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UDGIVNE AF
KOMMISSIONEN FOR VIDENSKABELIGE UNDERSØGELSER I GRØNLAND
Bd. 206 • Nr. 1

DEVONIAN SEDIMENTS OF EAST GREENLAND I

INTRODUCTION, CLASSIFICATION OF SEQUENCES, PETROGRAPHIC NOTES

BY

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J. NICHOLSON AND A. K. YEATS

WITH 24 FIGURES, 2 PHOTOS AND 6 TABLES

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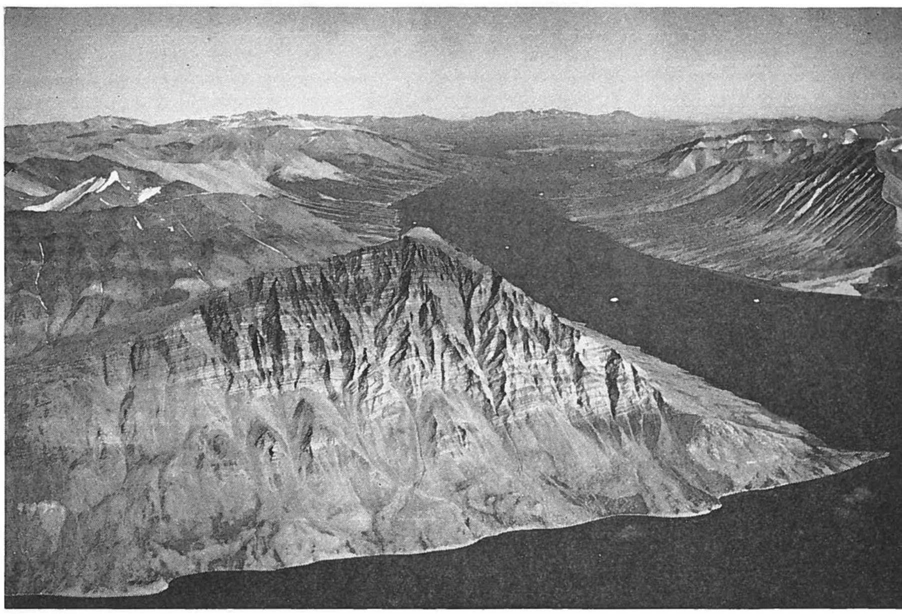

Frontispiece. In the foreground is Kong Oscars Fjord, and Vega Sund extends into the distance. Geographical Society Ø forms the left side of the photograph, with the southwest peak of Svedenborgs Bjerg (1548 m) prominent nearest to the camera in the centre. Devonian sediments form most of the mountains in the foreground and middle distance, belonging largely to the Kap Kolthoff Supergroup. The clearly banded outcrops on the face of Svedenborgs Bjerg are sandstones, deposited on alluvial fans, by rivers flowing from source mountains to the west (behind the camera). The banding results from regular shifting of the river distributary patterns. The light-coloured, relatively smooth mountains beyond Svedenborgs Bjerg are formed of sandstones that were deposited on a major alluvial plain by rivers flowing from the north (to the left of the photograph). (LAUGE KOCH expedition photograph, numbered 4105—1950).

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BIANCO LUNOS BOGTRYKKERI A/S

Contents

Abstract

The object of this project has been to apply the methods of detailed sedimentology to the Devonian rocks of East Greenland. This work has been based on the investigations of palaeontology, stratigraphy and structure carried out by the major series of Danish expeditions that was active in the area between 1926 and 1958.

The results of this project are being published in the various numbers of this volume. This number provides some introduction.

Four field parties spent three summers working in the area.

A standard method of recording sedimentary log observations depended on use of printed forms that were read by machine after the end of the field season. The resulting data were then available for a variety of computer-based analyses.

Multivariate analytical techniques were used in arriving at a classification of standard (usually 10 m) lengths into which all sedimentary logs were divided. The resulting thirty-one classes have been used throughout the project to describe variation in sediment types.

Certain petrographic features are described that benefit from general consideration, as compared with the local analysis presented in later numbers of this volume. These features include the types of clasts in the conglomerates and sandstones, the petrology of the rare limestones, and the petrology of concretions. The distribution and origin of colouring of the sediments are discussed, and some clay mineral analyses are presented.

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1. THE AREA AND PREVIOUS WORK

It was not until 1870 that an expedition first penetrated the East Greenland drift ice (Fig. 1), and discovered the existence of an extensive fjord region of ice-free land, north and south of the latitude 73° N.

In 1899, NATHORST's Swedish expedition explored the fjord network (Fig. 2) and made many discoveries, including the first fossils of Devonian age.

The year 1926 saw the first of Dr. LAUGE KOCH's remarkable series of expeditions that worked in this area, and also the first of the expeditions from the University of Cambridge (WORDIE, 1927). This work firmly established the existence of a major area of non-marine Devonian sediments unconformably overlying deformed Lower Palaeozoic rocks.

In the following years, the Devonian rocks of East Greenland became increasingly famous for the enormous quantities of fossil vertebrate materials which they yielded. This material, collected mainly on KOCH's expeditions but also on Norwegian expeditions, created major scientific interest through the publications of HEINTZ, JARVIK, SÄVE-SÖDERBERGH, STENSIÖ and others.

Dr. HEINRICH BÜTLER, of Schaffhausen, Switzerland, working as a member of Dr. LAUGE KOCH's expeditions from 1933 to 1957, carried out the major stratigraphical and structural work on the Devonian areas. His detailed reports (listed in BÜTLER, 1959) described the great thickness of the successions, the local occurrence of strongly angular unconformities within the Devonian sequences, and the existence of contemporaneous volcanic and plutonic igneous bodies. Knowledge of the geology of this area, as gathered by BÜTLER and others on KOCH's expeditions, is admirably summarised by HALLER (1971).

It is this work which has formed the foundation of our investigations. It has been our intention to apply systematically the techniques of detailed sedimentary analysis that have been developed largely since the end of KOCH's expeditions. We aimed to find out more about the accumulation of a sedimentary succession which BÜTLER had shown to be the result of unusually active tectonic circumstances.

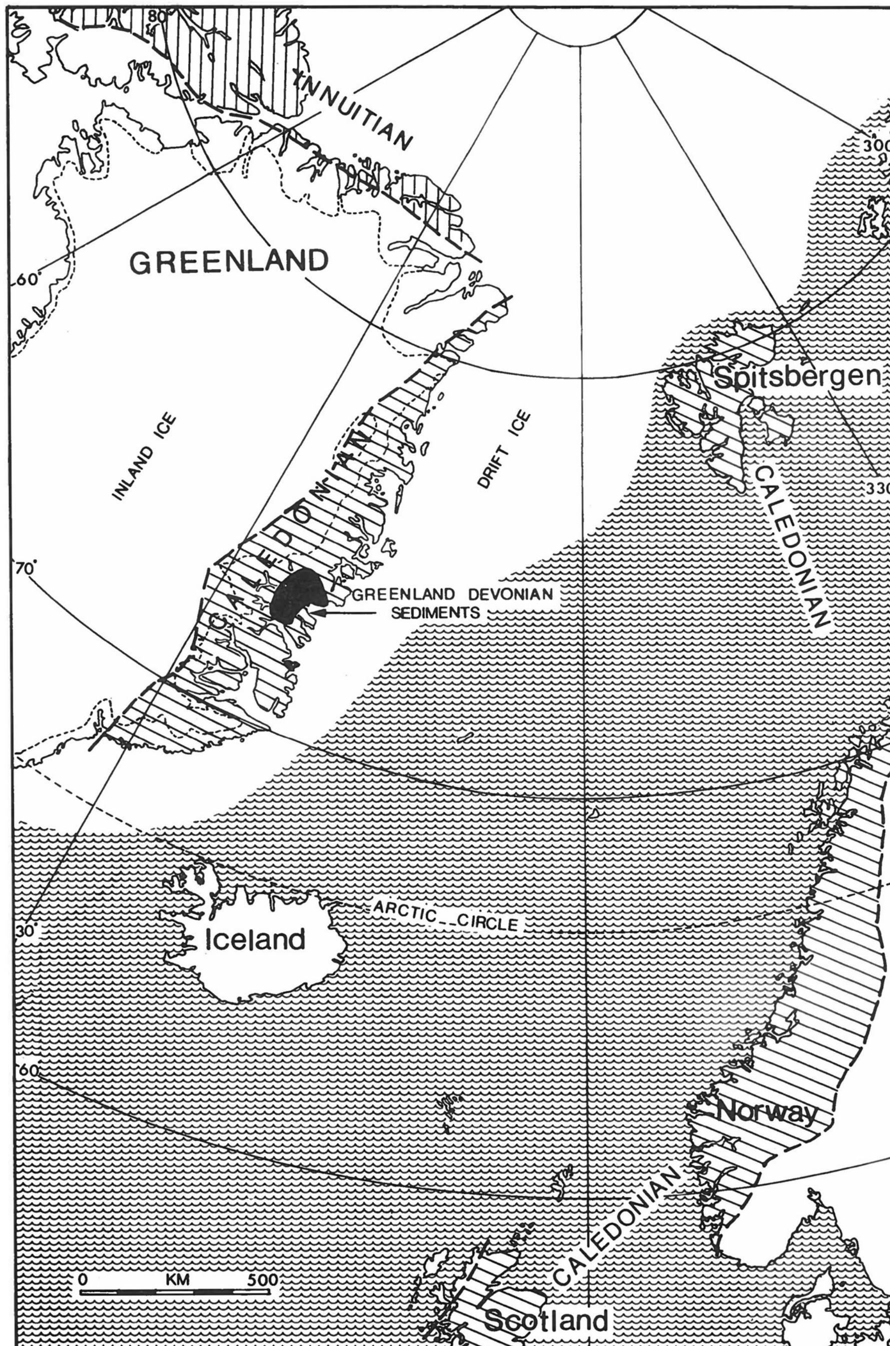

Fig. 1. Location of the area of Devonian sediments in East Greenland, in relation to the northern most Atlantic Ocean. Oblique ruling shows the land areas with Palaeozoic folding.

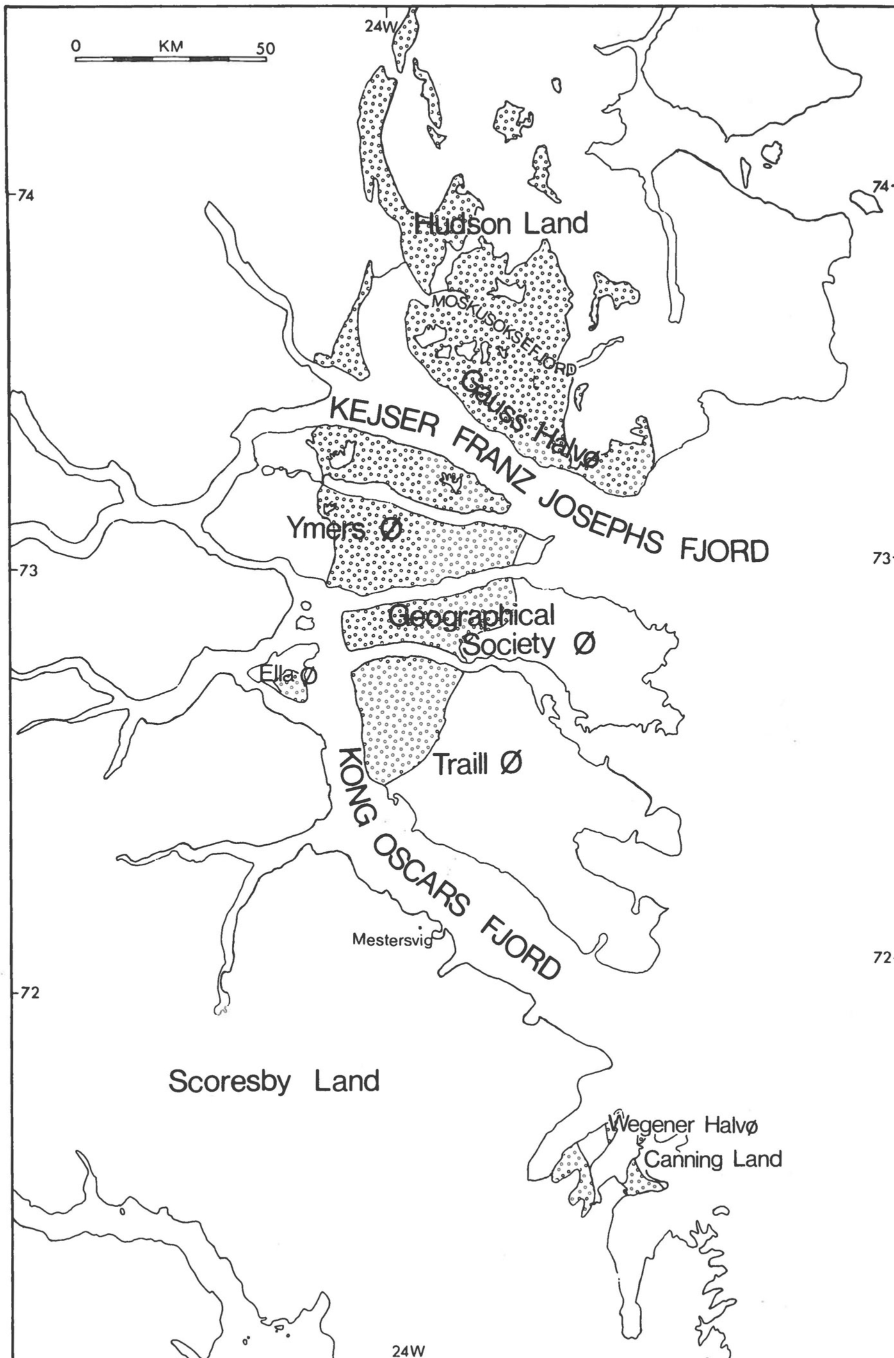

Fig. 2. The fjord area of Central East Greenland, showing areas of Devonian outcrops, and the most important place names.

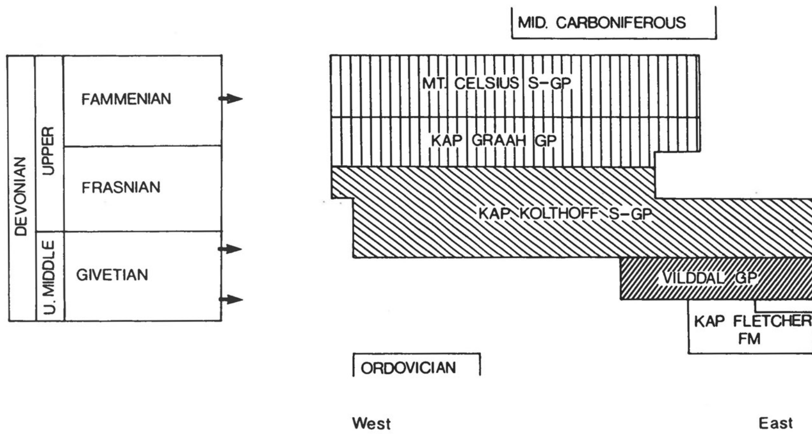

Fig. 3. Summary of the main Devonian lithostratigraphic units of East Greenland, and their ages. Relationships to older and younger rocks are also shown. 'VILDDAL GP' should be 'VILDDAL S–GP'.

2. STRATIGRAPHICAL OUTLINE, PRESENTATION, FIELD ORGANIZATION AND ACKNOWLEDGEMENTS

BÜTLER's latest view (1959, 1961) of the stratigraphy of the Devonian rocks of East Greenland formed our starting point.

Above the volcanic Kap Fletcher Formation, we have adopted a division into four major stratigraphic units (Fig. 3) applicable over the whole area. All the names are old ones, used by BÜTLER, although we have used the unit terms Supergroup and Group rather than Series, because these terms are now generally preferred for the purposes of rock stratigraphy (HARLAND and others, 1972).

We use the terms Mt. Celsius and Kap Graah for units which are more or less the same as those used by BÜTLER. Our use of the terms Kap Kolthoff and Vilddalen is more extensive than that of BÜTLER.

The ages of these units, and the details of our work on them, will be discussed in three stratigraphical papers which are to follow this one. The subjects of these papers (Fig. 4) will be:

1) The Eastern Sequence
2) The Western Sequence
3) The Central Sequence

Each of these three papers is based, to a major extent, on the work of one of the graduate students working under the supervision of FRIEND:

Eastern sequence (ALEXANDER-MARRACK): Vilddal Supergroup, eastern parts of Kap Kolthoff Supergroup.

Western sequence (YEATS): part of Kap Kolthoff Supergroup.

