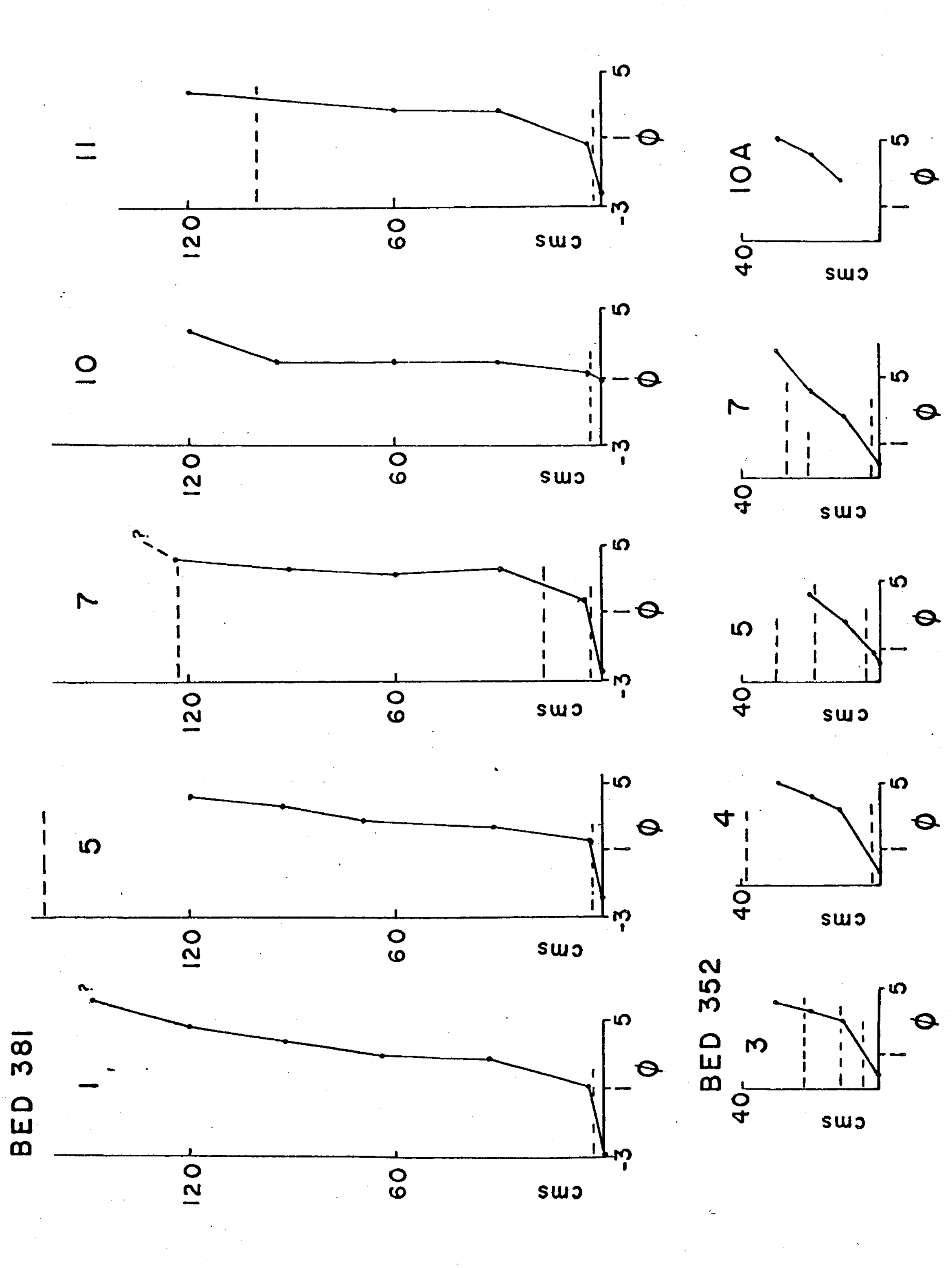
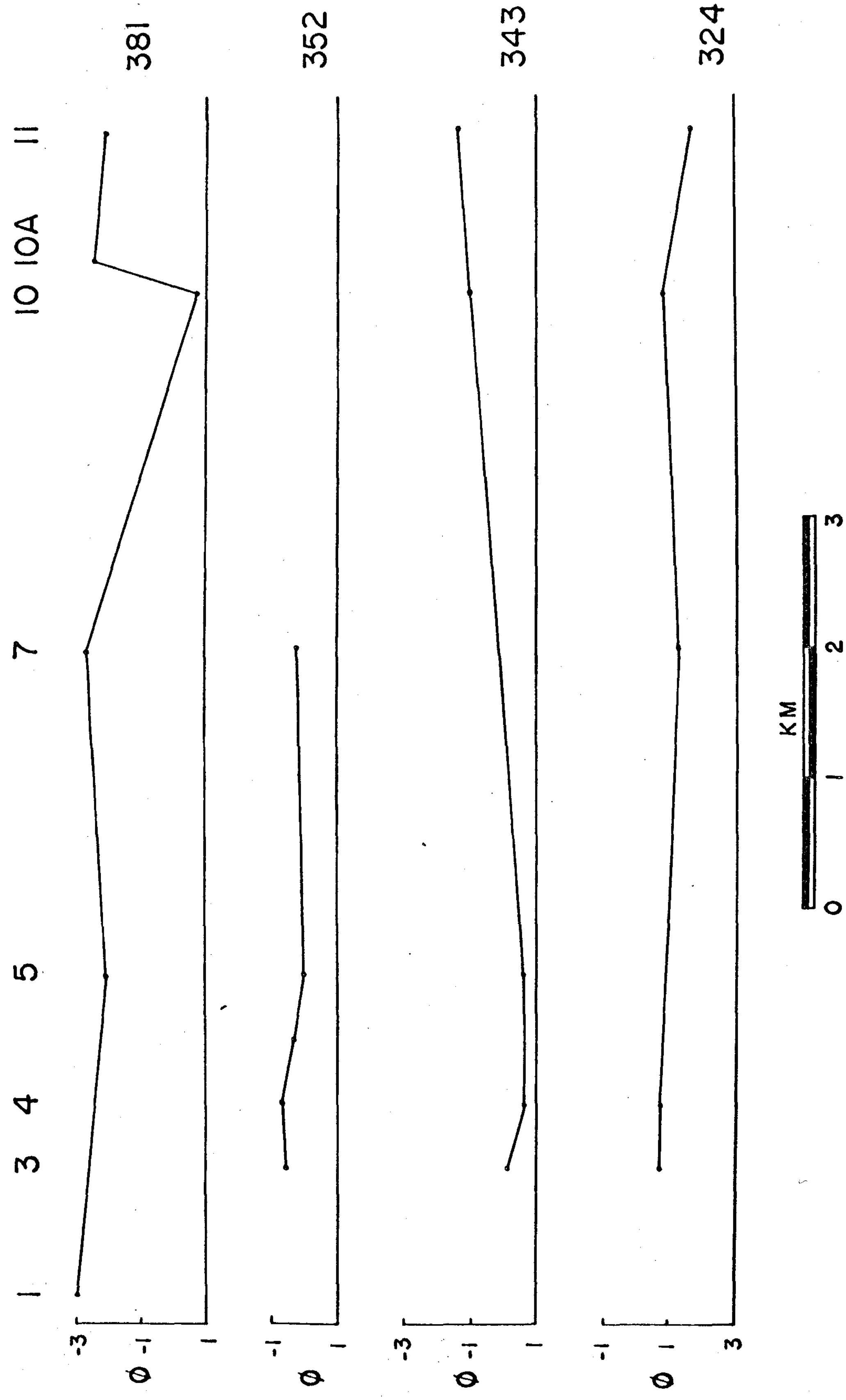

BED 381
1
5
7
10
11
BED 352
3
4
5
7
10A
120
60
cms
-3
1
5
40
φ
?

Figure 12. Downcurrent changes in maximum size of quartz grains at base of beds 381, 352, 343 and 324. Paleocurrent from right to left.



