THE GEOLOGY OF NORTH-WESTERN SOUTH GEORGIA: II. SEDIMENTOLOGY

By R. A. S. CLAYTON

ABSTRACT. The concept of proximal and distal deposition is applied to turbidites of the Cumberland Bay Formation (Stone, 1976), resulting in the recognition of two sub-facies. On the basis of a sandstone/shale ratio of 2, five distal and six relatively proximal members have been identified in the Nilse Hullet area. Walker's proximality index is found to be a fairly reliable guide to proximality when compared with other accepted standards, both qualitative and quantitative. Facies variation within the Cumberland Bay Formation is attributed to fluctuations in intensity of volcanic activity or derivation of volcaniclastic sediment from more than one volcanic centre.

Although the Cumberland Bay Formation is divided into relatively proximal and distal members, current-ripple laminations indicate that the bulk of the sediments are most probably medial in terms of absolute proximality with respect to the source area. Load casts, slumps and sedimentary dykes typify the unstable conditions which prevailed during and shortly after turbidity current deposition. Convolute lamination is thought to have been due to current action on unconsolidated sediment in a hydroplastic state. Four types of trace fossil have been recognized in the Cumberland Bay Formation. They are restricted to the pelitic units where they are often found in great abundance.

THE greywackes of the Cumberland Bay Formation were first described as turbidites by Trendall (1959). He used the recently formulated turbidity current theory to explain the sedimentary features observed in this sequence of volcaniclastic rocks. Since the pioneering work on turbidity current transport and deposition in the 1950's, some of the most important contributions have been the recognition of Bouma's (1962) ideal turbidite sequence, its interpretation in terms of deposition under decreasing flow regimes (Harms and Fahnestock, 1965; Walker, 1966) and the recognition of proximal and distal characteristics (Wood and Smith, 1959; Potter and Pettijohn, 1963). These concepts have been applied to the sedimentological data collected in north-western South Georgia in an attempt to explain the sedimentary structures observed and to reconstruct the palaeo-environment.

TURBIDITES

Variations in lithology within turbidite sequences have been interpreted in terms of different environments and processes of deposition, and their relationship to the source of the current has led to the concept of proximal and distal deposition (Wood and Smith, 1959; Potter and Pettijohn, 1963; Unrug, 1963; Walker, 1966). In order to distinguish between the two facies types, suitable criteria must be established by which a vertical turbidite sequence can be divided into units of varying proximality. The ratio of the thickness of sandstone to shale is the most popular parameter used to define changes in a turbidite sequence and, in the first sandstone/shale analysis by Nederlof (1959), a moving average was used to smooth the vertical sandstone/shale ratio trend. Only recently have sedimentary structures been used in vertical sequence analysis (Walker, 1967).

Bouma's (1962) definition of an ideal turbidite unit divides the flows internally into a graded division (A), a lower division of parallel lamination (B), a division of current-ripple lamination (C), an upper division of parallel lamination (D) and a pelitic division (E). Walker (1967) plotted a moving average ABC index (ABC index $= A + \frac{1}{2}B$, where A and B are the percentages of turbidite units in the group beginning with Bouma divisions A and B, respectively) for turbidite sequences. Natural groups of turbidites are defined when the difference between one peak and the adjacent trough is 30 per cent or greater.

The Cumberland Bay Formation is a thick, very sparsely fossiliferous sequence of alternating sandstones and shales, interpreted by Trendall (1959) as belonging to the turbidite facies. In the field, the breaks between the proximal and distal turbidite members can often be seen as an abrupt change in bed thickness and sandstone/shale ratio. However, where the change

Br. Antarct. Surv. Bull., No. 51, 1982., p. 55–78.

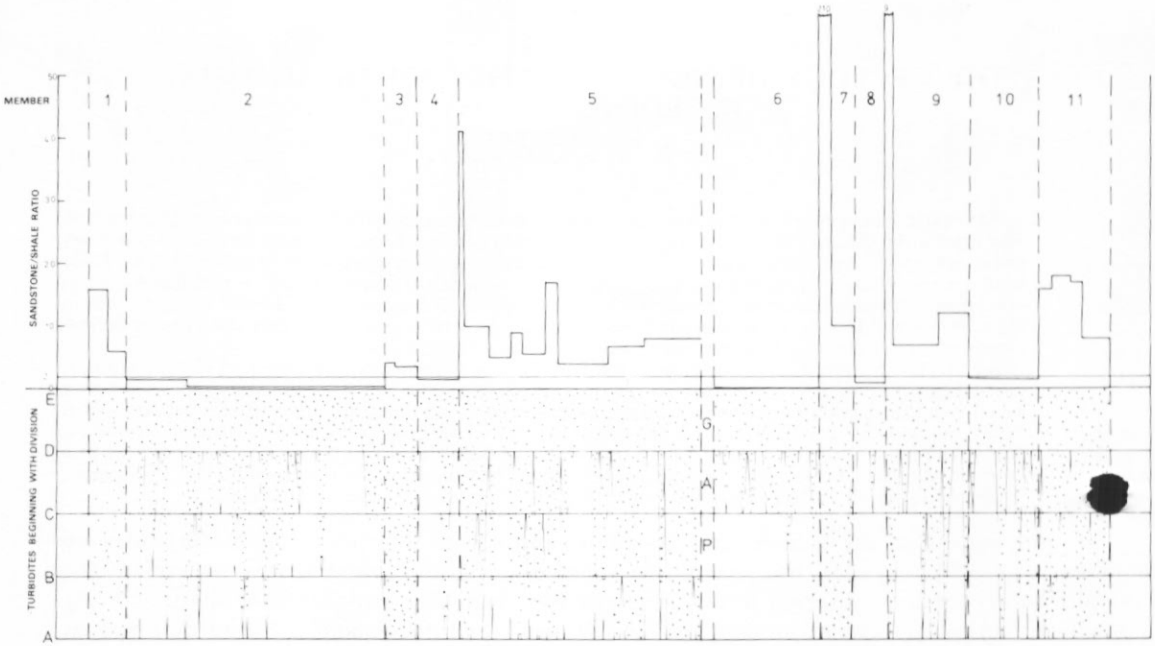

Fig. 1. Division of a turbidite sequence into units of varying proximality using a histogram of sandstone/shale ratio. The number of units beginning with each Bouma division is represented diagrammatically in the bottom part of the figure.

is gradational, the break must be chosen using such parameters as sandstone/shale ratio or Walker's ABC index. Internal divisions within the Cumberland Bay Formation have been determined from the proportion of Bouma A-division sandstone to shale, calculated as a ratio of the total thickness of Bouma A to E sets for 5 m. thick units of sediment (Fig. 1). The calculation was based on 5 m. divisions because thinner units would not cancel out small-scale fluctuations in sandstone/shale ratio and thicker units would tend to give poor definition of the change from a proximal to a distal member. A continuous coastal section in the Nilse Hullet area was studied, noting thickness of Bouma divisions, grain-size and occurrence of grading and amalgamation. On the basis of a sandstone/shale ratio of 2, five distal and six relatively proximal turbidite members were recognized within a 171 m. thick section (Fig. 1). A sandstone/shale ratio of 2 was chosen because it divided the units along a fairly well-defined natural break into distal and more proximal members (Fig. 1).

Proximal sub-facies

The six proximal members consist of 134 turbidite flows, ranging in thickness from 10 to 600 cm. with an average thickness of 116 cm. The mean thickness of the six proximal members is 24 m. Middle-absent, AE and ADE turbidites are the commonest (Table I), forming 51 per cent of the total number of flows in this sub-facies. Ideal (ABCDE) units are the second most abundant type and comprise 17 per cent of the flows (Table II). The proximal members contain few bottom-absent, DE and CDE units (6 per cent), and of the remaining types, ACDE turbidites (forming 5 per cent of the flows in this sub-facies) are the commonest.

Only four out of the six proximal members contain amalgamated units (Table III), giving an overall amalgamation value for this sub-facies of 12 per cent. All amalgamated units are massive A-division sandstones, the intervening E divisions having been either removed by turbidity current erosion or incorporated in the base of subsequent flows as mudflake-

TABLE I. THICKNESS AND NUMBER OF EACH TURBIDITE TYPE

Member *Thickness (cm.) and number of turbidite types*	1	2	3	4	5	6	7	8	9	10	11
ABCDE	140 2%	98 3%			1,666 5%		69 1%		500 1%	115 1%	93 1%
BCDE		264 13%				32 1%		24 1%			108 2%
CDE		118 11%		31 1%	120 4%	145 11%		34 2%	68 4%	21 2%	48 2%
DE		446 30%	35 1%	126 9%	428 28%	240 19%		92 8%	87 9%	137 13%	
ADE	80 3%	30 1%	14 3%	87 1%		53 2%			450 5%	164 5%	816 3%
AE	606 7%	108 4%	845 5%		2,659 14%		663 3%		577 2%		483 5%
ACD			91 1%			32 1%					
CE		8 1%			32 2%						41 2%
AD				26 1%							
AB					52 1%						
ACDE	26 1%				34 1%	38 1%	472 2%		59 2%	37 1%	119 2%
BDE		22 2%									

[face page 56

TABLE II. NUMBER OF TURBIDITE TYPES EXPRESSED AS A PERCENTAGE OF TOTAL NUMBER OF TURBIDITES

Member *Percentage of turbidite types*	1	2	3	4	5	6	7	8	9	10	11
ABCDE	15%	5%			9%		17%		4%	5%	6%
BCDE		21%				3%		9%			12%
CDE		17%		8%	7%	32%		18%	17%	9%	12%
DE		48%	10%	75%	51%	56%		73%	39%	59%	
ADE	23%	1·6%	30%	8%		6%			22%	23%	18%
AE	54%	6%	50%		25%		33%		9%		29%
ACD			10%			3%					
CE		1·6%			4%						12%
AD				8%							
AB					2%						
ACDE	8%				2%	3%	50%		9%	5%	12%
BDE		3%									

TABLE III. PROXIMALITY INDICATORS

Members	1	2	3	4	5	6	7	8	9	10	11
Amalgamation (per cent)			11				17		4		17
Sand/shale ratio	5	0·3	11	0·6	7	0·14	15	0	13	1·5	13
Proximality index (per cent)	100	24	90	16	38	13	100	4·5	43	27	71
Total number of turbidites	13	63	10	12	55	34	6	11	23	22	17
Mean turbidite thickness (cm.)	67	18	110	24	118	16	307	15	76	25	139
Mean A-division sandstone thickness (cm.)	47	20	108	48	137	18	268		140	29	132

conglomerates. These slate clasts are generally surrounded by bleached aureoles.