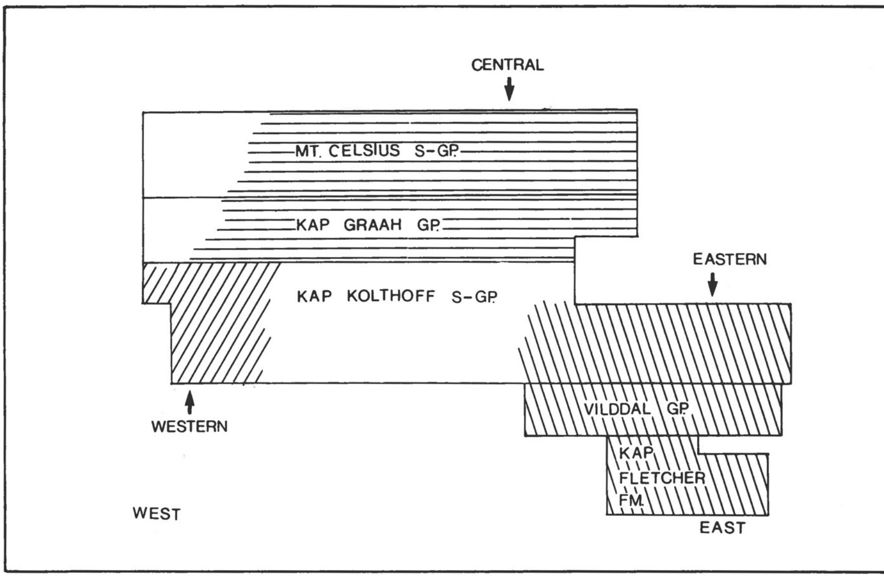

Fig. 4. Diagram showing the three main sequences studied in relation to the main Devonian lithostratigraphic units of East Greenland.
'VILDDAL GP' should be 'VILDDAL S–GP'.

Central sequence (NICHOLSON): northern part of Kap Graah Group and Mt. Celsius Supergroup.

FRIEND contributed field results to each of these papers, and has also had the ultimate responsibility for rearranging and preparing this work for publication. Miss ANNE SWITHINBANK has redrawn the figures and helped in many ways with the editorial work.

These regional papers will be preceded by this present one, and by a paper on "Sedimentary Structure and Fossils".

In these general papers, we describe certain specific studies, for instance involving numerical surveys, that were carried out by individuals using data collected by themselves. These studies are reported by reference to the eastern, central and western areas (Figs. 4, 5).

Our work was carried out on three summer expeditions (1968, 1969 and 1970), and brief accounts giving dates, and comments on conditions, have been published (FRIEND, 1969a, 1970, 1971). Each year we flew into Mesters Vig (Fig. 2) by charter-plane from Iceland, and then continued to Ella Ø by Danish Air Force Catalina. Thereafter we worked in parties of two to four men, moving by inflatable rubber-boat (FRIEND, 1969b). Fuel for our outboards was parachuted to us on one occasion beside Moskusoksefjord by the British Royal Air Force. Some idea of our coverage of the area may be gained from our map of campsites (Fig. 6).

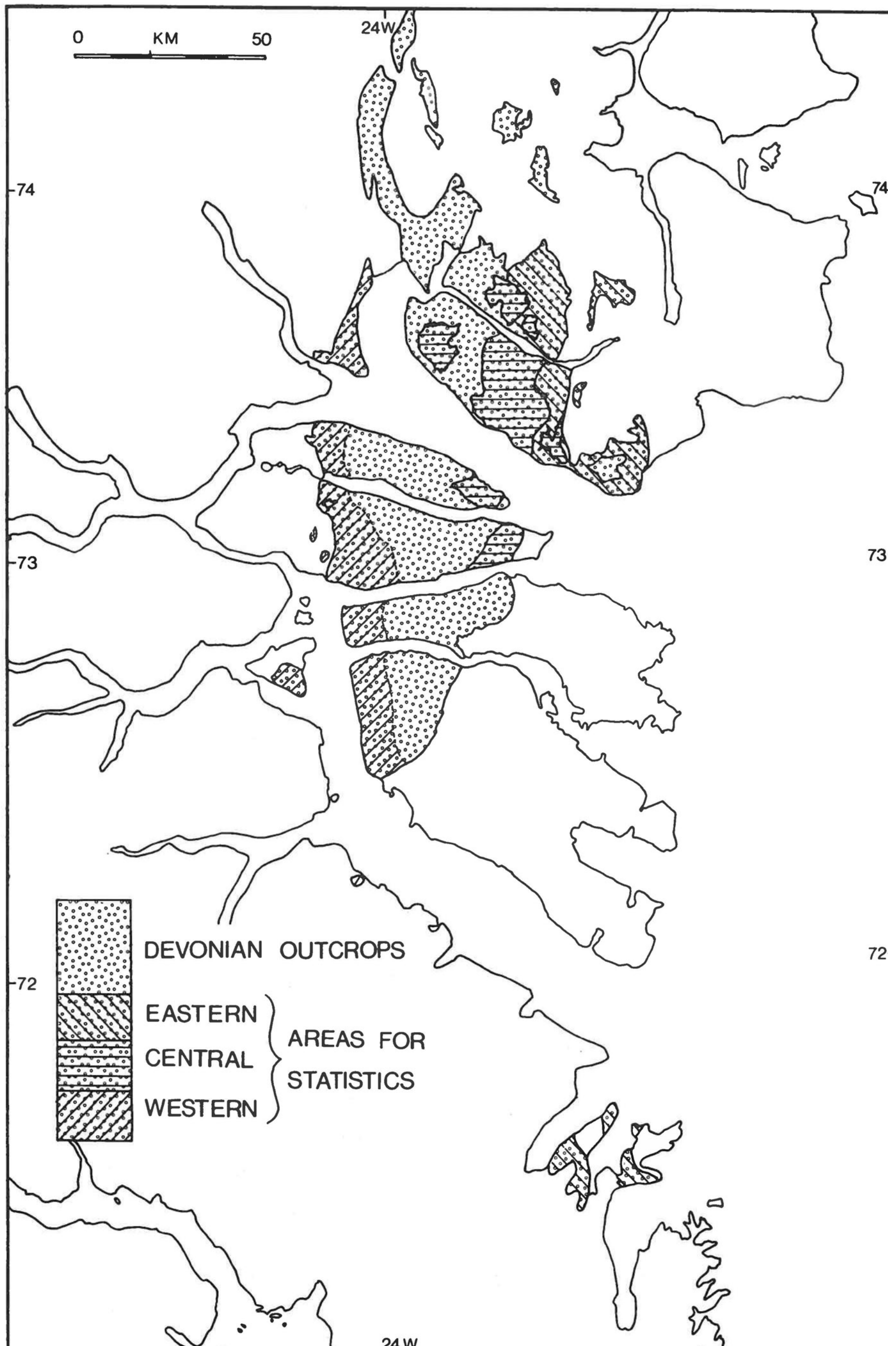

Fig. 5. Map showing the areas in which the three special studies were carried out, and their relationships to the Devonian outcrop area as a whole.

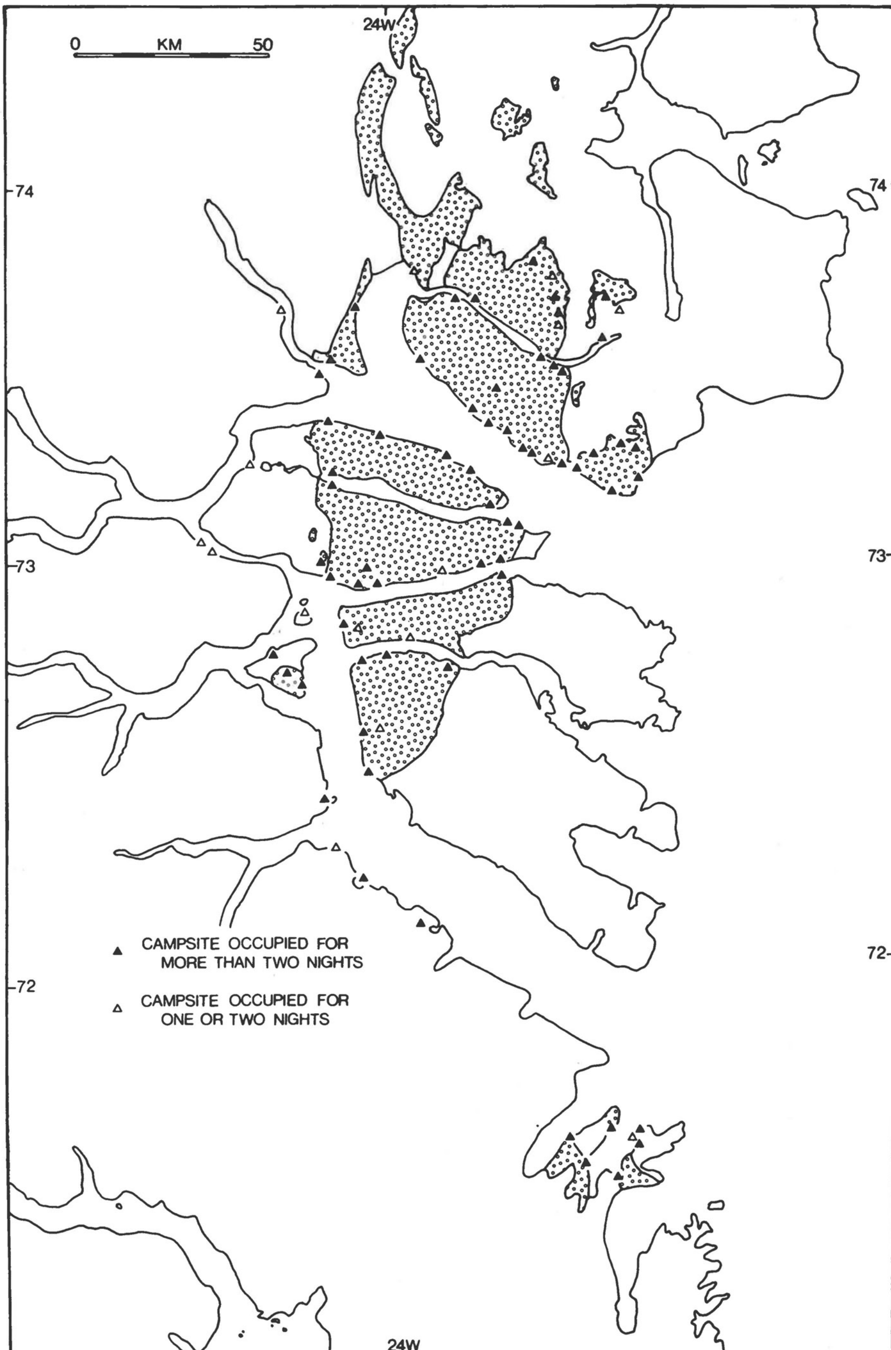

Fig. 6. Map designed to give some indication of the coverage achieved in the Devonian outcrop area.

Below we list the members of our expeditions:

1968:

P. D. ALEXANDER-MARRACK, P. F. FRIEND, J. S. HILL, E. M. HIMSWORTH, J. V. C. HOWES, I. KNIGHT, J. NICHOLSON, M. PARR, R. W. PATTULLO, A. M. SPENCER, A. K. YEATS.

1969:

P. D. ALEXANDER-MARRACK, K. C. ALLEN, P. BIBBY, P. F. FRIEND, I. KNIGHT, J. NICHOLSON, J. G. PAREN, G. P. SIMMONS, L. G. TAYLOR, A. K. YEATS.

1970:

P. D. ALEXANDER-MARRACK, P. H. COSLETT, P. F. FRIEND, D. T. MELDRUM, J. NICHOLSON, G. PATTERSON, L. D. SIDDALL, G. P. SIMMONS, D. E. SMITH, K. SWETT, R. H. THOMAS, A. K. YEATS.

The major grant towards the field costs of our work was made by the British Natural Environment Research Council. In addition to this, all the members of our expeditions made personal financial contributions, and grants were received from the Shell International Petroleum Company Limited, the Mount Everest Foundation and the John Spedan Lewis Trust for the Advancement of the Natural Sciences.

In Cambridge, our home was the Scott Polar Research Institute, and we would like to acknowledge the great help provided by Dr. G. de Q. ROBIN and many other members of the Institute. Professor H. B. WHITTINGTON and staff of the Department of Geology, University of Cambridge have also provided support, and a base for the writing up of our work. We wish particularly to acknowledge the help of Mr. W. B. HARLAND, whose Arctic methods and scientific example we followed to a large extent.

Many Danish organisations provided help at different stages. These include Civilair, Grønlands Geologiske Undersøgelse, Arktisk Institut, Nordisk Mineselskab, Royal Danish Navy. Mr. J. K. HANSEN, Colonel J. V. HELK, Dr. N. HENRIKSEN, Mr. E. HINTSTEINER helped us particularly.

We have also received scientific encouragement and advice from Dr. S. E. BENDIX-ALMGREN, Professor T. BIRKELUND, Dr. H. BÜTLER, Dr. J. HALLER, Dr. E. JARVIK and Dr. R. MILES.

The air-drop of outboard engine fuel by the Royal Air Force solved a difficult problem for us, and we acknowledge the help of Wing Commander D. le R. BIRD in arranging this.

Three of us were awarded research studentships for the period of this project. P. D. ALEXANDER-MARRACK and J. NICHOLSON were supported by the British Natural Environment Research Council. A. K. YEATS was supported by Shell International Petroleum Ltd.

3. DATA COLLECTING IN THE FIELD

Logging Technique

The most usual way of collecting systematic sedimentological data from ancient rocks is to record a detailed continuous vertical section through a succession of stratification units. In our case the unit of data was the set, defined by McKee & Weir (1953) as "a group of essentially conformable strata or cross-strata, separated from other sedimentary units by surfaces of erosion, non-deposition or abrupt change of character". In practice, the field definition of these sets was often rather arbitrary, and, in the case of cross-strata, the coset (a group of similar sets) was sometimes a more convenient logging-unit.

Our sections were irregularly distributed both areally and within the local stratigraphy, because of tectonic structure and outcrop pattern, variability of exposure, and accessibility. They vary from a few metres to about 300 m in length, again depending on exposure.

Design of the Mark-sense Form

The brevity of the field-season (mid-July to early September) made it desirable to devise a system of collecting a large amount of data systematically and rapidly. For this, a printed form was necessary. In addition, in order to speed up the task of analysing the data on our return to Cambridge we arranged that our data could be transferred directly from the record-sheets to computer storage without the tedium of punching by hand, with consequent risk of introducing errors. A machine-readable mark-sense form was therefore designed by Friend and Dr. J. L. Cutbill, and was used during all three field-seasons. The lay-out and use of the mark-sense form are summarised below: for a fuller account see Alexander-Marrack, Friend & Yeats (1970).

The form (Fig. 7) comprises an identification panel at the top, in which the station number (observer's code-letter plus number, eg. A105) and the sheet number for that locality are marked, followed down the sheet by nine sets in which the observations are recorded set by set from the top downwards. Each set box consists of five rows of twenty positions, labelled with numbers and abbreviated names of properties in red ink (which is not read by the machine). In the field, the geologist shouts his observations from the rock-face to his assistant, who fills in the relevant "tram-line" position in the set with a black pencil-mark (a 2B pencil gives the best results). Additional notes which cannot be included on the form are entered on the detachable stub on the left-hand margin of the sheet. Flexibility in data-recording was also retained by the use of the "restart" position (see below).