381
352
343
324
1
3
4
5
7
10 10A
11
KM
0
1
2
3

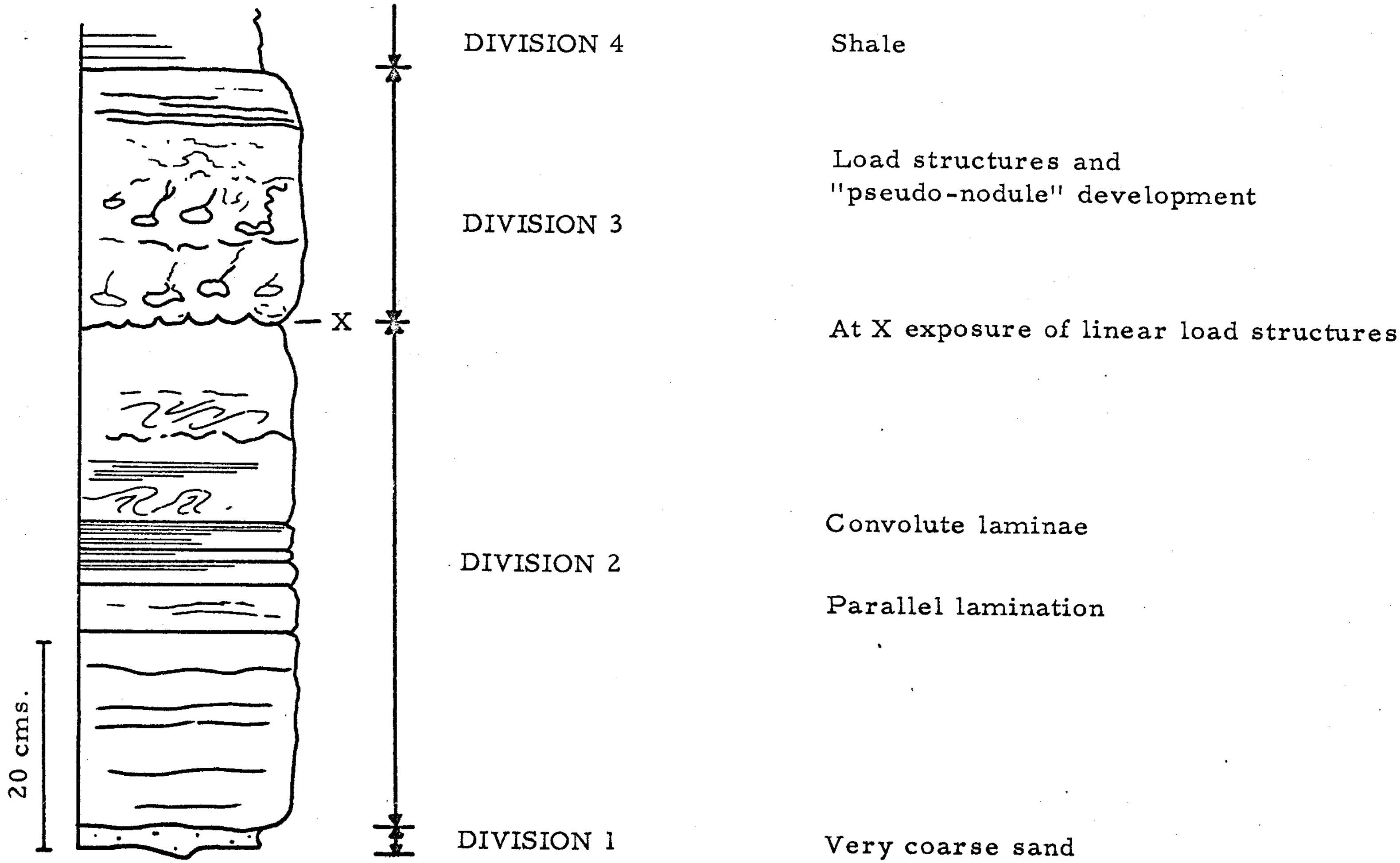
iations of the maximum grain size at the base of beds 324, 343, 352 and 381 are shown in figure 12. The variations between sections are negligible; all beds show that the maximum size at their bases changes less than 2 phi divisions for all beds (except bed 381 at section 10) when traced downcurrent. There is no consistent downcurrent decrease in maximum grain size at the base of beds except, perhaps for bed 343. In fact, beds 324 and 381 show an irregular increase in maximum size downcurrent.

3.5 Occurrence of similar beds

Three beds displaying a similar sequence of vertical characteristics to the 'pseudo-noduled' beds of the β_1 member, occur in the α_3 member to the east of the Canning Factory at St. Maurice. The sequence is dominated by the occurrence of ripple-drifted and convoluted beds with a paleocurrent direction (from flutes and cross-stratification) towards the west.

The sequence of structures in beds 43 and 87 are shown in figure 13. Four divisions are recognized. The lowest basal division is about 4 cms thick and is graded from very coarse sand to coarse sand. The second division is composed of medium of fine sand and may exhibit parallel lamination, convolute lamination and load structures. Division three shows the development of 'pseudo-nodules' in various states of formation. The uppermost division is

Figure 13. Vertical characteristics of beds at St. Maurice. Compare with figure 5.


20 cms.
X
DIVISION 4
Shale
Load structures and
"pseudo-nodule" development
DIVISION 3
At X exposure of linear load structures
Convolute laminae
DIVISION 2
Parallel lamination
DIVISION 1
Very coarse sand

composed of argillite. Flutes occur on the base and the junction between divisions two and three displays linear load structures, their direction of lineation being parallel to the paleocurrent trend. Grains at the base of these features have a preferred orientation with their long axis perpendicular to the trend of the load structures.

Bed 121, with a total thickness of 840 cms (including the argillite above), forms a small point jutting eastwards into the cove at St. Maurice. The base of the bed (less than 5 cms thick) is composed of angular quartz grains up to 0.4 cm in diameter. For 19-28 cms above this, sets of trough cross-stratification of medium sand occur, followed by about 90 cms of slightly convoluted parallel laminations. The remaining 220 cms of the sandy part of the bed is characterised by parallel laminations, local load structures and injection features. Isolated load structures occur in the upper 50 cms, and from observations parallel to bedding, they appear to be orientated east-west. However, they do not appear to be continuous features as in the case of beds 43 and 87.

3.6 Special characteristics of beds requiring further explanation

Several facets of 'pseudo-noduled' beds require further discussion because they bring to light some important aspects of turbidites and turbidity currents little emphasized before.

The most important observations made on these beds are discussed in the following paragraphs:

(a) their lateral persistence, almost unchanged, for over five miles;

(b) the absence of any decrease in the maximum size of quartz grains at the base of several beds over this distance. The presence of coarse grains, some almost one centimeter in diameter at Grand Étang, shows that these grains have been transported over considerable distances certainly more than 7 1/2 miles. This indicates that the parent current possessed the competence to transport material of this size;

(c) the actual grain size distribution within the beds (except in the basal layer), although unmeasured, is dominated by material less than fine sand size. The percentage, by volume, of grains coarser than 2 phi is certainly less than 10%, probably as low as 1%, in some beds.

(d) The occurrence of the so-called 'pseudo-noduled' division itself is unusual. The writer is not aware of similar occurrences outside the Cloridorme Formation. Since in all cases the 'pseudo-noduled' division forms the bulk of any bed (excluding the argillaceous division) and its massive nature between the profile 'breaks' shows that it did not accumulate by traction of individual particles along the bed, it must have presumably resulted from deposition from suspension. The nodules in these beds add to the complexity of their characteristics. They appear to resemble features produced by the movement in a gravitational field, of denser material into less dense material.

(e) The 'breaks', which appear intimately connected to the production of the nodules, probably indicate short breaks in the depositional process.

(f) The lateral persistence, almost unchanged, of the 'pseudo-noduled' division shows that the parent current must have achieved some degree of uniformity. Turbidites are usually considered to change in the nature of their vertical characteristics downcurrent. Yet there are only small variations of thickness of, and the nature of the structures in, 'pseudo-noduled' division downcurrent over a distance of 5 to 7 1/2 miles.

(g) The presence of unusual hemi-ellipsoidal internal structures within the second division, combined with the remark that the second division appears to have resulted from deposition from suspension, suggests an unusual form of mass movement of material downslope. The presence of flutes on the soles of some beds and the inference that the sole marks and beds were produced by a single current, shows that at an early stage in its history, the current was moving in a turbulent manner so that the mechanism of flow separation neccessary for the production of flutes was able to take place. The presence of a moving mass of grains in the later stages of the current's history must be related to the depositional processes operative in a current transporting large amounts of fine material.

(h) The presence of cross-stratification and parallel lamination in the basal divisions of some beds, means that the current formed features on the bed (ripples and flat beds) which are produced under conditions when tractional movement of grains predominates over grain fall-out from suspension. The presence of upstream inclined laminae, later interpreted as produced by antidunes and hitherto unknown from turbidite sequences, must itself be a reflection of the deposition and transport mechanics of the current.

In order to establish an interpretation of the genetic significance of many of these observations, it is necessary to have a basic understanding of the depositional behaviour of turbidity currents. However, not all of the observations are explicable in terms of depositional processes. Some, for example, the 'pseudo-nodules', have developed in response to the mechanical properties of stratified sediment layers. The following two chapters outline the theory for the complete interpretation of the observed features of these beds. Chapter four outlines the flow and depositional behaviour of turbidity currents, and chapter five the development of 'pseudo-nodules' and similar load structures.

CHAPTER FOUR

FLOW AND DEPOSITIONAL BEHAVIOUR OF TURBIDITY CURRENTS

The hydraulic behaviour and the transporting and depositional mechanisms of turbidity currents are dependent on several variables (see Middleton, 1966a). Not least important of these are the current density and apparent viscosity. This chapter explores the importance of grain size distribution properties and different concentrations of sediment suspended in a turbidity current. These variables control the settling velocity of particles, the flow behaviour of the current and the different modes of deposition from it by controlling the current's density and viscosity.

Much of the information is drawn from the recent experimental studies of Middleton (1966b, c, 1967a) and Riddell (1969) and literature familiar to chemical engineers whose interests are directed towards the transport of suspensions by pipelines.

It is now well known that the properties of a pure fluid may be altered by the presence of foreign material. Further addition of particles to an aqueous dispersion increases its density and viscosity (see, for example, Richardson and Meikle, 1961; Simons, Richardson and Haushild, 1963). Increases in the density and viscosity of a suspending fluid decreases the settling velocity of its constituent particles. In turbulent flows a particle may be given increased mobility because of its reduced settling velocity (Simons, Richardson and Haushild, 1963).

Kuenen (1951) has measured the settling velocities of various grain sizes in clay suspensions and it was shown that the settling velocities of even large particles may be negligibly small if the concentration of small particles is large. However, the thixotropic properties of such suspensions break down under shear so that it is doubtful if the result has much meaning in turbulent flows (Middleton, 1966a, p. 205).