Overall, the proximal sub-facies consists mainly of Bouma A-division sandstone (80 per cent), graded vertically from coarse to fine upwards and passing through thin laminated horizons before being capped by bands of dark mudstone (E). The soles of these thick sandstones are invariably sharp and sometimes marked with load casts. The coarse units sometimes contain rare fragments of fossil wood. The lower division of parallel lamination, B, is considerably thinner than division A, forming only 2 per cent of the total thickness of the proximal sub-facies. The most likely explanation of the almost total absence of beds beginning with B is that this division was deposited under very restricted flow conditions relative to divisions A and C (Walton, 1967). If only a thin set of laminations was formed, they could easily be re-worked into cross lamination.

The division of current-ripple lamination (C) also constitutes 5 per cent of the total sub-facies by thickness (Table IV). Proximal sub-facies C divisions average 6 cm. in thickness and only rarely exceed 20 cm.

The upper division of parallel lamination, D, is generally poorly developed and forms only 6 per cent of the proximal sub-facies. Individual Bouma divisions average 9 cm. in thickness [illegible]nd never exceed 30 cm.

The uppermost division, E, consists of intensely cleaved dark slates which form 9 per cent of the sub-facies. The thickness of the pelitic division averages 7 cm. but it ranges from 2 to 30 cm.

Member 11, with a proximality index of 71 per cent (Table III), is described in detail as an apparently typical member of this sub-facies. It consists of 17 turbidite units with an average thickness of 139 cm. Individual turbidites range in thickness from 12 to 400 cm. The A division constitutes 78 per cent of the thickness of the member (Table IV) and consists of medium- or coarse-grained graded sandstones varying considerably in thickness (10–350 cm.). The units of parallel and current-ripple lamination are thin and poorly developed. The commonest turbidites in this member are middle-absent AE types (Table II), the relatively well-developed pelitic units being responsible for the formation of thick bleached layers in the bases of the overlying A-division sandstones by producing conditions suitable for prehnitization.

In an attempt to quantify proximality, Walker (1967) devised a proximality index, P_1 which is defined by: $P_1 = (A - (A \rightarrow E)) + \frac{1}{2}B$ (where A and B are the percentages of flows beginning with divisions A and B, respectively, and $A \rightarrow E$ is the percentage of flows in each group 3 cm. or less in thickness with perfect gradation from division A into division E without evidence of laminae or cross laminae). In the section measured to the east of Nilse Hullet, no $A \rightarrow E$ turbidites thinner than 3 cm. were observed so that all calculations of proximality index gave the same result as Walker's (1967) ABC index, i.e. $A + \frac{1}{2}B$.

Walker's proximality index for member 11 gives a value of 71 per cent, indicating [illegible] distinctly proximal depositional environment as does the sandstone/shale ratio of 13 (Table III). This quantitative analysis is in agreement with the qualitative indicators of proximality shown in Table V.

Distal sub-facies

The distal sub-facies turbidite units average only 19 cm. in thickness and are grouped into five members with an average thickness of 5·3 m. Of the 142 turbidite units forming the distal sub-facies, bottom-absent, CDE and DE units are the commonest, forming 52 per cent of the flows (Fig. 1). Middle-absent, AE and ADE units are the second most abundant type, forming 17 per cent of the total (Table II). 12 per cent of the distal group consist of the unusual BCDE turbidites (Table II). Only four ideal ABCDE turbidites were observed, forming 8 per cent of the flows in the sub-facies.

The fine- to medium-grained Bouma A-division sandstones of this sub-facies comprise only 17 per cent of the total thickness. These muddy sandstones are generally thinly bedded and rarely display bottom structures. There is no amalgamation or mudflake-conglomerate but grading is well developed. Bouma A-division sandstones average 30 cm. in thickness but range from 5 to 80 cm. The lower division of parallel lamination, B, forms only 4 per cent of the sub-facies, individual divisions ranging from 1 to 10 cm. in thickness with a mean of 5 cm.

The C division forms 12 per cent of this sub-facies, individuals varying in thickness from 2 to 25 cm. The D division is quite thick and comprises 29 per cent of the distal sub-facies. Divisions range from 1 to 20 cm. in thickness and average 7 cm. The pelitic E divisions, although only averaging 7 cm. in thickness, form 39 per cent of the sub-facies. They are often intensely bioturbated and are cut by a well-developed cleavage.

Member 6 with a proximality index of 13 per cent and a sandstone/shale ratio of only 0·14 (Table III) is typical of the distal sub-facies. It contains 34 turbidite units (Table III) ranging from 3 to 32 cm. in thickness with an average of 16 cm. The member is 5·5 m. thick and consists predominantly of C, D and E divisions (Table I). Turbidites are generally of the bottom- or middle-absent type (Table II) but one top-absent ACD turbidite was observed. Grading is good in the fine-grained sandstones, the bedding is regular and there are no sole marks. Cross-bedding data indicate a westerly palaeocurrent direction but suitably exposed C divisions are rare.

Proximality indicators

In Fig. 2, Bouma A-division sandstone is combined graphically with sandstone/shale ratio to illustrate the natural division between turbidite members of varying proximality. The illustration also emphasizes the difficulty of selecting a suitable criterion for division of the sequence, because on this graph member 1 appears to be the most distal of the proximal sub-facies yet it has a proximality index of 100 per cent. Many criticisms have been levelled at Walker's proximality index (Griggs and Kulm, 1970; Haner, 1971; McCabe and Waugh, 1973), which was intended to be a comparative rather than an absolute measure. Nevertheless, despite the original quantitative sub-division of the sequence at Nilse Hullet, proximality index values for the 11 members are in close agreement with other accepted indicators (Tables III and V).

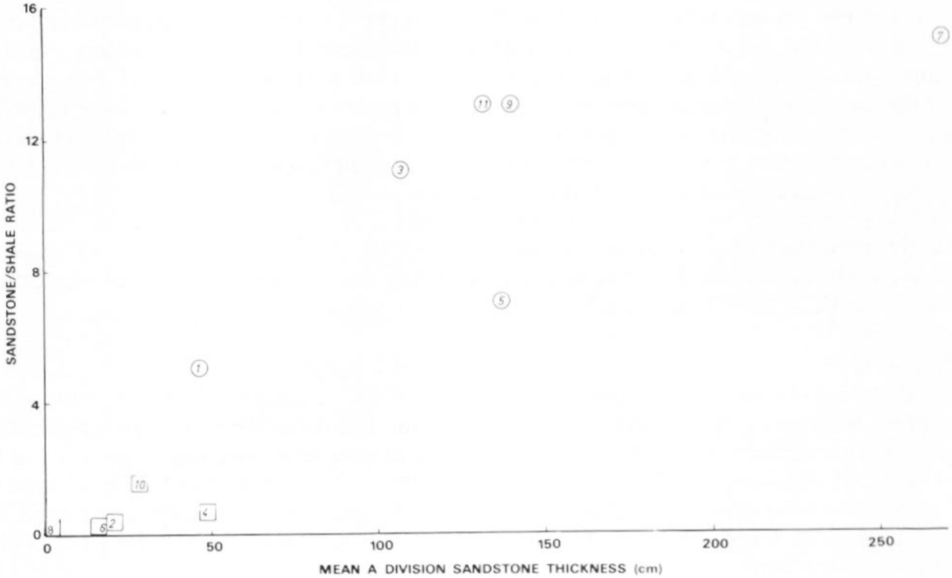

Fig. 2. Division of turbidite members into distal and more proximal sub-facies using a graphical combination of sandstone/shale ratio and mean A-division sandstone thickness.

TABLE IV. BOUMA DIVISION THICKNESS EXPRESSED AS A PERCENTAGE OF TOTAL MEMBER THICKNESS

Members *Thickness (cm.) and percentage of divisions*	1	2	3	4	5	6	7	8	9	10	11
A	662 76%	143 13%	970 87%	95 32%	5,193 80%	35 6·5%	1,605 87%	— —	1,408 80%	200 36%	1,850 78%
B	18 2%	86 8%	— —	— —	126 2%	2 0·3%	10 0·5%	2 1%	18 1%	8 1·5%	137 6%
C	15 2%	151 14%	8 0·7%	4 1%	114 1·8%	97 18%	30 16%	27 17%	58 3%	31 5·5%	77 3%
D	48 6%	296 27%	43 4%	35 12%	342 5%	151 28%	94 5%	72 44%	161 9%	184 33%	164 7%
E	129 15%	429 39%	87 8%	158 54%	722 11%	253 47%	107 6%	61 38%	108 6%	138 25%	144 6%
TOTAL	872	1,105	1,108	292	6,497	538	1,846	162	1,753	861	2,372

Table V. A comparison of the proximality of members 1 and 6 as defined by qualitative indicators

Indicator *Characteristics of decreasing proximality*	*Member 1 (proximal)*	*Inference*	*Member 6 (distal)*	*Inference*
1. Beds decrease in thickness	Maximum bed thickness 310 cm. Mean thickness 22 cm.	Indecisive	Maximum thickness 20 cm. Mean thickness 6 cm.	Distal
2. Beds become finer-grained	Mud to coarse sandstone	Proximal	Mud to fine sandstone	Distal
3. Amalgamation decreases	Not observed	Distal	Not observed	Distal
4. Beds more regularly bedded	Massive sandstones irregular	Proximal	Bedding planes parallel	Distal
5. Scours, wash-outs and channels decrease in abundance	Not observed	Distal	Not observed	Distal
6. Mudstone layers between sandstones better developed	15 per cent of member is E-division mudstone	Proximal	47 per cent of member is E-division mudstone	Distal
7. Beds better graded	Grading moderate	Indecisive	Well graded	Distal
8. Upper part of turbidite grades into finer material rather than being sharp; AE sequences rarer	54 per cent of member is of AE-type turbidite	Proximal	0 per cent of member is of AE-type turbidite	Distal
9. Laminations and ripple laminations more common	0 per cent of member is of CDE-type turbidite	Proximal	32 per cent of member is of CDE-type turbidite	Distal
10. Sole to tool marks ratio decreases	Sole marks rare, tool marks not observed	Indecisive	Not observed	Distal
11. Decrease in mudflake-conglomerate	Mudflake-conglomerate common	Proximal	Not observed	Distal

The mean proximality index for the distal sub-facies is 17 per cent and for the more proximal sub-facies 74 per cent. The sandstone/shale ratio, which takes bed thickness into account, gives a similar result, 11 for the proximal sub-facies and 0·5 for the distal sub-facies. Clearly Walker's proximality index serves as a very useful and quite precise indicator of relative proximality in this case.