STATION NUMBER									
A	B	C	D	E	F	G	H	J	K
000	100	200	300	400	500	600	700	800	900
00	10	20	30	40	50	60	70	80	90
0	1	2	3	4	5	6	7	8	9

SHEET NUMBER									
00	10	20	30	40	50	60	70	80	90
0	1	2	3	4	5	6	7	8	9

WRITE STATION AND SHEET NUMBERS ON STUB

0	1	2	3	4	THICK	5	6	7	8	9	NO	CEM	$CaCO_3$	ROCK	DOL	FLAT	SY.P	AS.R	PL.X	TR.X
·0	·1	·2	·3	·4	(M)	·5	·6	·7	·8	·9	LIN	DEF	CONCR.- CO_3 OR STUB			FOSSILS	NO	VERT	OTHR	TR
·00	·05	EXPOSED	COVERED			RED	P.RD	GN	GY	OTHER	NO DIR	2.DIR	1.DIR	-----	-----	-----	000	100	200	300
F.SL	M.SL	C.SL	VF.SS	F.SS		M.SS	C.SS	VC.SS	CON	PEBBLY	00	10	20	30	40	50	60	70	80	90
GRAD	SHP	SMTH	SCR	TOOL	MKS.	TR.FOS.		MD.CR		RIPPLES	STUB←SPEC			RESTART		1	2	SPARE	4	CANC'L
0	1	2	3	4	THICK	5	6	7	8	9	NO	CEM	$CaCO_3$	ROCK	DOL	FLAT	SY.P	AS.R	PL.X	TR.X
·0	·1	·2	·3	·4	(M)	·5	·6	·7	·8	·9	LIN	DEF	CONCR.- CO_3 OR STUB			FOSSILS	NO	VERT	OTHR	TR
·00	·05	EXPOSED	COVERED			RED	P.RD	GN	GY	OTHER	NO DIR	2.DIR	1.DIR	-----	-----	-----	000	100	200	300
F.SL	M.SL	C.SL	VF.SS	F.SS		M.SS	C.SS	VC.SS	CON	PEBBLY	00	10	20	30	40	50	60	70	80	90
GRAD	SHP	SMTH	SCR	TOOL	MKS.	TR.FOS.		MD.CR		RIPPLES	STUB←SPEC			RESTART		1	2	SPARE	4	CANC'L
0	1	2	3	4	THICK	5	6	7	8	9	NO	CEM	$CaCO_3$	ROCK	DOL	FLAT	SY.P	AS.R	PL.X	TR.X
·0	·1	·2	·3	·4	(M)	·5	·6	·7	·8	·9	LIN	DEF	CONCR.- CO_3 OR STUB			FOSSILS	NO	VERT	OTHR	TR
·00	·05	EXPOSED	COVERED			RED	P.RD	GN	GY	OTHER	NO DIR	2.DIR	1.DIR	-----	-----	-----	000	100	200	300
F.SL	M.SL	C.SL	VF.SS	F.SS		M.SS	C.SS	VC.SS	CON	PEBBLY	00	10	20	30	40	50	60	70	80	90
GRAD	SHP	SMTH	SCR	TOOL	MKS.	TR.FOS.		MD.CR		RIPPLES	STUB←SPEC			RESTART		1	2	SPARE	4	CANC'L
0	1	2	3	4	THICK	5	6	7	8	9	NO	CEM	$CaCO_3$	ROCK	DOL	FLAT	SY.P	AS.R	PL.X	TR.X
·0	·1	·2	·3	·4	(M)	·5	·6	·7	·8	·9	LIN	DEF	CONCR.- CO_3 OR STUB			FOSSILS	NO	VERT	OTHR	TR
·00	·05	EXPOSED	COVERED			RED	P.RD	GN	GY	OTHER	NO DIR	2.DIR	1.DIR	-----	-----	-----	000	100	200	300
F.SL	M.SL	C.SL	VF.SS	F.SS		M.SS	C.SS	VC.SS	CON	PEBBLY	00	10	20	30	40	50	60	70	80	90
GRAD	SHP	SMTH	SCR	TOOL	MKS.	TR.FOS.		MD.CR.		RIPPLES	STUB←SPEC			RESTART		1	2	SPARE	4	CANC'L
0	1	2	3	4	THICK	5	6	7	8	9	NO	CEM	$CaCO_3$	ROCK	DOL	FLAT	SY.P	AS.R	PL.X	TR.X
·0	·1	·2	·3	·4	(M)	·5	·6	·7	·8	·9	LIN	DEF	CONCR.- CO_3 OR STUB			FOSSILS	NO	VERT	OTHR	TR
·00	·05	EXPOSED	COVERED			RED	P.RD	GN	GY	OTHER	NO DIR	2.DIR	1.DIR	-----	-----	-----	000	100	200	300
F.SL	M.SL	C.SL	VF.SS	F.SS		M.SS	C.SS	VC.SS	CON	PEBBLY	00	10	20	30	40	50	60	70	80	90
GRAD	SHP	SMTH	SCR	TOOL	MKS.	TR.FOS.		MD.CR		RIPPLES	STUB←SPEC			RESTART		1	2	SPARE	4	CANC'L
0	1	2	3	4	THICK	5	6	7	8	9	NO	CEM	$CaCO_3$	ROCK	DOL	FLAT	SY.P	AS.R	PL.X	TR.X
·0	·1	·2	·3	·4	(M)	·5	·6	·7	·8	·9	LIN	DEF	CONCR.- CO_3 OR STUB			FOSSILS	NO	VERT	OTHR	TR
·00	·05	EXPOSED	COVERED			RED	P.RD	GN	GY	OTHER	NO DIR	2.DIR	1.DIR	-----	-----	-----	000	100	200	300
F.SL	M.SL	C.SL	VF.SS	F.SS		M.SS	C.SS	VC.SS	CON	PEBBLY	00	10	20	30	40	50	60	70	80	90
GRAD	SHP	SMTH	SCR	TOOL	MKS.	TR.FOS		MD.CR		RIPPLES	STUB←SPEC			RESTART		1	2	SPARE	4	CANC'L
0	1	2	3	4	THICK	5	6	7	8	9	NO	CEM	$CaCO_3$	ROCK	DOL	FLAT	SY.P	AS.R	PL.X	TR.X
·0	·1	·2	·3	·4	(M)	·5	·6	·7	·8	·9	LIN	DEF	CONCR.- CO_3 OR STUB			FOSSILS	NO	VERT	OTHR	TR
·00	·05	EXPOSED	COVERED			RED	P.RD	GN	GY	OTHER	NO DIR	2.DIR	1.DIR	-----	-----	-----	000	100	200	300
F.SL	M.SL	C.SL	VF.SS	F.SS		M.SS	C.SS	VC.SS	CON	PEBBLY	00	10	20	30	40	50	60	70	80	90
GRAD	SHP	SMTH	SCR	TOOL	MKS.	TR.FOS		MD.CR		RIPPLES	STUB←SPEC			RESTART		1	2	SPARE	4	CANC'L
0	1	2	3	4	THICK	5	6	7	8	9	NO	CEM	$CaCO_3$	ROCK	DOL	FLAT	SY.P	AS.R	PL.X	TR.X
·0	·1	·2	·3	·4	(M)	·5	·6	·7	·8	·9	LIN	DEF	CONCR.- CO_3 OR STUB			FOSSILS	NO	VERT	OTHR	TR
·00	·05	EXPOSED	COVERED			RED	P.RD	GN	GY	OTHER	NO DIR	2.DIR	1.DIR	-----	-----	-----	000	100	200	300
F.SL	M.SL	C.SL	VF.SS	F.SS		M.SS	C.SS	VC.SS	CON	PEBBLY	00	10	20	30	40	50	60	70	80	90
GRAD	SHP	SMTH	SCR	TOOL	MKS.	TR.FOS.		MD.CR		RIPPLES	STUB←SPEC			RESTART		1	2	SPARE	4	CANC'L

Fig. 7. Example of one of the "mark-sense" forms, designed for this project. These forms were the basis of most of our systematic data collection.

Mark-sense Data

The data-categories which could be recorded in the field for each set are as follows:

(a) Thickness of set: 0.05–9.95 m, recordable in 5 cm increments. Thicknesses greater than 9.95 m were noted by using two or more set boxes with the restart mark. Measurements were made with a retractable 3m tape.

(b) Exposed or covered: Parts of the section covered by scree or vegetation were marked "Covered" and the thickness recorded. Data from partially covered sets were recorded in the same way as for exposed sets, but the "covered" position was again marked.

(c) Colour: Five colour categories were recorded as follows:

Red: includes 10R4/2, 5R4/2, 5R5/2. (Rock-colour chart: GODDARD 1951).

Part-red: used for sets in which red colour was not homogeneously distributed (ie. red streaks or blotches): sometimes used for pale red colouring.

Green: includes 5Y4/1, 5GY6/1, 5GY4/1, 10Y6/2.

Grey: includes N7, N6, N5, N4, 5G8/1, 5YR8/1.

Other: any other colour usually black (N3), weathering to yellow (5Y7/2).

(d) Grainsize: The modal grainsize of the set was estimated visually by reference to sieve-fractions mounted on a formica strip 15×9 cm, small enough to fit in a small notebook. The mark-sense form categories correspond to the WENTWORTH (1922) grades, from fine, medium, coarse siltstones, through very fine, fine, medium, coarse, very coarse sandstones, to conglomerate. Rapid inspection of thin sections from collected specimens indicates that the modal grainsize was correctly estimated for coarse siltstones and all the sandstone grades. However, the category "medium silt-stone" was used for muddy siltstones, and "fine siltstone" for silty mudstones or shales. Early attempts to express poor sorting by marking more than one grainsize in a set were abandoned because of possible confusion with interlamination of grainsizes on a scale less than 5 cm.: thus the dominant grainsize was marked in both cases, and the subordinate grainsize was noted in the stub.

(e) Pebbles: marked if intraclasts or extraclasts were present in a sandstone or siltstone set. Composition and clastsizes were noted in the stub.

(f) Basal surface: Gradational, sharp, or left blank if not visible.

(g) Basal surface: smooth (for smooth and flat), scoured (for flute casts, etc., and for smooth curved surfaces which truncated the underlying lamination), tool marks, trace fossils, mudcracks, ripple marks. (Internal mudcracks were recorded by marking basal mudcracks in a restarted set box).

(h) Carbonate: none, as cement, whole rock (limestone), dolomitic. Most of the rocks contain a trace of carbonate, detected with dilute hydrochloric acid, and in later seasons this property was only rarely tested. 'Whole rock' was used for fine-grained sets with more than 30 % carbonate.

(i) Internal structures: Flat stratification, symmetrical ripple marks, asymmetrical ripples (small-scale cross-stratification) planar cross-stratification (cross-sets with linear traces in all sections, trough cross-stratification (curved traces in section). Lenticular bedding was recorded by marking both 'Flat' and 'Asymmetrical Ripples'.

(j) Lineation: parting lineation.
Deformation: soft sediment folding.
Concretions: if not carbonate, composition was entered on the stub.

(k) Fossils: none, vertebrate, other (in practice restricted to plants), and trace fossils (burrows, bioturbation);

(l) Palaeocurrent directions of primary structures: none, ambiguous two-ended directions, or unidirectional indicator; followed by the azimuth of the direction, measured to the nearest 10°. Local bedding dip was recorded as often as necessary in the stub.

(m) Stub: marked where an entry was made in the stub.

(n) Specimen: marked where a specimen was collected, the number (eg. *A 356*) being noted in the stub. Photographs were also numbered and recorded in the stub (eg. A.5.23).

(o) Restart: This position was marked where further information was recorded in the set box, referring to the set recorded in the previous box. Thus gradations in grainsize or changes of colour upwards within a set could be recorded as a succession of restarts following the main set box. Also where a set contained two or more possible palaeocurrent indicators, each could be isolated with its azimuth in successive restarts.

(p) Spare 1, 2, 3, 4: These were used for special purposes eg. recording concordant igneous bodies.

(q) Cancelled: marked when a mistake could not be easily rectified by erasing marks in the field.

Processing

The mark-sense forms were read by the IBM 1232 optical mark page reader. The program sheet for the reader was devised by Dr. D. B. WILLIAMS, and the card-punch control card by Dr. J. L. CUTBILL. Three cards are punched to each sheet. In 1970, about 1500 sheets (representing 8 man-months of collected data) were processed in 7 hours. The only failures in reading occurred (1) when sheets with dog-eared leading edges were screwed up inside the reader (these had to be disengaged, copied onto new sheets and reprocessed) and (2) when faint or poorly-made marks were missed. The failure rate was very low (c. 0.001 %). Stains on the forms only rarely caused failure.

Checking

The punched card output was taken to the Computing Centre, University of Wales at Cardiff, and input to a program package devised by Dr. J. L. CUTBILL as part of the Cambridge Geological Data Systems project. The binary data were copied onto magnetic tape, and converted to print-out text form and stored on disc. The program also checks the data for card sequence errors, presence of a station and sheet number, numerical errors in thickness and palaeocurrent azimuth, etc. In 1969, a type-written text-listing of one-third of the season's data was produced within 48 hours of the expeditions' return to England. The text-data were punched onto 7-track paper tape, and transferred in this form to the University of Cambridge Titan computer, where they were stored on magnetic tape.

Formation of basic Data Files

The text-data were edited to remove headings, blank lines, and cancelled records, and other errors were corrected before filing. A Cambridge editing language enabled us to do this quickly and easily. The filing package was partly written for us by Dr. J. L. CUTBILL: by reconverting the text-data to binary form it was possible to pack the data for each set into four computer words, and a file of this condensed format was set up on magnetic tape, indexed by station. The data collected by the four of us occupied 360 blocks of tape in the reduced format file, as opposed to 4,500 blocks in the original form. Our package provided random access to the file by station number and delivered the data on successive sets expanded to a form suitable for analysis by Fortran programs.

The array structure of the data necessarily resulted from the lack of hierarchy in the set-by-set collection of the data. The use of the restart, however, represented the crude beginnings of a tree-structure (LOUDON, 1970), and while it added flexibility to the collecting of the data, it made programs for analysing the mark-sense data that much more complicated.

Graphic Display of Mark-Sense Data

A useful preliminary step towards analysis of the data was the preparation of a graphic display of each section, so that variation in colour, grainsize and sedimentary structures was conveyed at a glance. This allowed us to distinguish critical phenomena for further investigation and analysis.

The format adopted displayed grainsize on the horizontal axis with divisions corresponding to the Wentworth grades recorded in the field; the bed thickness was measured vertically, and the resultant rectangular sets were filled with an ornament representing the relevant internal structure. Colour (red or non-red) was shown as a line to the left of the section. The time required to prepare these displays was drastically reduced by arranging for an on-line digital incremental plotter to draw the grainsize, thickness, colour and basal structure framework of the display straight from the data on file, using our Fortran program "Section Plotter". Internal structures were rapidly added by hand, and flexibility was retained by reference to stub details.

Conglomerate Data

The design of the mark-sense form was based on FRIEND's experience with Devonian sandstone and siltstone successions in Spitsbergen (FRIEND, 1965): the rather different sorts of properties observable in conglomerates could therefore only be recorded in the stub of the mark-sense form, or in field-notebooks. Systems for recording conglomerate data were therefore developed independently in the field in 1968, and amalgamated into a record sheet.

All the conglomerate outcrops were vertical sections. Observations were made on:—colour; thickness of set (often arbitrary in the more massive conglomerates); matrix grainsize; sorting; roundness (by reference to the diagram in KRUMBEIN & SLOSS, 1951, Fig. 4–9); principal diameters of the ten largest clasts in the sample; composition (percentage of clast types); internal structure (if any); external structure; ratio of clasts to whole rock (volume percent). Clasts were measured to the nearest cm (or 0.5 cm in the case of small pebbles); composition was either estimated crudely as proportions of the sample area consisting of each component, or measured by counting clasts. The sampling area per set was 50×50 cm, in some localities increased to 100×100 cm. This means that results are not comparable between all localities, though they are so within sections.

The data for each set were reduced by calculating the square root of the mean product of the principal clast diameters of the ten largest clasts. This is referred to below as the 'mean maximum clast size'. These methods were crude compared with those adopted by BLUCK (1965, 1967) but were necessarily so because of the short time available in the field.

4. METHOD OF CLASSIFICATION OF STANDARD LENGTHS OF SEDIMENTARY LOG

Aims of analysis

In analysing the data collected in the field, we endeavoured to recognise and describe patterns within the multitude of observations.

Some brief idea of the classification we adopted, and of our method of devising and applying it, may be got by referring to figs 8, 9, 10, 11, 12 and 14, Ultimately, we wished to construct from these patterns a model relating tectonic and sedimentary processes to features preserved in the rocks.

Approaches

There are two complementary ways of approaching the problem of analysing sedimentological data:

(a) Univariate analysis: In this we consider one variable at a time, and investigate its variation in three dimensions (ie. areally and with time). For example, lateral, and vertical variations in grainsize can be systematic within formations, as can the abundance of individual sedimentary structures. Trend surface analysis is a natural extension of this approach, but, because of the irregular distribution of sample locations, its usefulness has been limited in our case: a Fortran IV program 'Cole Contour', written by B. M. E. SMITH, based on COLE's (1968) algorithm, was used.

(b) Multivariate analysis: Consideration of a large number of variables simultaneously allows one to distinguish rock sequences of similar facies, ie. exhibiting similar assemblages of observable properties. This entails multivariate classification procedures, in that one allocates a sequence of rocks to a group, containing rocks of similar facies defined on a number of variables.