Suspensions of clay are not so dense as those with sand for the same volume concentration though they may be more viscous for the same density, hence when in motion they have increased carrying power. Clay suspensions are also more easily maintained in a suspended state because particles have a large surface area to volume, hence a high drag coefficient. We might therefore expect that coarse particles existing in a turbidity current will be transported greater distances in currents with a high concentration of fines than they would in low concentration flows.

There must, however, exist an upper limit to the amount of material which can be added to a suspension to increase its density because of the increase in viscosity which affects the flow behaviour of the suspension. De Vaney and Shelton (in Taggart, 1967, p. 11-107) have shown that the viscosity of a suspension increases at a slow linear rate with increase in density until a critical point is reached at 17-30 volume per cent of solids whereupon the rate of change of viscosity increases rapidly through a relatively small change in density until the mixture will no longer flow. Figure 14 shows a graph of the effect of density on the viscosity of quartz grains of coarse silt to fine sand size. The estimated maximum bulk density obtainable is approximately 1.8 gm/cm^3 with the critical point at approximately 1.4 gm/cm^3 and a volume concentration of 23%. In turbidity currents with a poly-mineralic and polymodal distribution of grains we might expect a maximum density of about 2 (Kuenen, (1950).

The influence of grain size distribution on the flow characteristics of suspensions, in particular turbidity currents, is often overlooked. Chemical engineers have long recognized that the longer the size range with a given size, the more self sustaining the suspension and the more it deviates from Newtonian behaviour. The ideal size distribution curve for the pipe transport of solids with the minimum of energy input is one that is bimodal, " with a hump in the coarse end

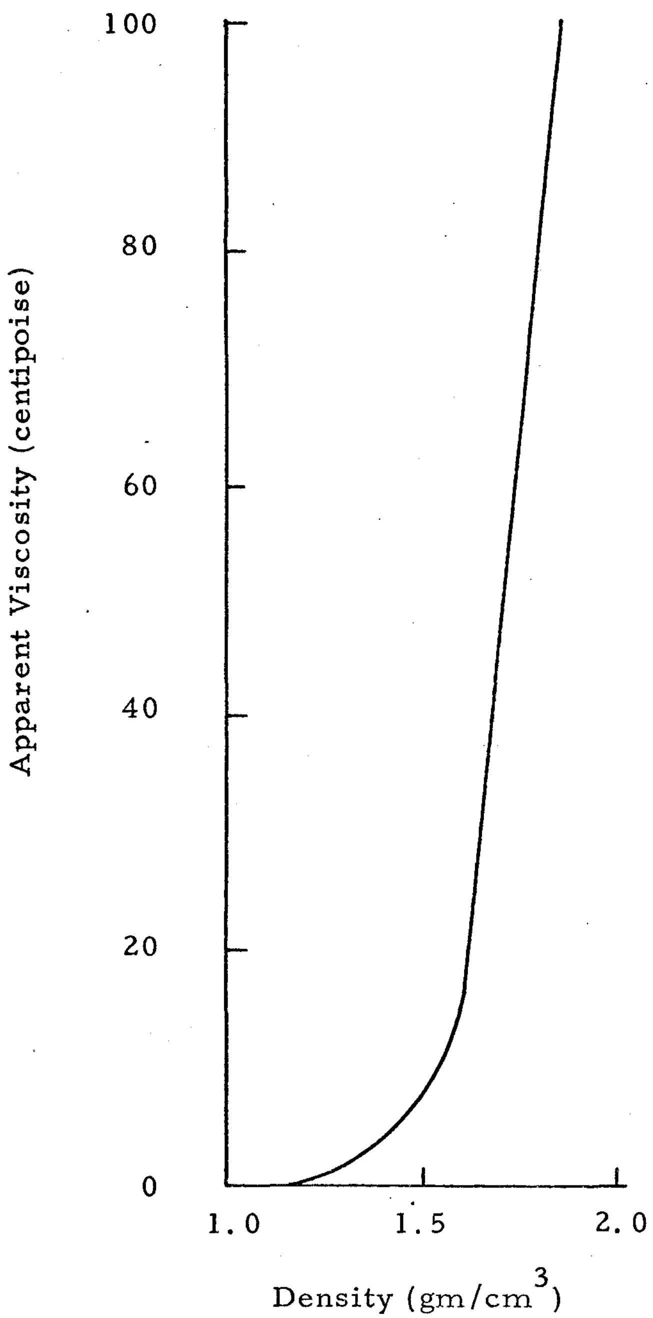


Figure 14. Effect of density on consistency of a quartz suspension (after DeVaney and Shelton in Dallavalle, 1948, p. 352).

adding density without a corresponding loss in fluidity, and another in the colloidal size range, contributing sustaining power or viscosity" (Taggart, 1967, p. 11-112). Riddell (1969) has demonstrated the effects of grain size distribution on turbidity current behaviour. By adding a quantity of finer material to a suspension of coarse size, the extension of the coarse material and the velocity of the finer material were both increased. An underflowing current of fine material may thus be given an increase velocity at all stages of extension by the addition of a quantity of coarse material to the initial suspension i.e. the coarse fraction increases the density difference between the current and the ambient fluid.

Thus a turbidity current composed of well sorted coarse sand, will have a high density and a high initial velocity, but will deposit rapidly since its sustaining power is small. We might expect a massive graded bed to be formed near to the source of the current. However, variations in the grain size distribution within the initial current will greatly change its behaviour and the type of deposit formed. Currents with a high percentage of fines in suspension and with a small percentage of coarser grains, might be expected to have greater basin extension because of their added density and the coarse grains might be expected to be transported a great distance.

The nature of the grain size distribution within natural turbidity currents will determine to what extent 'autosuspension' is possible. 'Autosuspension' (Bagnold, 1962) is operative where there is no net energy expenditure by the fluid to maintain particles in suspension. Middleton (1966a) believes that 'autosuspension' is only possible for silt and clay. This is probably correct because, in general, the coarser the average grain size, the more fluid the suspension, but the more 'agitation' is required to maintain suspension.

So far we have discussed the effects of sediment in suspension on the settling velocity of particles and the effects of the grain size distribution on the flow behavior of a suspension. We continue with a discussion of the effects of concentration on the depositional mechanisms of turbidity currents.

In experimental turbidity currents of plastic beads, Middleton (1967b) has observed that in low concentration flows individual particles accumulated on the bed accompanied by some traction, followed by rapid deposition from suspension as the velocity of the current decreased. In high concentration flows (more than 30% by volume) the bed did not appear to accumulate grain-by-grain or layer-by-layer. Instead, it was first difficult to distinguish a well defined bed and when a distinct interface appeared the bed was up to 30% thicker than it was in its final form. At the boundary between this expanded 'quick' bed and the flow above, waves formed, which were either almost stationary or moved downstream. The effect is related to the very high concentration in preventing the segregation of grain sizes. "Particle-to particle interactions (the "dispersive pressure" of Bagnold, 1956) maintained by strong shearing motions prevent or delay the consolidation of the bed as it forms by mass settling of the suspension.... Segregation of grain sizes is also precluded except for some segregation of the largest grain sizes. The majority of the bed is deposited first in an expanded state and behaves as a pseudoplastic (Metzner and Whitlock, 1958). Such a highly concentrated sediment-water mixture has a low viscosity and behaves much like a normal (Newtonian) liquid at high rates of shear (corresponding to high shear stress), but as the shear stress decreases the viscosity increases rapidly and a yield stress may be rapidly reached. Further plastic deformation of the suspension is not possible below the yield stress. In simple terms, the bed consolidates to the point where the 'quick' bed rapidly 'freezes' " (Middleton, 1967b).

The application of these results to large scale turbidity currents poses an interesting problem. Where we see sedimentary structures attributed to the formation and migration of bed forms, for example ripples, in turbidites, we may infer that deposition has taken place in a manner resembling that from 'low' concentration flows. These structures are usually composed of sand size particles that have been carried far from source. From what has been mentioned earlier about the rapid deposition from suspensions of sand sized particles, we might expect that the settling velocity of the particles forming the bed forms had been reduced by the presence of fines in the suspension.

The effects of fines in suspension on the development of bed forms has been reported by Simons, Richardson and Haushild (1963). Their results are important when applied to the development of bed forms by turbidity currents. In the lower flow regime, the effect of low concentrations (less than 10,000 ppm) is relatively small but in the upper flow regime, a large percentage of fine sediment increases the bed material transport. The increase in bed material load occurs because the fine sediment increases the specific weight and viscosity of the fluid, decreasing the fall velocity of the bed material, and increasing the resistence to flow and fluid shear. Antidune activity is increased with very large concentrations of fine material because of the increase in 'particle mobility'.

Even an initially low concentration flow possessing some sustaining power because of the presence of fines, may become a high concentration current in the later stages of flow. The process operating is akin to 'hindered settling' in still suspensions (see Brodkey, 1967) except that the grain mass is subjected to shearing forces which arise from the inertial effects of the current as it slows down. This readily suggests that the 'quick' bed might be expected on a large scale to flow as a concentrated grain dispersion, maintained in an expanded state by dispersive pressures and the escape of pore fluids. It would cease motion when a certain initial yield stress is reached (dependent on the rheological behaviour of the dispersion). This may correspond to the liquid limit of the material (Dott, 1963).

