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DEVONIAN SEDIMENTS OF EAST GREENLAND II

SEDIMENTARY STRUCTURES AND FOSSILS

BY

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WITH 49 FIGURES, 29 TABLES AND 28 PLATES

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Abstract

Although this number contains morphological information about all the sedimentary structures and fossils seen in the Devonian sediments of East Greenland, a deliberate attempt has been made to provide information about their occurence in relation to the other features of the sediment. Special use has been made of our method, described in Number one of this volume, of classifying 10 m lengths of sedimentological log.

Scour structures on stratification surfaces are almost ubiquitous in the different types of sediment sequence. Most scours are underlain by material that is finer-grained than the material overlying them. However in some finer-grained sequences, fine-sediment fills scour structures. Tool marks are commonest in finer-grained sequences, as are various types of cracking. A 'dimple' structure is described.

Large-scale cross-stratification is described as 1) sandstone, planar foreset, 2) sandstone, curved foreset, 3) sandstone, low-angle, 4) siltstone. Planar foreset cross-stratification is only common in a few types of sequence and sandstone, low-angle and siltstone cross-stratification are more-or-less restricted to dominantly siltstone sequences. Many measurements of set thickness are presented. Symmetrical ripples are common in some siltstone sequences, and their morphology and size are described. Assymmetrical ripples (forming small-scale cross-stratification) and flat-bedding in sandstone and in siltstone are described. Parting lineation is commonest in fine-grained sandstone sequences. A variety of sedimentary deformation structures is described, and the importance of pore-water pressure and grain-size is discussed.

The important vertebrate faunas are reviewed briefly, and their occurrence in the sediment is described. Almost all finds have been of disarticulated bones, although there are a small number of articulated bone assemblages. However, observations on the occurrence of the various taxa allows one to make some suggestions about environments of life. Coarser-grained deposits usually include mixtures of genera and evidence of current scouring, though not abrasion. Finer-grained deposits sometimes show less taxonomically mixed assemblages, presumably reflecting less transport of bones.

Plant fossils, up to 2 m in length, always appear to have been transported, in both sand and silt depositing environments. Burrows are abundant in some parts of the sequence, particularly in finer-grained (siltstone) sequences. Rootlets occur locally, usually in siltstone and finer-grained sandstone lithologies. One exposure shows two sets of large tracks, interpreted as the resting tracks of *Bothriolepis*.

In most sequences large cross-stratification is coarser-grained, or the same grade as flat sandstone bedding, which is coarser-grained or the same grade as asymmetrical ripples. The range of grain-sizes of these structures conform with those predicted from laboratory experiments. Flat bedded sandstones most commonly occur above large cross-stratification sets, and below small cross-stratification (if present), and this may reflect grain-size availability or changes of water depth.

The thicknesses of sequences (cosets) of large cross-stratification vary considerably in the different types of sediment, and these may reflect differences in river channel depths. In contrast small cross-stratification and flat-bedding tended to accumulate to more-or-less similar thickness, perhaps in smaller depths. Grain-size cyclicity is not the dominant feature of the accumulation of the East Greenland Devonian that it is in some other Old Red Sandstone areas.

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INTRODUCTION

In this paper we describe and analyse the structures and fossils we found in the Devonian sediments of East Greenland.

This 'Number' is the second of a series of papers, gathered together in one volume. The volume, as a whole, describes our work on the Devonian sediments of East Greenland. Number one of the series is an introduction to the whole project and a description of our methods. Numbers three, four and five describe the work regionally and stratigraphically. Number six is a summary of our general conclusions.

The special feature of our work on structures and fossils, is the quantity of systematic field observations we made. We used a standard method of detailed sedimentary logging (involving machine-readable 'Mark-sense' forms described in Number 1). These allowed us to make detailed records, throughout the area, of a total of about 10,000 m of sediment log. These records were stored on magnetic tape. They were, therefore, in a form that made it possible to carry out rapid analysis of occurrences of features and their association with other features.

In this Number, our analysis of the occurrence of structures and fossils makes extensive use of our method of classification of 10 m 'samples' chosen from the sedimentary logs. This classification method, based on a technique of multivariate analysis, is fully described and illustrated in Number 1. Here we illustrate (Fig. 1) some typical 10 m samples, measured in the field. All our samples were classified into 'sample groups' using a computer-based technique. The complete classification scheme, and the average grain size and structure distribution of each sample group, are illustrated in Figs 2 and 3. So also is the scheme of labels (eg. 3 D) and brief standard description (eg. grey-m., co. sst.-trough X).

2. SEDIMENTARY STRUCTURES ON STRATIFICATION SURFACES

Scour Marks

Regular scour structures are essentially features of the soles of sandstones (or coarse siltstones or conglomerates) that rest on siltstones. In the entirely sandstone outcrops of parts of the western area, only five structures (four sets of flutes and one of welts) were seen. Elsewhere they are more common, and the following observations were mainly made in the eastern area.

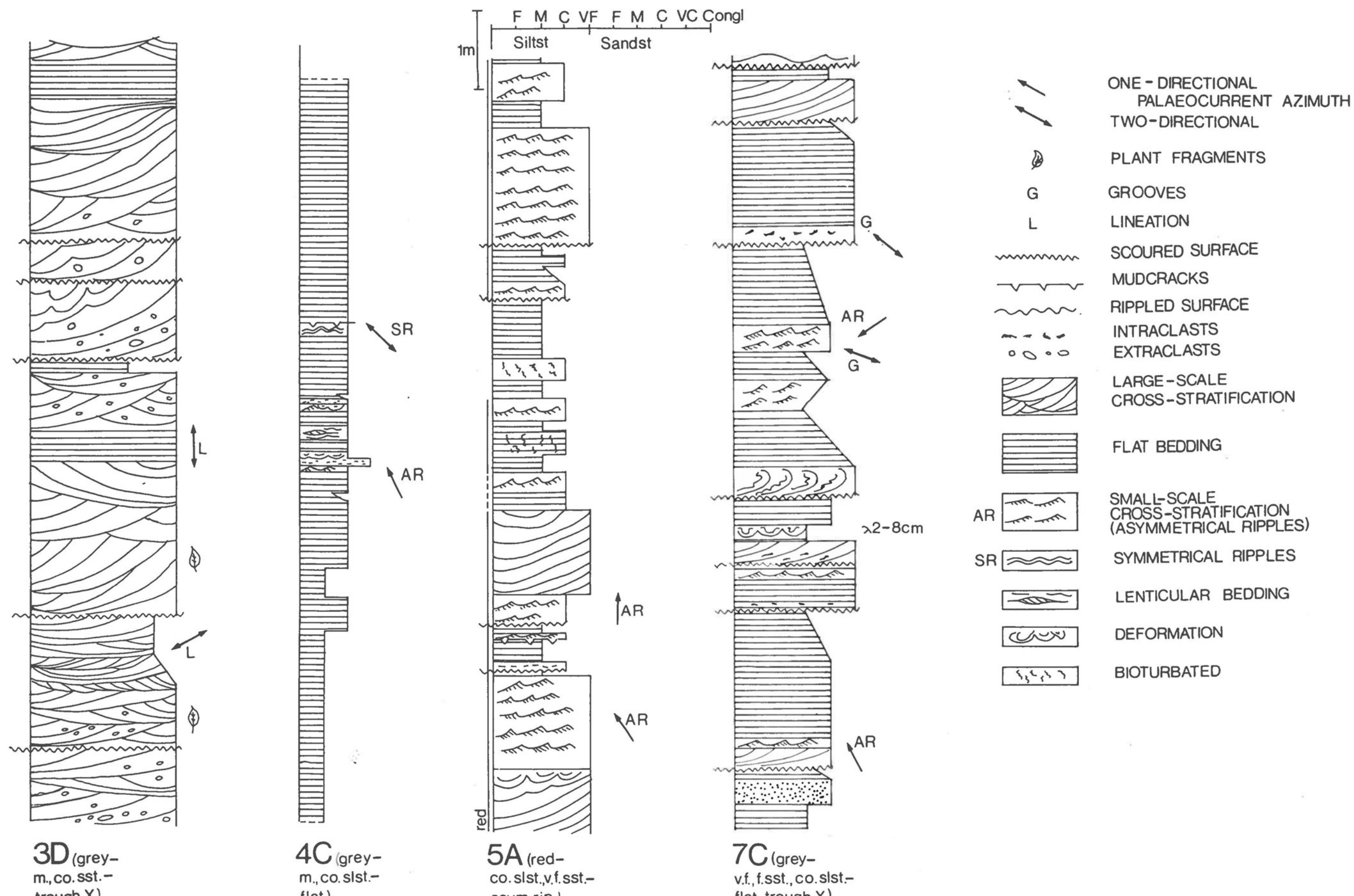


Figure 1. Examples of four 10 m samples of sedimentary logs from the eastern area, along with the classification sample group to which each was assigned (3D etc.), and a standard brief description of the sample group (grey-m., co-sst.-trough X).

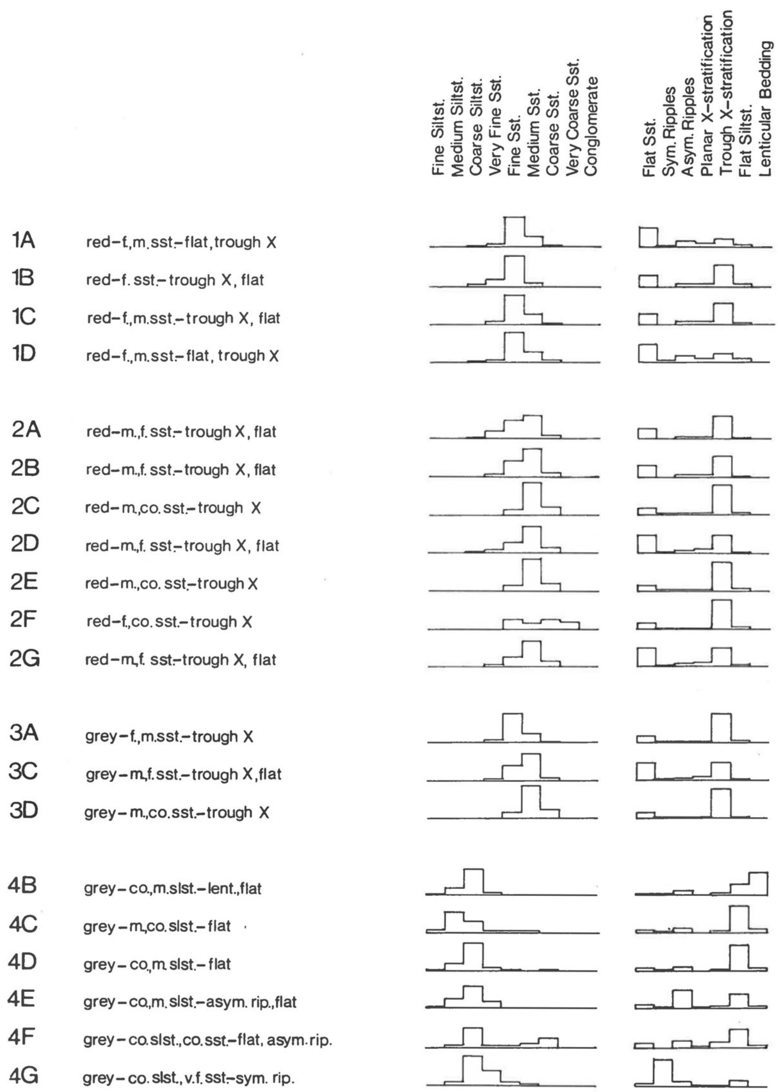


Figure 2. List of classification sample groups. Standard brief descriptions of each are given, based on the average proportions (of the 10 m thickness) of different grain-sizes and different internal structures, using eastern area data. Average proportions and descriptions from the western and central areas differ slightly in a few cases, but classify in the same groups.