Possible mechanisms for facies variation within the Cumberland Bay Formation

Trends in proximality index and sandstone/shale ratio provide important data relating to the long-term control of turbidite sedimentation. The recognition of repeated trends is important because it implies that the deposition of turbidite flows was controlled by a cyclical mechanism. To explain cyclic deposition, Kimura (1966) proposed four changes in physical parameters which could control changes in turbidite thickness:

i. Angle of slope.
ii. Rate of sedimentation.
iii. Intensity of the trigger.
iv. Distance of the depositional point from the point of origin.

Changes in the distance of the depositional location from the point of origin might resu[illegible] from frequent transgression and regression of the sea over the land source area. However, it [illegible] unlikely that such changes would take place sufficiently quickly to produce the abrupt changes in facies type observed in north-western South Georgia.

Fluctuations in facies type could possibly be caused by local variations in the sea floor of the depositional area. Once a turbidity current has reached the flat basin floor, it moves with a precarious balance between deposition and non-deposition. Considerable changes in grain-size and bed thickness can be brought about by small irregularities in the sea floor (Enos, 1969). Consequently, it is possible that fairly frequent oscillations between a distal and a more proximal facies could be brought about by small changes in local topography.

Stone (1980) suggested that the cyclicity of deposition is caused by variation in the strength and size of the turbidity flows which are probably controlled by differences in sedimentation rate and/or trigger intensity. If the Cumberland Bay Formation was derived from an active volcanic archipelago, as suggested by Trendall (1959), the eruptions could have supplied material in pulses for re-sedimentation, and seismicity could have acted as an effective trigger.

Recent geochemical analyses of greywackes from the Cumberland Bay Formation (Clayton, 1981) suggest that this formation may have been derived from more than one volcanic centre. It is therefore possible that the two facies types were associated with different source areas.

SEDIMENTARY STRUCTURES

Turbidites are characterized by an abundance and variety of sedimentary structures, most of which are due to current action or post-depositional movement of one bed in relation [illegible] another. They can be subdivided into three main and several subsidiary groups on the basis of the origin of the forces which produced them.

Exogenetic structures

These are formed at the sediment/fluid interface and are due to the operation of external forces.

Small-scale current ripples

These are particularly abundant at certain horizons within the turbidite sequence. Groups of ideal ABCDE turbidites with thick C divisions and abundant current ripples are asymmetrical in vertical profile with a steep lee angle of 25–45° and a gentle stoss angle of 1–10°. In cross-laminated sets, the stoss is rarely preserved as the ripple migrates down-stream. Small-scale ripples range in height from 1 to 3 cm. with wave-lengths from 8 to 18 cm. and have an average wave-length to height ratio of 8.

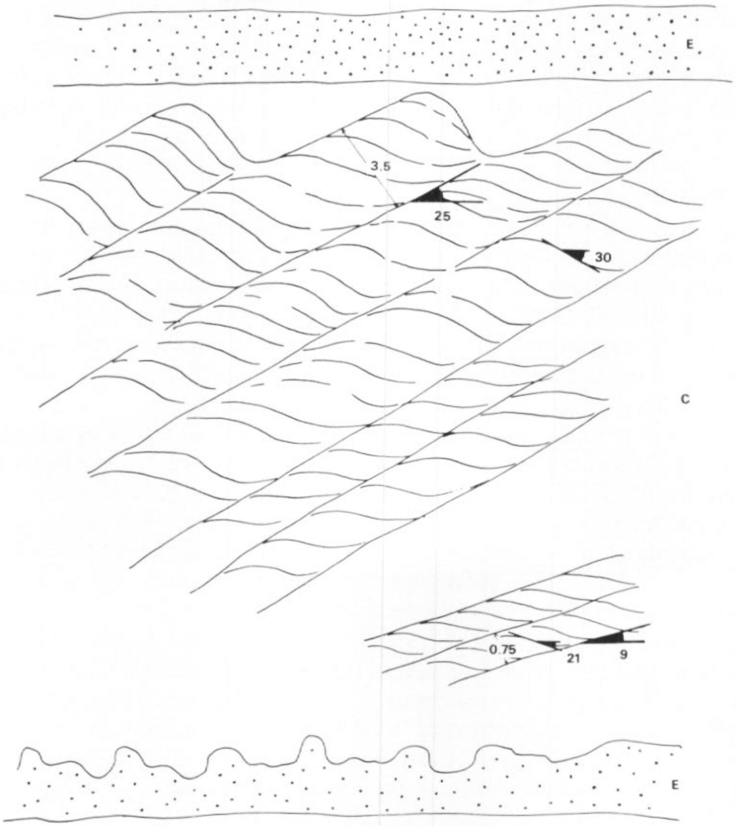

Fig. 3. Field sketch of thick C-division sandstone in the Elephant Cove area.

Straight-crested and undulatory small ripples are rare; the majority have short, strongly curved crests and a breadth of the same order as the wave-length. The crest line is generally convex in the direction of flow and often branches. This type of small ripple is termed linguoid and is formed at higher stream velocities than the long-crested types (Allen, 1970*a*). Composite ripples are occasionally found with nodes and saddles along the ridge crest.

Small-scale current ripples are intrinsically variable structures; their shape, height and angle [illegible] climb are governed by a number of physical parameters including flow depth and current velocity. Current-ripple laminations are therefore very useful palaeo-environmental indicators.

i. *Ripple height*. Individual ripples often change in form upwards, from long and low at the bottom of the division (wave-length/height ratio of 10) to short and tall in the upper part (wave-length/height ratio of 5). A 23 cm. thick C division with a 0·75 cm. cross-laminated unit at the base has a top unit exceeding 3 cm. in thickness (Fig. 3). In a waning turbidity current, this change is thought to be due to the mean rate of deposition decreasing less rapidly than the rate of bed-load transport.

ii. *Angle of climb*. Allen (1970*b*) has suggested that the angle of climb of small-scale ripples in cross-laminated deposits can be used as a tool to state their environmental significance in hydraulic terms. He classified cross-laminated units as: type A, characterized by a low angle of climb and the absence of stoss-side laminae; type B, with stoss-side laminae preserved and a moderate angle of climb; and type S, with thick stoss and lee-side laminae and steep angles of climb. In the Elephant Cove area, the cross-laminated sets usually climb at a low angle of about 10° in the lower part of the division but they increase in steepness of climb upwards, commonly to an angle of 30–40° at the top of the thicker C divisions. These ripples fall into Allen's (1970*b*) type B1 (angle of climb 10–35°) class, indicating a medial depositional environment. Although the Cumberland Bay Formation is subdivided into units of varying proximality, the relatively proximal and distal members represent the extremes of a facies which in terms of absolute proximality is medial.

iii. *Shape of fore-set laminae*. The shape of the fore-set laminae can be used as an indicator of current strength, because with increasing current velocity the character of the contact between fore-set and bottom-set changes from angular through tangential to sigmoidal in shape (Jopling, 1966). The majority of cross-laminated units in the Elephant Cove area are tangential with an asymptotic contact between cross stratum and unit base, thus indicating deposition from a turbidity current of moderate velocity.

iv. *Slope of fore-set laminae*. The slope of the fore-set laminae can also be used as a palaeoenvironmental indicator (Jopling, 1966), an angle of climb of approximately 30° being formed at low current velocities, whereas at higher velocities the slope angle is redu[illegible] to less than 20°. Fig. 4 shows a typical cross-laminated C division with a basal unit which has a low angle of climb and a fore-set slope angle of approximately 20°. The top cross-laminated unit climbs steeply and the fore-set slopes at 40°. These upward changes are in accordance with successive cross-laminated units being deposited by a waning turbidity current of constantly falling velocity.

v. *Height and wave-length*. It has been suggested that the height and wave-length of small current ripples can be used to determine flow depth at the time of deposition. For hydraulically rough flow, wave-length is approximately equal to five times the flow depth (Allen, 1970*a*). The height and wave-length of 30 small current-ripple marks in the Elephant Cove area gave mean values of 2·91 and 14·56 cm., respectively. This suggests that the flow depth at the time of deposition of a typical Cumberland Bay C-division turbidite was approximately equal to $14 \cdot 56/2 \cdot 91 = 5 \cdot 2$ cm.