The actual flow mechanics of dense natural dispersions of sediment and water moving downslope (for example, mud flows and presumably 'quick' beds) are poorly defined. However, there is little doubt that they behave as non-Newtonian fluids. A nearly endless variety of models has been proposed for the portrayal of purely viscous non-Newtonian behaviour, particularly for pseudoplastics (see Skelland, 1967, p. 8-9). Of particular interest is the Ostwald-de-Waele or Power Law model where:

$$T = K(u)^n$$

T is the shear stress, K is a consistency index with units $lb_m\ sec^{n-2}\ ft^{-1}$, u the shear rate and n a dimensionless flow behaviour index. For pseudoplastic behaviour n is less than unity and ranges from unity to zero with increasing pseudoplasticity. It represents the slope of a determined flow curve on a rheological diagram. K is usually calculated from the intercept on the shear stress axis at unit shear rate. For the Power Law to be of use, n and K are usually considered to be constants, but they may very with the rate of shear.

In non-Newtonian flows obeying the Power Law, the transition from laminar to turbulent flow is dependent on the value of a particularly defined Reynolds Number and the value of n. The transition or critical Reynolds Number increases with decreasing values of n. For pipes the value of the critical Reynolds Number is approximately the same as in Newtonian flows (Skelland, 1967, p. 227) and hence it is to be suspected that the critical Reynolds Number for free surface mass flows will be approximately 5×10^2. It is important to note that the transition from laminar to turbulent flow with increasing velocity in most flow systems is dependent particularly on the roughness of the flow boundaries and a wide spectrum of critical Reynolds Numbers can be obtained (see Brodkey, 1967, p. 228). However, in flows which are turbulent where the velocity is decreased, the transition to laminar flow is independent of boundary roughness and the critical Reynolds Number has a more consistent value. Natural mass flows satisfying this critical Reynolds Number should therefore exhibit turbulence. However, it must be made clear what is meant by turbulence. Turbulence may be on a fine scale, composed of a great many small eddies (microturbulence), or on a large scale, composed of huge vortices and swirls like those commonly observed in rivers and gusts in the atmosphere (macroturbulence). Townsend (1956) has suggested that the small scale motions, which develop within the large scale motions, determine the turbulent properties of the flow. This suggests that true hydraulic turbulence is independent of the large scale motions.

It is now well established that particles in suspension tend to affect the nature of turbulence (Vanoni, 1953; Bobkowicz and Gauvin, 1965; Ellis and Round, 1963). Usually particles behave as turbulence inhibitors although work by Bobkowicz and Gauvin (1965) on fibre suspensions also suggests that they may act as turbulence generators when turbulent wakes are associated with individual particles. The net effect of high concentrations of particles must certainly inhibit the formation and damp small scale fluctuations within a moving grain dispersion. To what extent they affect the large scale eddy motions is uncertain.

Spiral motions have been observed as cross-currents in dilute suspensions even when the forward velocity was reduced to a minimum (Dzulynski, 1966). Thus even at low Reynolds numbers, eddy-like motions may occur in moving suspensions although these ordered motions are not turbulent in the usual hydraulic sense. Similar motion has been observed in the laminar boundary layer by Kline and others (1967). Hence, even though the fluid itself can be considered to move in a laminar fashion (with viscous effects dominant), individual parcels of fluid follow spiral paths as they move forward.

This leads us to the general conclusion that large scale eddy motions could exist in slowly moving dense suspensions although they may not achieve a Reynolds number sufficient for true hydraulic turbulence, which is characterised by random eddy motions superimposed on these larger scale motions. Why this kind of instability should exist is probably a result of the disequilibrium of shearing behaviour within the moving dispersion arising from boundary effects.

There is however, one further point which ought to be raised. The early stages of flow in the downslope movement of turbidity currents is accompanied by much flow turbulence and the sediment in suspension is probably well distributed within the current. As the current velocity wanes, the concentration of sediment increases towards the base of the current. This will presumably dampen microturbulence in these lower levels. However, the presence of macroturbulence, particularly of the type with continuous rotary motions with quasi-horizontal axes (Matthes, 1947), might persist even after the separation of a thick liquefied 'quick' bed, due to the momentum effects of the flow. The dissipation and disappearence of these instabilities will be a function of how fast the bed consolidates because consolidation is accompanied by an increase in 'viscosity' or consistency of the dispersion. It is questionable if these motions will disappear before motion ceases because of the rapidity of the gain in strength of the sediment mass. We might then expect to find evidence of these motions in arrested mass flow deposits.

Despite the doubt shed earlier on the validity of the critical Reynolds number, it seems clear that instabilities should persist more easily in flows decelerating from above the critical Reynolds number for hydraulic turbulence, than they form in accelerating flows where the transition from the laminar to the turbulent regime is not so well marked.

In dense dispersions, particle interactions will be frequent. Particle interactions are responsible for the production of grain orientation in several different depositional processes. Parkash (1969, p. 166-174) has reviewed the literature pertinent to this phenomenon. All mass depositional processes, by which particles are transported 'en masse' to their final site of deposition and in which the depositional process is a fast solidification of the sediment-fluid mass, produce beds with current parallel grain orientation. Wherever there has been particle interactions and shearing we might expect to find grain orientation, the long axis of grains paralleling the local flow lines.

Conclusions

(i) The presence of fines in a suspending medium reduces the settling velocity of coarser grains giving them greater "particle mobility".

(ii) Coarse grains might be transported over long distances by turbidity currents composed of a high percentage of fines in suspension. The coarse fraction assists in the basinal extension of the current by increasing the density difference between the current and the ambient fluid.

(iii) Deposition from turbidity currents is a function of the concentration of sediment in the flow. In low concentration flows sediment accumulates on the bed particle by particle; high concentration flows produce a so-called 'quick' bed which is sheared by the entrained flow before coming to rest.

(iv) Large scale natural 'quick' beds developing from decelerating high concentration turbidity currents might exhibit macroturbulence. We might expect to find evidence of eddy-like motions in arrested mass flow deposits.

CHAPTER FIVE

'PSEUDO-NODULES' AND SIMILAR STRUCTURES

The term 'pseudo-nodule' was originally defined by Macar (1948). 'Pseudo-nodules' consist of laminated sandstone arranged in pillow-like masses sometimes isolated, sometimes contiguous and varying in size from a few centimeters to perhaps a meter across (large examples are akin to the ball and pillow structure of Potter and Pettijohn, 1963). "Internally the laminae show varying degrees of curling upwards with the outline of the structure. Deformation is much greater in the isolated 'pseudo-nodules', which are found "floating" in mudstone with only a thin tread of sand connecting the nodule to the overlying sandstone" (Dzulynski and Walton, 1965, p. 152).

'Pseudo-nodules' are considered by Dzulynski and Walton (1965, p. 149-152) to fall into the class of sedimentary structures referred to as "load structures" which owe their origin to the sinking down of sediment into underlying material. They commonly occur where a sand bed has locally sunk down into an underlying mud paste. This suggests that their origin results from a difference in the mass physical properties of the two materials, particularly density. For their development, a denser sediment layer must overlie a less dense sediment layer i.e. there must exist a reverse density gradient.

Sediment layers are commonly deposited with a reversed density gradient due to the super-position of relatively high density layers on layers of lower density (Anketell, Cegla and Dzulyski, 1969). Reversed density gradients may result from differences in lithology, grain packing, moisture content and hence there usually exists differences in sediment strengths. These differences may occur singly or repeatedly within beds, between beds, or between sets of beds in a stratified system. Reversed density stratification represents an instability in any system and there is the tendency for the denser substance to reach its most stable position within the system. The stability of the system is dependent on the viscosity. 'Pseudo-nodules' and similar load structures are considered to arise because of a similar instability to that which occurs in pure fluid systems when there exists a reversed density gradient. (Stewart, 1963; Dzulynski, 1966).

"It is, for example, possible for a layer of fluid to remain in equilibrium with higher density at the top than at the bottom so long as the condition