Flute casts

These are the casts (plate 1) of heel-shaped hollows, bulbous at one end (CROWELL, 1955) and are the most common type of scour mark (Table 1). A few measured examples were, on average, 1.3 cm deep (0.5 to 2 cm range), and 6.7 cm long (3 to 10 cm range). Widths averaged three-quarters of the length. They are similar to the flute casts described by FRIEND (1965, p. 56) from the Devonian of Spitsbergen, and are best

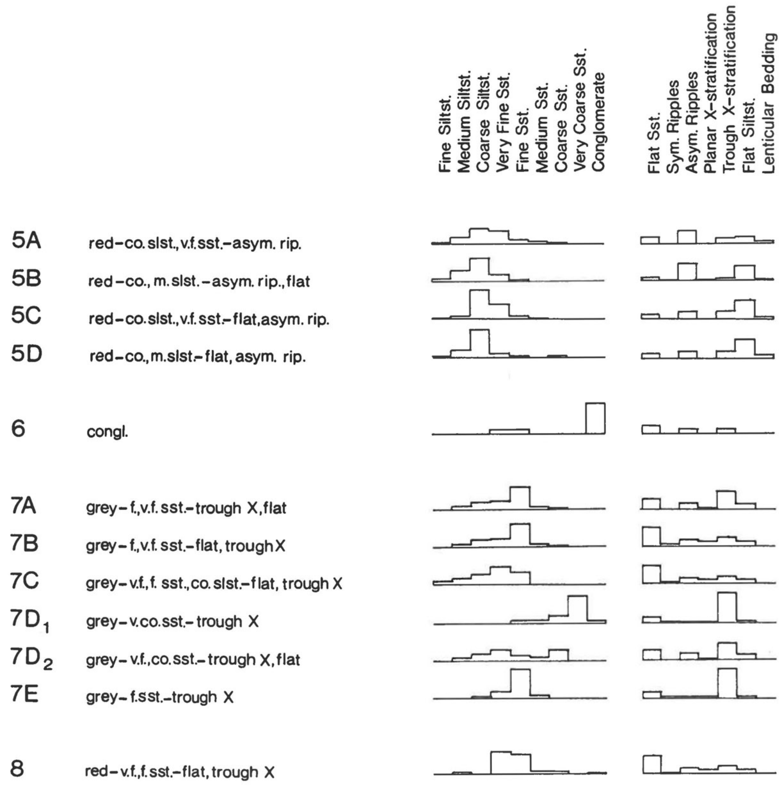


Figure 3. Continuation of Figure 2.

developed on the soles of coarse siltstone and sandstone sets overlying a finer-grained siltstone; a number of cases were noted of flute casts occurring adjacent to large (up to 30 cm) intraclasts of siltstone, partially incorporated within the overlying sandstone (Fig. 4). Allen (1969a) experimentally obtained flute marks scoured on cohesive mud beds at intermediate ranges of stream power.

Crescents

First described by Peabody (1947), these horse-shoe shaped ridges, ranging between 3 and 6 cm wide (Plate 2) are comparable to the smaller crescents described by Friend (1965). Modern examples form by scouring around clusters of coarser grains or a pebble on a finer-grained floor.

Welts, or Longitudinal Ridge Patterns

On the soles of sandstone beds, overlying siltstones, these structures consist of longitudinal, somewhat sinuous ridges. Typically (Plate 3), they are 2–5 cm wide, and have a transverse spacing of 10 to 15 cm. They are similar to long welts of the irregular type described by Friend (1965, Plate 3A). Occasional records of welts on the same surface as flute

Table 1. *Scouring and scour marks, eastern area*

Sample Group	No. 10m units logged	% units with stouring	Modal grain size	Flute	Flame	Welt	Cres.	Other	Silt-filled Channel
1A	2	100	Fsand	–	–	–	–	–	–
1B	2	100	Fsand	–	–	–	–	–	–
1C	7	100	Fsand	–	–	–	–	–	1
1D	1	100	Fsand	–	–	–	–	–	–
2A	10	100	Msand	1	1	1	–	–	–
2B	2	100	Msand	–	–	–	–	–	–
2C	1	100	Msand	–	–	–	–	–	–
2F	1	100	Msand	–	–	–	–	–	–
2G	8	75	Msand	3	–	1	–	–	–
3A	13	100	F,Msand	2	–	–	–	–	1
3C	26	92	Msand	6	–	1	–	–	–
3D	37	100	Msand	2	1	1	–	–	1
4B	15	13	VFsand	–	–	–	–	–	1
4C	33	43	Csilt	7	–	–	–	–	–
4D	18	56	Msand	1	–	–	–	–	–
4E	27	85	VFsand	4	–	–	1	–	2
4F	8	100	Csand	–	–	–	–	–	1
4G	7	14	VFsand	1	–	–	–	–	–
5A	38	71	VFsand	7	–	3	–	cracks	2
5B	16	94	Csilt	2	–	1	–	–	3
5C	20	92	Csilt	–	–	1	1	–	–
5D	28	68	Csilt	–	–	1	2	–	5
7A	25	100	Fsand	2	–	–	–	various	8
7B	14	79	Fsand	3	–	–	–	–	3
7C	12	92	Fsand	2	–	–	–	–	–
$7D_1$	3	100	VCsand	–	–	–	–	–	–
$7D_2$	6	100	Csand	1	–	–	2	–	1
7E	12	100	Fsand	–	–	1	–	–	2
8	3	100	Fsand	–	–	–	–	–	–

casts (Plate 4) support the conclusion of FRIEND (1965) and DZULYNSKI & SANDERS (1962), that they are erosional in origin.

Similar features also occur on the bases of conglomerate beds (Plate 5). In this case they are larger, ranging in depth up to 40 cm, and in width up to 60 cm.

There is no doubt that they formed as a result of aqueous erosion of the underlying silt or sand either

1) into small features of flute dimensions, which were formed by scour below a continuous cover of flowing water, and

or 2) into large features of 'channel' size which may have been cut with emergent banks. Similar structures have been named 'scour-and-fill', and illustrated from the bases of Cenozoic fluvial conglomerates in the Pyrenees by NAGTEGAAL (1966).

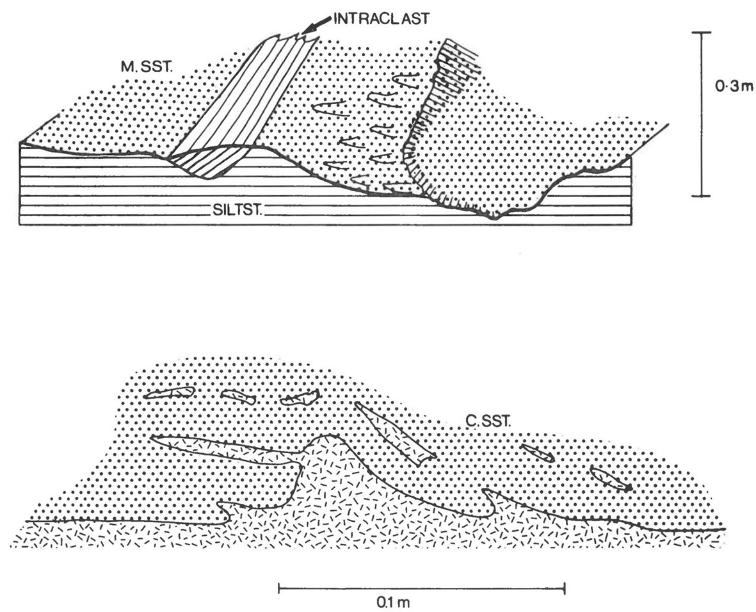


Figure 4. Upper sketch: block showing flute casts adjacent to siltstone intraclast, Kap Franklin, eastern area, Østreplateau Grey Sandstone Member. Lower sketch: rock face perpendicular to general stratification, showing flame structures and detached intraclasts, Saxos Bjerg, eastern area, Randbøl Formation.

Flame Structures

Flute casts in which the underlying siltstone has been deformed into 'flames' around the cast were noted. In one case (Fig. 4) clasts were torn off the extruding flame of silt into the body of the sandstone presumably during deposition immediately following the scouring phase.

'Squamiform Marks'

One section (A513) in the Rødedal Formation (Kap Kolthoff Supergroup) yielded blocks showing structures like those figured on a larger scale as "squamiform load-casts" by POTTER & PETTIJOHN (1963, Plate 16). These are casts of low transverse ridges, spaced longitudinally every 5 to 15 cm, with miniature flutes superimposed. The smaller-scale features are about 5 mm wide and equidimensional in the troughs, but elongated to 5×30 mm approaching the next ridge. ALLEN (1969a, Fig. 15) produced somewhat similar transverse features experimentally under super-critical flow conditions.

'Shear Wrinkles'

Another structure (Plate 6), collected from the same locality, closely resembles the 'shear wrinkles' of DZULYNSKI & SANDERS (1962, p. 83, Plate 2B); it consists of sharp ridges about 10 to 30 mm long, and up to 1 mm in relief, with a transverse spacing of 1 to 3 mm. The ridges are asymmetrical, the steeper sides facing consistently downcurrent (as deduced from ripple cross-lamination azimuths in the same section). They are at right-angles to, and superimposed on, another set of ridges, superficially resembling small and closely spaced sinuous welts, spaced at 1 to 2 mm intervals, which are parallel to the local palaeocurrent direction. The overlying sediment forming the cast is a very fine sandstone. This structure has a remarkable similarity to the small transverse shear structures produced experimentally by ALLEN (1969a, Fig. 17, 18) by flow under super-critical conditions—the geometry of the transverse ridges on sole structure precisely matches the upstream-facing fault-scarps on the mud bed inferred by ALLEN (Fig. 18).

General Points

The majority of scoured surfaces show no regular sole markings. They vary from smooth curved 'scoops' to irregular surfaces with local relief up to 50 cm. Scouring is virtually ubiquitous in all 10 metre samples of all sample groups except 4B (grey-co., m. slst.-lent., flat), 4C (grey-m., co. slst.-flat), 4G (grey-co. slst., v. f. sst.-sym. rip.), and 4D (grey-co., m. slst.-flat), all grey silt-rich facies. The modal grain size of sediment overlying scoured surfaces in a given group tends to be the same as the most abundant grain size of the group. However, in siltstone sample groups (eg. 4B (grey-co., m. slst.-lent., flat), 4C (grey-m., co. slst.-flat), 4E (grey-co., m. slst.-asym. rip., flat), 5A (red-co. slst., v. f. sst.-asym. rip.), 5C (red-co. slst., v. f. sst.-flat, asym. rip.), 7C (grey-v. f., f. sst., co. slst.-flat, trough X)) the scour mode is one Wentworth grade coarser or several grades coarser (4D (grey-co., m. slst.-flat), 4F (grey-co. slst., co. sst.-flat, asym. rip.)).