Field observations suggest that the wave-length of a ripple is equal to $1 \cdot 16d^{1 \cdot 55}$ (Allen, 1970*a*), where d is the flow depth. For a typical C division in the Elephant Cove

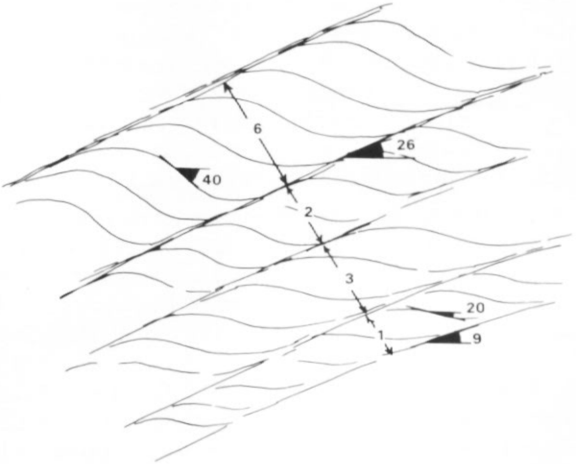

Fig. 4. Field sketch of C-division sandstone in the Elephant Cove area, showing increase in fore-set angle with decrease in current velocity, i.e. slope angle increases upwards.

area, flow depth is equal to $1 \cdot 55w/1 \cdot 16$, where w is the wave-length of a ripple. Substituting 14·56 cm., the average ripple wave-length for w gives a flow depth of about 4 cm. Such a shallow flow depth seems unlikely and it is suspected that such an application of ripple-height and wave-length is of dubious value.

vi. *Ripple cross lamination as an indicator of palaeocurrent.* Although groove marks and flute casts are occasionally observed in the turbidite succession of north-western South Georgia, the commoner cross-laminated units provide the basic data for palaeocurrent analysis. Ripple cross lamination has several drawbacks as an indicator of palaeocurrent, perhaps the most important to the field geologist being the lack of well-exposed three-dimensional sections from which the palaeocurrent direction can be determined. In north-western South Georgia, the majority of ripples are linguoid so that trough cross lamination predominates. This is a much more reliable and precise palaeocurrent indicator than planar cross lamination (High and Picard, 1974) but, as it is only broadly directional compared with groove or flute casts, it is used as an indicator of flow towards a quadrant rather than in a specific direction.

In north-western South Georgia, 80 observations of current-ripple laminations were made and these indicate that the dominant dispersal of the Cumberland Bay-type sediment was towards the north-western quadrant. Orientation data collected by other workers from the Cumberland Bay Formation (Trendall, 1959; Dalziel and others, 1975; Stone, 1980) suggested a similar north-westerly sediment dispersal pattern.

Tool marks

i. *Prod marks.* In the Elephant Cove area, prod marks with lengths of about 2 cm., widths of 0·5 cm. and depths of 2 mm. were occasionally found as casts on the bases of coarse sandstones.

ii. *Groove marks.* Long even ridges called groove casts are sometimes found on the soles of thick sandstones in the Cumberland Bay Formation. The ridges, rarely exceeding 2 mm. in height and 5 mm. in width, are often found with other types of moving tool mark, especially prod and bounce marks.

Endogenetic structures

Endogenetic structures result from the action of mechanical forces which arise within the sediments after deposition but before lithification.

Load casts

Load casts occur in the bases of most moderately to thick-bedded sandstones overlying mudstones. The density difference between sands and muds in the more proximal sub-facies of the Cumberland Bay-type turbidites leads to gravitational instability (Shrock, 1948). Downward swellings develop with a spacing between their centres which may be dependent on the relative density and viscosity of the mud and sand. Load casts vary in width from 1 to 50 cm. and give rise to a linguoid pattern on the bedding surface. The intervening mud plumes or flame structures are often overturned consistently in a north-westerly direction.

The tendency for flame structures to be inclined obliquely in one direction has been explained by relating their formation to antidune ripple development (Lamont, 1938) or to the drag involved during deposition from a turbidity current (Kuenen and Menard, 1952). The inclination can most probably be attributed to the subsequent compaction of the coarse-grained beds (Kelling and Walton, 1957), when any slight slope would tend to favour the development of a fairly regular asymmetry in the mud plumes. Flame structures in north-western South Georgia are occasionally overturned to the east in an area where more reliable palaeocurrent indicators suggest a north-westerly sediment dispersal pattern. The overturning is clearly not of current origin but could be due to irregular topography on the north-westerly dipping palaeoslope.

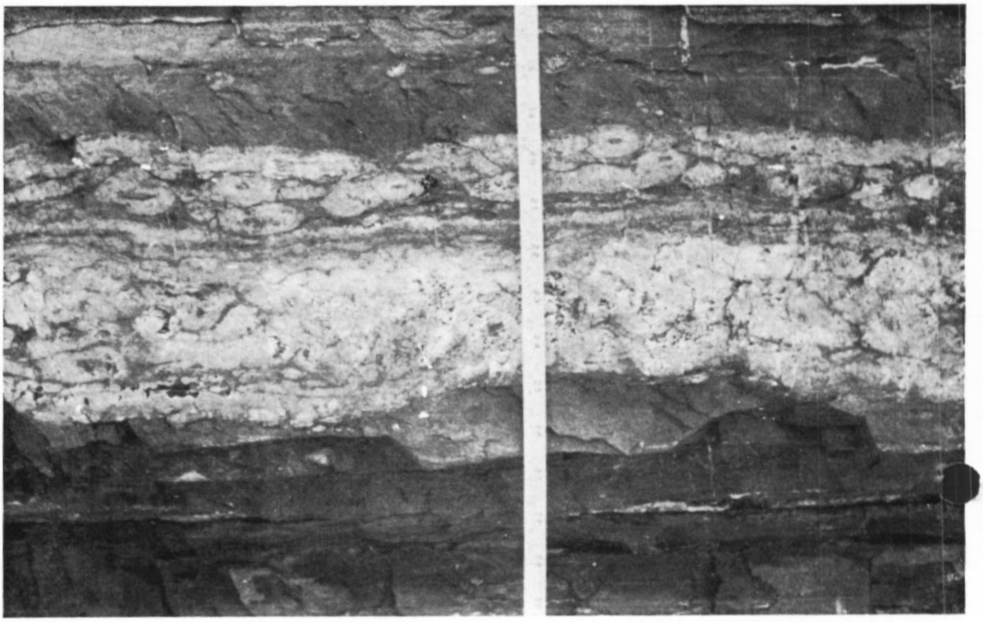

Fig. 5. Pseudo-nodules in volcanic greywacke.

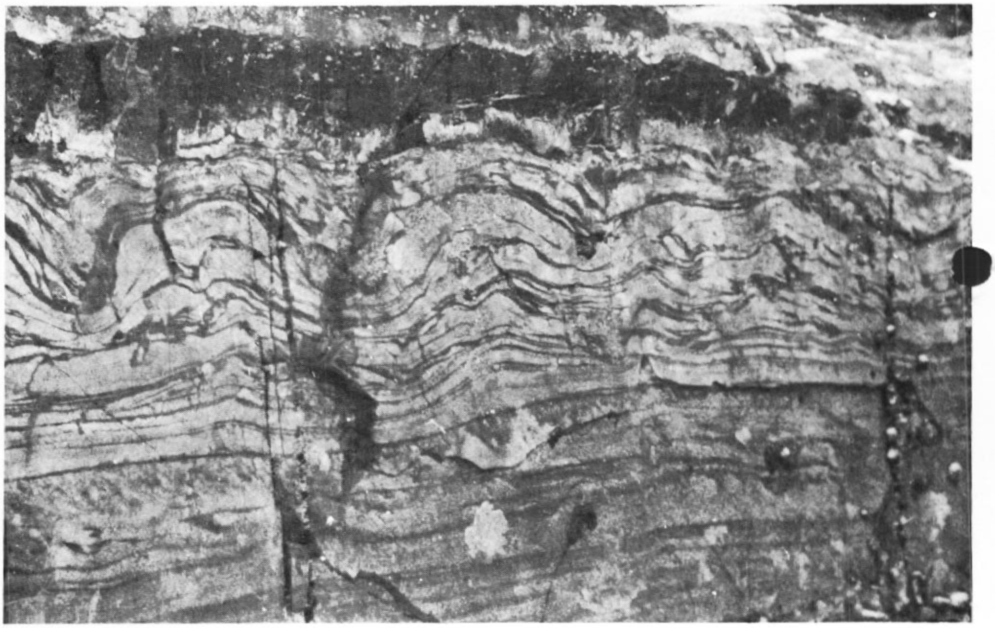

Fig. 6. Convolute laminations in volcanic sandstones to the north of Elephant Cove.

Pseudo-nodules

Prehnitized pseudo-nodules are often found in thin-bedded volcanic greywackes as creamy white-weathering ellipsoids which rarely exceed 5 cm. in length (Fig. 5). The pseudo-nodules often contain a slate clast which could have acted as a nucleus for nodule growth and as a catalyst for subsequent prehnitization. Skidmore (1972) suggested that the nodules in the Cumberland Bay Formation were formed by differential loading and earthquake shocks but a down-slope slump mechanism cannot be ruled out.