$$(d_1 - d_0)/ d_1 < (652\, k \nu)/ (gh^3)$$

is fulfilled (Rayleigh, 1916), where: d_1 = density of the fluid at the top,

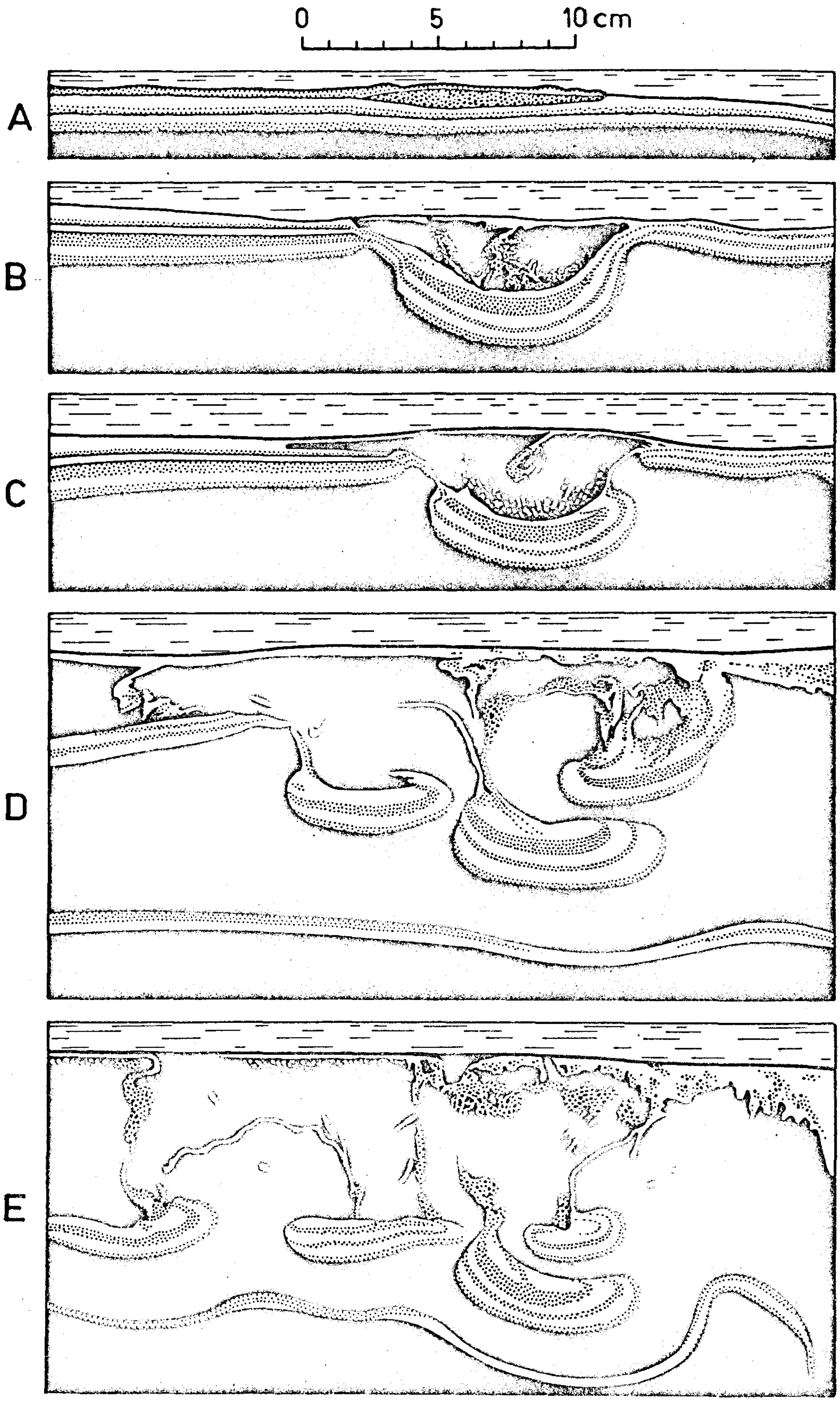
d_0 = the density of the fluid at the bottom, k = coefficient of molecular diffusivity, ν = kinematic coefficient of viscosity, g = the acceleration of gravity, h = the depth of the layer." (Dzulynski, 1966, p. 5). With declining viscosity in fluids, the instability gives rise to a number of ascending and descending movements which may follow a highly regular pattern. "Thomson and Newell (1886) showed that a liquid drop falling through a second liquid with which it was miscible, would not only flatten into a disc shape but, if it was of suitable viscosity, be filled by vortex motion and break up into the vortically stable arrangement of an anchor ring. This ring then starts to sink preferentially at certain points so that it finally becomes a series of graceful loops linked at their lower extremities in small blobs which themselves gradually degenerate into tiny vortex rings.

It should be noted that if the viscosity of the drop does not fall within certain critical limits a vortex ring will not develop. If the viscosity is too small the vortex motion does not diffuse into the drop fast enough and if it is too large it diffuses too rapidly and is dissipated before the drop becomes disc-shaped. These effects can, however, be neutralized by altering the size of the drop or the viscosity of the surrounding liquid." (Stewart, 1963, p. 209).

In experiments on the genesis of 'pseudo-nodules', Kuenen (1958) used a sand layer supported on a thixotropic bed of clay, which was subjected to a mild vibration simulating an earthquake. The sand layer broke into slabs which settled down into the clay. In a few seconds, the slabs were bent up into balled or ellipsoidal shapes by the relative movement of the surrounding clay. The enveloping clay flowed around and over the sand folding back the edges (see figure 15). These experimental 'pseudo-nodules' could continue their downward movement until they would be completely detached from the parent supply. The term 'isolated load cast' has been introduced to describe this behaviour (Bouma, 1962, p. 64). 'Isolated internal load cast' has been used to describe these structures when the contact with the overlying sand disappears completely. Dzulynski and Walton (1965, p. 142) proposed that the term 'cast' be replaced by structure; this proposal is welcomed here. The production of these structures is clearly convective in nature, the downward migration of sand setting up subsidiary upward moving currents in the clay. Their pattern is identical with that of density controlled deformations in unstable plastic and liquid media (see Dzulynski, 1966; shapes of bubbles in fluidised beds in Rowe and Partridge, 1962, p. 141, figure 10; shapes of drops and droplets in Brodkey, 1967, p. 541).

These and similar structures can be divided into two major

Figure 15. Experimental 'pseudo-nodules' (from Kuenen, 1965a).


0
5
10 cm
A
B
C
D
E

groups; those produced in the absence and those produced in the presence of unidirectional horizontal shear (cf Anketell and Dzulynski, 1968a). These groups are equivalent to the load structures and flow structures respectively of Dzulynski and Walton (1965, p. 142). Load structures, including the 'pseudo-nodules' described above, can develop a variety of forms depending on the density and viscosity differences across a potentially unstable interface. Other kinds of structures, which do not concern us here, have also been grouped with these structures (see bibliography of Davies, 1965).

In three dimensions these structures can achieve a variety of forms depending on the actual processes involved in their formation. Experiments (Kuenen, 1958; Anketell and Dzulynski, 1968b) and inferences (cf Dzulynski, 1966) show that they can be essentially globular with circular cross section, polygonal or linear.

Anketell and Dzulynski (1968b) have produced linear load structures in the absence of shear by the movement of a "liquefaction front". A plaster of Paris turbidite was deposited on a thixotropic clay in a small tank. The system was subjected to a mild shock at one end (the slightly thicker proximal end). After an initial instantaneous deformation over the greater part of the turbidite bed where rising clay columns formed a polygonal pattern on the surface of the system, disturbances were observed, spreading very slowly and intermittently towards the distal end, breaking the plaster of Paris layer into elongated bodies arranged transverse to the direction of propagation of the disturbance. As a result of the higher kinematic viscosity, the plaster of Paris formed narrow bands, resting between broader clay intrusions.

Structures produced in the presence of unidirectional horizontal shear and within the bounds of experiment, usually form linear structures. Anketell and Dzulynski (1968b) produced structures similar to those described above by releasing successively dilute suspensions of plaster of Paris to form turbidite laminae resting upon a soft clay substratum. A denser suspension was then intruded onto the still soft, laminated sequence. Elongate structures were produced, roughly rhomboidal in shape in vertical cross section and displaying typical 'pseudo-nodule' features with almost complete closure of the warped laminae. The longer axis of the rhomboids were inclined consistently in the downcurrent direction so that diapiric clay ridges separating the 'pseudo-nodular' structures were deflected upcurrent. The trajectory of the sinking bodies was deflected in a downcurrent direction as a result of the slight horizontal translation of the laminated sequence inherent in the formation of the initial warping.

Linear convolutions, interpreted as produced by horizontal shearing are also reported by Anketell and Dzulynski (1968a). The structures described consisted of a series of ridges arranged parallel to the inferred current direction given by paleocurrent indicators. A rippled layer was assumed to have sunk down into a soft substratum combined with slight horizontal displacement. The displacement was probably caused by the shearing effect of the current, and facilitated by partial liquifaction of the sediment underlying the rippled layer.

All of the structures described above result from the movement of one granular material relative to another across an interface. As movement takes place, shear of the grain dispersion near to an interface should take place because particle collisions should be frequent. Shearing of granular materials should be expected to produce grain orientation with the long axis of grains orientated parallel to the local flow field (see Hamilton et al., 1968; Rees, 1968). Hence, on the under surfaces of 'pseudo-nodules' and similar structures, depending on the nature of the interfacial shearing during formation, we might expect to find grain orientation. This should be expected particularly when these structures occur in granular materials.

In nature, 'pseudo-nodules' and related structures could probably develop on a variety of scales, depending on the mechanical properties of the materials liable to failure and their boundary conditions. Boundary conditions will be important to those processes where excess pore pressures assist in the instability of stratified sediments. For example, a build up in pore water pressure in a bed with tight boundary conditions prohibitive to the migration of fluid, might lead to liquefaction with a subsequent loss in density and strength leading to the collapse of material above it. The complexity of these structures in natural systems will be enhanced by the time of their development relative to the deposition of their parent material. Structures that develop in response to flow conditions shearing the sediment mass will form syndepositionally. If, as could occur with thixotropic materials, sediment strength is not regained rapidly, the structures may be obliterated completely. In most geological processes, however, movement is stopped before the stable density stratification is achieved because of the limited fluidity and plasticity of the sedimentary materials involved.

Conclusions

(i) 'Pseudo-nodules' consist of laminated sandstone arranged in pillow-like masses, sometimes isolated, sometimes contiguous. They commonly occur where a sand bed has locally sunk down into an underlying mud paste.

(ii) Load structures and 'pseudo-nodules' develop when sediment layers are deposited so that a relatively high density layer rests on a layer of lower density. Their pattern is identical with that of density controlled deformations in unstable plastic and liquid media.