Small channels up to 30 cm deep and 2 to 3 m wide, infilled with silt or fine sand, finer than the underlying sediment, were noted most commonly in red silt sample groups (5A (red-co. slst., v. f. sst.-asym. rip.), 5B (red-co., m. slst.-asym. rip., flat), 5D (red-co., m. slst.-flat, asym. rip.)) and grey fine sandstone sample groups (7A (grey-f., v. f. sst.-trough X, flat), 7B (grey-f., v. f. sst. -trough X)), and probably represent small anabranches scoured across sediment bars within the river channel at low stage, a feature noted from modern braided streams (eg. SMITH, 1970) and from Torridonian (late Pre-Cambrian of Scotland) sediments of probable fluvial origin (SELLEY, 1969).

Tool Marks

In the eastern area, surfaces with tool marks occur much less commonly than scoured surfaces, but are about as abundant as flute casts (Table 2). Apart from the anomalous Rødedal facies (43%), the only sample groups with more than three records are 4E (grey-co., m. slst.-

Table 2. *Tool Marks, eastern area*

Sample groups	No. 10m units	%No. 10m + tool	Modal grain size	Grooves	Prod
1A	2	0	–	–	–
1B	2	50	FMsand	1	–
1C	7	0	–	–	–
1D	1	0	–	–	–
2A	10	0	–	–	–
2B	2	0	–	–	–
2C	1	0	–	–	–
2F	1	0	–	–	–
2G	8	0	–	–	–
3A	13	0	–	–	–
3C	26	8	FMsand	2	–
3D	37	3	Msand	1	–
4B	15	7	Csilt	1	–
4C	33	6	VFsand	3	–
4D	18	11	Csilt	2	–
4E	27	18	VFsand	7	1
4F	8	12	Fsand	1	–
4G	7	0	–	–	–
5A	38	13	VDsand	5	–
5B	16	25	VFsand	4	–
5C	20	15	VFsand	3	–
5D	28	7	Csl/Msd	2	–
7A	25	32	Fsand	11	–
7B	14	14	Fsand	2	–
7C	12	17	VFsand	4	–
$7D_1$	3	0	–	–	–
$7D_2$	6	0	–	–	–
7E	12	0	–	–	–
8	3	0	–	–	–

asym. rip., flat), 5A (red-co. slst., v. f. sst.-asym. rip.), 5B (red-co., m. slst.-asym. rip., flat), 7A (grey-f., v. f. sst.-trough X, flat), 7C (grey-v. f., f. sst., co. slst.-flat, trough X), with a maximum probability of finding a tool marked surface in a 10 metre unit at 32% (7A (grey-f., v. f. sst.-trough X, flat).

All but one of the records consisted of *groove casts* (SHROCK, 1948); generally straight ridges, V-shaped in cross-section, 1 to 3 mm wide and 10 to 20 cm long (Plate 7), without regular transverse spacing, though sometimes bunched in clusters. They occur modally at the base of fine and very fine sandstone sets: presumably in coarser sediments the structure tends not to be preserved, while in finer silts, the stream power is not sufficient for the current to drag a suitable tool along the mud bottom. CUMMINS (1958) has reported groove casts from fluvial sediments

(Triassic) in England, and they also occur in the Devonian of Spitsbergen (FRIEND, 1965).

One example of short (ca. 6 cm) longitudinally asymmetrical prod casts associated with normal groove casts, was recorded from sample group 4E (grey-co., m. slst.-asym. rip., flat) on Agassiz Bjerg; it probably represents the prodding action of a tool in saltation near the mud bottom.

Possible tools responsible for these marks include pebbles (both extra- and intraclasts), plant fragments and vertebrate bones. Out of 50 sets with tool marked bases, however, possible tools were seen in only 6(2 plant fragments, 3 mudflakes, and one mudflakes and bones) Within the 10 metre units containing these sets, tools can often be found in other sets: mudflakes seem to be most common, with plant fragments in 7A (grey-f., v. f. sst.-trough X, flat), and vertebrate bones available in 4B (grey-co., m. slst.-lent., flat), 4C (grey-m., co. slst.-flat), 5B (red-co., m. slst.-asym. rip., flat), 5C (red-co. slst., v. f. sst.-flat, asym. rip.). Some 10 m samples, however, contained no possible tools to account for recorded marks: the tools were presumably not deposited in these localities.

Twenty five percent of tool mark records were from surfaces yielding evidence of scouring.

Mudcracks and Crack-fill Ridges

The most common type of mudcrack (Table 3) is between 1 and 5 cm wide, and up to 5 cm deep, and, where bedding surfaces can be seen, forms polygonal patterns, 10 to 25 cm in diameter, with 5 or 6 sides (Plate 8). The fill is of fine or very fine sandstone, less compressible than surrounding siltstones. The mudcracks occur at the base of sandstone sets overlying siltstones, and also as internal features within sets of siltstone. On northeast Saxos Bjerg, interlaminated very fine sandstone and silstone occurs, in which all the silt laminae are broken into polygonal segments 10 cm in diameter with upcurled edges. This records a very low rate of sediment accumulation with frequent periods of desiccation, almost certainly subaerial.

A larger type of mudcrack ('sand-crevice'), in some ways resembling a sedimentary dyke, was recorded. From 5 to 40 cm deep, and 5 to 10 cm wide, they taper downwards within a thick unit of siltstone, and are filled by fine or very fine sandstone. The largest example (Plate 9) showed that the cracks in plan view, formed part of a complex intersecting system. They probably formed by subaerial desiccation and shrinkage of thick sets of siltstone (part red and non-red), and differ only in scale from the commoner type of mudcracks. The are found in siltstone groups 4E (grey-co., m. slst.-asym. rip., flat), 4D (grey-co., m. slst.-flat), 5A (red-co. slst., v. f. sst.-asym. rip). 5D (red co-.,m. slst.-flat, asym. rip), and

Table 3. *Distribution of mudcracks and crack-fill ridges, eastern area*

Sample groups	No. 10m units	%No. units +· Mdcr	Normal Mudcr.	Large	Narrow	Crackfill
1A	2	0	–	–	–	–
1B	2	0	–	–	–	–
1C	7	0	–	–	–	–
1D	1	0	–	–	–	–
2A	10	0	–	–	–	–
2B	2	0	–	–	–	–
2C	1	0	–	–	–	–
2F	1	0	–	–	–	–
2G	8	0	–	–	–	–
3A	13	8	2	–	–	–
3C	26	4	3	–	–	–
3D	37	11	7	–	–	–
4B	15	20	–	–	3	4
4C	33	39	–	–	22	3
4D	18	22	–	1	9	–
4E	27	33	17	3	–	–
4F	8	0	–	–	–	–
4G	7	72	–	–	20	–
5A	38	13	12	1	–	–
5B	16	37	7	–	–	–
5C	20	25	12	–	–	–
5D	28	25	9	1	–	–
7A	25	12	5	1	–	–
7B	14	14	2	–	–	–
7C	12	42	10	1	–	–
$7D_1$	3	0	–	–	–	–
$7D_2$	6	33	9	–	–	–
7E	12	22	2	–	–	–
8	3	0	–	–	–	–

in silt intercalations in 7A (grey-f., v. f. sst.-trough X, flat), 7C (grey-v. f., f. sst., co. slst.-flat, trough X).

Mudcracks in grey silt groups 4B (grey-co., m. slst.-lent., flat), 4C (grey-m., co. slst.-flat), 4D (grey-co., m. slst.-flat), 4G (grey-co. slst., v. f. sst.-sym. rip.), differ from the type common in sandstone and red silt groups (Table 3) in that they are narrower on average (5 mm, ranging 2 to 13 mm), and the fill material tends to be coarse or medium siltstone within a finer siltstone or shale. In plan, polygons of 10 to 40 cm diameter were observed (Plate 10). Larger mudcracks up to 20 mm wide and filled with very fine sandstone are less common in these groups and tend to form rectangular polygons. If montmorillonite was an original clay constituent of the sediment, the narrow cracks could have formed by shrinkage under water due to changes in salinity (BURST, 1965), but

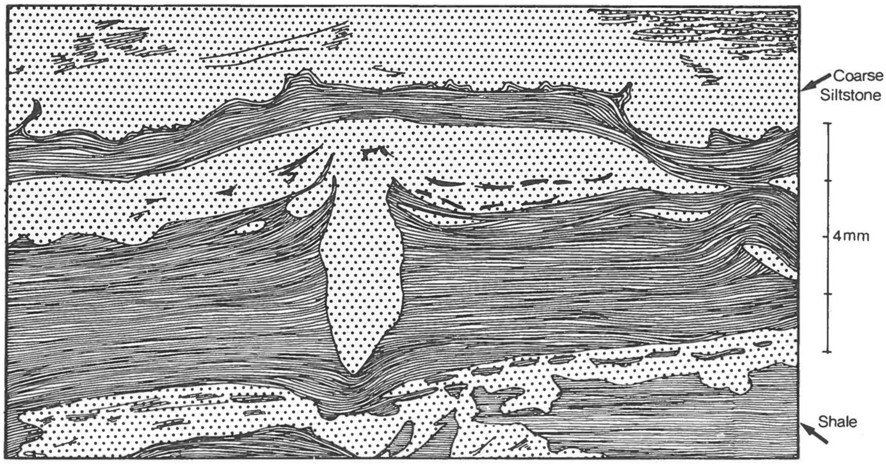


Figure 5. Crack-fill ridge, transverse vertical section, Kap Brown, eastern area Nathorst Fjord Group.

subaerial desiccation cannot be ruled out. The smaller cracks may include some of the crack-fill ridges described below.

Crack-fill Ridges

These crack-fill ridges, recorded only from grey siltstone groups, 4B (grey-co., m. slst.-lent., flat), 4C (grey-m., co. slst.-flat) are very similar to the 'crack-fill ridges' described from the Bembridge Marls by DALEY (1968, p. 122, Figs. 6, 7D, 9, 10), and to the 'oriented linear-shrinkage cracks' in the Green River Formation of Utah (PICARD, 1966), both non-marine, probably lacustrine sedimentary sequences of Tertiary age.

The lithology in which they occur consists of interlaminated silt and shale: light grey lenticular laminae, 0.5 to 4 mm thick, are composed of about 60 percent coarse quartz silt, in a carbonate matrix without clay, and alternate with dark grey to black laminae of shale, composed of clay with 10 percent of medium silt grains. The bases of the lighter laminae are often deformed into minute load casts. On the shale bedding-planes (Plate 11), the cracks appear as ridges about 1 mm above their surroundings, between 1 and 3 cm long (rarely up to 5 cm), and 1 to 3 mm wide in the middle, tapering to a point at each end. The degree of orientation of the cracks is not a great as in DALEY's (1968) examples, but is comparable to that of PICARD (1966, Fig. 3). The strike of the cracks (rarely measurable in situ) is approximately parallel to the strike of symmetrical ripple crests in the same mark-sense sections. In transverse section, the crack fills exhibit a variety of shapes, many indistinguishable from small ordinary mudcracks and vertical burrows (Plate 12). However, one characteristic shape can often be seen in thin section and on suitable surfaces (Fig. 5) the cracks appear lenticular, tapering upwards into a coarse silt lamina, and downwards into clay laminae (cf. DALEY, 1968, Fig. 7D). Their vertical length varies between 3 and 8 mm, and they are filled with the same coarse silt as the overlying lamina. Many are distorted into an oblique orientation (cf. PICARD, 1966, Fig. 5), while others show ptygmatic folds, no doubt in response to compaction of the surrounding shale (BRADLEY, 1930).