Convolute bedding

Convolute bedding consists of a series of crumples or corrugations of the depositional laminae which affect the interior of the bed but not its top or bottom. They are widely developed in the fine-grained, non-cohesive volcaniclastic greywackes of north-western South Georgia (Fig. 6). Convolutions may be intensely folded but they normally range from 5 to 50 cm. from crest to crest and from 2 to 20 cm. in height. A striking feature is the constant size of convolutions in any particular set but this can change markedly from one bed to the next (Fig. 7). ten Haaf (1956) described the dominant feature of convolute lamination as the anticlinal fold which is sharp-ridged and narrow, whereas the intervening troughs are generally wider and rounded in shape. Fig. 6 illustrates an unusual example with narrow troughs separated by broad anticlines. Some anticlines are composite with the development of two or more anticlinal

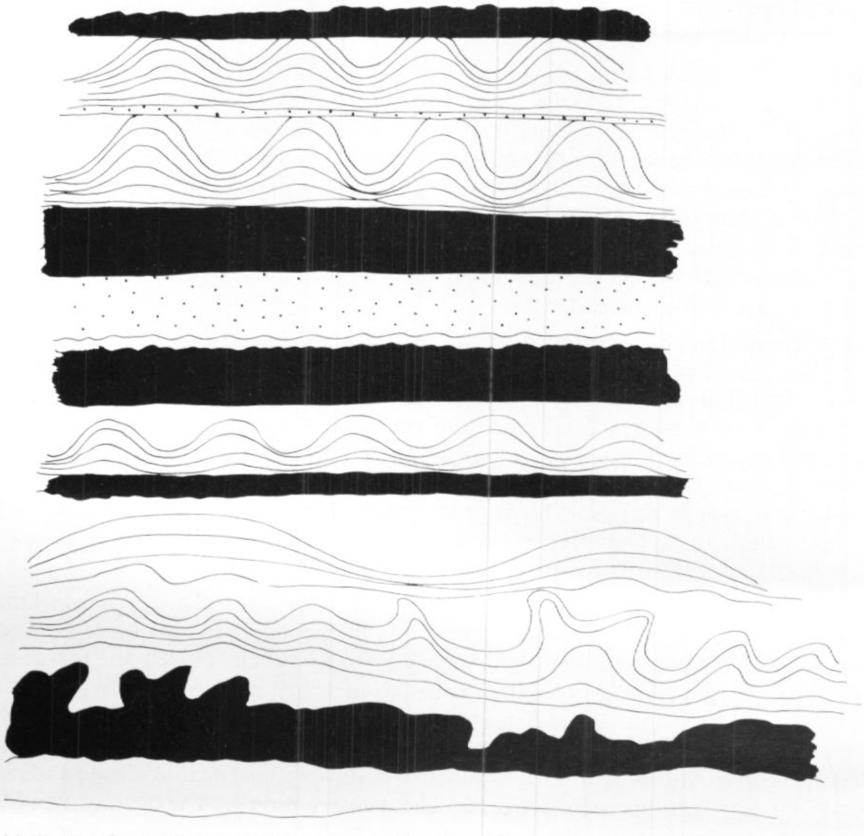

Fig. 7. Field sketch of convolute laminations in the Elephant Cove area, showing the constant size of convolutions in any particular set.

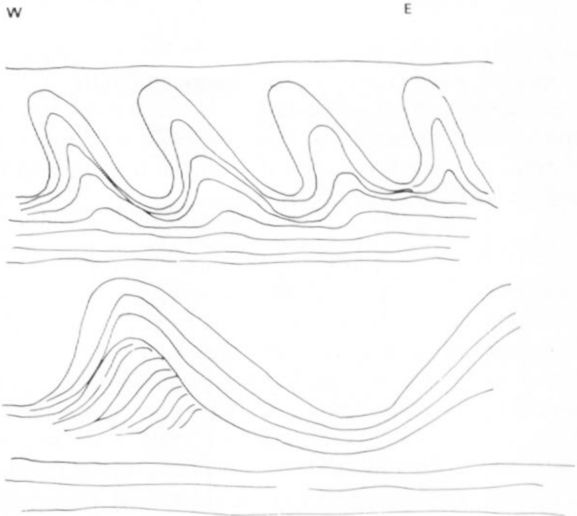

Fig. 8. Field sketch of convolute laminations in the Elephant Cove area. East to west down-current direction is indicated by cross lamination and overturning of anticlines.

crests in their upper parts and it is not uncommon for several small anticlines to underlie a corresponding single larger structure in the upper part of the bed (Fig. 7).

Signorini (1936) suggested that the difference in shape between crests and troughs could be used as a way-up criterion but in this area the convolutions have troughs which are often broader than the anticlines. However, truncation of laminations by subsequent erosion of the top of the bed could be used for this purpose. Several discrete series of convolutions may be superimposed in a single bed (Fig. 7), indicating that deformation of each set occurred independently. Fig. 8 shows the combination of convolution and cross lamination on the down-current flank of an anticline. In some beds the anticlines are not symmetrical (Fig. 8) but are overturned systematically towards the north-west quadrant, probably indicating a general down-current or down-slope direction.

Convolute laminations have formerly been considered to have resulted from gravity sliding in unconsolidated sediments but, since only the interior of a bed is affected in these examples, a post-depositional slide or slump mechanism cannot be invoked. Kuenen (1953) suggested that convolute laminations are formed from the deformation of current-ripple marks by a current exerting unequal pressure on troughs and crests, thus throwing the hydroplastic sediment into convolutions. Sanders (1960) believed that the shearing action of a current flowing over [illegible] cohesive sediment layer is sufficient to drag the layer into décollement-like convolutions. By nature of their origin these convolutions would tend to be highly irregular, whereas those in Fig. 6 show marked regularity of height, wave-length and shape.

The formation of convolute lamination is most probably controlled by a combination of current action and hydroplastic flow. The grains in a hydroplastic sediment are separated by a film of water which facilitates convolution. According to Migliorini (1950), the forces necessary for convolution could be generated by the expulsion of water from the lower part of the bed. ten Haaf (1956) suggested that the differential stresses are generated by current rippling, not of the fore-set type but containing a continuous undulating lamination. This type of rippling, exaggerated into convolutions by hydroplastic flow, could explain the magnitude and characteristic shape of the corrugations seen in Fig. 6, whilst interaction by the current would explain the regular wave-length (Fig. 7), the frequent interstratal erosion of the upper parts of the convolutions (Fig. 7) and the overturning of the crests in the same sense (Fig. 7).

Biogenetic structures

Sedimentary structures formed by the activity of organisms during periods of quiet sedimentation are very common in the pelitic units of the Cumberland Bay Formation. Four types of trace fossil have been recognized, their common association in the same pelitic units indicating that they are not mutually exclusive.

Chondrites

Chondrites, the commonest trace fossil in the Cumberland Bay Formation, occurs as colonies of branching tubes approximately 1 mm. thick. They are found in dark grey or black slates as fine, white to cream-coloured dendritic clusters, 3–4 cm. wide (Fig. 9a). In light grey siltstones the original tunnel infilling is often replaced and the colonies are dark grey to black in colour (Fig. 9b). The tunnels are circular in cross-section and, despite the intense deformation of the surrounding slates, they show only slight compression. The tunnel walls are smooth and appear to have a fairly constant diameter of 0·8–1·2 mm. (Fig. 9c). Fourth-order branching was the

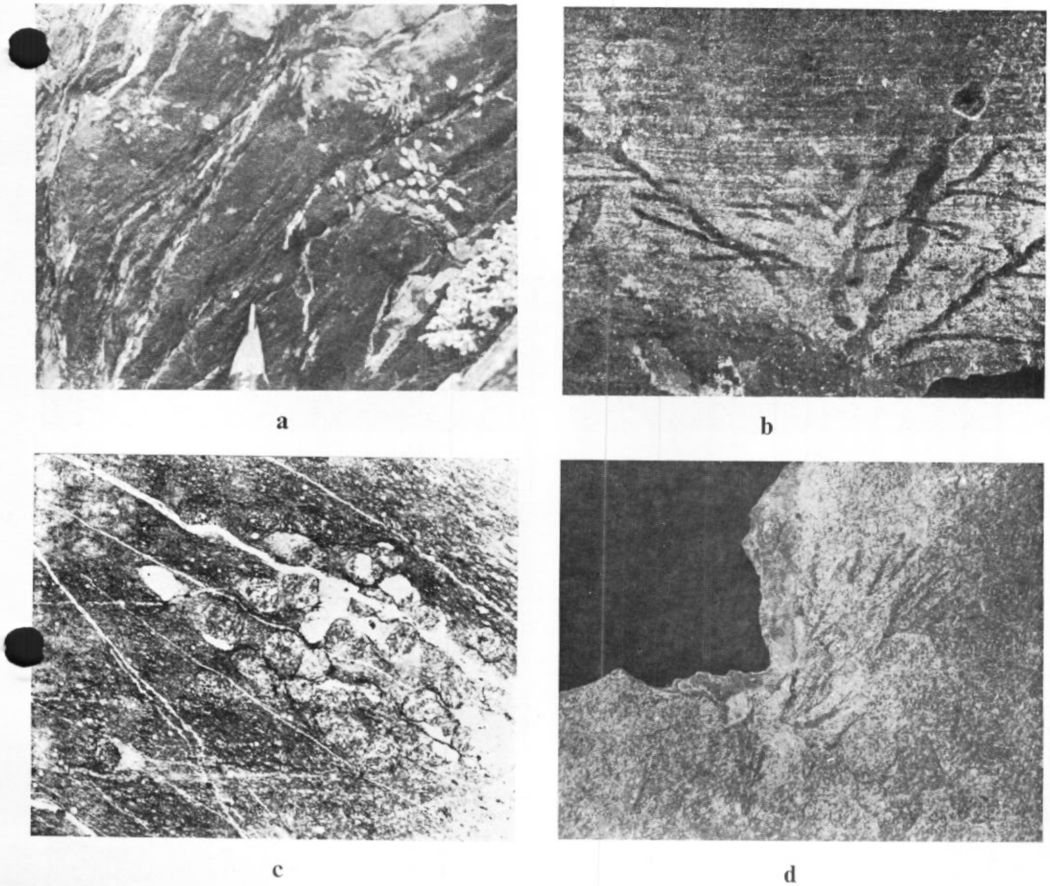

Fig. 9. a. White to cream-coloured *Chondrites* colony in a dark mudstone. The pencil is 0·7 cm. thick.
b. Dark grey *Chondrites* colony in a light grey siltstone. The original tunnel infilling has been replaced and the lateral branching shows a constant inter-branch angle of 30–40° (×1·5).
c. *Chondrites* tunnels in a cross-section showing constant diameter and undeformed state (M.1191.1; ordinary light; ×7·5).
d. Tectonically flattened *Chondrites* colony with an inter-branch angle of 20° (×2).

highest found but fifth- and sixth-order patterns have been recorded elsewhere (Simpson, 1957). The branching is lateral with a constant inter-branch angle of 30–40°. Fig. 9d shows a tectonically stretched colony in which the angle of branching has been reduced to 20° and the original tunnel infilling completely replaced. In addition to the common type of colony, much finer tunnels have been found with an average width of 0·2 mm. Like the wider tunnels, they appear to radiate down from a point on the surface, adjacent branches rarely crossing one another.