The need for quantitative analysis

Traditionally, the operations of estimating the similarity of several rock sequences and classifying them take place in the brain of the individual experienced geologist. A small number of diagnostic properties are used to allocate an outcrop to a particular sedimentary type.

Five factors influenced us in choosing a completely quantitative approach here:

(a) We felt that all properties should be used in defining the sedimentary types. It was found, after completion of the analysis, that particular features were diagnostic, but these were not based on an inherent assumption.

(b) In many of the Greenland rocks, variation proved to be too subtle and gradational for sedimentary-types to be picked by eye in the field, at least to begin with.

(c) If the sedimentary types are precisely defined, the classification system is not dependent on the personal subjective bias of the individual research worker, which may change with time, ie. it is reproduceable.

(d) We felt the need for objective processing of the data of all four research workers in this project, although comparison between workers depends on consistent field observations being made.

(e) The use of computer-based methods of data retrieval and analysis meant that large amounts of data could be classified very rapidly. It allowed us to spend less time on collation and recovery of data, and more time on thinking and designing further analysis.

Choice of Sample

Measured sections were variable in length from 7 to over 300 m so that the amount of data and internal variability differed considerably from section to section. The rock units to be classified necessarily had to be the same order of magnitude, either in length or content, if numerical methods were to be used, and a simple objective criterion for dividing up sections was therefore needed. The readily distinguishable units of the sandstone and siltstone facies which constitute fining-up cycles in the Old Red Sandstone of South Wales (ALLEN, 1964), Spitsbergen (FRIEND, 1965), and the Catskill Mountains (ALLEN & FRIEND, 1968), were only sporadically encountered in East Greenland, and could not be used as the basic sample units.

Samples containing equal numbers of sets (McKEE & WEIR, 1953) were also ruled out, for unlike turbidite sequences, sets in these dominantly fluvial sediments were usually not the product of comparable depositional events. We chose an arbitrary stratigraphic fixed thickness of rock into which the sections were divided. In our work 10 metres has generally been used as standard thickness of a sample unit. This thickness, in most successions, was greater than the bed by bed variation, and much less than the grosser trends, which we wished to examine.

Some work was carried out using 5 m units (see Western Sequence). Four examples of 10 m samples, and the classification label ultimately assigned to each, are illustrated on Fig. 8.

In all cases, our 10 m samples were selected in sequence, each following immediately on the previous one, up a succession. We did not use overlapping samples.

Quantitative assessment of properties for each 10 m sample

Selley (1968) introduced the concept of a 'Facies Profile'—a graphic presentation of the abundance of various sedimentological properties in terms of the thickness proportion in which they occur in a section. We have used this method to summarise the lithofacies of each sample unit. For each 10 metre sample up a section, our Fortran IV program 'Facprof' printed out the total thickness in metres in which each of the following properties occurs:

Red colour; Non-red colour; Fine, medium, coarse silt; very fine, fine, medium, coarse, and very coarse sandstone; conglomerate; limestone; flat bedding (sandstone); symmetrical ripples; asymmetrical ripples; planar cross-stratification; trough cross-stratification; deformation; concretions; trace fossils; flat bedding (silt); lenticular bedding (silt).

Parting lineation was not included because its occurrence would be missed in some sorts of exposures. Surface features such as scours, tool marks and mudcracks, were measured not in thickness units but as frequency per standard thickness. Had they been included in the list of facies-profile parameters, we should have had to re-express the data for each parameter as a proportion of the maximum value of that parameter. Since the consequences of this in the analysis were uncertain, we decided to leave out the surface features.

We now had a sample of fixed stratigraphic thickness, labelled with its station number and position up the section (eg. A147.2), and its lithofacies was defined by a 'facies-profile': an array of 22 parameters.

Comparison of sample facies profiles

The sample could be considered as a point in 22-dimensional space, the coordinates of which are given by the 'facies-profile'. There are several measures of similarity between this and other samples. Two simple ones are summarised below.

(a) We could measure the Euclidean distance between two points. The greater the distance, the more dissimilar are the units.

(b) We could measure the angle (θ) between the vectors joining the points to the origin. The larger the value of $\cos \theta$, the greater is the similarity (Imbrie & Purdy, 1962).

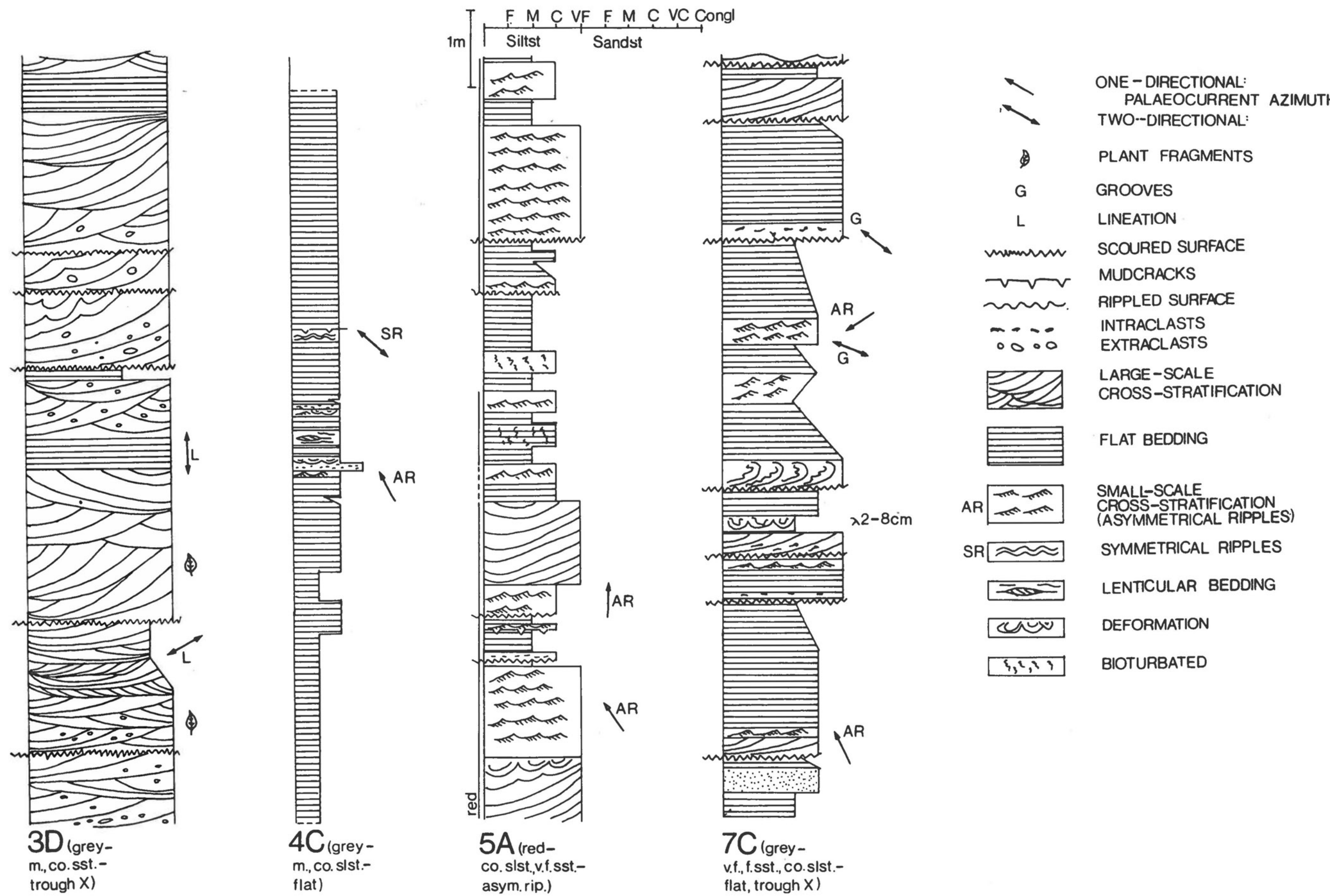

Fig. 8. Examples of four 10 m samples of sedimentary log, along with the classification "sample group" to which each was assigned (3D etc.), and a standard brief description of the sample group (grey-m,, co. sst.-trough X).

However, the parameters chosen included two colours, nine grainsizes, seven internal structures and two secondary internal structures. One might therefore expect bias towards one or more parameter types (perhaps grainsize or structure), if the raw data from the facies-profile were used in further analysis. Further, experiments with a simple correlation matrix of parameter against parameter revealed that most parameters were partially correlated with each other, and a few strongly so. This may be partially due to the closed number effect, described by CHAYES (1960), as the maximum value for any parameter is ten metres. But, unlike geochemical data, where all values add up to 100%, our facies profile array might have a variable sum. We therefore concluded that real interdependence between parameters was involved, which could distort relationships if similarity measures were computed from raw data. This was confirmed by the results of the program 'Search', described later in this paper. There was therefore a need to re-express the facies-profile array in terms of independent parameters. If the number of parameters could be reduced at the same time, without losing information on variation, this would also facilitate later interpretation.

Construction of the Classification System

Principal Components Analysis

This is a method for computing the linear transformation of the original variables into the new independent ones. The latter could be considered as composite variables made up of certain proportions of the original parameters. A detailed exposition of the theory would be out of place here: a mathematical treatment has been given by KENDALL (1957) and HARMAN (1960), and the principles behind the theory are discussed by CATTELL (1965). Expositions for geologists are included in the following geological applications: facies analysis (HARBAUGH & DEMIRMEN, 1964), geochemistry (MIESCH *et al.*, 1966), sedimentary petrology (GRIFFITHS, 1963, 1966). Other examples of principal components analysis in the literature include: palaeontology (PITCHER, 1966; ELDREDGE, 1968), mineralogy (WEBB & BRIGGS, 1966), stratigraphic correlation (MCCAMMON, 1966), palaeoecology (FOX, 1968; HOWARTH & MURRAY, 1969), sedimentary petrology (KLOVAN, 1966; DAHLBERG & GRIFFITHS, 1967; WAHLSTEDT & DAVIS, 1968; MCMANUS *et al.*, 1969), and facies analysis (TOOMEY, 1966).

The method can be used in either of two ways: we may consider variables (properties) in terms of the objects which they describe (R-mode) leading to the investigation of which properties are linked to a common factor; or the objects may be considered in terms of their properties (Q-mode). This leads to a classification of the objects into groups, and this was the option chosen here. We used a computer program 'Identcompon', written in Titan Autocode by D. B. WILLIAMS: The input for this was the data on a maximum of 50 samples described by up to 50 parameters. The data matrix was row normalised, and was then subjected to the principal components analysis. We can visualise this procedure as locating a new set of reference axes in the 22-dimensional object space, such that the sum of squares of vector projections on the first axis is a maximum, and then the second axis is placed at right angles to the first, but in a position where vector projections on it are a maximum, and so on. The criterion for determining the minimum number of new reference axes is the size of the eigenvalues (characteristic roots) of the correlation matrix. The new components are represented by the new axes, and may be identified in terms of proportions of the original parameters; the eigenvalues may be regarded as the variance accounted for by each successive component.

The resultant Q-mode principal components are independent, but are not immediately useful to the geologist: the first component, for example, generally represents the 'ground-swell' or factor of variation common to all the data, and in this project we were more interested in factors which would separate the data into groups. Because the sample vectors may cluster around the new reference axes, a more efficient reference system can be found by the rotation of the Q-mode axes in 22-space. The varimax criterion (KAISER, 1959) was used to determine this 'simple structure'.

The output from the program included the following:

(a) The eigenvalues of the correlation matrix, and the cumulative percentage of the total variance represented by them.

(b) The 'communality', which is the sum of squares of loadings of an object vector on the new principal components, and which represents the proportion of the variance of that vector accounted for by the system, was listed for each subject.

(c) The loadings of each object vector on each of the new varimax components were listed.

(d) An 'identification' matrix relating the varimax components to the original parameters was printed.

The fifty samples which were input as data to this program were selected to exhibit as wide a variation of rock types as possible. The remaining data were expressed in the new terms by multiplying each sample facies-profile A (22) by the component identification matrix B(22, n), where 'n' is the number of principal components selected, to give a product array C(n). The communality for each object was derived from this and if it was less than 0.5, the object was rejected by the new system, that is, it represented too much variation of a type not yet explained by the combination of principal components. All rejects were then selected, together with equal numbers of objects for the original data set, which had high loading values on successive components, and these data were input to 'Identcompon'. In this way all extremes of data variation could be encompassed by the system. All the remaining data should have now fitted into this revised scheme of principal components, which should have remained stable when further data were subsequently collected in the field, provided that no rock types vastly different from those already examined were encountered. If this did occur, some new sample facies-profiles would again be rejected by the system, with low communality values, and the whole procedure of principal components analysis would have to be repeated, as described above.

Results: We found that 7 varimax principal components explained 94 % of the total variation exhibited by all 10 metre sample facies-profiles on rocks examined by YEATS and ALEXANDER-MARRACK in 1968 and 1969. Data supplied by NICHOLSON and FRIEND were accommodated in this system, with only 2 % rejects.

Grouping the data: Cluster Analysis

In most of the published geological applications of Q-mode principal components analysis, grouping of the data is achieved by visual examination of plots of data on two component axes at a time. Groups may overlap on one or more projections, and it is only by examination of all possible projections that the groups, if present, can be sorted out. With a system of three components only three such projections are needed and so a visual approach to the task of grouping is feasible. However, with several hundred objects to group and a seven component system, involving 21 projections, this is impractical.

We therefore turned to cluster analysis as a somewhat more objective and painless way of grouping. The theory is discussed by SOKAL & SNEATH (1963), BONHAM-CARTER (1967), and PARKS (1966). Published geological applications include: palaeoecology (VALENTINE & PEDDICORD, 1967; FOX, 1968; HOWARTH & MURRAY, 1969; KAESLER, 1970), mapping of recent biofacies (MELLO & BUZAS, 1968), and classification of subsurface localities on lithology and structure (KAESLER & McELROY, 1966).

The procedure used here started with a measure of similarity (cos θ, as used by IMBRIE & PURDY, 1962) between each pair of objects, based on the component loadings data for each object. Our Fortran IV program 'Costheta' took up to 100 10-metre sample facies profiles, row-normalised and re-expressed them in component terms, and then computed the cos θ values as a matrix, which was printed and also stored on magnetic tape ready for the cluster program.

The Fortran IV program 'Cluster Analysis' was adapted from BONHAM-CARTER's (1967) published program. This operated on the similarity data matrix, using the pair-group linkage method (SOKAL & SNEATH, 1963). In other words, pairs of objects, which were more similar to each other than to any other object, were linked to form groups. After each cluster cycle, the similarities between groups and ungrouped objects were recalculated, and individuals and smaller groups were linked progressively at each cycle, until finally all the objects were clustered. A sample of 100 facies profiles, representative of the total variation in the data, was analysed in this way. Our program printed out the level of similarity of successive linkages, and a list of the object names rearranged in an order suitable for drawing a dendrogram.

When we tried to simplify data by 'pigeon-holing' objects into groups, there were two approaches: a natural classification, and an arbitrary classification (see IMBRIE & PURDY, 1962). In the arbitrary case, boundaries between groups are quantitatively constructed, without any justification, except in the cause of convenience: the petrology of sandstones (PETTIJOHN, 1957) was a case in point. In a natural classification, there are concentrations of similar objects in the data.

Cluster analysis has been criticised as a grouping method, because of the artificial 'hierarchical' nature of the results, and also because, given a complete spectrum of variation in data with no apparent concentrations, the method will still create clusters. The method will not necessarily select natural groups. But it seems likely that a dendrogram derived from a data set without groups would look very different from one derived from inhomogenous data, in which concentrations occur.

It must be emphasized that we did not expect the data to occur in exclusive groups, nor was there an analogy with samples from overlapping normally distributed populations (as in biology). We expected transitions between groups to be numerous. but hoped that they were not so densely concentrated as the objects forming the groups. In preliminary experiments with principal components analysis, two sets of 50 sample facies-profiles were selected using alternate 10-metre samples from sections on Rødebjerg (Ymers Ø). Both sets yielded similar principal components and subdivided into three similar groups; suggesting that the classification was stable.

The extraction of groups from a dendrogram seems to be entirely arbitrary, and a matter of convenience, although chi-square has been proposed (JOHNSON, 1962) for testing the significance level of clusters.

In our case, the 0.95 level of similarity provided six primary groups, a convenient number to handle.