Both PICARD and DALEY suggest gravitational creep down the local palaeoslope with the formation of miniature "crevasses" as a factor in the origin of these structures. The Devonian examples are consistent with this interpretation, though desiccation or subaqueous shrinkage of clays may also be involved. VAN STRAATEN (1954, Fig. 12) has recorded similar, but larger-scale, sand-filled fissures in mud at the floor of modern tidal channels: they also wedge out downwards and the fillings are sometimes ptygmatically folded. He states that they must have formed at least 9 metres below low tide level.

Dimple Structure

A rare structure preserved on the top surface of certain very fine sandstone sets in the eastern area, consists of raised pimples, with up to 2 mm relief and 2 to 8 mm in diameter, irregularly spaced over the surface a few mm apart. The surface is coated with a thin (less than 0.5 mm) veneer of red clay, which is often broken by long narrow (2 mm wide) mudcracks. The pimples show a variable degree of asymmetry, with preferred orientation: larger ones resemble miniature linguoid ripples (Plate 13). Unfortunately the preferred orientation azimuths were not measured in the field. "Dimple" structure was recorded 11 times (Table 4) in the mark-sense data. The sand bodies tend to be thin (10 to 20 mm) and lenticular.

We have observed similar pimples and blisters in sand in modern ephemeral streams in Greenland and South Wales, under conditions of low stage: they measure 3 to 8 mm in diameter, and are associated with

Table 4. *Distribution of dimple structure, eastern area*

Sample groups	No. 10m units	No. of records	Colour	Grain size
2C	1	1	Red	Msand
3D	37	2	R, G	VF, Msand
5B	16	2	Red	VF, Fsand
5C	20	2	Red	VFsd, Cslt
5D	28	2	Red	VFsand
7C	12	1	Red	Csilt
$7D_2$	6	1	Grey	Fsand

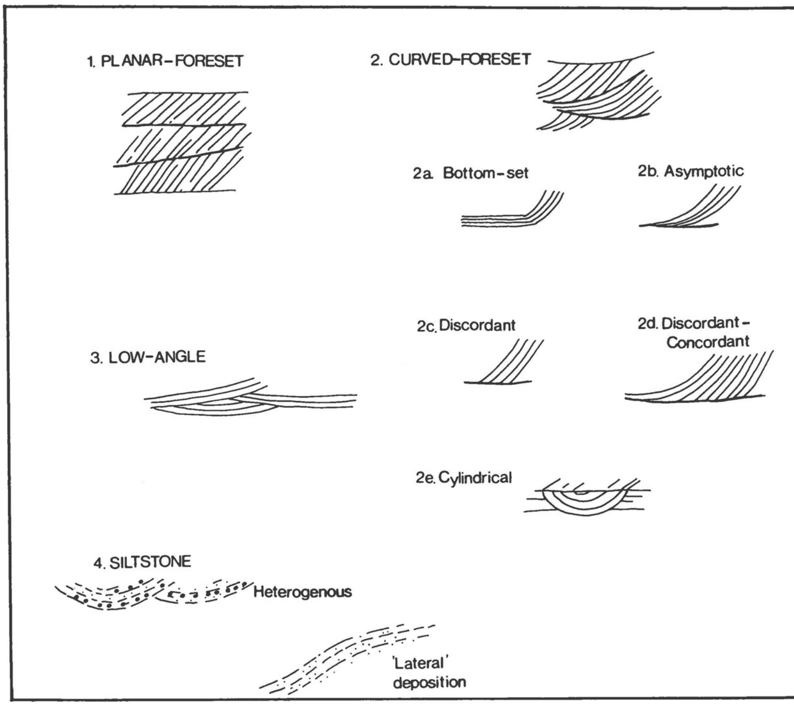


Fig. 6. Field classification of types of cross-stratification.

gas bubbles just beneath the sediment-water interface. On exposure to air, the pimples collapse somewhat, with steeper sides facing upstream and towards the retreating water-line, perhaps due to the direction of local water drainage. EVANS (1965, p. 221) also reports pimple-structures from intertidal flats in the Wash, and attributes them to trapping of gas in the sediment.

3. STRATIFICATION STRUCTURES

Large-scale Cross-stratification

Description and Interpretation of Types

We use the term "large" in the sense suggested by ALLEN (1966), for any cross-stratification with sets "mostly greater than 5 cm". We started our Greenland work using a two-fold classification of large cross-stratification into "planar" and "trough" types. However, we used these terms to describe the shape of the cross-strata rather than the shape of the lower bounding surface of the cross-stratified set (the definition used by McKEE & WEIR, 1953). We found this two-fold division of very limited value, because "trough" examples made up an overwhelming

	1	2	a	b
Type	planar foreset	curved foreset	+ bottomset	asymptotic
Grouping	grouped	grouped	solitary/ grouped	grouped
Relation of lower surface to underlying strata	non parallel	parallel/ non parallel	parallel/ non parallel	parallel/ non paralle[l]
Shape of lower surface	planar	planar-scoop	planar-scoop	planar-scoo[p]
Relation X strata to lower surface	discordant	discordant -asymptotic -concordant	concordant	asymptotic
lithological uniformity	homog. c. m. sst.	homog. c. m. sst.	homog. c. m. sst.	homog. c. m. sst.
Trace of X-strata:				
Bedding section	linear	concave up	concave up	concave up
strike section	linear	concave up	concave up	concave up
Dip section	linear	concave up	distinct bottomset	concave up
other notes				

proportion of the total, and there are many other distinctive variants. We have found very valuable the review of cross-stratification features produced by ALLEN (1963c), and the comments by CROOK (1965). By our last season, each of us, working in his own area, had decided on field classifications with four or more subdivisions. The types distinguished and described below (Table 5, Fig. 6), result from a combination of these classifications. The categories grade into each other, and, in some cases, overlap.

(1) Sandstone, planar-foreset cross-strata

Cross-strata of this type, and of the following type (2) occur modally in medium sandstone, and show greater geometrical similarity to each other than to other types. There can be little doubt that both types 1 and 2 originated by deposition on the lee-side of dunes or deltas. The frequent grouping of these cross-stratified units in thick sequences suggests that deposition by solitary delta-like bodies (eg. chute-bars

c	d	e	3	4
lant	discordant concordant	cylindrical	low-angle	siltstone
d	solitary/ grouped	solitary/ grouped	grouped	solitary/ grouped
l/ rallel	parallel/ non parallel	parallel/ non parallel	non parallel-indeterminate	non parallel/ parallel
-scoop	planar-scoop	cylindrical	scoop	planar-scoop
lant	discordant concordant	concordant	concordant-asymptotic	discordant-concordant
. st.	homog. c. m. sst.	homog. c. m. sst.	homog. c. m. sst. f. sst.	heterogeneous or homogeneous f. sst. and slst.
e up e up e up	concave up concave up concave up	linear linear concave up	concave concave up concave up	concave up concave up concave up
			foreset dip 3–15°	sometimes evidence of lateral deposition

(McGowen & Garner, 1970); point dunes (Hickin, 1969)) is unlikely. A variety of bed-forms, all of which occur in trains, could be responsible for types 1 and 2.

Although this planar foreset type is recognised by the lack of curvature in the foresets (Plate 14), the feature often appears to be associated with relatively flat surfaces bounding the bases of the cross-stratified sets. This category therefore corresponds generally to the "planar cross-stratification of McKee & Weir (1953). It is probably largely covered by the "omikron" cross-stratification of Allen (1963).

Planar-foreset cross-strata probably formed by the migration of dunes or sand waves with essentially straight crests (Allen, 1963a). Similar cross-stratification has been reported in the deposits of straight-crested dunes in the Wadden Sea (Hulsemann, 1955), transverse bars in a braided stream (Smith, 1970), straight-crested sand waves in the Rio Grande (Harms & Fahnestock, 1965), and large linguoid bars in the Tana River (Collinson, 1970). Clearly most of these sand bodies have

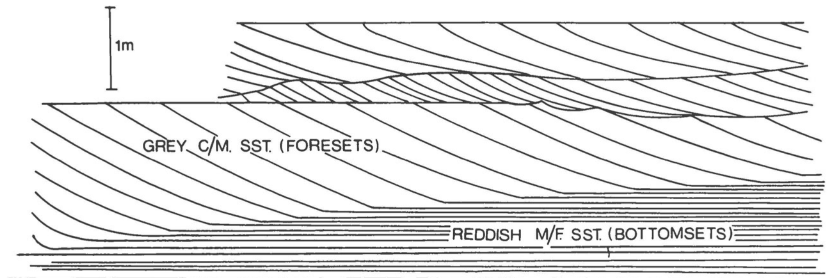


Figure 7. Type 2a cross-stratification, southern Gunnbjørns Bjerg, eastern area, Hjelmbjergene Group.

down-stream slopes which show curvature if traced far enough. None of them, therefore, is likely to form cross-strata which are strictly planar for any distance.

(2) Sandstone, curved-foreset cross-strata

As described above, this cross-stratification probably resulted from the migration of dunes or sand waves. However in this case, they had curved crests. Each dune was accompanied by an erosional hollow scoured out by currents associated with the three-dimensional structure of the dune (ALLEN, 1963a). Concave-upward cross-stratification in Mississippi point-bar deposits is formed by sinuous crested dunes on the lower part of the point-bar (FRAZIER & OSANIK, 1961). The structure has also been found preserved beneath lunate dunes in an Australian ephemeral stream (WILLIAMS, 1968), and in sinuous crested megaripples in the braided Brahmaputra River (COLEMAN, 1969).

Cross-strata of this type may also be formed by sinuous crested dunes migrating over large hollows scoured in the point-bar surface as a separate event in time, as in the Red River (HARMS and others, 1963). This process has been described by JOPLING (1965) from laboratory deltas; however, the occurrence of ellipsoidal scours in front of the avalanche faces of larger sand waves, reported by HARMS & FAHNESTOCK (1965) is more akin to ALLEN's (1963a) scouring by sinuous-crested dunes. We shall describe five sub-categories of this structure.

Sets of the *Bottom-set* type (2a) differ from other types in the presence of thick and distinct flat-bedded bottomsets beneath the foresets (Fig. 7). JOPLING (1965) interpreted the preservation of bottomsets as due to increasing depth ratio (flow depth-over-topset/flow depth-over-bottomset), and/or to an increasing proportion of suspended load. ALLEN (1968a) pointed out that bottomsets could be formed without any suspended load, by reworking bed material in the back-flow current of the separation eddy in the lee of the dune or delta. ALLEN (1968b, Chap. 16) suggested that bottomset deposits could become thicker relative to slip-face deposits by increasing the ratio of: 1) characteristic path-length of grains settling through the separation layer to 2)dune height.

This is achieved by increasing the flow velocity or decreasing grain size. In none of the observed sets can the bed-load transport rate on the bottomsets have been large enough to generate small-scale "back-flow" current ripples as described by BOERSMA and others (1968). Moreover the presence of such clearly distinct bottomsets suggests that the bottomset transport rate was small compared with the settling rate.

In the *Asymptotic* (2b) subcategory, the cross-strata are asymptotic to the underlying scoured surface. Both in this type and in the following two types, the bottomset is not clearly distinguished from the foresets. Using ALLEN's analysis (1968b p. 338) of the origin of distinct bottomsets, this lack implies a high bottomset transport rate relative to the bottomset settling rate. The asymptotic lower ends of the strata show that the characteristic grain paths were great relative to ripple height. This is a sign of high stream power, relative to that which produced bottomset (2a) cross-strata.