Simpson (1957) has suggested that the branched burrow system was excavated by a siphunculoid worm feeding on sediment by means of an extendable proboscis. *Chondrites* colonies in the Upper Aptian of Alexander Island (Taylor, 1967) were seen to radiate out from circular or kidney-shaped swellings of larger tubes. The tubes probably represented movement of the whole *Chondrites* structure, the swellings being formed when the organism rested on the surface. Taylor (1967) explained the absence of crossing branches by suggesting that all the tunnels were occupied by a part of the organism and he concluded that the tunnel systems were produced by an animal with many tentacles.

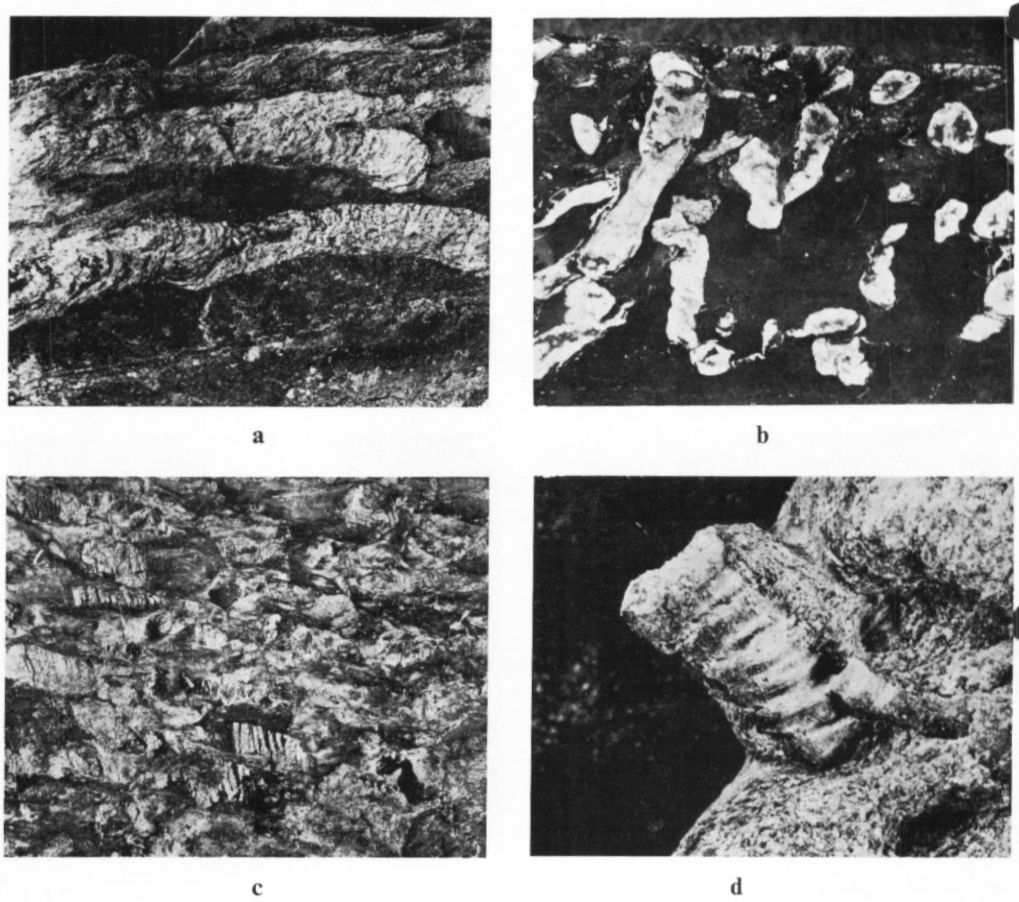

Fig. 10. a. *Zoophycus* burrows with segmented infilling (× 1).
b. Obliquely to sub-vertically inclined tubular burrows (× 1·5).
c. Tubular burrows with well-developed infilling segmentation lying parallel to the bedding (× 1).
d. Vermicular structure with well-developed segmentation (× 4).

Zoophycus

The trace fossil *Zoophycus* is a planar sheet-like burrow, 0·5–1 cm. in width and up to 20 cm. in length. The burrow is infilled by concave segments 0·5–1 mm. wide (Fig. 10a). These cream-coloured hemi-cylinders appear as crescentic lamellae in sections perpendicular to the bedding. In an intensely bioturbated 30 cm. thick E set, 25 *Zoophycus* burrows were counted in a 20 m. long section; the same section contained 25 *Chondrites* colonies. Burrows are generally orientated parallel to the bedding, suggesting a sediment-surface grazing pattern.

Zoophycus ranges from the Ordovician to Pliocene and, like other flysch trace fossils, is thought to indicate a deep-water environment. However, it has been found in sediments deposited in neritic or even estuarine conditions (Taylor, 1967). The most significant feature of the *Zoophycus* burrows, the arcuate lamellae, has been attributed to a rhythmic defaecation phenomenon (Wilckens, 1947) or an amalgamation of mud and faecal layers (Seilacher, 1964). The absence of animal shells in association with these burrows suggests that the trace fossils were formed by a soft-bodied animal such as a worm.

Tubular burrows

In the top 3 cm. of pelitic units, tubular burrows up to 4 cm. long are often found in association with *Zoophycus* and *Chondrites*. The burrows are circular in cross-section and range from 1 to 10 mm. in width; they occur as small and large tubes with average diameters of 2 and 7 mm., respectively. In a 3 cm. thick E set, an average density of 40 small burrows per 10 cm.^{2} was recorded. The burrows are generally obliquely to sub-vertically inclined to the bedding (Fig. 10b) but the wider forms are occasionally flat-lying (Fig. 10c). The burrows are characterized by transverse laminations up to 1 mm. thick, a segmentation that Greensmith (1956) attributed to annelids.

Vermicular structures

Vermicular structures are commonly found in light grey sandy mudstones and siltstones unlike the other trace fossils which generally occur in the fine-grained pelitic units. They are elliptical in cross-section, ranging in width from 2 to 4 mm., and weather out from the surrounding sediments to resemble small gastropods (Fig. 10d). This type of trace fossil is characterized by a distinct infilling segmentation with individual segments about 1 mm. wide. Similar vermicular structures described from the Fossil Bluff Formation of Alexander Island (Taylor, 1967) were believed to represent the trace of a soft-bodied worm or its faecal pellets. The pseudo-segmentation is so strongly developed in the vermicular structures of north-western South Georgia that a faecal pellet origin seems more feasible.

Slump structures

Slump structures are typically developed in turbidite sequences because rapid sedimentation leads to instability. However, large-scale slumping was not seen in north-western South Georgia and only a few small-scale "slump-like" structures were recorded. These structures are not typical of the slump folds defined by Helwig (1970) and usually develop when the base of a thick sandstone unit is ruptured, allowing the underlying sandstones and mudstones to flow upwards. The resulting chaotic mixture of sandy and muddy sediments is generally restricted to a thickness of 2 m. and rarely extends more than a few metres along the bedding. This type of disturbance probably develops in response to localized water saturation of small areas of sediment. The water facilitates sediment flow whilst the surrounding layers are not affected.

Compaction faults are very common in this type of unstable environment and are well displayed in the thin-bedded distal turbidites of the Cumberland Bay Formation (Fig. 11).

Injection structures

Sandstone dykes are widely developed in north-western South Georgia and typify the unstable environment which predominates in geosynclinal areas of turbidite sedimentation

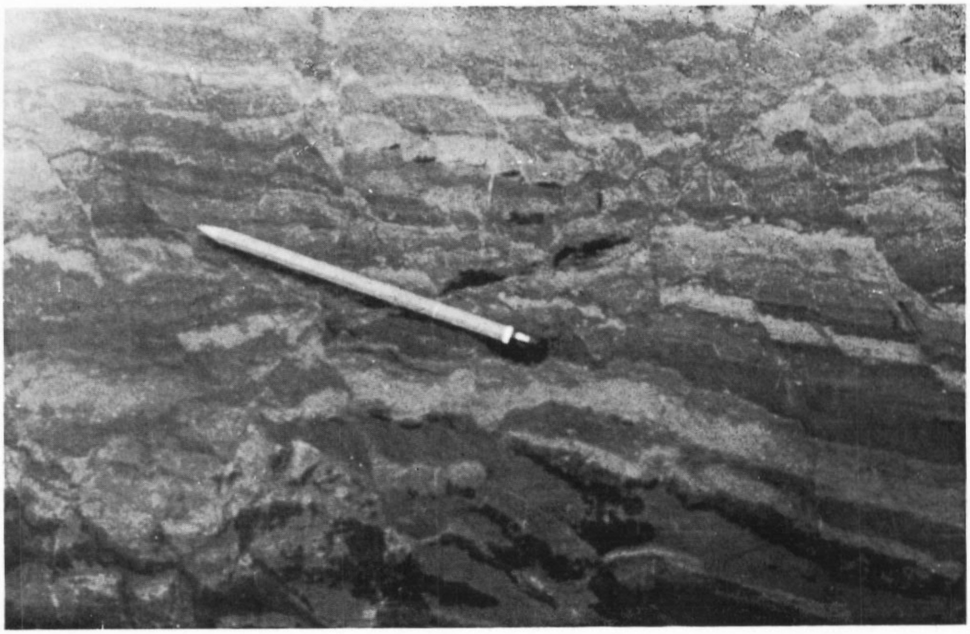

Fig. 11. Compaction faults in thin-bedded distal turbidites.