Multiple Discriminant Analysis

The next stage was to define quantitatively the boundaries of the groups. Simple discriminant analysis (KRUMBEIN & GRAYBILL, 1965, pp. 359–367) works out the equation of the plane in n-dimensional space which most efficiently separates two given groups of objects, such that the probability of misclassification of an object is the same for both groups. Multiple discriminant analysis extends this to more than two groups, and similarly defines planes between successive pairs of groups. More efficient discrimination can be achieved by fitting polynomial surfaces instead of planes, either as quadratic functions (BURNABY, 1966) or by iterative discrimination methods (CASSETTI, 1964). Expositions of the theory for geologists are included in the following papers: palaeontology (WOLLEBEN *et al.*, 1967), general (GRIFFITHS, 1966). Other applications of the method include: sedimentary petrology (WOOD, 1961; MELLON, 1964), and igneous petrography (CHAYES & VELDE, 1965).

For simplicity we chose a linear multiple discriminant technique to separate our six groups. The components loading data for each object were reordered into clusters for input to our Fortran IV program 'Multidiscrim', a modification of the WOLLEBEN *et al.* (1967) published program. This prints out for each pair of groups a discriminant index (R_0), and the discriminant function coefficients for each component (k_1, k_2, k_3, k_4, ...). An analysis of variance was included for each pair, giving F values which could be used to test how statistically different two groups were. In our case, we had no means of knowing if our groups were multivariate normal distributions, so strictly we were not justified in using the F-test, but it did give some indication of how separate the groups were on the basis of the data supplied. This allowed us to change the data or modify the number and content of groups to achieve the best classification.

Reclassification of the original 100 10 m samples using the discriminant functions produced only two misclassifications: the two objects were clearly transitional objects.

Classification of further data

We now used the discriminant functions to classify further data. Our Fortran IV program 'Classfac' took facies profile data on up to fifty sample units at a time, converted into component loadings and printed out communalities. The value of the discriminant function, for each object was given by:

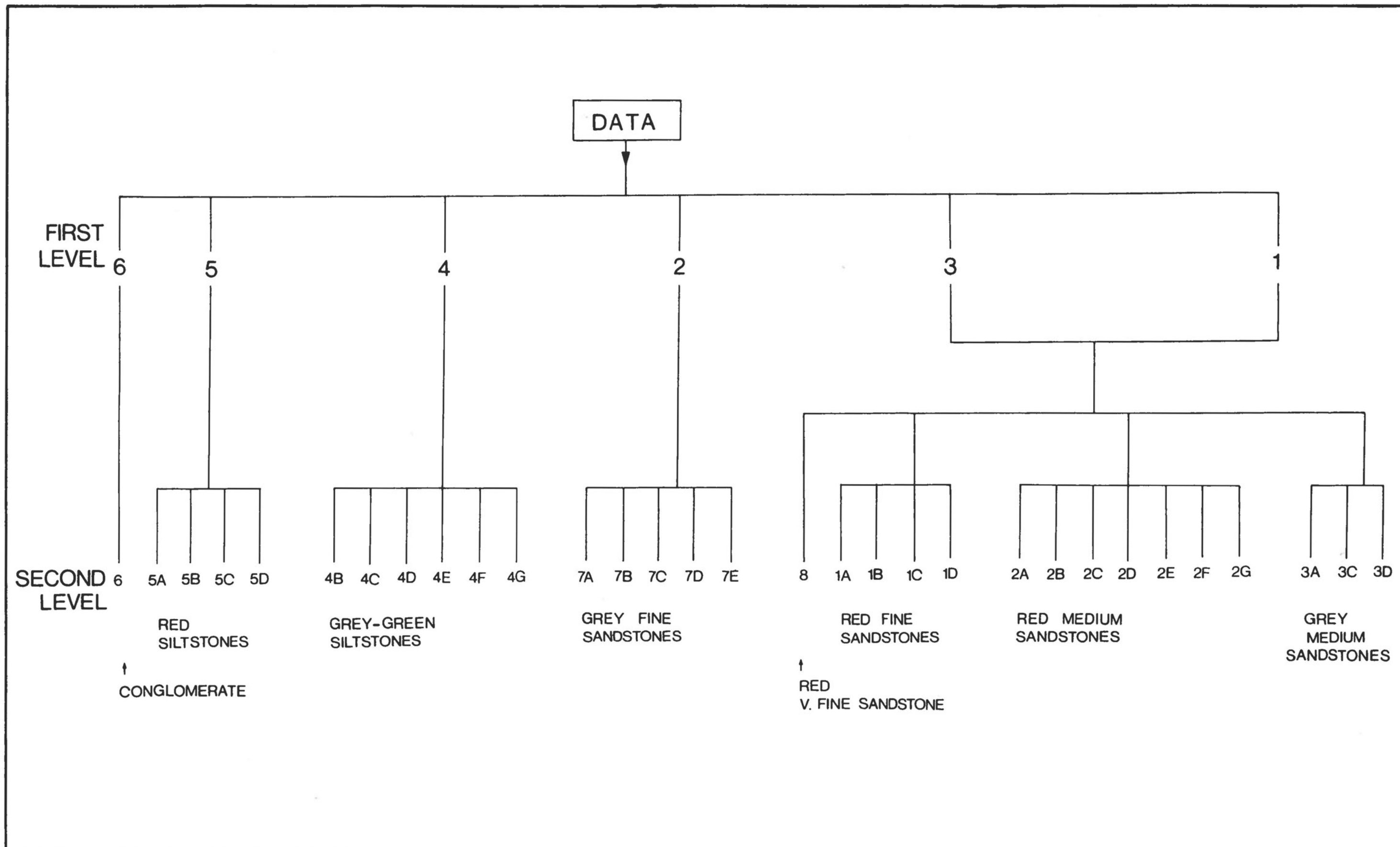

Fig. 9. The structure of the classification into sample groups.

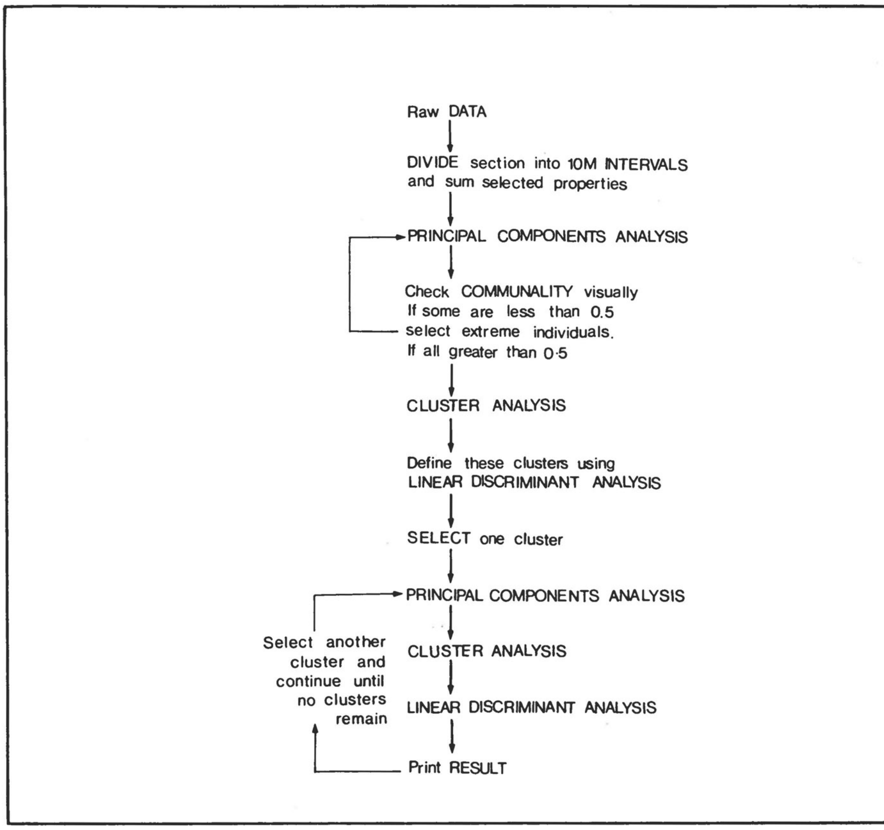

Fig. 10. Diagram illustrating the construction of the classification.

$$\mu = (k_1C_1 + k_2C_2 \ldots\ldots\ldots + k_nC_n) - R_0$$

where C_1, C_2, ... C_n were the values of the component loadings (for n components). If μ was greater than or equal to zero, the object belonged to the first of the two groups, but if it was less than zero the object went into the second group. For a system of more than two groups, the testing procedure was as follows:

For groups 1 and 2, if $\mu_{1,2}$ suggests group 1, go on to test groups 1 and 3. If $\mu_{1,2}$ suggests group 2, test group 2 against group 3. This continued until we had tested against the last group (6 in our case). The number of the group into which the object has been classified was then printed.

Subdividing the primary sample groups

The characteristics of the 6 primary groups selected were as follows:

Group 1 Grey-green, dominantly medium sandstone.

Group 2 Grey-green, dominantly fine sandstones.

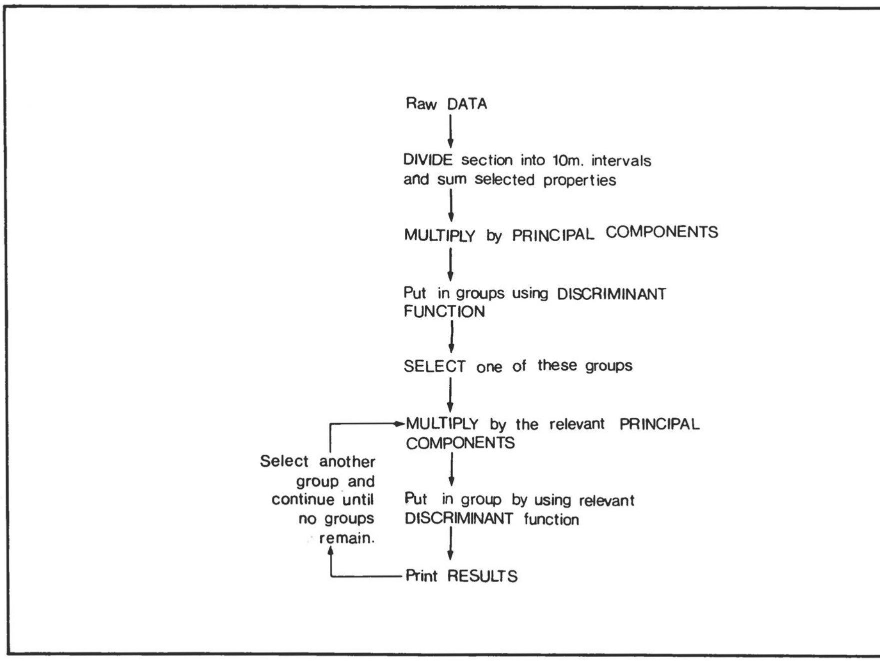

Fig. 11. Diagram illustrating the assignement of new data to the classification after its construction.

Group 3 Red sandstones.

Group 4 Grey-green siltstones.

Group 5 Red siltstones.

Group 6 Conglomerates.

With this classification level, we had not gained much insight into more subtle aspects of variations in grainsize and internal structures in the data. We therefore took up to 50 members of each group at a time, and repeated the whole process from components analysis through to classification. The final renumbered classification system is shown in Fig. 9 and the construction of the classification, and its subsequent use, are summarised in Figs 10 and 11.

Operation of classification

The classification is hierarchical and very tedious to operate on a large data set. To overcome this, a more advanced version of the program 'Classfac' was devised, which read a file of 10-metre sample facies-profiles and worked through the various levels of the classification, allocating each individual finally to one of the 31 groups labelled on Fig. 9.

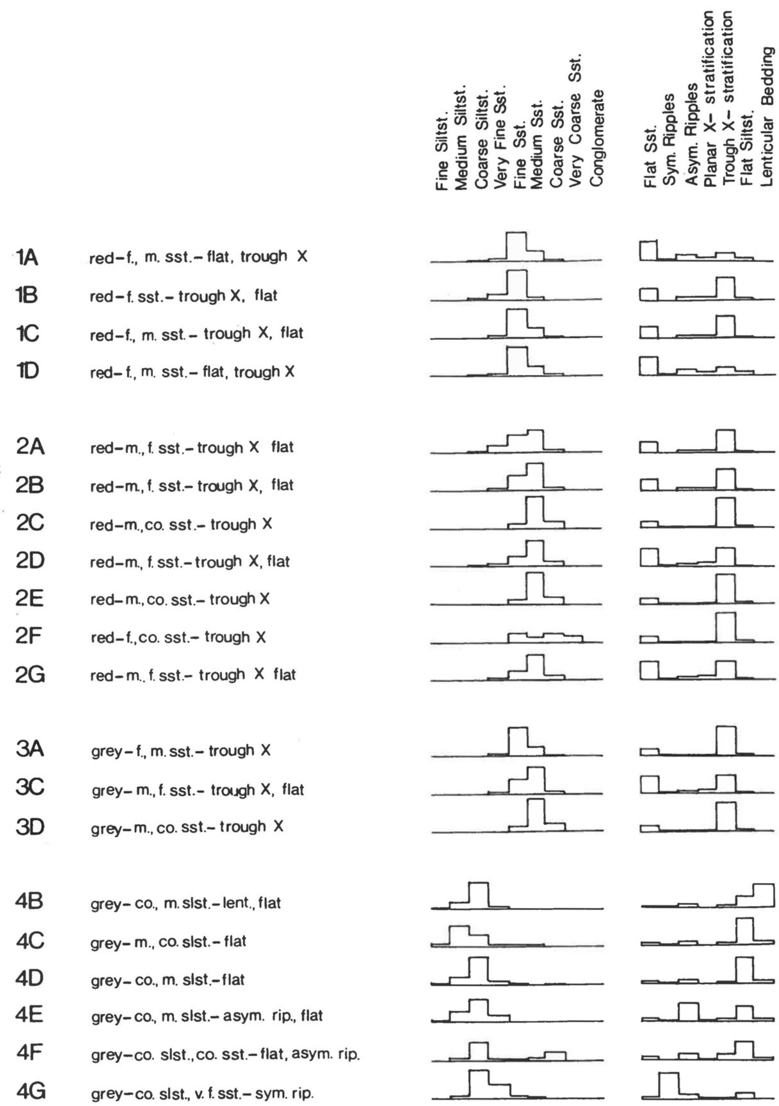

Fig. 12. List of classification sample groups, and standard brief description of each. Also given are average proportions (of the 10 m thickness) of different grainsizes and different internal structures. Fig. 13 completes this list. The average proportions, and the brief descriptions, are based on samples measured in the eastern sequence, and these differ, in small details of a few groups, from the proportions and descriptions in the other sequences.

Average 10-metre sample facies-profile for each sample group

The mean values for original parameters in 10-metre sample facies-profiles from all available classified samples in each group were calculated using a simple Fortran IV program, and the range for each parameter was printed as well. The average properties of each subgroup gave some idea of its nature. These averages are presented, for grain-size and internal structure, in Figs 12 and 13.

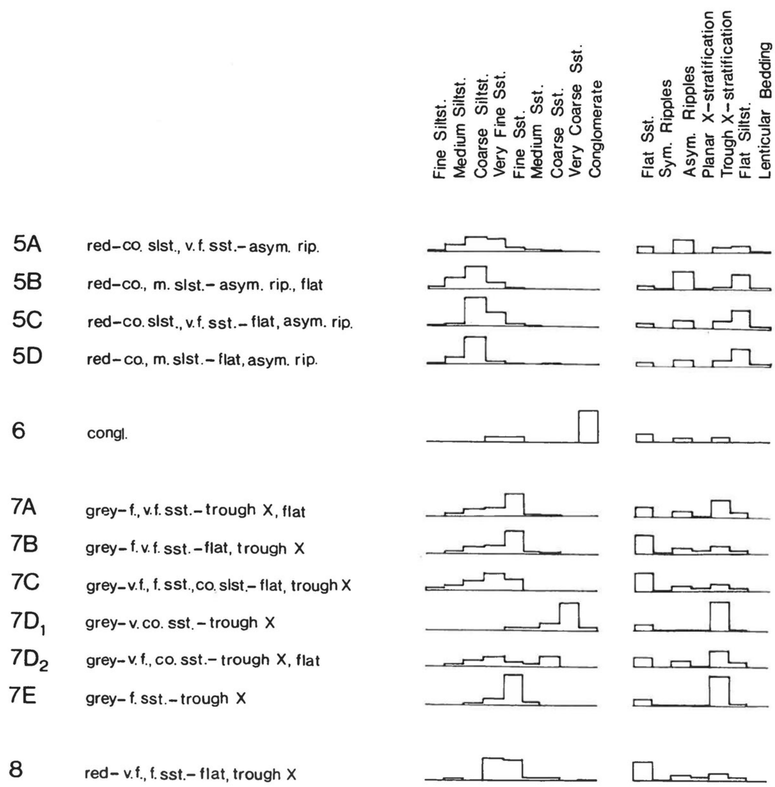

Fig. 13. Continuation of Fig. 12.