(iii) In three dimensions, load structures may be essentially globular with circular cross-sections, polygonal or linear. Linear load structures develop in the presence or absence of unidirectional horizontal shear.

(iv) The under surfaces of 'pseudo-nodules' and similar structures may show grain orientation.

CHAPTER SIX

INTERPRETATION, DISCUSSION AND CONCLUSIONS

This chapter offers an interpretation of the observed features of the 'pseudo-noduled' beds in the β_1 member.

6.1. Downcurrent persistence and related problems.

The downcurrent persistence of 'pseudo-noduled' beds from beyond Fame Point Lighthouse to St. Hélier, a distance of approximately 12 kilometers (7-1/2 miles) is clearly a function of the transport capacity of the depositing current. As outlined in chapter four, the transporting properties of a turbidity current will depend on its grain properties, in particular the grain size distribution and concentration. If these deposits are a fair reflection of the nature of the parent current, the grain properties of the flow were characterised by a large proportion of fines (less than fine sand size) and a small proportion of coarser grains (coarse sand to pebble) in suspension. The presence of the coarse grains in the flow assisted in its basinal extension by adding excess density, which increased the velocity at all stages of extension (cf Riddell, 1969). The large proportion of fine grains added sustaining power to the current by increasing the viscosity and also assisted in maintaining the coarser grains in suspension by increasing the density, thus retarding their settling velocity.

For those beds with sandy basal divisions, it is not unreasonable to expect, in the early stages of flow, that the turbulence and density of a low density turbidity current (density less than 1.1 gm/cm^3; see Kuenen, 1966, p. 288) could counteract the tendency of sand size material to settle. For beds displaying quartz and limestone granule and pebble conglomerate at their bases the problem is more severe. Quartz spheres up to one centimetre in diameter have a fall velocity in still clean water at $20^{o}C$ of the order of 100 cm/sec. To transport a small quantity of quartz granules and pebbles a long distance from their source probably demands either very severe turbulence or a high density and viscosity to maintain them in suspension. Density and viscosity can be increased by increasing the concentration but this will have an adverse effect on the turbulence. Some balance between these three parameters is more likely. Limestone clasts are not as dense as clasts of quartz so that relatively lower densities of the transporting medium would be required.

A related problem of more interest is the absence of a downcurrent decline in the maximum size of quartz grains at the base of many beds except perhaps for bed 343. However, at sections 10 and 11, maximum grain size measurements for this bed were for coarse grains in the bottom of flutes. Since grains can accumulate in such hollows by being trapped within the separation zone which accompanies their formation (Allen, 1969), grains on the smoother parts of beds might be expected to be finer in grain size. To have very coarse grains persisting over such a long distance, the currents responsible for each bed must have attained some form of equilibrium in their transporting behaviour; an equilibrium which was favourable to the maintenance of coarse grains in suspension. Perhaps the currents achieved a close approach to "autosuspension". This is a possibility since sediment hydraulically finer than silt grade certainly formed a high proportion of the material in the depositing currents (cf. Middleton, 1966a).

Beds 324 and 363 show downcurrent changes in the internal structures of their basal divisions which indicate variations in flow regime (Harms and Fahnstock, 1965). They appear to show that the flow regime may increase (bed 363, section 10A to 3 and bed 324 section 5 to 3), or decrease (bed 324 between section 7 and 5) down-current. Apparent increases in flow regime downcurrent should not lead to the inference however that there was necessarily a significant change in the relationship of the many variables involved in the transport and deposition of material. The effect can be interpreted as a preservation effect. For example, antidune cross-stratification may have been produced at section 10A in bed 363, but the changing characteristics of the flow did not favour its preservation. The current simply reworked the material existing on the bed into an equilibrium bed form which chanced to be preserved.

The reworking of material in upcurrent sections and the absence of a decline in the maximum size of quartz grains at the base of beds, suggests significant bypassing of material in sections nearer to source. This is a reflection of the transport behaviour of the current and supports the notion that the currents approached 'autosuspension'.

6.2. Structures within the 'pseudo-noduled' division.

Ideas for the interpretation of the structures and characteristics of the 'pseudo-noduled' division came from examining similar beds along the Gaspé coast, particularly those at St. Maurice, and the better examples of these beds within the β_1 member, particularly bed 255 (see Plates 3, 4 and 5). The beds at St. Maurice clearly displayed structures attributed to 'pseudo-nodule' development, including linear load structures resembling those described by Anketell and Dzulynski (1968a) arranged parallel to the current direction inferred from flutes.

In their vertical succession of structures these beds had divisions which closely parallelled the 'pseudo-nodule' division of beds in the β_1 member. For the development of 'pseudo-nodules' it is necessary that there exists a reversed density gradient within the stratified sediments and the mechanical properties of these sediments must be favourable to failure. This is best realised if the strata are deposited in a very liquefied condition such as would occur if deposition of the material was quite rapid. This would prevent the escape of pore fluids and the high pore pressures would assist in maintaining the bed in a very liquid state. Such a state could exist if sediment settled '<u>en masse</u>' as occurs in the deposition of a 'quick' bed from high concentration turbidity currents.

The sedimentary structures of the 'pseudo-noduled' division of the beds in the β_1 member show a predominant lack of structures, such as ripples, produced by dominant traction along the bed. There do exist isolated occurrences of thin laminae within the division composed of coarse sand (bed 8-300). The absence of ripples and parallel laminations within this division is not a function of the absence of particular grain sizes for ripples and flat beds form in fine sand. Rather, their absence is attributed to conditions unfavourable to their formation, i.e. dominant grain fall from suspension. The massive nature of the division, save for the breaks, suggests that it was formed by mass settling from suspension. The 'breaks' separate different phases of deposition. It is proposed that these intervals developed from 'quick' beds. The complex nature of the current was such that several 'quick' beds developed from different pulses within the current producing the several breaks.

It was noted in chapter three that the lower portions of division two showed more complex structures than those parts towards the top, the upper portions containing only spindle-shaped nodules, their longer axis orientated parallel to the base of the bed. It has already been suggested that the second division is composed of a series of consolidated 'quick' beds produced from highly concentrated flows, the breaks marking the upper surface of each 'quick' bed. As a 'quick' bed is being formed it is sheared by the overlying fluid entrained by the motion of the current. This, accompanied by the dissipation of pore pressures, delays consolidation of the bed. If the entrained flow is represented by a secondary turbidity current head or pulse within the major current, its coarsest particles will be deposited possibly as a layer over the previous unconsolidated 'quick' bed. If the consistency of the particle layers is sufficient to assist in the damping of the interfacial waves between the 'quick' bed and the flow above, load structures might form. These will be assisted in their formation by the liquefied state of the underlying sediment. We should expect 'pseudo-nodule' development.

Shear within the underlying 'quick' bed will tend to obliterate by mixing many of the structures produced. The thin thread of sediment connecting a 'pseudo-nodule' to its parent laminae will be obscured. The 'pseudo-nodules' will then appear detached and isolated; their long axis probably aligned in the direction of flow. The buff coloured calcareous nodules within the second division are considered to have arisen by this mechanism.

It is to be expected that the formation of load structures in the presence of horizontal shear will tend to incline the axes of the remnants of these structures downcurrent. Although this is observed in plates 4, 5 and 6, Anketell and Dzulynski (1968b) have produced experimental structures with axes inclined upcurrent. However, in their experiments the underlying material was consolidated and was not displaced by shear. In the case of a 'quick' bed, where the sediment is liquefied, displacement of material will take place and be greatest in the zone near the interface between the sediment and the shearing fluid. Axes of load structures will therefore be inclined downcurrent.

The process of loading and shearing could operate for the development of several 'quick' beds. Continued shearing would lead to the obliteration of load structures. The higher portions of division 2 would probably have been subjected to prolonged shear because of the diminishing concentration of material in the succeeding flows, since a longer time would be required for the formation of a 'quick' bed. In this way, the higher portions of division 2 would show only those structures which could withstand a prolonged period of shear - namely, the 'pseudo-nodules'.

It was noted in chapter four that a large-scale 'quick' bed might develop convection-like motions because of instabilities within the moving grain dispersions. The hemi-ellipsoidal and similar structures described in chapter three, represent a condition of macroturbulence consisting of eddies with continuous rotary motion about quasi-horizontal axes aligned in the direction of flow. The actual motion of individual cells (one hemi-ellipsoid) is inferred from the nature of the orientation of grains and graptolite stipes.

The hemi-ellipsoid structures do not reach the base of the blocks in which they occur, the lower portions of blocks seemingly consisting of planar surfaces. The production of the structures can be likened to the development of a laminar sublayer dominated by viscous forces where individual layers of material slide over one another; the spiral motions above representing the "turbulent" flow of the main stream.

The 'parting' characteristic shown in plate 7 may also have resulted from similar internal instabilities existing in the beds at the time of deposition.

6.3. Antidune cross-stratification.

The occurrence of ripple cross-stratification and parallel lamination in the basal division of calcareous wacke beds, represents stages in the history of the current when ripples and flat beds characterised the bottom surface over which the current moved. Ripple cross-stratification and parallel lamination are not unusual in turbidites and we shall not discuss them further here.

Upstream inclined laminae are unusual and will be discussed below.