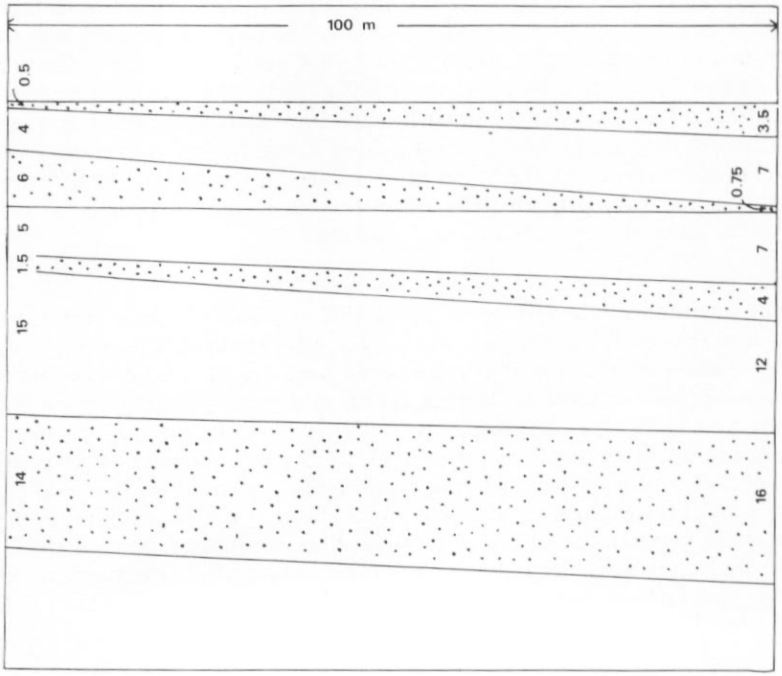

Fig. 12. Compensatory thickening and thinning in a dyke swarm exposed along the south side of Elephant Cove.

(Helwig, 1970). The dykes trend roughly east–west but, in the Elephant Cove area, subsequent F3 re-folding has caused slight variation. Individual dykes range in width from 1 to 250 cm. but the majority are between 10 and 50 cm. thick. Dykes generally occur in swarms of up to 15, spread over a distance of 20–50 m. Although dyke swarms can be traced for several kilometres, individual dykes invariably die out along the strike over relatively short distances. The total thickness of the dykes within the swarm remains fairly constant as the narrowing of one dyke is often compensated by a corresponding thickening in adjacent dykes (Fig. 12). The injected material is usually medium-grained volcaniclastic greywacke derived from source horizons lower in the succession. Dykelets and stringers emanating from massive sandstone source horizons contain a high proportion of brecciated slate clasts. These clasts, which are generally surrounded by bleached aureoles, are aligned parallel to the dyke margins and concentrated in the central zone. The stringers range from 0·5 to 1 cm. in width and show frequent anastomosing bifurcation; joining together upwards they form substantial intrusive bodies. The pelitic horizons are occasionally mobilized sufficiently to flow upwards as injection structures. At Klutschak Point, a 20 cm. wide dyke of brecciated slate clasts set in a dark grey mudstone matrix cuts up through 5 m. of distal sub-facies turbidites before terminating irregularly amongst thick pelitic units. Flow differentiation is well developed with a 6 cm. wide outer

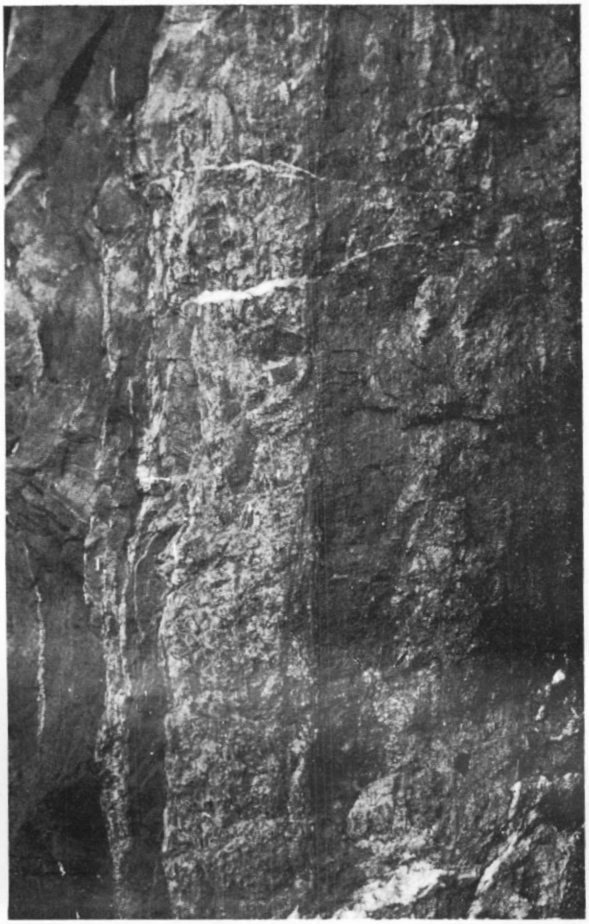

Fig. 13. Flow differentiation in mudstone dyke, Klutschak Point.

zone of lighter mudstone containing smaller clasts than the central zone (Fig. 13). Flow differentiation in the sandstone dykes generally gives rise to narrow fine-grained margins with coarser central zones.

Sedimentary sills are cut by the east–west trending dyke system. Dyke injection is thought immediately to post-date the intrusion of sedimentary sills, because in the Elephant Cove area a thick sedimentary dyke cuts an incompletely lithified sill, resulting in a chaotic mixture of the two types of sediment. Sills are distinguished from the surrounding sediments by their tendency to transgress the bedding and their lack of grading. Similarities in lithology and distribution suggest common source horizons for both sills and dykes. The sills differ from the dykes in maintaining a fairly uniform width along their strike and by being subject to the same stress fields as the surrounding sediments; hence quartz veins cut sills and country rocks alike but are terminated at the margins of dykes. The sedimentary sills are generally highly tuffaceous with well-developed flow banding emphasized by pale-coloured, prehnitized ash fragments. They range in thickness from 50 to 250 cm. but few exceed 150 cm. in width. Dykes and sills in the Elephant Cove area are commonly paralleled by one or more thick quartz veins. The resulting composite intrusive body may attain a total thickness in excess of 3 m.

Two phases of sedimentary dyke intrusion have been recognized in north-western Sou

Fig. 14. Displacement of lithological boundaries by fault movement along a sedimentary dyke wall.

Georgia: the first trends west-north-west and in the coastal area to the north-west of the Samuel Islands it is cut by a major swarm with an east–west strike. Although both sets of dykes are cut by normal and thrust faults, implying that intrusion took place before the main fracture system developed, fault movement along the dyke walls has displaced lithological boundaries by up to 30 cm. (Fig. 14). As there is no apparent distortion of the dyke sediments, dyke intrusion probably followed an initial period of minor faulting. Almost all dykes are cross-cut by quartz veins, indicating that later tensional movement developed preferentially along the plane of intrusion. The thickness and frequency of quartz veining bear a close relationship to the thickness of the sandstone dyke. The relationship between intrusion and folding is seen in coastal cliffs to the south of Anvil Stacks, where dykes cut across the first folds with no apparent deformation, thus suggesting a post-F1 age. In Wilson Harbour, sedimentary dykes injected along first cleavage planes on the northern margin of Schrader Glacier have been folded about F3 hinges, indicating that intrusion occurred before the final fold episode (Fig. 15).

Calcareous concretions

The greywackes of north-western South Georgia are characterized by an abundance and variety of calcareous concretions randomly distributed through all lithologies. Nodules in the sandstones range in shape from ellipsoidal to spheroidal and in diameter from 3 to 300 cm. The contacts of the nodules with the enclosing sandstone are generally well defined but some nodules merge imperceptibly into the host sandstone. Relict sedimentary structures, especially cross-lamination and parallel lamination, are often preserved within a concretion, indicating that calcite is of replacement origin. Distortion of bedding around the nodule may be due to differential compaction prior to complete lithification.

Nodules in the finer-grained sediments are ellipsoidal or tabular in shape and are composed of a dark grey, brittle calcitic mudstone. They range in size from small lenses with a diameter of 2 cm. to massive tabular bodies 6 m. long and 0·4 m. thick formed by calcification of a

Fig. 15. Folding of sedimentary dykes about F3 hinges on the northern margin of Schrader Glacier. The central dyke is 20 cm. thick.

Fig. 16. Re-orientation of a calcareous concretion into parellelism with F1 cleavage planes forming an asymmetric fold in the host sandstone.

complete pelitic horizon. These concretions have sharp contacts with the enclosing mudstones, often falling out after erosion of the surrounding sediment and leaving lens-shaped holes.

Where F1 deformation is minimal, the concretions retain their original attitude with their long axes parallel to bedding. Most nodules have suffered re-orientation into parallelism with the F1 cleavage, rotation of the larger nodules sometimes forming asymmetric folds in the host sandstone and immediately adjacent sediments (Fig. 16).

Horne and Taylor (1969) suggested that similar concretions in Alexander Island were formed by the accretion and precipitation of calcium carbonate around some nucleus of deposition. They believed that the origin of these concretions was related to the grain-size and permeability of the host rock, and the migration of carbonate ions in solution. In both Alexander Island (Horne and Taylor, 1969) and Colombia (Weeks, 1957), the concretions frequently contain organic nuclei. The decay of these nuclei is thought to release ammonia and amin[illegible] resulting in a local rise in pH (Weeks, 1957). This may be sufficient to precipitate calcium carbonate from the circulating pore fluid in the uncompacted sediment. Although no obvious organic nuclei were found in the concretions of north-western South Georgia, soft-bodied organisms may have been involved. Intense bioturbation may account for the complete calcification of pelitic horizons and the formation of large tabular bodies broadly conformable with the bedding. The source of the carbonate necessary for nodule formation may be related to the release of carbon dioxide through bacterial activity (Chilingar and others, 1967).