Relations between sample groups

The subdivisions of a first-level group may be related to each other by examination of the varimax principal components. For relations between subdivisions of different groups, however, we chose the mean facies-profile for each group, extracted all the grain-size data alone and used the resultant 10-parameter arrays as input to the principal components and cluster analysis programs. This procedure was also applied to the average primary internal structure data for each group. This allowed us to examine the effect of colour: some groups clustered together both on similar grainsize distributions and similar structures, but differed in colour (eg. 2C, 2E, 3D; red through red-and-green to green).

Three principal components were extracted from mean 10-metre facies-profiles, using only grainsize and primary internal structure data, and loadings are plotted in Fig. 14. The more important facies are arranged with grainsize more or less decreasing from left to right; trough cross-stratification is dominant in the coarser-grained facies, giving way to flat bedding and then to asymmetrical ripples and flat-bedded siltstones.

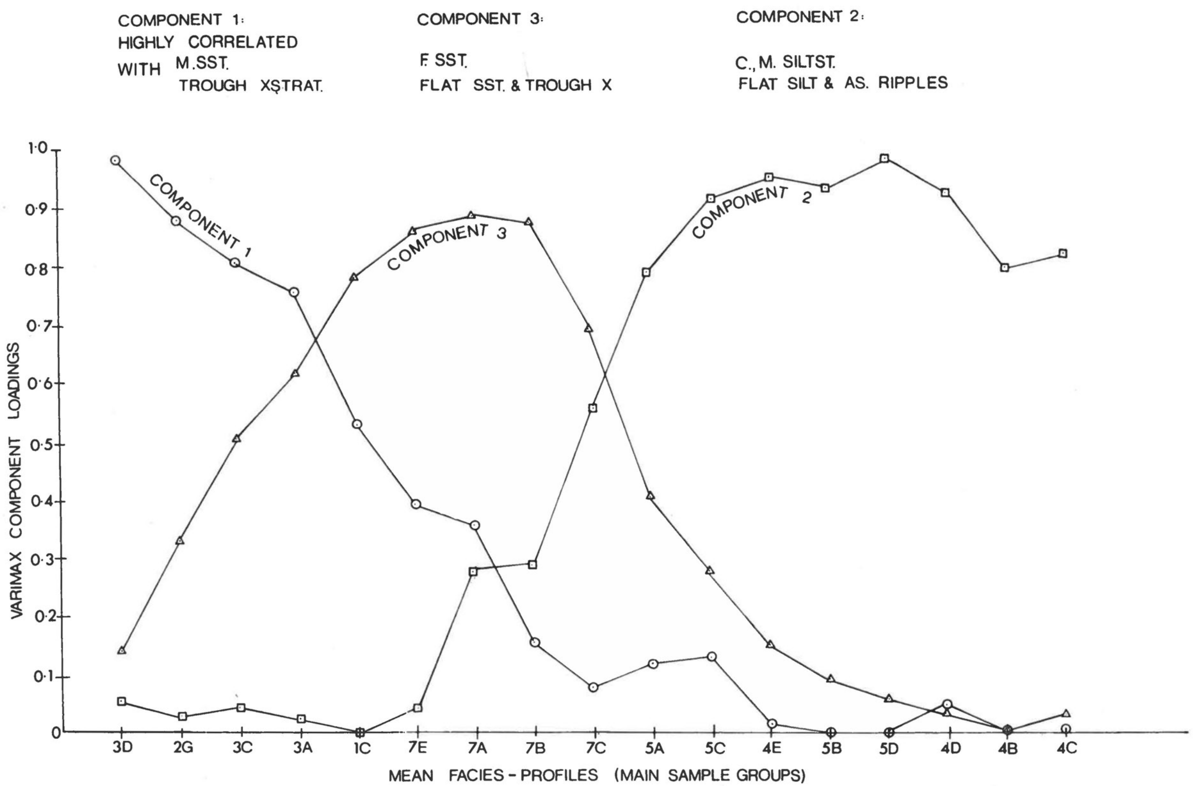

Fig. 14. Principal component loadings of the mean facies profiles of the main sample groups. Grain-size and internal structure information only have been used.

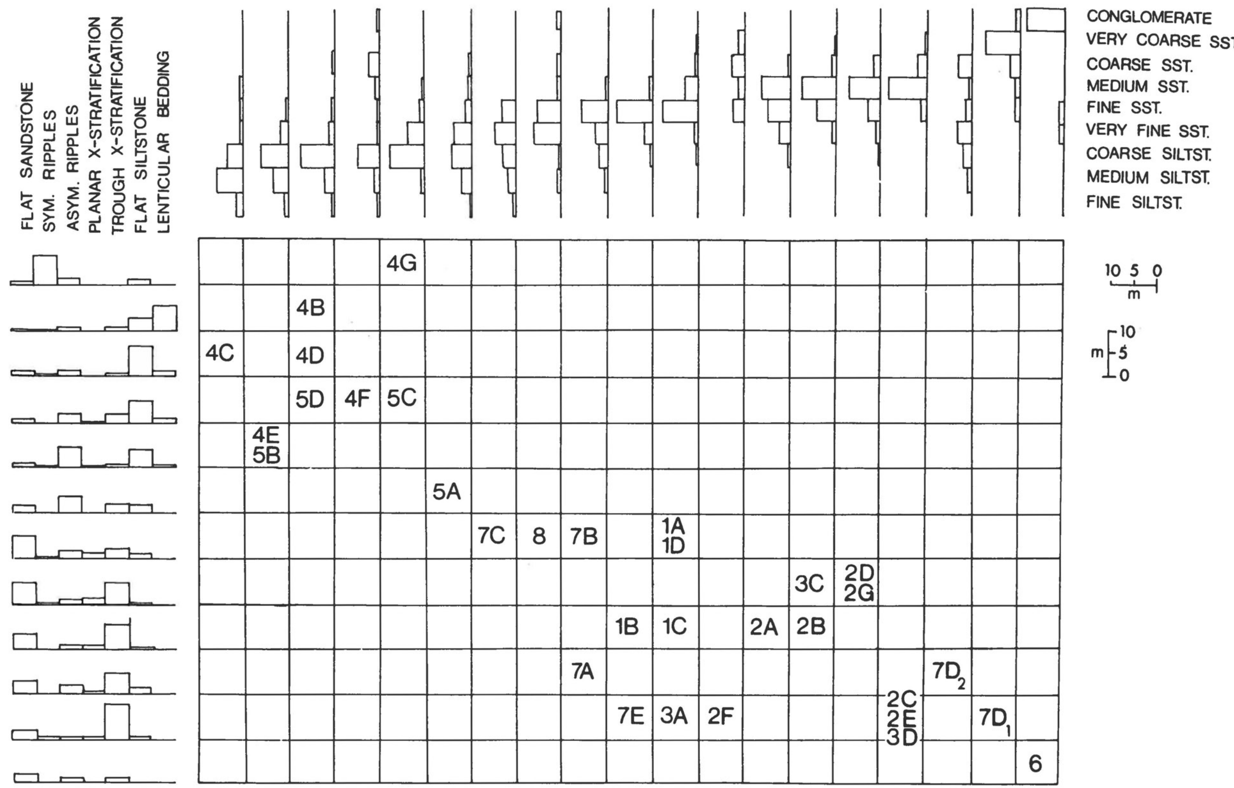

Fig. 15. Grid illustrating the distribution of grain-size and internal structure in the classification sample groups.

A grid showing increasingly coarser grainsize distributions from left to right and internal structure combinations from dominantly asymmetrical ripples and flat-bedded siltstone through flat-bedded sandstone to dominantly trough cross-stratification, from top to bottom (Fig. 15), was constructed to illustrate the relation between the 10 m sample groups. It is noteworthy that the sub-groups tend to concentrate about the principal diagonal of the grid suggesting a correlation between primary structures and grainsize.

For the purpose of displaying results in the rest of these papers, the groups have been arranged into this linear order, corresponding approximately to the diagonal (Fig. 15).

Characterisation of 10 m sample groups

For a given 10 m sample group, we retrieved data from the relevant parts of mark-sense sections and stored them consecutively on magnetic tape using the Fortran IV program 'Facfile'. These selected data were then analysed using the following Fortran IV programs:

(a) Tpm: This computed random, tally and transition probability matrices of transitions upwards from one feature to another (see KRUMBEIN, 1968; SELLEY, 1970). The program worked set by set, recording transitions between different features, as outlined by CARR *et al.* (1966), and did not include the transitions from a given feature to itself, as occurred in point-counting at fixed intervals up a section (KRUMBEIN, 1967). Data for grainsizes were treated separately from data for internal structures.

(b) Search: This listed the number of records of associations of different properties in the same set.

(c) Bedthickness: This printed out the set thickness distribution of each primary internal structure and each grainsize in turn.

(d) Fining-Cycles: This analysed grainsize variation up each section, printing out the thickness of each fining-upwards and coarsening-upwards semi-cycle (Fig. 16; ALEXANDER-MARRACK *et al.*, 1970), mean grainsize of cycle and maximum and minimum grainsizes per cycle. The relevant information for each sample-group could be extracted from the printout.

Other data for each 10 m sample group could be retrieved by hand from mark-sense stub notes, field notebooks, thin sections of petrological specimens, and photographs. The following properties could be examined in this way:

Scour frequency, tool marks, mudcracks, rippled surfaces, bedding geometry, abundance of extra-basinal clasts, and of intraformational

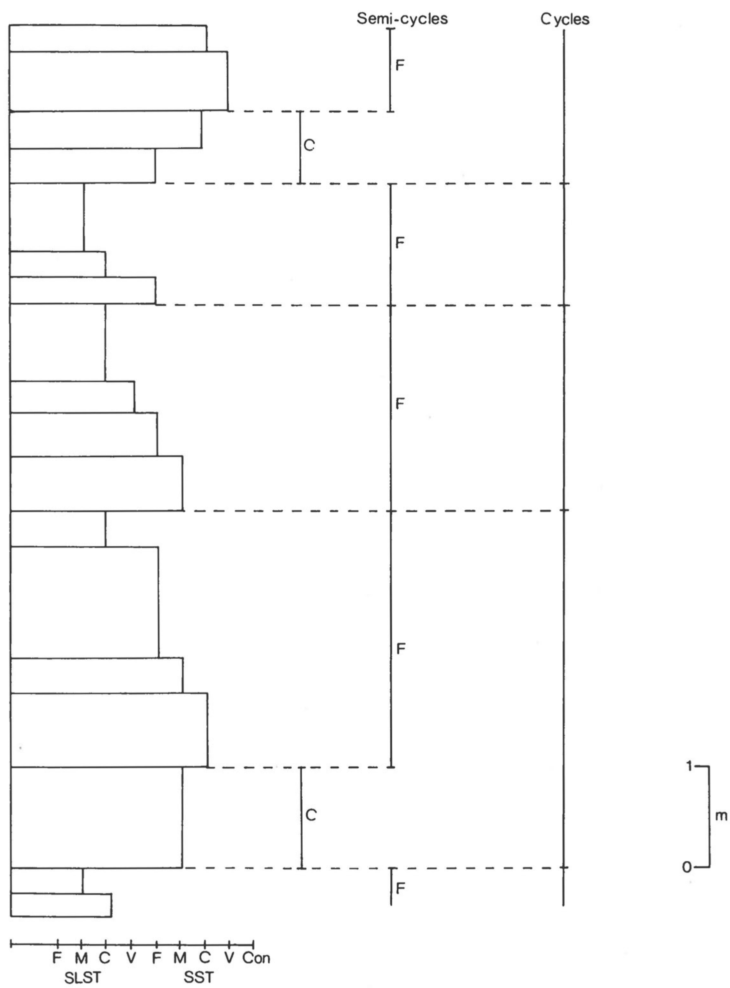

Fig. 16. Diagram showing the division of a sedimentological section into fining-up (F), and coarsening-up (C) semi-cycles, and cycles.

clasts, nature and preservation of fossils, sediment composition and sorting, nature of concretions, and deformation, etc.

Examples of the value of the sample group classification

In this section we illustrate some of the different ways we have used the sample-group classification.

We have used the sample groups to describe the distribution of particular structures or other features. For instance, later in this paper, we describe the occurrence of concretions in the eastern area (Table 5). Data are presented for some twenty-nine different sample groups eg.

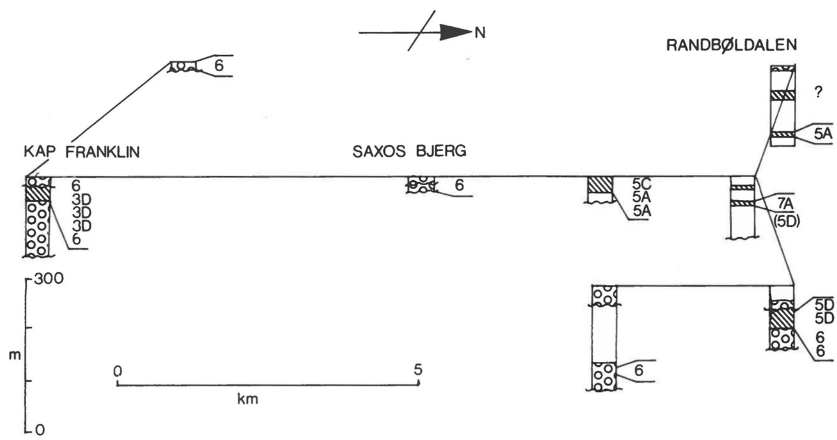

Fig. 17. Example of the use of the sample-group classification in showing stratigraphic variation of lithology. This fence diagram refers to the Saxos Bjerg Member of the Kap Franklin Formation.

(a) Sample group 1A, (red-f., m., sst.-flat, trough X) was found twice in the area, and contained no concretions.

(b) Sample group 3D (grey-m., co. sst.-trough X) was found thirty seven times in the area. 8 % of samples contained concretions; the biggest concretion was 3 cm. in diameter. The modal grain-size of the sets containing concretions was coarse siltstone; the sets were red, and they occupied, on average 0.2 m of the 10 m sample.

(c) Sample group 4F (grey-co. slst., co.sst.-flat, asym. rip.) was found eight times in the area. 62 % of samples contain concretions. The biggest concretion was 16 cm in diameter. Concretions most frequently occurred in beds of red, coarse siltstone, occupying, or average, 1.8 m of the 10 m sample.

In this way, the sample groups provide a method of investigating the distribution of a particular feature (concretions) in the context of the general variation of sedimentation and environment.

Sample groups also allow concise labelling of general sediment variation on stratigraphical fence diagrams (Fig. 17).

Lateral variation of sedimentation (Fig. 18) and downstream variations (Fig. 19) are also described in terms of sample groups much more completely than by means of one or two characteristics.

Palaeocurrent analysis

Our Fortran IV program analysed palaeocurrent azimuths in the mark-sense data for each section. Azimuths were corrected for tectonic dip, using a generalised dip value for the section. Data were retrieved and stored separately for the following indicators: asymmetrical ripples,

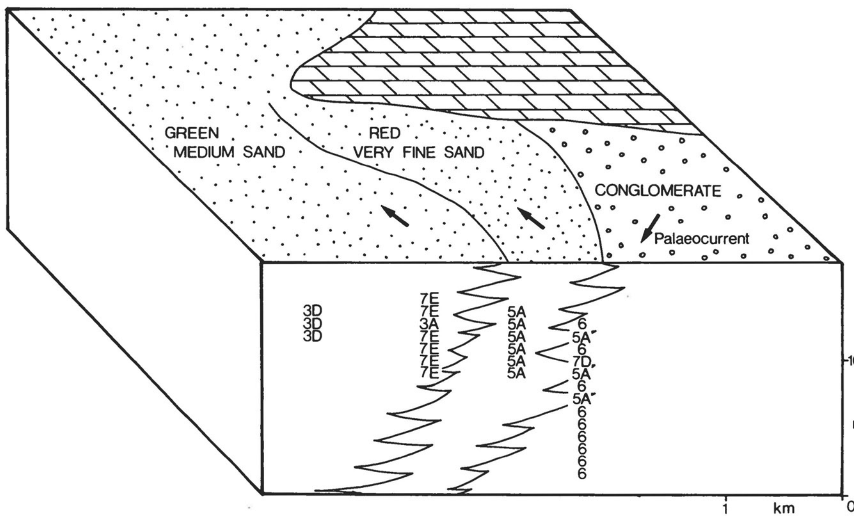

Fig. 18. Example of the use of the sample-group classification in the reconstruction of three-dimension lithological variations. This diagram refers to Scott Bjerg, north of Dusén's Fjord.

planar cross-stratification, trough cross-stratification, one-directional scour marks; parting lineation, tool marks and two-directional scour marks, and miscellanea (plant orientations, etc.). The vector analysis method of CURRAY (1956), was used. Vector mean azimuths, vector magnitude (percent), and number of readings (n) were printed for each indicator, and for all one- and two-directional data. A grand overall mean was calculated for each section by treating the end of the two-directional mean nearest to the one-directional mean as one-directional. Vector mean azimuths, corrected for magnetic declination were plotted on maps by hand, together with 95 % confidence limits of the mean ($= 2\sigma / \sqrt{n}$). The standard deviation, σ, was obtained from the vector magnitude on CURRAY's (1956, Fig. 3) graph.