In the *Discordant* type (2c), the cross-strata end discordantly at their junction with the underlying scoured surface. This feature implies (ALLEN, 1968b, p. 338) a relatively low ratio of grainpath-length to ripple height. This suggests lower stream power than that which produced bottomset (2a) cross-strata.

In the *Discordant-concordant* (2d) subcategory, upstream cross-strata are discordant to the underlying scoured surface, but downstream cross-strata are increasingly asymptotic. Following ALLEN's arguments used above (ALLEN, 1968b, p. 338), this change suggests an increase of stream-power during sedimentation.

In the *Cylindrical* (2e) subcategory, the cross-strata are concordant with the cylindrical shape of the underlying scoured surface. This type is ALLEN's (1963) zeta type.

(3) Sandstone, low-angle cross-stratification

It is generally difficult to record palaeocurrent azimuths from this low-angle type of cross-stratification (Plate 15). Some records of low-angle discordances may perhaps be attributed to cross-cutting sets of "flat-bedding", as in the floodplain deposits of Bijou Creek (McKEE and others, 1967). However other examples of these cross-strata were probably formed by the migration of low amplitude dunes of fine sand. BAGNOLD's (1966 p. 116) suspension criterion predicts that for fine sand and finer sediments, a suspended load is developed when the bed shear stress exceeds the threshold for particle movement. ALLEN (1968b p. 391), experimenting with fine sand (2.38 phi), noted that with most deposition occurring from suspension, at all his experimental values of bed-shear stress, the slip face deposit grew very slowly and was "combed down" by vortices generated in the lee of the dune. However cross-stratification of types 1) and 2) also occurs in fine sandstone. Thus type (3) could possibly result from transitional conditions between dunes and upper phase plane beds (the "sheared out" dunes of SIMONS and others (1965), and ZNAMENSKAYA's (1964) "Zone 4").

(4) Siltstone cross-stratification

This category includes a number of different forms. All of them are characterised by rather fine grain size (fine sand to silt grade), and many of them contain numerous siltstone strata. We shall describe two sub-categories of this structure.

The *Heterogeneous* (4a) subcategory is characterised by cross-strata of very fine sand and siltstone (Plate 16). The cross-strata are usually concordant with the cylindrical or scoop-shaped lower surface. We interpret this structure as the result of deposition largely from suspension, in shallow channels scoured out previously during flood (McKEE, 1957). Some muddy sediment may accrete by deposition on the sides of the channel (SCHUMM, 1961). McKEE (1939) has reported this scour and fill structure from the Colorado River delta, and from the Triassic Moenkopi Formation (McKEE, 1954), interpreted as mud-flat deposits.

The *Lateral* (4b) subcategory is characterised by evidence of "lateral" deposition on the cross-strata. It is an essential feature of these structures that there are two hierarchical levels of bed forms (ALLEN, 1966). The major cross-strata include small-scale cross-strata which often indicate flow more or less parallel to the strike of the major cross-data. This process of lateral accretion is similar to that which occurs when channels migrate on modern intertidal flats (TRUSHEIM, 1929; HÄNTZSCHEL, 1936; VAN STRAATEN, 1954; REINECK, 1958), and in modern alluvial floodplains (BERNARD, and others, 1970). Comparable, though not identical structures were described by ALLEN (1965a), MOODY-STUART (1966), ALLEN & FRIEND (1968) as 'epsilon' cross-stratification, in the Devonian fluvial deposits of Anglesey (N.Wales), Spitsbergen, and the Catskill Mountains, and by WILLIAMS (1966) from the Torridonian of N.W. Scotland.

Occurrence of Cross-stratification Types in 10 m Sample Groups

We have listed (Table 6) the relative proportions of the different cross-stratification types in the major sample groups. The figures only give general indications, because of the inherent difficulty of classifying sets of a gradational type, and because different observers used slightly different criteria.

Table 6. *Occurrence of cross-stratification types in 10 m sample groups*

Western Area

Group	No. of records	% 2b	% 2c	% 2d	% 2e
1A	17	18	71	0	12
1B	15	93	0	7	0
2A	99	37	56	1	6
2B	82	55	37	7	1
2C	162	47	48	4	1
2D	32	31	56	9	3
2E	53	25	73	2	0
3A	46	48	52	0	0
3C	491	39	51	8	2
3D	899	52	40	5	2
5A	51	12	86	0	2
8	18	11	89	0	0

Central Area

Group	1	2	2a	3	4
1B		maj.			
1C	maj.	maj.			
2A	min.	maj.			
2B	min.	maj.			
2C		maj.			
2E	min.	maj.			
2F		maj.			
2G	maj.	min.	min.		
3A		maj.			
3C	min.	maj.	–	min.	–
3D	min.	maj.	–	–	–
4E	–	–	–	maj.	
5A	–	–	–	maj.	min.
5C	–	–	–	maj.	min.
5D	–	–	–	maj.	–
7B	maj.	–	–	maj.	–
7D	min.	maj.	–	min.	–
7E	min.	maj.	–	min.	–

Eastern Area

Group	No. of records	% 1	% 2	% 2a	% 3	% 4
1C	43	0	76	0	24	0
2G	50	43	24	18	14	0
3A	91	2	81	1	16	0
3C	34	0	45	0	55	0
3D	131	18	76	0	6	0
4E	20	0	10	0	70	20
4F	15	0	53	7	40	0
5A	31	0	16	0	55	29
5C	49	0	35	0	51	14
5D	9	0	0	0	55	45
7A	104	3	64	0	30	3
7B	8	12	25	0	63	0
7C	20	5	60	0	35	0
$7D_1$	11	18	73	9	0	0
$7D_2$	23	9	65	0	22	4
7E	29	7	41	0	52	0

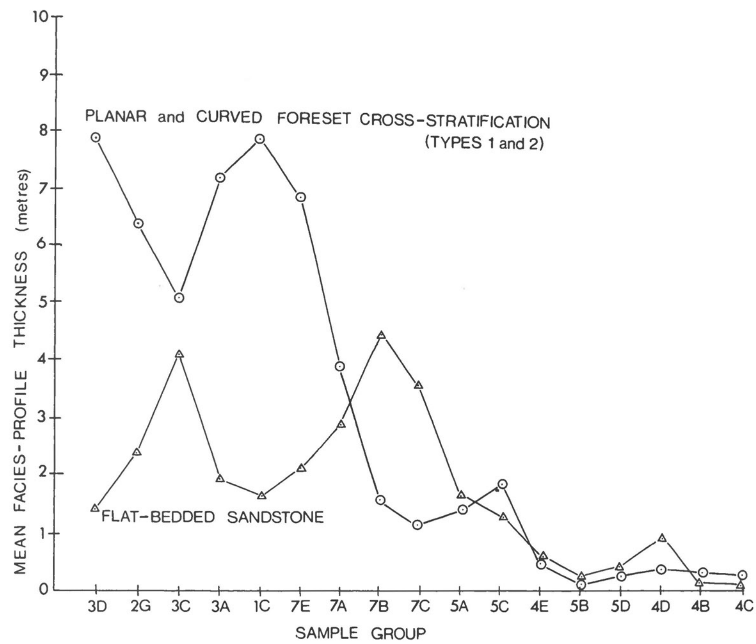


Figure 8. Average proportions of flat-bedded sandstone and cross-stratified sandstone in different sample groups, eastern area.

Type 1 (planar foreset) was not recorded at all in the western area, and elsewhere, it is only of major importance in three of the 10 m sample groups (1C (red-f., m. sst.-trough X, flat), 2G (red-m., f. sst.-trough X, flat), 7B (grey-f., v. f. sst.-flat, trough X)).

Type 2 (curved foreset) is the only type recorded in the western area, and here the asymptotic and discordant subcategories are completely dominant. In the central and eastern areas this type dominates the sandstone sample groups (Fig. 8). Subcategory 2a (with bottomsets) is only abundant in the sandstone group 2G (red-m., f. sst.-trough X, flat), where type 1 is also dominant.

Type 3 (low angle) is the dominant type in the siltstone groups of the central and eastern area (4E (grey-co., m. slst.-asym. rip., flat), 5A (red-co. slst., v. f. sst.-asym. rip.), 5C (red-co. slst., v. f. sst.-flat, asym. rip.), 5D (red-co., m. slst.-flat, asym. rip)), and it is also important in the sandstone groups which contain a greater than average proportion of flat bedding (3C (grey-m., f. sst.-trough X, flat), 7B (grey-f., v. f. sst.-flat, trough X), 7E (grey-f. sst.-trough X).

Type 4 (siltstone) is more or less restricted to the siltstone groups, but even in these, it only forms a small proportion of the observed structures.

Thickness of Cross-stratified Sets

Because set thickness is a possible indicator of water depth, it was systematically noted during part of our work.

The feature that was noted was the maximum apparent thickness of the set on the outcrop surface. Apparent thicknesses vary considerably, of course, within a 10 metre sample.

It is difficult to know how set thickness corresponds to the height of the dune which formed it. HARMS & FAHNESTOCK (1965) believed that only the part of a sand wave that was deposited in an erosional hollow, would be preserved. SALSMAN and others (1966) found sets deposited by dunes which were 2.5 to 5 times the set thickness in height. The ratio of suspended load transport rate to bed-load transport rate (ALLEN, 1968b, Chapter 5) is clearly an important factor in determining how much of a dune is shaved off before migration of the next dune over it.

The relationship between dune height and flow depth is probably complex. ALLEN (1963a) illustrated an empirical relationship between flow depth and height of large-scale, mostly straight, dunes. Flow depths ranged between 3 and 22 times the dune height. YALIN (1964) predicted theoretically that two-dimensional dunes should not exceed one-sixth of the flow depth, while SIMONS *et al.* (1962) observed that the maximum dune height attainable is of the order of the average depth of flow. CAREY & KELLER (1957) found sand waves up to 10 feet high at high stage in the Mississippi (depth 70 feet), but they diminished to 2 to 3 feet at low stage, in much the same depth. COLEMAN (1969, p. 190) stated that dune height was independent of water depth, except in flows less than 6 m deep, in the braided Brahmaputra. ZNAMENSKAYA (1966) showed experimentally that when flow depth is very large compared to grain size (ratio 10^4), the dune height averages one-tenth of the flow depth, but for shallower flows, it varies between 20 and 60 percent of the flow depth, depending on flow velocity. GRIGG (1970) found that the increase in dune height with stream power was greater in fine than in medium sand.

The only certain inference from set thickness, therefore, is that a cross-stratified set must have been deposited in a depth of water greater than or equal to its thickness. It follows that the maximum set thickness in a 10 m sample is a minimum estimate of the maximum flow depth for the dune phase for that environment.

We collected some data on the variation of set thickness with different types of cross-strata.

The arithmetic mean set thickness for each of the following categories was calculated for the western area, using one season's data (Table 7).

Table 7

		mean
2b	(asymptotic)	23 cm
2c	(discordant)	32 cm
2d	(discordant-concordant)	28 cm
2e	(cylindrical)	14 cm

Another analysis showed that in one 40 m section (10 m samples of groups 2B (red-m., f. sst.-trough X, flat), 2F (red-f., co. sst.-trough X) and 2G (red-m., f. sst.-trough X, flat)), sets of type 2 (curved foreset) were less than half the thickness of sets of type 2a (curved foreset — bottomset). (Table 8). This supports our earlier suggestion that an increased thickness of bottomset deposits required greater flow depths than those with negligible bottomsets.