The grain size characteristics of the upstream inclined laminae do not appear to have been produced by processes operating in the lee of ripples or dunes, either by avalanching or in a similar fashion to laminae produced in Jopling's (1965) experiments. Laminae produced by avalanching during low sediment discharges show a size sorting where the coarsest grains are concentrated towards the toe of the avalanche face. At high sediment discharges, avalanching ceases to be a significant mechanism of grain sorting and emplacement on the lee-side of ripples and dunes (see discussion in Allen, 1968a, p. 323). Here, asymptotic bottomsets are produced by grains being carried over the ripple or dune crest and falling to the bed from suspension a short distance downstream of the crest. Usually, laminae produced in this manner show a size gradation towards finer grain sizes at their toes. The visible grain size properties seen in plate 3 do not show either of these characteristics. Coarse grains do not appear to be concentrated towards the toe or the crest of the individual laminae.

From the occurrences of these laminae, either below a sinuous profile or as lensing sets with downstream inclined laminae, combined with their characteristics, and the excellent paleocurrent control on the beds in which they occur, there is little doubt that they were produced by unidirectional currents within the antidune phase of bed transport (see criteria for the recognition of antidune cross-stratification in Middleton, 1965).

Antidunes (Gilbert, 1914) are bed forms produced under high flow intensities of the upper flow regime (Allen, 1965; Harms and Fahnstock, 1965). They have a sinuous profile which is 'in phase or strongly interacts with the gravity water-surface waves' (Kennedy, 1966). As yet, despite the experiments of Kennedy (1961) and Middleton (1965) and the recent publication by Hand et al. (1969), little is known of the internal structure of antidunes. Upstream inclined laminae, occurring in a lenticular portion of a bed from the Pennsylvanian of N. Devon, have been attributed by Walker (1969, p. 137; also see ibid., plate 7B) to possible formation in the antidune phase of bed transport.

Allen (1966, p. 165) observed that 'thin laminae accumulate over the crests of the waves or on one or other of the sides, depending on whether the bed waves remain stationary or migrate with continuing flow'. Sediment layers inclined against the general direction of flow are deposited on the upstream sides of antidunes as accretionary laminae. That sediment layers formed in this way are potentially preservable, at least under laboratory conditions, is shown by photographs published by Kennedy (1961) and the figures of Middleton (1965).

Many turbidites show sedimentary structures (Bouma's massive and graded division 'A' and the lower division 'B' of parallel lamination) which are considered to have been produced by flows reaching the upper flow regime (Walker, 1965; Harms and Fahnstock, 1965). Moreover, the massive graded division has been attributed to stream power conditions pertaining to the antidune phase of bed transport (see Allen, 1968b). It is therefore expected that sedimentary structures produced by the formation, migration and preservation of an antidune bed form should be found in the base of some turbidites.

The formation of antidunes in flumes and their occurrence in streams has shown that they are extremely sensitive to changing flow conditions (see Harms and Fahnstock, 1965, p. 92). Middleton (1965) has discussed the importance of net sediment deposition for the preservation of antidunes and kindred structures. Such a condition could probably be met under waning conditions of flow in river flood systems and in turbidity currents, by the rapid fall-out of sediment from suspension. In semi-arid environments, for example on slopes of alluvial fans, preservation could be achieved temporarily, and possibly permanently, by the rapid evaporation, or more probably, the rapid seepage into the bed of thin flows which produced antidunes. For preservation by turbidity currents, the only plausible mechanism of preservation is a high rate of net sediment deposition from suspension. The development of 'quick' beds by the settling of grains '*en masse*', as considered here for the production of the 'pseudo-noduled' division, provides a suitable mechanism for the preservation of antidunes by turbidity currents.

In free surface aqueous flows, the formation of antidunes is dependent on the value of the Froude Number. The Froude Number (Fr) defines the ratio between the inertial and gravitational forces within a flow. It is given by

$$Fr = V/(gD)^{1/2} \qquad \ldots\ldots \qquad (1)$$

where V is the mean flow velocity, g the acceleration due to gravity and D the depth of flow. Strictly, the gravitational acceleration g actually denotes the ratio of the specific weight γ to the density ρ and the quantity γ represents the effective force per unit volume due to gravitational action (Rouse, 1950, p. 54). A more general form of the Froude Number is therefore

$$Fr = V \;/\; (gD \,\Delta\rho/\rho)^{1/2} \qquad \ldots\ldots \qquad (2)$$

where the quantity ($g\,\Delta\rho/\rho$) represents the effective gravitational acceleration, which may vary from the limit g to zero. Equation (2) is the densiometric Froude Number. In the flow of turbidity currents the quantity $\Delta\rho/\rho$ represents the difference in density between the turbidity current and its ambient fluid divided by the density of the ambient fluid, the latter usually considered to be clear water. In open channel flows $\Delta\rho$ is approximately equal to ρ because the density of the ambient fluid (air) is so small in comparison to that of water that it is neglected, and equation (1) is sufficient to define the value of Fr.

The Froude Number indicates to what extent gravitational forces enter into a flow phenomenon. For a particular form of flow boundary and a particular value of the Froude Number, gravitational conditions will be dynamically similar at all scales of flow. Thus the Froude Number is the primary similitude parameter for gravity flows.

For the production of antidunes in free-surface aqueous flows the Froude Number must be approximately unity, but antidunes can probably be formed when the Froude Number is as low as 0.8

(Kennedy, 1963). Since the formation of antidunes is so clearly dependent on the gravitational phenomena existing in the flow, similar values of the densiometric Froude Number will be required for the production of antidunes by turbidity currents.

For antidunes, Kennedy (1961) has shown that, both in flumes and rivers, the wavelength is related to the mean flow velocity by the expression

$$U^2 = gL/(2\pi) \qquad \ldots\ldots \qquad (3)$$

where U is the mean flow velocity, g the acceleration due to gravity and L the wavelength of the antidune. Reynolds (1965) extended Kennedy's work and showed that equation 1 should be amended to the more general form

$$L = \frac{(2\pi U^2)}{g} \quad \tan h\ (2D/L) \qquad \ldots\ldots \qquad (4)$$

where D is the flow depth. For values of tan h (2D/L) equal to unity, equation (3) applies.

For the sedimentary structures described here, the wavelength of the antidunes may be estimated directly from the wavelength of the sinusoidal profile at the top of the basal division. For a wavelength of 64 cms, equation (3) yields a value for the mean velocity of approximately 100 cm/sec. Assuming a densiometric Froude Number close to unity and assuming a density of 1.05 for a turbidity current, equation (2) yields a depth of flow suitable for antidune cross-stratification of approximately two metres.

This value may possibly be too small but may suffice as a rough approximation. For U = 100 cm/sec, D = 200 cms and assuming, for the suspension, a kinematic viscosity of 0.02 cm^2/sec (twice that of water) the Reynolds number, $R = UD/\nu$, has a value of 10^6. At this Reynolds Number, the Darcy-Weisbach resistance coefficient of the lower boundary (f_o) assumed to be hydraulically smooth, is found to be approximately 0.012 on the Moody diagram (see Streeter, 1966, p. 260). Using equation (2) of Middleton (1966a) where

$$U = (8\ g'\ DS/(f_i+f_o))^{1/2} \qquad \ldots\ldots \qquad (5)$$

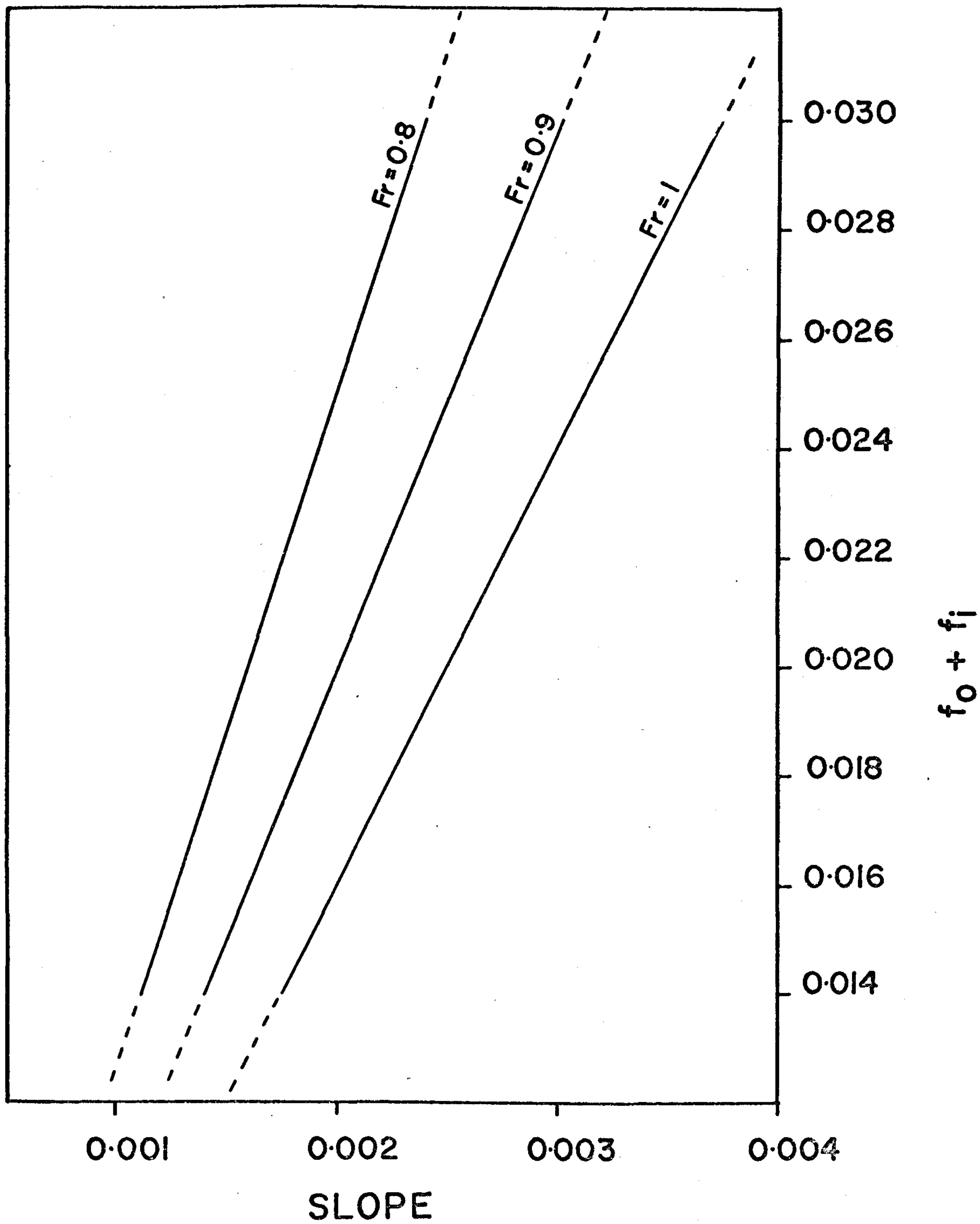
and a suitable value for the resistance of the upper interface (f_i) of 0.004, it is found that the slope is 0.002. Strictly speaking, this is the slope of the energy grade line. Other possible values for the slope can be found by using a rearranged form of equation (5) of Middleton (1966a) which shows that the slope is dependent on the Froude Number and the total resistances, namely,