5. PETROGRAPHIC NOTES ON LITHOLOGICAL FEATURES

General

We have carried out no systematic regional studies on compositions or textures of hand-specimens or thin-sections. Many of the petrological observations we have made are interesting only in the context of their local stratigraphy, and we will deal with them in the stratigraphical papers which follow this one. Here we deal only with petrographic points of general interest.

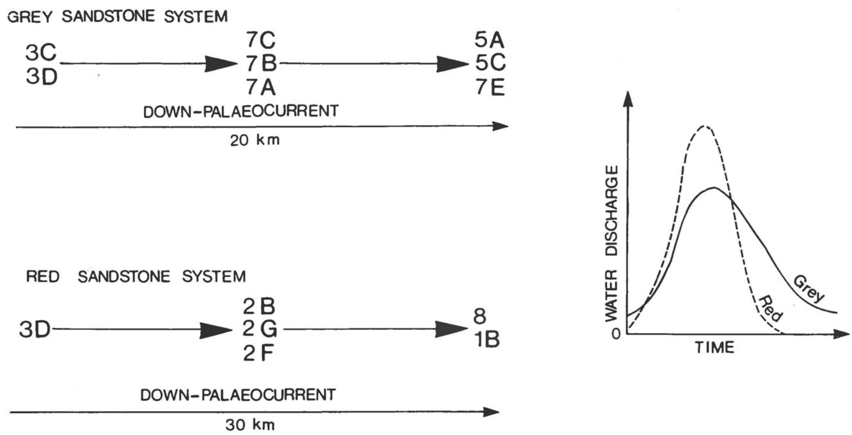

Fig. 19. Example of the use of the sample-group classification in summarising downstream variation in major fluvial systems, and a possible interpretation. This work was based on the eastern sequence.

Clastic Sediments

Sandstones and siltstones are the commonest sediments in almost all the successions examined. Their grain-size, bed thickness and structures form the basis of the classification used here (Figs 12, 13) so there is no need to describe them further in this number.

Conglomerates and breccias form major exposures particularly towards the edges of the outcrop area. For example, the conglomerate succession on Ella Ø is at least 1000 m thick. Great variations of texture and composition of these rudaceous rocks occur locally, and will be described in the stratigraphical papers to follow.

Clasts

Clasts within the sediments were not used as a basis for our classification, so some general comments on their varieties are necessary.

We use the term intraclast for clasts of sedimentary material derived from within the depositional basin. Most of the intraclasts are mudflakes. They reach a maximum length of 40 cm in sample groups 7A (grey-f.,v.f.sst.-trough X, flat) and 7E (grey-f.sst.-trough X). With progressively decreasing mean grain-size, the average number of sets with mudflakes per 10 m sample group also decreases; when more silt is being deposited, the shear stress due to water flow less often reaches values critical for erosion of clay beds. However, in the environment in which the very coarse sandstones of sample-group $7D_1$ (grey-v. co. sst.-trough X) were deposited, no mudflakes were present, either because no silt and clay-grade particles were available, or because finer sediment was continually flushed out of the area by water or wind.

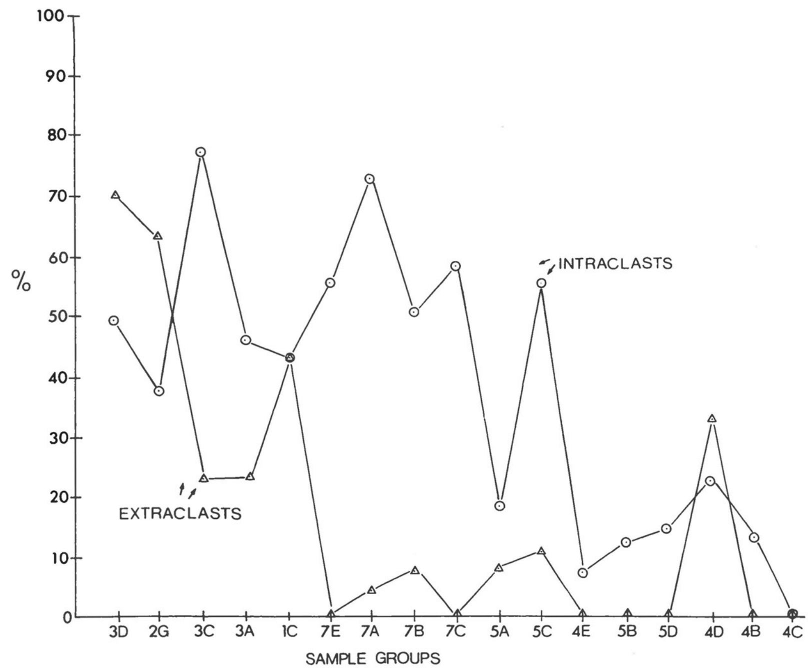

Fig. 20. The probability (%) of finding a clast in a 10 m sample of each sample-group. This is based on eastern sequence data.

Only two examples of sandstone intraclasts were seen: sand, lacking the cohesion of the silty-clays, tends to disaggregate during erosion. Carbonate concretions were recorded as clasts only where fine and coarser sandstones occur in association with red siltstones with concretions in situ, sample groups 4F (grey-co. slst., co. sst.-flat, asym. rip.), 5A (red-co. slst., v. f. sst.-asym. rip.), $7D_2$ (grey-v. f., co. sst.-trough X, flat), and some examples of 3D (grey-m., co. sst.-trough X). Ferruginous concretions were also seen in sample group 3D.

The majority of 10 m samples contain intraclasts in all the major sandstone sample groups (Fig. 20). In siltstone sample groups they are rare, except in 5C (red-co. slst., v. f. sst.-flat, asym. rip.), where they are very small in size. Intraclasts are commonest in fine and medium sandstone sets (Fig. 21), and are more widespread then extraclasts except in the coarsest sample groups (3D, grey-m., co. sst.-trough X) (2G, red-m., f. sst.-trough X, flat). The association with finer sands can be attributed to three factors: a) mudflakes have a lower density than extraclasts; intraclasts can therefore be transported by flows of lower stream power than extraclasts of the same size; (b) mudflakes tend to be disc-shaped, allowing them to move in suspension or saltation

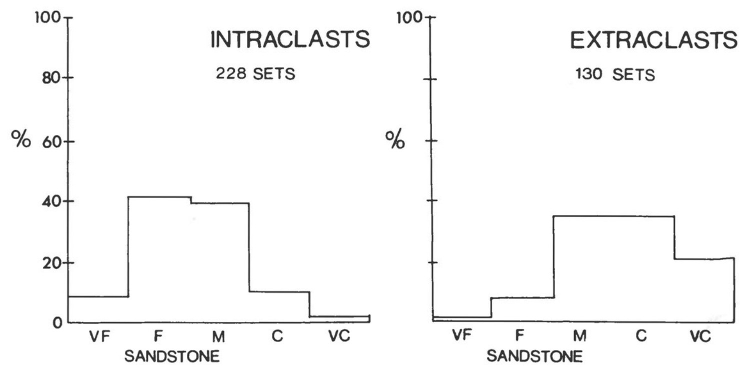

Fig. 21. Distribution of clasts in sediments of various grain-sizes in the eastern sequence.

more easily than the more spherical extraclasts; and (c) they may be derived very close to their locus of deposition and are relatively unaffected by the sorting processes applicable to the transport of extraclasts.

Extraclasts derived from source areas outside the depositional basin include:—granite (sensu lato), feldspar, quartzites, vein quartz, schist, limestone (and dolomite), rhyolite and rhyodacite, chert. Extraclasts occur modally in medium and coarse sandstones (Fig. 21) and are widespread only in sample groups containing appreciable thicknesses of these grades (Fig. 20). Sample group 7 D_1 (grey-v. co. sst.-trough X) is particularly rich in extraclasts, and in 3 D (grey-m., co. sst. trough X) the average number of extraclast records per 10 m is higher than that for intraclasts. The silty sample groups 4 D (grey-co., m. slst.-flat) and 4 F (grey-co. slst., co. sst.-flat, asym. rip.) have an anomalously high number of extraclasts compared with other facies of similar mean grain-size due to the intercalation of coarse sandstone beds.

Limestones

In the eastern area (Vilddal Supergroup) grey to black flatbedded marlstones (25–75 $^0/_0$ lime carbonate) form continuous sets up to 2.1 m. thick. They are restricted mainly to certain non-red siltstone groups (Table 1). Alternate bands, 5–20 cm. thick, of dark-grey "shale" and paler grey silty "shale" are common within sets: the textural differences appear to be due not to different proportions of carbonate (Table 2), but to slight differences in grain-size and, perhaps, organic content. Other types have quartz silt and mica particles concentrated along laminae between carbonate-rich layers (Table 3).

Table 1. *Distribution of Limestone in Eastern Area.*

Sample Groups	No. of 10 m units	% No. units with Lst.	No. of Limest. records	Mean facies-profile thickness (metres)	% No. of 10 m units with concretns as well	Geometry
4C.......	33	18	9	0.76	0	Beds
4E.......	27	7	7	0.10	0	Beds + lenticles
4F.......	8	25	6	0.13	12	Lenticles
5B.......	16	12	2	0.03	0	Beds
7B.......	14	7	1	0.08	0	Beds

Table 2. *Composition of Limestone in Eastern Area.*

Specimen	Field Descrip-tion	Carbonate grainsize	% Quartz silt	% Weight soluble in cold chloro-acetic acid
A 060........	Grey silty limest.	ca. 8 μm	1	33
A 061........	Dark fine limest.	ca. 1 μm	2	30

Table 3. *Composition of Limestone with silt laminae.*

Specimen	Field Descrip-tion	Carbonate grainsize	Carbonate laminae mm	Quartz-mica silt laminae	% Weight soluble in cold chloro-acetic acid
A 304......	Black m. silt stone	80 μm aggregate	0.6–2.0	0.1 mm; 10 % Q, (20 μm)	60
A 299......	Black limest.	15–30 μm rhombs	4	0.2–0.4 mm 10 % Q, (40 μm)	47

In the western area (Kap Kolthoff Supergroup), thin (up to 5 m.) sheets of siltstone and limestone occur amongst the major conglomerates of the western edge. These have been mapped and examined particularly on Ella Ø. The limestone beds range in thickness from 0.5 cm. to 10 cm., and are usually interbedded with siltstone. Red, green and black 'limestones' were examined in thin sections. There are small hematite crystals in the red, and pyrite crystals in the green limestones. The black limestone contains some disaggregated plant material. Some of the limestones are laminated, with laminae 0.5 mm. to 3 mm. thick. Other limestones contain abundant ovoid pellets from $^1/_2$ mm. to 1 cm. in diameter. Most pellets are round but some are angular in form and they appear to be concentrated at particular horizons. Long axes of the pellets are often sub-parallel.

Faint laminations bend around the pellets or wedge out. The pellets may have been the result of agitation of fine carbonate mud on the floor of a lake, perhaps by wind-produced waves.

Lenticular limestones, similar to those of the Kap Kolthoff Supergroup, were seen in two localities in the Kap Graah Group.

Table 4.
Composition of a carbonate concretion and surrounding siltstone.

Specimen	Carbonate grainsize	% Quartz silt	Quartz grainsize	% Weight soluble in cold chloro-acetic acid
A 113				
concretion.....	4 μm	2	10–40 μm	69
siltstone	4–80 μm	20	10–80 μm	22

Concretions

Calcareous Concretions

Except for a few individuals, all the concretions examined in the East Greenland Devonian were of calcium carbonate.

Table 4 shows the result of thin-section and acid examinations of a concretion and its siltstone matrix from the Vilddal Supergroup. 69% of the concretion was calcium carbonate.

These concretions are most distinctive where they form lumpy, irregular nodules in siltstones (photo 1, p. 45). Lamination in the siltstones, defined by detrital mica, is deflected round the concretions. Although this may be partly due to bending of the lamination by growth of the concretion, it is also the result of compaction of the matrix after concretion growth. The idea of relatively early diagenetic formation of the concretions is given extra support by the presence of concretions as detrital clasts in associated sediments.

This form of the concretions is similar to that found in most other Devonian fluvial successions. It has generally been interpreted (ALLEN, 1964b; FRIEND & MOODY-STUART, 1970) as the result of precipitation from ground-water during lowering of the water-table within floodplain alluvium. This is a process similar to the formation of caliche, or kankar in arid and semi-arid soils.

In the eastern area (Table 5), concretions are generally of this sort. They are most abundant in sample groups 4F (grey-co. slst., co. sst.-flat, asym. rip.) and 7 D_2 (grey-v. f., co. sst.-trough X, flat), where they average 1 to 6 cm. in diameter and range up to 16×7 cm. Although they are commonest in red siltstone sample groups, they also occur in non-red sample groups (4B, 4C, 4D). Rather distinctively small calcareous concretions 1 to 5 mm in diameter, occur in red and grey very-fine sandstones in sample group 5C (red-co. slst., v. f. sst.-flat, asym. rip.), associated with traces of rootlets, burrows and small mudstone fragments.

In the central area, 10 to 40% of each of the mean facies profiles of the siltstone sample groups, 5A, (red-v.f.sst., co. slst.,-trough X, flat);

Table 5. *Distribution of concretions, eastern area.*

Sample Group	No. 10 m units	% No. 10 m with concr.	Max size cm	Modal grain size	Colour of sed.	Other	Mean Facprof thick (m)
1A	2	0	..	..	..	..	..
1B	2	0	..	..	..	..	..
1C	7	0	..	..	..	..	..
1D	1	0	..	..	..	..	..
2A	10	20	?	Msilt	Red	..	0.37
2B	2	0	..	..	..	..	..
2C	1	0	..	..	..	..	..
2F	1	0	..	..	..	..	..
2G	8	12	?	FMsand	Grey	..	0.37
3A	13	15	3	Csilt	Red	..	0.10
3C	26	8	8	Csilt	R/G	..	0.04
3D	37	8	3	Csilt	Red	..	0.21
4B	15	20	3	Csilt	Green	..	0.08
4C	33	9	2	Csilt	Green	2 cht	0.10
4D	18	27	15	Csilt	Green	..	0.22
4E	27	0	..	..	..	..	..
4F	8	62	16	Csilt	Red	..	1.84
4G	7	0	..	..	..	..	..
5A	38	18	3	Csilt	R/G	..	0.16
5A	38	18	3	Csilt	R/G	..	0.16
5B	16	6	1	Msilt	Red	..	0.05
5C	20	25	6	Csilt	Red	..	0.34
5D	28	4	?	VFsand	R/G	..	0.02
7A	25	8	9	VFs/Csl	R/G	1 Fer.	0.03
7B	14	7	?	Msilt	Green	..	0.11
7C	12	0	..	..	..	..	..
7D_1	3	0	..	..	..	..	..
7D_2	6	50	8	Csilt	Red	..	0.54
7E	12	8	?	Msilt	Red	..	0.05
8	3	0	..	..	..	..	..

5C, (red-co. slst., v. f. sst.-flat, asym. rip.); 5D (red-m. slst.-flat, asym. rip); 4C (grey-co. slst.-flat); and 4E (grey-co. slst., f. sst.-flat, trough X) contain concretions of this sort. Associated pebble beds and intraformational conglomerates are sometimes entirely composed of concretion clasts, and at other times consist of a mixture of concretion and siltstone clasts. In sample group 4C (grey-m., co. slst.-flat), carbonate concretions 1 to 2 mm in diameter occur in the upper, reddened part of flat bedded coarse siltstones.

Similar concretions also occur in lenticular bodies of red siltstone and very-fine sandstones in the western area (Kap Kolthoff Supergroup). They range up to 8 cm. in diameter, and are always associated with rootlet or burrow traces.