Table 8. *Section A 520, Hjelmbjergene Red Sandstone Formation Thicknesses of cross-stratified sets*

Type	Mean cm	log mean	log SD	min.	max.	No.
2a	65	4.2	1.1	15	300	16
2	28	3.3	0.8	5	130	19

SD = Standard deviation

We then analysed our data to find out how set thickness varies with 10 m sample groups. In the eastern area, the means, for each group, of maximum set thicknesses are smaller in the finer grained groups. (Fig. 9, Table 9). They are also smaller where the proportion of cross-

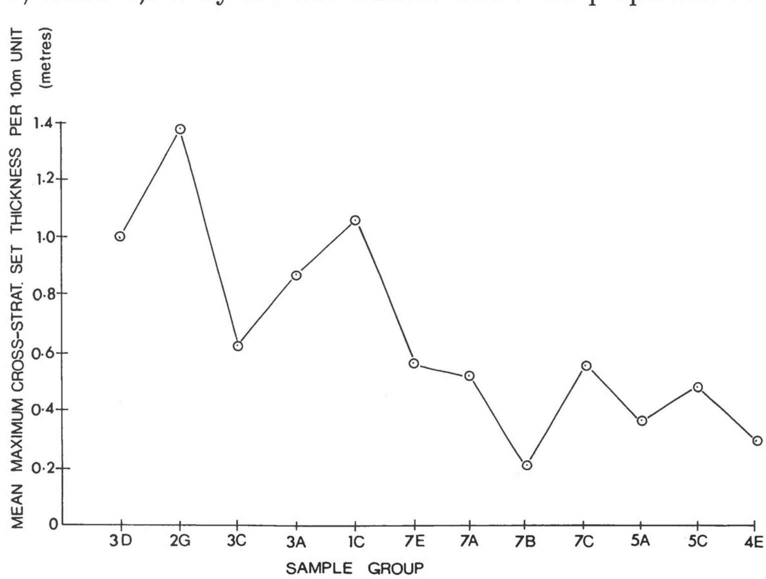


Figure 9. Maximum cross-stratification set thickness averaged for samples in each sample group, eastern area.

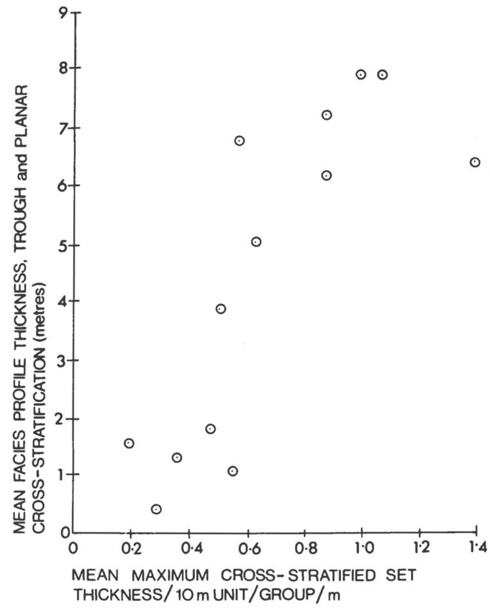


Figure 10. Maximum cross-stratification set thickness averaged for samples in each sample group, compared with the thickness of cross-stratified sediment in the same group. Data come from the eastern area.

Table 9. *Eastern Area.*
Mean for each group of maximum cross-set thickness per 10 m sample

10 m Sample group	Mean Max. cm	No. of samples
1C	106	4
2A	66	4
2G	138	5
3A	87	11
3C	63	13
3D	100	23
4E	29	9
5A	36	7
5C	48	11
7A	51	15
7B	20	2
7C	55	2
$7D_1$	87	2
7E	57	6

stratification is less (Fig. 10). Exceptions, in which set thickness is anomalously small, relative to grain size, are groups with particularly thick flat-bedded sandstone (3C (grey-m., f. sst.-trough X, flat), 7B (grey-f., v. f. sst.-flat, trough X)). Data for groups coarser than 3D (grey-m., co. sst.-trough X), that is $7D_1$ (grey-v. co. sst.-trough X), are scarce: however, a decrease in set thickness is suggested in these very coarse sandstones. Set thickness appears to reach a maximum in medium sandstone groups. The same tendency was found in the central area. This is consistent with the hypothesis that finer grained groups represent deposition from shallower flows than coarser grained groups, though this cannot be proved.

In the western area, means for all sets for each group were calculated (Table 10). The means tended towards the 20–30 cm range and showed no clear pattern of variation in this. In the western area, means were then calculated for each group for maximum set sizes. Smaller maximum thicknesses appear to be associated with small proportions of cross-stratification. But the western area does not contain significant numbers of 10 m samples belonging to siltstone groups, so the grain size correlation found in the eastern area, was not apparent.

Table 10. *Cross-stratified set thicknesses in sample groups, western area*

Mean set size (cms)	Total number of sets
3D – 30	1228
2C – 33	372
2E – 41	139
2B – 31	137
2D – 31	60
2A – 23	119
3A – 31	137
1B – 36	33
1D – 18	20
8 – 14	19
5A – 25	77
2G – 27	155
3C – 27	523
1A – 20	86

Ripples and Small-scale Cross-stratification

Small-scale ripple-marks are the bedforms of lowest stream power in which sediment particles ranging in grade from medium silt to medium sand can be transported as bed-load by aqueous flows (Simons & Richardson, 1966; Inman, 1957). In many of the silt-rich facies, they constitute the only current- or wave-generated structures.

Symmetrical Ripple Marks

These occur modally in coarse silt and very find sand. They are nearly perfectly symmetrical, with relatively straight crests. Bifurcation of crests, noted in 6 cases in the eastern area (Plate 17), is a characteristic found almost exclusively in wind-and wave-type ripple patterns (Tanner, 1967). The crests are sometimes sharp, more often rounded in profile and

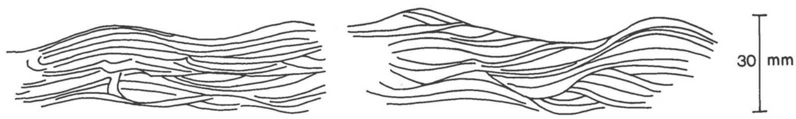


Figure 11. Two perpendicular vertical sections through sets of interfering symmetrical ripple marks, Karins Dal, eastern area, Karins Dal Grey Siltstone Formation.

sometimes flattened. Internal lamination varies from symmetrical draping of parallel laminae, to small-scale cross-lamination within externally symmetrical ripple-mark (comparable with those of Newton (1968)). In one case the lamination was horizontal; in others no structure was discerned. One ripple mark changed from symmetrical draping to cross-lamination within 10 cm along its length. Sections through a coset of interfering symmetrical ripples revealed cross-lamination (Fig. 11) similar to the 'truncated wave-ripple laminae' figured by Campbell (1966). Some ripple surfaces are traversed by narrow mudcracks, indicating possible desiccation by exposure above local water level.

Table 11. *Ripple Data. Symmetrical, eastern area*

	Symmetrical Ripples	Lenticular Bedding
Grain size:		
Mode	C silt/VF sand	M,C silt
Range	F silt-VF sand	M-C silt
Crest spacing: mm		
Mean	54	51
Range	20 to 200	25 to 100
Number	16	5
Ripple Height: mm		
Mean	6	6
Range	3 to 20	3 to 11
Number	13	23
Ripple Index:		
Range	4 to 15	5 to 20

Geometrical data are summarized in Table 11. The range of ripple indices (4 to 15) is characteristic of ripple-marks formed by waves or water-currents, while the well developed symmetry indicates that a wave origin is most likely (Tanner, 1967). Harms (1969), using the Airy wave model, was unable to predict unique solutions for wave height, wave length, and water depth from grain size and crest-spacing data. Tanner (1971) pointed out that wave models, as presently known, may not be applicable in the case of shallow lakes. According to his empirical equations, most of the measured ripples could have formed in water between 0.5 and 1.5 metres deep.

Symmetrical ripple-marks are most abundant in and characteristic of sample group 4G (grey-co. slst., v. f. sst.-sym. rip.), but are also quite common in 4B (grey-co., m. slst.-lent., flat), 4C (grey-m., co. slst.-flat), 4D (grey-co., m. slst.-flat), (all grey siltstone groups). In most red siltstone groups (5) they are absent, and they are rare or absent in sandstone groups coarser than 7A (grey-f., v. f. sst.-trough X, flat), 7E (grey-f. sst.-trough X). In planar cross-stratified medium sandstones (variants of 3D (grey-m., co. sst.-trough X)), symmetrical ripples were sometimes found as falling-stage wave modifications of foresets and topsets, similar to those described from the Tana River (COLLINSON, 1970).

Table 12. *Ripple Data. Asymmetrical, eastern area*

Type:	Linguoid	Straight	Climbing
Grouping	Grouped	Grouped	Grouped
Scale	Small	Small	Small
Relation lower surface to underlying Str.	Non parallel	Non parallel	Non parallel/ gradational
Shape lower surface	Scoop	Planar	(Planar)
Relation Xstrata to lower surface	Discordant	Discordant	Discordant/ asymptotic
Lithological uniformity	Homogeneous	Homogeneous	Homogeneous
Trace of Xstrata bedding section	Concave downdip	Linear	?
Strike section	Concave-up	Linear/	?
Dip section	Concave-up	Linear/ concave-up	Linear/ concave-up
cf. ALLEN (1963c)	Nu	Mu	Kappa/Lambda
Grain size: mode	C silt	VF sand	VF sand
range	Msilt-Msand	Csilt-Fsand	Csilt-Fsand
Set thickness:			
(mm) mean	11	5	13
range	4 to 30	3 to 13	5 to 20
number	(34)	(5)	(8)
Angle of climb	–	–	8° to 50°

Asymmetrical Ripple Marks and Small-scale Cross-stratification

The commonest type of small-scale cross-stratification (Table 12) occurs in cosets whose top surface sometimes consists of small-scale asymmetrical ripple-marks of linguoid type (Plate 18), but more often exhibits rib-and-furrow structure characteristic of the eroded remnants of the

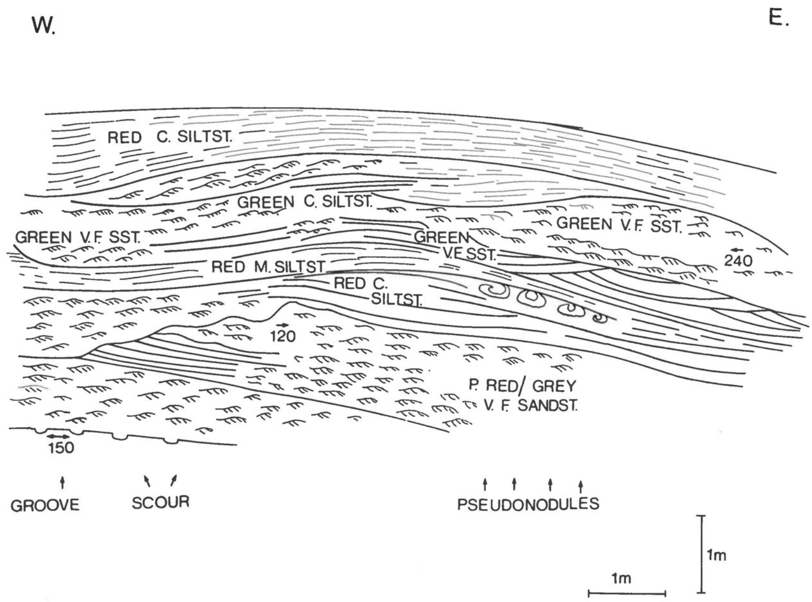


Figure 12. Bedding relationships, sample group 4E, Vilddal, eastern area, Vilddal Red-and-green banded Siltstone Formation.

ripples. The cross-stratified sets are formed as a result of the migration of trains of linguoid ripples (Hamblin, 1961; Allen, 1963a), by lee-side deposition from two adjacent ripples in the erosion trough on the stoss side of the ripple in front. The sets do not climb regularly downcurrent: the rate of deposition from suspension must therefore have been small compared with the rate of bed-load transport (Allen, 1970b). Ripple cross-stratification of this type is the dominant feature in groups 4E (grey-co., m. slst.-asym. rip., flat), 5B (red-co., m. slst.-asym. rip., flat), and is also well developed in other red and grey siltstone groups; it is rare in the sandstone groups.