$$S = (Fr^2\ (f_i+f_o)/8) \qquad \ldots\ldots \qquad (6)$$

For Reynolds Numbers of the magnitude envisaged above, the value of f_o for hydraulically smooth boundaries can be considered to have a limiting lower value of 0.01 to 0.012. For hydraulically rough bottom surfaces, f_o is independent of the Reynolds Number provided the flow is fully turbulent, but depends upon the relative roughness of the bottom. For flows of the thickness envisaged here, f_o will be quite small. Simons, Richardson and Nordin (1965, p. 41) give a value of $C/(g)^{1/2}$ in the range 10-20 for breaking antidunes in shallow laboratory flows, equivalent to a value of f_o of 0.02. The value might be expected to be smaller for deeper flows. The value of f_i, the resistance of the upper interface, is dependent on the Froude and Reynolds Numbers, however, increasing the Reynolds Number decreases the value of f_i, so that the Froude Number effect is probably more important (Middleton, 1966a, p. 203). A suitable range of values for the total resistances is therefore from 0.014 to 0.03.

A plot of f_i+f_o versus slope is given in figure 16 for Froude Numbers of 0.8, 0.9 and 1. A minimum value for the slope at a Froude Number of 0.8 is approximately 0.00112. Maximum possible slopes are of the order of 0.00375 for Froude Numbers of unity. Higher values of slope can be obtained by increasing the Froude Number, but for values larger than unity, experimental evidence suggests that mixing and turbulence increase very rapidly with increase in Froude Number (Middleton, 1966a, p. 207). It should be noted that variations in the thickness and density of the flow do not directly control the

Figure 16. Plot of $f_o + f_i$ versus slope.



Fr=0·8
Fr=0·9
Fr=1
0·030
0·028
0·026
0·024
0·022
0·020
0·018
0·016
0·014
$f_o + f_i$
0·001
0·002
0·003
0·004
SLOPE

angle of the required slope, but affect the angle directly by their effects on the Froude Number.

The calculated values of the slope are much less than those calculated by Hand and others (1969) for antidunes in a non-marine environment. They obtained minimum values of 2.7^{o}. Equation (6) is similar to the modified Darcy-Weisbach equation used by Hand and others (1969, p. 1313, equation 2) where

$$S = f_o \; \bar{v}^2)/(8\, g\bar{d}) \; = f_o \, Fr^2/8 \qquad \ldots\ldots \qquad (7)$$

$\bar{v}$ being the mean velocity of the flow, $\bar{d}$ the mean depth and f_o the bed resistance.

Inspection of these two equations (6) and (7) show that for similar values of the Froude Number, the slope is proportional to one-eighth the total resistances. Values for the resistance of the bed (f_o in equations 6 and 7) are equatable to values for the relative roughness on a Moody diagram. The relative roughness expresses the ratio between the height of the roughness elements and the pipe diameter. In open channel flows, 4 times the average depth is used in place of the pipe diameter. Hence, the magnitude of f_o is a function of the depth of flow. Lower values of f_o are associated with deeper flows, e.g. turbidity currents.

Therefore, despite the fact that the resistance of the upper interface (f_i) has to be considered in the flow of turbidity currents, the total resistances are less than those met in free surface aqueous flows. Hence we obtain lower values for the slope.

6.4. Discussion

Descriptive and quantitative sedimentological studies of turbidites frequently utilise the Bouma (1962) model; its validity and usefulness is not disputed. In this thesis, a sequence of turbidite internal structures has been described which departs considerably from the Bouma model. This sequence has been interpreted in the light of recent experimental studies (Middleton, 1966, b, c, 1967a; Riddell, 1969).

The production of a sequence of structures in turbidites is, at least in part, a function of the sediment concentration and grain size distribution within the parent current. These properties assist in controlling the hydraulic behaviour, the transport competence and the mode of deposition of the current. For these reasons, the Bouma model, despite its wide application, defines just one possible model sequence of structures. The complexity of fluid-sediment interactions which would occur in natural turbidity currents, might lead to some very unusual sequences.

The discovery of antidunes and antidune cross-stratification in the basal divisions of some of the beds suggests that the factor termed "preservation potential" (Allen, 1967) is also important in controlling the observed sequence of structures. The "preservation potential" in turbidity currents is primarily controlled by the rate of deposition. A high rate of deposition subsequent to the formation of bed forms which are sensitive to changing flow conditions (e.g. antidunes) is necessary to preserve them.

The grain properties of a turbidity current also control its transport competence and basin extension (cf. Riddell, 1969). In turbidites, coarse grains (sand grade) are usually considered to be found near to the source of the parent flow ("proximal" of Walker, 1967). The presence of quartz pebbles, scattered or thinly distributed in the basal divisions of some beds at St. Hélier, suggests that particles, hydraulically equivalent to quartz pebbles, may be carried over long distances by certain types of flow.

The presence of structures interpreted to result from eddy-like motions in dense grain dispersions has interesting repercussions. Similar eddy-like motions might possibly have existed during the formation of the massive graded division of some turbidites. Such motions could explain the presence and nature of certain unusual structures found in these divisions (for example, the "dish structures" of Wentworth, 1967; see also Laird, 1970).

6.5. Conclusions

Lateral correlation of a turbidite sequence has been achieved over a total distance of 7-1/2 miles. This has enabled the examination of the downcurrent changes of sedimentary structures in thick (1-8m) turbidite beds. These beds display a sequence of internal sedimentary structures which differs from the Bouma (1962) sequence of internal structures.

The beds are considered to have three broad divisions. A basal division is composed of coarse sand calcareous wacke (0-15 cm thick) or quartz limestone pebble conglomerate (24 cms thick). The basal divisions of calcareous wacke frequently display ripple cross-stratification, parallel lamination or upstream inclined laminae. The upstream inclined laminae have a low angle of dip and, in most cases, occur below a sinuous profile.

A second division, up to 3m. thick and separated from the basal division by a fissile layer of argillite clasts, is composed predominantly of fine sand to silt size particles. Clay flakes are in abundance. Scattered through this division are isolated buff-coloured calcareous nodules. Thin threads of carbonate bearing material may connect them to thin laminae above them. Other structures, of immense variability, consisting of carbonate streaks, etc., are seen to be associated with these nodules. No structures attributable to the migration of bed forms were seen in the second division. The third division is composed of argillite.

Fallen broken blocks of the second division show its internal structures. Hemi-ellipsoid structures, arranged en echelon and concave towards the base of the blocks, were seen at one locality. Planar surfaces occur below these structures, nearer to the inferred base of these blocks.

The upstream inclined laminae occurring in the basal divisions of calcareous wacke beds do not show any visible characteristics which resemble laminae produced by the migration of ripples or dunes. The laminae may be sigmoid or with truncated 'foresets' (? backsets). Their occurrence beneath a sinuous profile and the presence of flutes on the base of some beds in which they occur, means that they have been produced by the upstream migration of a bedform, namely antidunes. Analysis of these structures suggests that the currents moved over very shallow slopes ($\ll 1^{\circ}$).

The hemi-ellipsoid structures occurring in the second division are considered to represent the remains of macroturbulent eddies in an arrested mass flow deposit (i.e. a 'quick' bed). The planar surfaces represent a laminar sublayer.

The beds have been produced by initially low concentration but high density turbidity currents which formed the basal division in the beds. The process of mass settling in the bodies of these flows led to the development of successive 'quick' beds, which were sheared by the entrained flow before coming to rest. Concomitant load casting and shearing led to the development of the structures seen in the second division (isolated 'pseudo-nodules' and flow structures).

The downcurrent persistence and the presence of pebbles at the base of some beds, suggests that the currents approached closely a state of 'autosuspension'.

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