All these records provide evidence for calcification soil-types forming in siltstones under conditions of at least seasonal aridity. We have found no evidence of the formation of continuous caliche horizons.

Calcareous concretions are also a feature of many of the sandstones of the area, but with sediments of this more permeable nature, there is more doubt about the time and environment of their origin.

In the sandstones of the central area concretions occur in between 10 and 50% of the mean facies profiles of each of the following sample groups:

Photo 1. Calcium carbonate concretions, West Ramsays Bjerg Conglomerate Formation (A 16.10.).

3 D (grey-m., co. sst.-trough X), 2 C (red-m., co. sst.-trough X) and 7 E (grey-f. sst.-trough X) in which the concretions are usually found in very fine sandstones and siltstones.

3 C (grey-m., f. sst.-trough X, flat), 3 A (grey-f., m. sst.-trough X), 2 B (red-m., f. sst.-trough X, flat), 1 C (red-f., m. sst.-trough X, flat), and 1 B (red-f. sst.-trough X, flat) in which the concretions are usually found in fine-grained sandstones and concretion clasts are particularly abundant.

In the western area, concretions, sometimes with cores of pyrite, occur in sandstones ranging from very-fine to very coarse in grade. They have been noted up to 1 m. in length, and are often elongated in the direction of bedding. They have been recorded in sample groups 2 A (red-m., f. sst.-trough X, flat), 2 B (red-m., f. sst.-trough X, flat), 2 C (red-m,. co. sst.-trough X), 2 D (red-m., f. sst.-trough X, flat) and 3 D (grey-m., co. sst.-trough X).

Chert concretions

Only two instances of chert concretions were observed, both from the Vilddal Red-and-green Banded Siltstone Formation in Randbøldalen, in sample group 4 C (grey-m., co. slst.-flat). They consist of smooth black ellipsoidal nodules, 2 × 1 cm. in section, enclosed in pale-grey weathering, black silty mudstone (5 %$_0$ silt). In thin section the concretions consist of yellowish very fine-grained silica with very few scattered silt particles. Very fine-grained opaque dust forms a possible ghost lamination unrelated to the concretion geometry. Clusters of iron-ore crystals, probably pyrite, 5 to 50 μm in size, form a discontinuous ring 1 to 1.5 mm. inwards from the circumference, 20 μm rhombs of carbonate and a few plant spores up to 0.06 mm are also recognisable within the concretion. Mica-defined foliation in the surrounding, slightly calcareous, silty clay is deflected around the concretion, which is therefore an early diagenetic feature. Siever (1962) proposed that bacterial decomposition of organic matter, by releasing CO_2, could set up local areas of lowered pH, allowing outward diffusion of dissolved carbonate due to concentric gradients between such sites and their surroundings. He further suggested that the solubility of silica could be lowered locally by adsorption onto organic matter. In our examples, abundance of organic matter is suggested by the black colour of the mudstone, and confirmed by the presence of spore material within the concretions, and, in both instances, vertebrate fragments in the surrounding beds. The pyrite may be related to the generation of H_2S by bacteria or other micro-organisms during decomposition of the organic matter (Love, 1958).

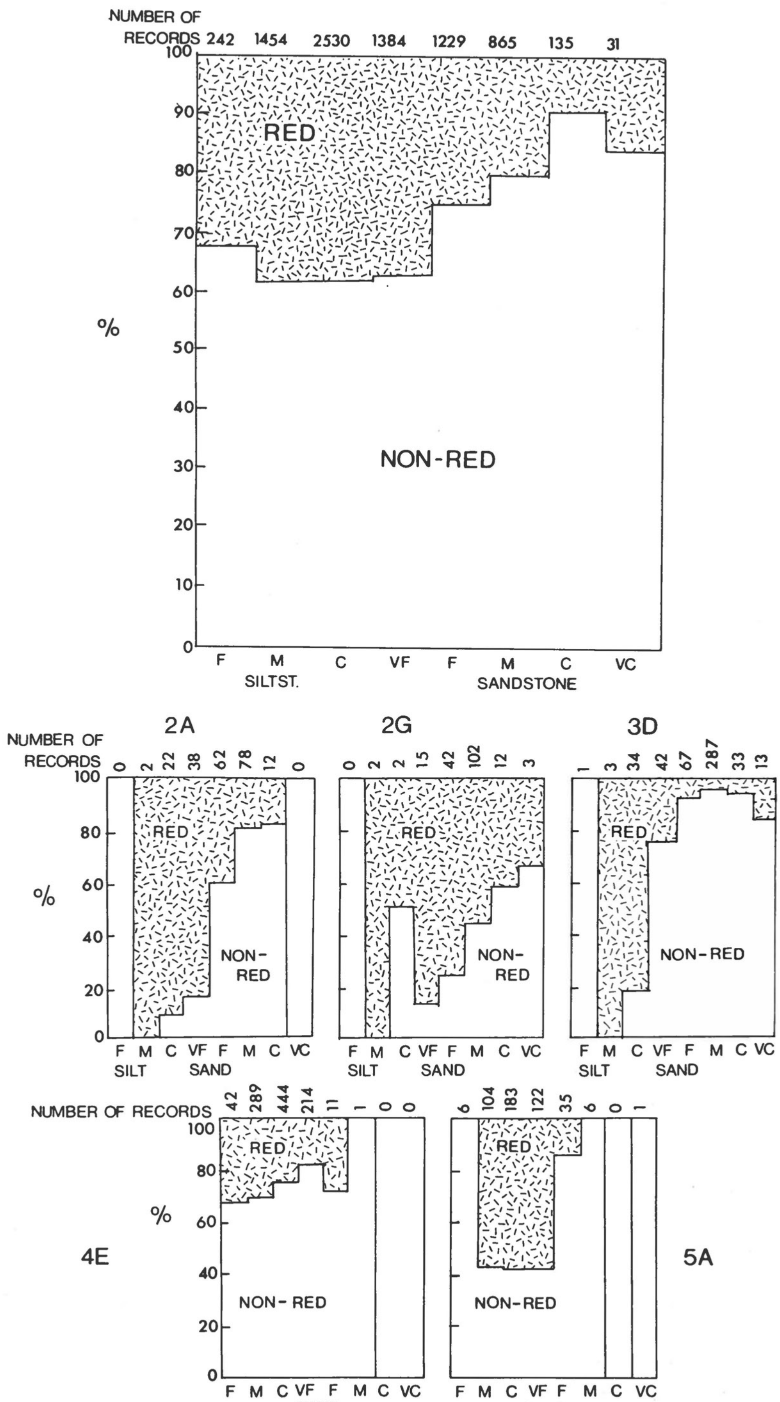

Fig. 22. Proportion of red units (sets) to non-red units (sets) in the eastern area. The upper plot presents all the data combined; the lower plots present data for five selected sample groups.

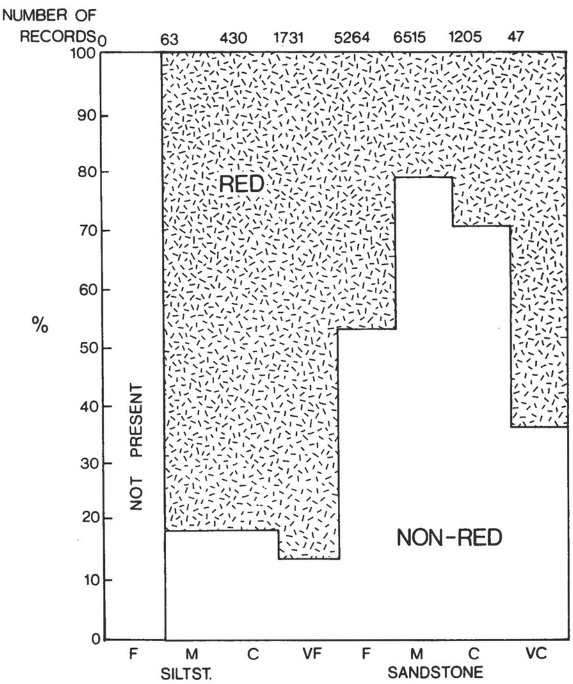

Fig. 23. Proportion of red units (sets) to non-red units (sets) in the western area.

Ferruginous concretions

In the eastern area, we noted one case in which brown concretions in grey silt were associated with plant fragments in 7A (grey-f., v. f. sst.-trough X, flat,); and 8 sets with brown pyrite concretions up to 1 cm. were noted in grey very fine sandstones in the Rødedal Formation.

Throughout the whole area, weathered pyrite concretions occur on fossil plant fragments.

Colour

Some of our work on stratigraphical and 10 m sample relationships leads to conclusions about the significance of colour in the sediments, but this will be described in the stratigraphical papers that are to follow. Here we restrict our consideration to some general points about the distribution and origin of redness.

In our discussion we use the term red to cover a wide variety of red hues, some browns and purples, and contrast it with 'non-red' colouration, which covers many shades of green, grey and even black.

Variation with grain-size

The proportions of red to non-red units recorded, of each grainsize, for the total c. 4000 m. measured in the eastern area are shown (Fig. 22). No clear pattern emerges, probably because of the great variety of facies

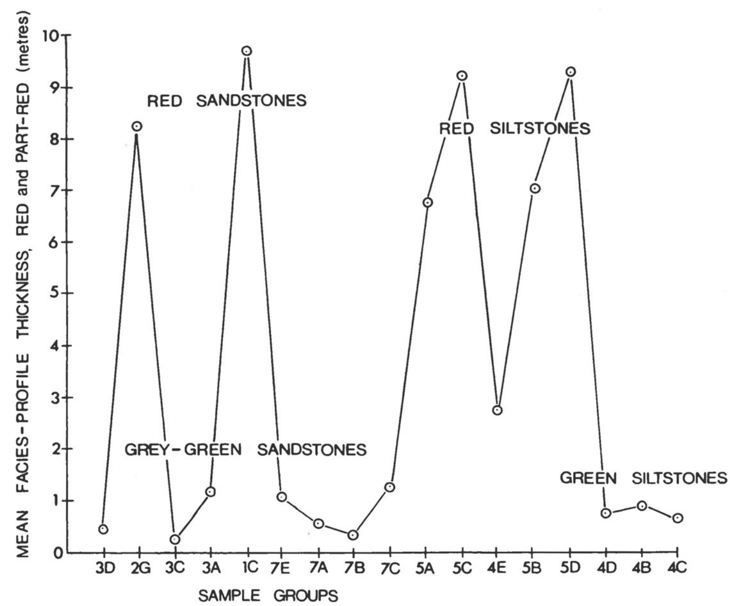

Fig. 24. The redness, and lack of redness, averaged for each sample-group in the eastern area.

present. In the rather less variable, dominantly sandstone, sections of the western area (Fig. 23), redness becomes more abundant with finer grainsizes if the rare very coarse sandstones are discounted. A clearer pattern emerges if 10 m sample group mean data are studied (Figs 22, 24). In many cases a larger proportion of sets with coarser grainsizes tend to be non-red, while siltstone sets tend to be red. There are many exceptions to this eg. group 4E (grey-co., m. slst.-asym. rip., flat) in which non-red siltstones are an important component.

Variation with other environmental factors

Our first-level sample group classification yielded red sandstone, grey sandstone, red siltstone and green siltstone groups. This might suggest that the colour is an additional factor dividing otherwise similar sandstone and siltstone samples. However this is not so; each of the second-level groups has distinctive facies profile structure and grainsize distribution, whatever the colour. Two exceptions are the pairs 4E (grey-co., m. slst.-asym. rip., flat)/5B (red-co., m. slst.-asym. rip., flat) and 2C (red-m., co. sst.-trough X)/3D (grey-m., co. sst.-trough X), which appear to differ only in colour. This distinctiveness shows that colour is, in some way, the result of environmental factors in the deposition of the sediment. Colour is not purely a later differentiation superimposed on the depositional pile.

In the western area, a study was made of the pattern of colour and internal structure variation. It was found that grain-size, internal structure and colour, while related and showing some degrees of association, showed considerable departures from these locally. In some samples almost all internal structures were red, and in others, almost all were non-red. A complex of environmental factors acting together, or individually, appear to have produced a wide variety of different associations of colour, grain-size and structure. This will be discussed further in our regional paper on the western sequence.

Origin of colour

Thin sections show that red sediments contain grains coated with dark, irregular skins, probably hematite. In non-red sediments, hematite is absent and interstitial chlorite may be present. Detrital biotite in red sediments is invariably highly altered to hematite and virtually opaque: only in non-red sediments is it relatively unaltered. In one intermediate case, *A 106*, a greyish siltstone contained biotite flakes converted at the edges into small hexagonal crystals of hematite. The redness therefore is at least partly due to alteration of ferromagnesian minerals in-situ, as demonstrated in Cenozoic rocks by T. R. WALKER (1967 a, b).

Although most of the redness is clearly due to hematite, pinkness is locally caused by the presence of reddish detrital feldspar.

We have seen examples of sharp red/non-red colour changes transgressing stratification. These were in sandstone sections of the Kap Kolthoff Supergroup in Strindberg's Land, and of the Kap Graah Group in Gauss Halvø. Diagenetic colour changes unrelated to sediment bodies are rare, however, and we conclude that colour is related usually to the local early post-diagenetic redox environments existing within the sediment bodies. This in turn must depend on the amount of time in which the sediment body is above local water-table, and the presence and quantity of organic matter, mainly plant debris (FRIEND, 1966). It also depends on grainsize, composition and permeability of the sediment. For example, large-scale foresets of cross-strata in medium sandstones group 2G, (red-m., f. sst.-trough X, flat), deposited largely by avalanching down the slip-face of a dune, were probably more loosely packed (HARMS & FAHNESTOCK, 1965, p. 92), than the bottom sets, allowing greater diffusion of ferrous-organic complexes in solution. The finer-grained bottom-sets in this case also contain more biotite flakes settled from suspension than the foresets, providing a greater proportion of hematite during subsequent oxidation.

In the western area we found green flat-bedded sandstones which contained remarkably large proportions of muscovite (as much as $^3/_4$ of the volume of the sandstone).

Clay Minerals

We sent fifteen samples of sediments for analysis of their fine-grained mineralogy by Dr. M. J. WILSON, Dept. of Pedology, Macaulay Institute for Soil Research, Aberdeen. We are grateful to him for this help. Below we provide some data on his methods of analysis, and on his provisional results (Table 6).

Clays ($< 1.4\ \mu m$) were separated from the rocks by sedimentation after grinding. Carbonate was removed from limestones by digestion in 4N acetic acid. Oriented aggregates were then prepared by sedimenting onto glass slides. These were then examined by X-ray diffraction before and after glycerol treatment and after heating for 2 hours at 600° C. CoKα radiation was used, and a scanning speed of $1°\ 2\theta$/minute through the range 2–15° 2θ. Electron micrographs were taken as part of the routine.

Varying proportions of chlorite and illite are present and form an assemblage similar to those reported from the Middle Old Red Sandstone of Scotland (WILSON, 1971) and the Upper Devonian of Catskill U.S.A. (FRIEND, 1966). In addition interstratified minerals of smectite with illite, chlorite or vermiculite are locally common. These are typically derived from volcanic debris eg. Lower Old Red Sandstone of Scotland (WILSON, 1971). Kaolinite was not detected in the Greenland samples, but this may indicate either its diagenetic loss, or absence of kaolinitic weathering in the source areas.

Table 6.

No.	Lithology	Mineralogy
Eastern area		
A096	Tuffaceous red siltstone	dioctahedral illite (abundant), 5–10 % expansible layers
A163	Accretion lapilli tuff	dioctahedral illite (abundant).
A299	Black siltstone	illite (abundant), chlorite (present).
A588	Black siltstone	illite (common), interstratified smectite/vermiculite (common).
A625	Black siltstone	chlorite (abundant), illite (present).
Central area		
G163	Green silty mudstone	dioctahedral illite (abundant).
G168	Red silty mudstone	illite (common), interstratified illite/smectite (common).
G575	Green agglomerate	chlorite (common), interstratified illite/smectite (common).
G641	Green spots in sandstone	chlorite (abundant), interstratified illite/smectite (common).
G819	Green-grey siltstone	interstratified smectite/chlorite.
Western area		
K432	Red sandstone	chlorite (common), illite (common).
K445	Green sandstone	chlorite (abundant), illite (present).
K476	Concretionary limestone	illite (abundant), interstratified illite/smectite (common), chlorite (present).
K797	Lacustrine limestone	chlorite (common), illite (common).
K776	Lacustrine limestone	chlorite (common), illite (common).

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