Small-scale straight-crested asymmetrical ripple-marks and their associated cross-stratification are much less abundant in the sections examined. They were most frequently recorded from the grey fine sandstone group 7A (grey-f., v.f. sst.-trough X, flat). Harms' (1969) experiments with medium sand produced straight-crested ripples at lower values of bed shear stress and stream power than curved-crested ripples. Znamenskaya (1964) obtained the curved-crested ripples at higher Froude numbers than the simpler two-dimensional forms, and Allen (1969c), finding an increase in transverse sinuosity of ripple crests with progressively shallower flow and increasing Froude number, attributed this to the increasing effect of secondary flow components. Lateral gradation of cosets formed from curved-crested ripples into flat-bedded coarse

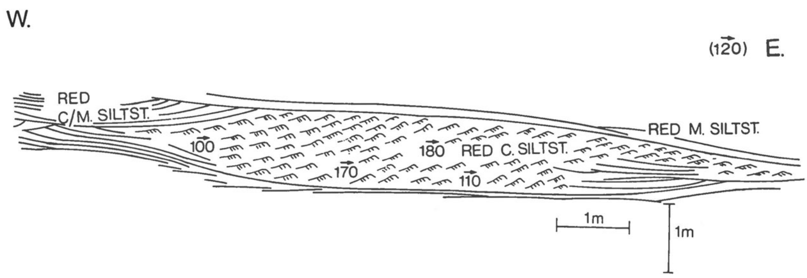


Figure 13. Channel form, sample groups 4E and 5C, Vilddal, eastern area, Vilddal Red-and-green banded Siltstone Formation. Numbers are azimuths of ripple orientations and face of exposure.

siltstone (Figs 12 and 13), also suggests that the ripples were deposited in water depths less than 10 cm average.

Small-scale cross-stratified sets which climb regularly up the back of underlying sets (Plate 19) (climbing ripple lamination, McKEE, 1966b) were recorded in only 9 cases in the eastern area groups (7A (grey-f., v. f. sst.-trough X, flat), 7C (grey-v. f., f. sst., co. slst.-flat, trough X), 5A (red-co. slst., v. f. sst.-asym. rip.), 4E (grey-co., m. slst.-asym. rip., flat), 4D (grey-co., m. slst.-flat), all of intermediate to finer grain size). In such cases, the rate of 'fallout' from suspension must have been large compared with the bed-load transport rate (JOPLING & WALKER, 1968; ALLEN, 1970b), suggestive of rapid deposition during the waning flow phase of a flood.

Lenticular-Bedding

This structure is named from the classification of REINECK & WUNDERLICH (1968), and consists of isolated small-scale ripple forms, of coarse or medium siltstone, embedded in darker finer-grained silt or clay with generally flat lamination. Externally the ripples may be symmetrical in shape, though many which were not measured appeared merely as shallow lenses. Internal structure, where visible, was often asymmetrical cross-lamination. Geometrical properties of the sample measured (Table 11 above) are very similar to those of the symmetrical ripples. This structure, mainly restricted to non-red siltstone groups, is abundant in, and characteristic of, group 4B (grey-co., m. slst.-lent., flat), though it is quite common in 4C (grey-m., co., slst.-flat), 4D (grey-co., m. slst.-flat) also.

Lenticular bedding has been recorded from subtidal zones (REINECK, 1963) and intertidal zones (HÄNTZSCHEL, 1936), and from the inter-distributary bay environment of the Mississippi delta (COLEMAN *et al.*, 1964). According to REINECK, it is formed where current or wave action alternates with periods of slack water, in which mud settles out from suspension. The exact sequence and pattern of the clay and silt is determined by the values of successive velocity fluctuations (TERWINDT & BREUSERS, 1972).

Flat-bedding in Sandstone

'Flat-bedding' refers to strata containing parallel and laterally continuous laminae which appear to have been more or less parallel to the general surface of deposition (definition modified from FRIEND, 1965, p. 47). In many cases the base of a flat-bedded set is plane, or concave upwards.

Laminae as seen in hand-specimens of flat-bedded sandstone range from 1 to 5 mm in thickness. Planes of fissility develop along laminae at intervals of 1 to 2 cm. In the field, these characteristics together with the lateral continuity of parallel laminae serve to distinguish flat-bedding from large-scale cross-stratification. Lamination is much cruder in the latter. Many sets of flat-bedded sandstone can be traced 10 metres or so along the outcrop, unless they are cross-cut by overlying units.

Parting lineation occurs along partings in 11 per cent of flat bedded sandstone sets in the eastern area (1158 records). A similar proportion was found in the central area. ALLEN (1964a) showed experimentally that parting lineation is a stable equilibrium bed configuration only in plane beds of the upper flow regime, with Froude numbers greater than 0.75. Therefore, in the eastern area at least 11 % of the flat-bedded sandstones were deposited in the upper flow regime. The other mode of deposition of flat-bedded sandstone is from suspension: this is the likely explanation of bottomsets in type 2a cross-stratification, but as the latter is a rather uncommon bedding type, the majority of flat-bedded sandstones were probably also deposited as upper phase plan beds. Absence of lineation from most of these sets may be attributed to (a) suitable bedding-plane exposure being infrebuent in mark-sense sections, and (b) the structure being easily destroyed during diagenesis or low grade metamorphism (ALLEN, 1970a, p. 301).

Flat-bedding in Siltstone

This term covers a wide variety of structures and textures in siltstones. Unlike the fine members of fining-upward cycles in the Devonian of Britain (ALLEN, 1964b) and Spitsbergen (FRIEND, 1965), siltstones showing no structure at all are rare. They often show signs of bioturbation and lamination.

A study of this lamination was made in the eastern area. Many red siltstones and some non-red ones characteristically show flat partings at intervals varying between 3 and 50 mm. Parting intervals tend to be smaller (2 to 3 mm) in 'medium siltstone' sets than in coarse siltstones (average 10 to 20 mm).

Very fine, even, flat lamination is uncommon and occurs more frequently in sets recorded as 'medium' and 'fine' siltstone than in those recorded as coarse siltstone. The main occurrences are in groups 4C (grey-m., co. slst.-flat) (6 records) and 4B (grey-co., m. slst.-lent., flat) (4 records). 2 to 3 laminae per mm can be discerned in the field, and sometimes partings develop along laminae to form a fine fissility. In thin section, the lamination is seen to be due to thicker laminae of coarse silt particles alternating with thinner laminae of clay grade (Table 13). In one specimen, the lamination proved to be lenticular in detail, a smaller-scale version of the lenticular-bedding, described above. In the others, very even lamination is disturbed only by occasional low-angle faults and recumbent folds, presumably soft-sediment deformation features. Silt grains are of quartz, feldspar and micas, in a carbonate-sericite matrix. Coarse laminae average about 10 grains thick; finer laminae are more variable in thickness. The clastic component of the coarse laminae distinguishes this lamination from the seasonal alternation of carbonate-rich and organic-rich laminae described from Ontario lake sediments (TIPPETT, 1964) and the Green River Formation (BRADLEY, 1931).

As soon as the threshold bed shear stress for movement of coarse silt grains is exceeded, a suspended load is developed (BAGNOLD, 1966). Many of the siltstones with flat partings probably record continuous settling of suspended load from a flow of low stream power. A crude grading from coarse into 'medium' siltstone was often noted on a scale of 10 to 20 cm, but on the whole the siltstones record no great fluctuations of sediment supply during their deposition. The effect of a clay fraction

Table 13. *Flat lamination in siltstones, eastern area*

Specimen	Coarse Lam grain size	Fine Lam grain size	Coarse Lam thickness mm	Fine Lam thickness mm	Comments
A455	C,Msilt	clay	0.58 (0.11–0.73)	0.26 (0.11–0.69)	gradational contacts
A025	VFsand-Msilt	clay	0.43 (0.18–0.73)	0.04–0.10	
A601	VFsand-Csilt	clay	0.35–0.45	0.07	gradational contacts. small folds & faults.
A626	Csilt	silty clay	0.4–0.9	0.2–0.9	lenticular lamination

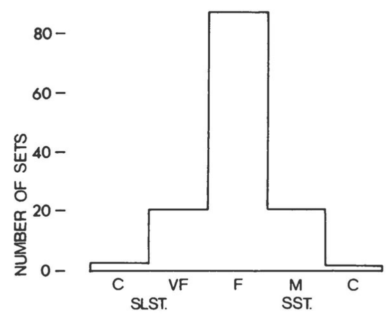


Figure 14. Grain-size of sets with parting lineation, eastern area

may be the bunching of silt particles with clay floccules (ALLEN, 1968b, p. 332; ETTER *et al.*, 1968), resulting in an accelerated rate of deposition. The finely laminated siltstones, however, record numerous fluctuations of sediment supply such that the silt grains periodically failed to reach the locus of deposition. The presence of the clay laminae suggests that sediment supply was a function of the power of local current systems.

There are numerous records of asymmetrical ripple cross-lamination in coarse and medium siltstones. Thus if bedload transport in the lower flow regime was possible for these grain sizes, we should also expect to find upper flow regime flat-bedding. Experiments by REES (1966) with a clay-free fine silt showed that such transport did occur; naturally-occurring silts, however, contain an appreciable clay fraction, and Rees's results are unlikely to apply when there is cohesion in the bed-load. Another experimental problem is that bed-form changes are difficult to detect when a large proportion of the load is in suspension (BAGNOLD, 1966). Nevertheless, a number of sets of flat-bedded coarse siltstone passing gradationally up into ripple cross-lamination were encountered, which could have been deposited in this way. BAGNOLD's (1966) very shallow depth mechanism may also be important: in Fig. 13, flat-bedded coarse siltstone appears near the margins of a channel form; siltstone with ripple cross-lamination occurs near the centre at the bottom of the channel, indicating that the flat beds formed in shallower water than the coexisting current ripples. These flat-bedding siltstones were not distinguished on the mark-sense form in the field, and therefore were included with suspended load deposits in the analysis. However, the ratio of bed-load to suspended load deposits for flat-bedded siltstones is probably small.