CONCLUSIONS

Variation in lithology within the Cumberland Bay Formation has been interpreted in terms of proximal and distal deposition. On the basis of sandstone/shale ratio, the turbidite sequence is divided into relatively proximal and distal members. Regular fluctuations in facies type indicate that turbidite deposition in north-western South Georgia was controlled by a cyclical mechanism. Cyclic deposition is attributed to variation in the intensity of volcanic activity (Stone, 1980) or supply of sediment from more than one volcanic centre.

Although the Cumberland Bay Formation is divided into units of varying proximality, the bulk of the sediments lie between the two extremes of proximal and distal deposition. These turbidites are therefore relatively proximal and distal members of a facies, which in terms of absolute proximality is thought to be medial. Current-ripple laminations, typically developed in a medial depositional environment, are widespread in north-western South Georgia and provide valuable palaeo-environmental data. Small-scale current-ripple laminations indicate medial deposition from a turbidity current of moderate velocity with a flow depth of 3–4 cm. They also suggest that the dominant dispersal of the Cumberland Bay Formation was towards the north-west quadrant, a direction supported by the north-westerly inclination of the majority of flame structures and the systematic overturning of convolute laminations in this direction. The abundance of small-scale slump and injection structures testifies to the instability of this thick, rapidly deposited turbidite succession.

ACKNOWLEDGEMENTS

Helpful advice and criticism was received from Drs. C. M. Bell, P. Stone and P. W. G. Tanner. Professor A. Williams kindly provided facilities in the Department of Geological Sciences, University of Birmingham. Dr. R. J. Adie gave much editorial assistance. Thanks are also due to my colleagues A. E. Gannon, J. Flick, R. N. Mortimore, D. Orchard and D. Habgood for their invaluable assistance in the field.

MS. received 8 January 1976

REFERENCES

Allen, J. R. L. 1970*a*. *Physical processes in sedimentation*. London, George, Allen and Unwin Ltd.

———. 1970*b*. A quantitative model of climbing ripples and their X-laminated deposits. *Sedimentology*, **14**, Nos. 1/2, 5–26.

Bouma, A. H. 1962. *Sedimentology of some flysch deposits: a graphic approach to facies interpretation*. Amsterdam and New York, Elsevier Publishing Company.

Chilingar, G. V., Bissell, H. J. *and* K. H. Wolf. 1967. Diagenesis of carbonate rocks. (*In* Larsen, G. *and* G. V. Chilingar, *ed. Developments in sedimentology. Vol. 8. Diagenesis in sediments*. Amsterdam, London, New York, Elsevier Publishing Company, 179–322.)

Clayton, R. A. S. 1981. A preliminary investigation of the geochemistry of greywackes from South Georgia. *British Antarctic Survey Bulletin*, No. 51, 89–109.

Dalziel, I. W. D., Dott, R. H., Winn, R. D. *and* R. L. Bruhn. 1975. Tectonic relations of South Georgia island to the southernmost Andes. *Geol. Soc. Am. Bull.*, **86**, No. 7, 1034–40.

Enos, P. 1969. Anatomy of a flysch. *J. sedim. Petrol.*, **39**, No. 3, 680–723.

Greensmith, J. T. 1956. Sedimentary structures in the Upper Carboniferous of north and central Derbyshire, England. *J. sedim. Petrol.*, **26**, No. 4, 343–55.

Riggs, G. B. *and* L. D. Kulm. 1970. Sedimentation in Cascadia Deep-sea Channel. *Geol. Soc. Am. Bull.*, **81**, No. 4, 1361–84.

Haner, B. E. 1971. Morphology and sedimentation of Redondo Submarine Fan, southern California. *Geol. Soc. Am. Bull.*, **82**, No. 7, 2413–32.

Harms, J. C. *and* R. K. Fahnestock. 1965. Stratification, bedforms and flow phenomena (with an example from the Rio Grande). (*In* Middleton, G. V., *ed.* Primary sedimentary structures and their hydrodynamic interpretation. *Spec. Publs Soc. econ. Palaeont. Miner., Tulsa*, No. 12, 84–115.)

Helwig, J. 1970. Slump folds and early structures, north-eastern Newfoundland Appalachians. *J. Geol.*, **78**, No. 2, 172–87.

High, L. R. *and* M. D. Picard. 1974. Reliability of cross-stratification types as paleocurrent indicators in fluvial rocks. *J. sedim. Petrol.*, **44**, No. 1, 158–68.

Horne, R. R. *and* B. J. Taylor. 1969. Calcareous concretions in the Lower Cretaceous sediments of south-eastern Alexander Island. *British Antarctic Survey Bulletin*, No. 21, 19–32.

Jopling, A. V. 1966. Some principles and techniques used in reconstructing the hydraulic parameters of a paleo-flow regime. *J. sedim. Petrol.*, **36**, No. 1, 5–49.

Kelling, G. *and* E. K. Walton. 1957. Load-cast structures: their relationship to upper-surface structures and their mode of formation. *Geol. Mag.*, **94**, No. 6, 481–90.

Kimura, T. 1966. Thickness distribution of sandstone beds and cyclic sedimentations in the turbidite sequences at two localities in Japan. *Bull. Earthq. Res. Inst. Tokyo Univ.*, **44**, No. 1, 561–607.

Kuenen, P. H. 1953. Significant features of graded bedding. *Bull. Am. Ass. Petrol. Geol.*, **37**, No. 5, 1044–66.

———. *and* H. W. Menard. 1952. Turbidity currents, graded and non-graded deposits. *J. sedim. Petrol.*, **22**, No. 1, 83–96.

Lamont, A. 1938. Contemporaneous slumping and other problems at Bray Senis, Ordovician and Lower Carboniferous horizons, County Dublin. *Proc. R. Ir. Acad.*, **95**, No. 1, 1–32.

McCabe, P. J. *and* B. Waugh. 1973. Wenlock and Ludlow sedimentation in the Austwick and Horton-in-Ribblesdale inlier, north west Yorkshire. *Proc. Yorks. geol. Soc.*, **39**, No. 21, 445–70.

Migliorini, C. I. 1950. Dati a conferma della sedimentazioni delle arenarie del Macigno. *Memorie Soc. tosc. Sci. nat.*, Ser. A, **97**, No. 1, 3–15.

Nederlof, F. H. 1959. Structure and sedimentology of the Upper Carboniferous of the upper Pisuerga valleys, Cantabrian Mountains, Spain. *Leid. geol. Meded.*, **24**, 603–703.

Potter, P. E. *and* F. J. Pettijohn. 1963. *Paleocurrents and basin analysis.* Berlin, Göttingen, Heidelberg, Springer-Verlag.

Sanders, J. E. 1960. Origin of convolute laminae. *Geol. Mag.*, **97**, No. 5, 409–21.

Seilacher, A. 1964. Biogenic sedimentary structures. (*In* Imbrie, J. *and* N. Newell, *ed. Approaches to paleoecology*. New York, London, Sydney, John Wiley and Sons, Inc., 296–316.)

Shrock, R. R. 1948. *Sequence in layered rocks: a study of features and structures useful for determining top and bottom or order of succession in bedded and tabular rock bodies.* New York, Toronto and London, McGraw-Hill Book Company, Inc.

Signorini, P. 1936. Determinazione del senso di sedimentazione degli strati nelle formazione arenacee dell'Appennino Settentrionale. *Boll. Soc. geol. ital.*, **55**, 259–66.

Simpson, S. 1957. On the trace-fossil *Chondrites*. *Q. Jl geol. Soc. Lond.*, **112** (for 1956), Pt. 4, No. 448, 475–96.

Skidmore, M. J. 1972. The geology of South Georgia: III. Prince Olav Harbour and Stromness Bay ar[illegible] *British Antarctic Survey Scientific Reports*, No. 73, 50 pp.

Stone, P. 1980. The geology of South Georgia: IV. Barff Peninsula and Royal Bay areas. *British Antarctic Survey Scientific Reports*, No. 96, 45 pp.

Taylor, B. J. 1967. Trace fossils from the Fossil Bluff Series of Alexander Island. *British Antarctic Survey Bulletin*, No. 13, 1–30.

ten Haaf, E. 1956. Significance of convolute lamination. *Geologie Mijnb.*, **18**, No. 6, 188–94.

Trendall, A. F. 1959. The geology of South Georgia: II. *Falkland Islands Dependencies Survey Scientific Reports*, No. 19, 48 pp.

Unrug, R. 1963. Istebria Beds—a fluxoturbidity formation in the Carpathian Flysch. *Roczn. pol. Tow. geol.*, **33**, No. 1, 49–92.

Walker, R. G. 1966. Shale Grit and Grindslow Shales: transition from turbidite to shallow water sediments in the Upper Carboniferous of northern England. *J. sedim. Petrol.*, **36**, No. 1, 90–114.

———. 1967. Turbidite sedimentary structures and their relationship to proximal and distal environments. *J. sedim. Petrol.*, **37**, No. 1, 25–43.

Walton, E. K. 1967. The sequence of internal sedimentary structures in turbidites. *Scott. J. Geol.*, **3**, No. 2, 306–17.

Weeks, L. G. 1957. Origin of carbonate concretions in shales, Magdalena Valley, Colombia. *Bull. geol. Soc. Am.*, **68**, No. 1, 95–102.

Wilckens, O. 1947. Paläontologische und geologische Ergebnisse der Reise von Kohl-Larsen (1928–29) nach Süd-Georgien. *Abh. senckenb. naturforsch. Ges.*, No. 474, 66 pp.

Wood, A. *and* N. T. Smith. 1959. The sedimentation and sedimentary history of the Aberystwyth Grits (Upper Llandoverian). *Q. Jl geol. Soc. Lond.*, **114**, No. 1, 163–95.