Parting Lineation

This refers to the elongate irregularities on parting surfaces described by CROWELL (1955) as 'parting lineation' and by STOKES (1947) as 'primary current lineation'. ALLEN (1964a) and FRIEND (1965) reported

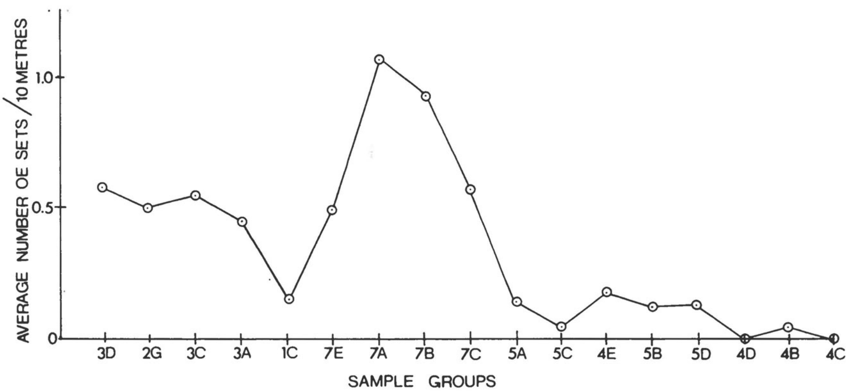


Figure 15. Number of sets with parting lineation in each sample group, eastern area.

this structure from Devonian fluvial sediments in Britain and Spitsbergen.

In the eastern area, it occurs modally in fine sandstones, but ranges from coarse silt to coarse sandstone (Fig. 14). 96 percent of parting lineation records occurred in flat-bedding; the remainder were recorded from stratification logged as 'trough cross-stratification', mainly type 3—(low angle). The structure is rare in siltstone groups (4, 5), and is most abundant in 7A (grey-f., v. f. sst.-trough X, flat), 7B (grey-f., v. f. sst.-flat, trough X), in which flat-bedded fine sandstone is well represented (Fig. 15). In the eastern area a total of 134 sets with parting lineation were recorded in 3,950 metres of section (7,396 sets).

The origin of parting lineation was discussed under 'Flat-bedding in Sandstone'.

In the western area, 5571 flat-bedded units were noted, and 294 of these showed lineation. 172 of these cases of lineation were formed in fine grained sand, 105 in medium sand, and 17 in very fine-grained sand.

Deformation

Types of Deformation

We have some difficulty in presenting a summary of our various studies of soft sediment deformation, because we worked independently on this topic. Our classification of types of deformation, therefore, includes categories which overlap each other. Below we describe the most distinctive types, in order of decreasing abundance. The statistics quoted were collected in the last field season.

In the central area, about 8% of sets in the sandstone sample groups were found to be deformed. In the siltstone sample groups of the central area, small-scale deformation was more abundant.

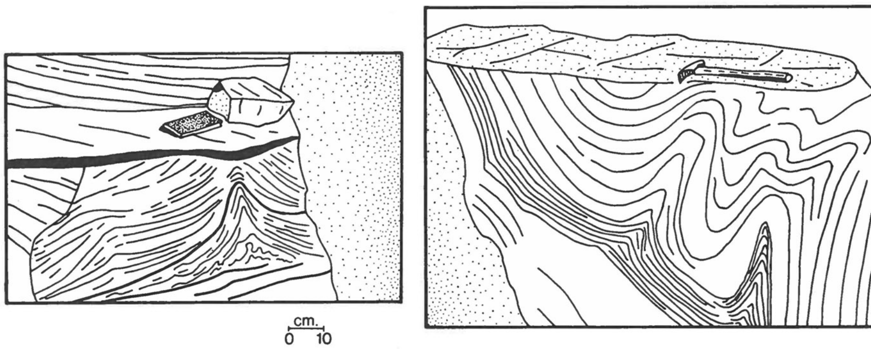


Figure 16. Left-hand sketch: example of cuspate deformation truncated by overlying set of cross-strata, west of Paralleldal, Gauss Halvø, central area, Kap Kolthoff Supergroup. Right-hand sketch: example of cuspate folding, south-west of Smith Woodward's Bjerg, central area, Kap Graah Group.

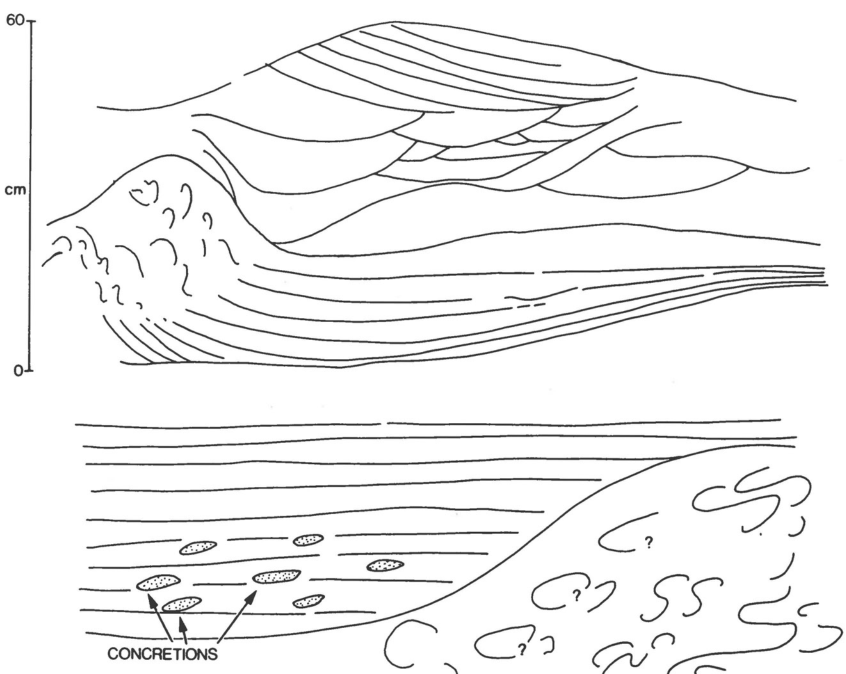


Figure 17. Upper sketch: deformation associated with lower bounding surface. Lower sketch: deformation associated with lower bounding surface and overlain by flat-bedding. Both examples come from the Kap Kolthoff Supergroup of the western area.

Folded and Cuspate Stratification

This category occurs characteristically in the bodies of sets. By this we mean that the deformation does not appear to have formed about the sole or the top of the set, and the disturbance fades out both upwards and downwards within the set (Fig. 16, Plate 20). In the third dimension, the structures were sometimes cylindrical folds with near horizontal axes, sometimes domes and basins.

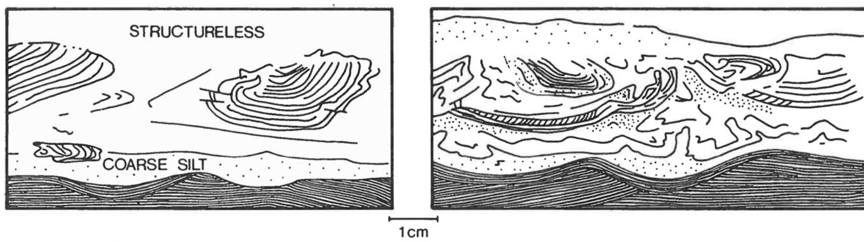


Figure 18. Convolute laminae in siltstone, sample group 4C, central area, Gauss Halvø, Wimans Bjerg Formation.

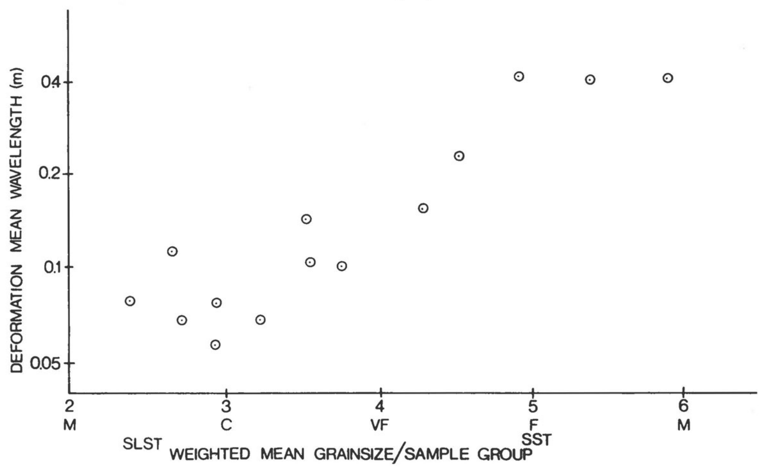


Figure 19. Variation of wavelength of deformation with mean grainsize of sample group. Data come from the eastern area.

About 90% (350 examples) of deformational structures noted in the eastern area belong to this category, and about 80% (160 examples) in the western area. The 'wrinkled lamination' category (see below) was used in the central area for structures put in this wider category in the other areas.

This category would include the 'convolute lamination' of many geologists (eg. SANDERS, 1960), and also the "diapiric" structures of many geologists (SELLEY, 1969; FRIEND, 1965) (Fig. 16).

Complex patterns of folding are often found specifically in the strata below high points in an irregular interface between two sets. (Fig. 17).

In the siltstone sample groups, siltstone sets often exhibit small-scale folding of this sort (Fig. 18).

Larger wave lengths of folding occur in groups with coarser mean grain size (Fig. 19), but this probably reflects the association between grain size and set thickness that is discussed below.

Wrinkled Lamination

This category was only systematically noted as a distinct form in the central area. The folds are characteristically gentle, with no high

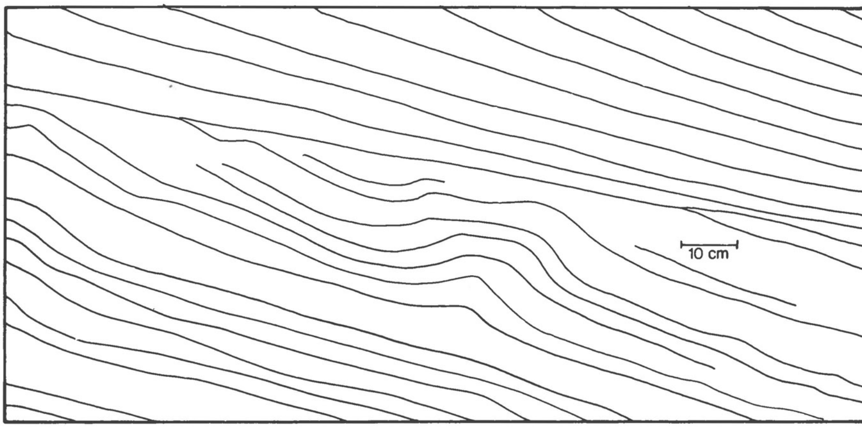


Figure 20. Gentle folding in large-scale cross-strata, Smith Woodwards Bjerg, Gauss Halvø, central area, Kap Graah Group.

dips or cusp formation. 80 % of the 310 deformational structures noted in the sandstone groups of the central area were of this category. Sets affected were modally 50 cm thick, but ranged from 10 to 170 cm. (Fig. 20).

Oversteepened Cross-strata

In this category we place all deformational structures which appear to have a simple geometrical relationship to the cross-strata in which they occur. The category is rather rare, not forming more than 5 % of observations in any area.

Load Casts and Pseudonodules

In this category, the sediment has deformed about the interface of materials of different grain size or density. Although grain size is the most common distinction, examples were seen in the western area in which quartz rich sets have deformed relative to sets rich in heavy minerals. Only a few examples of this diapiric deformation were seen in each area.

Fracture Deformation

In a small number of cases, we have seen curved faults bounding displaced blocks of sediment on the banks of channels (Plate 21).

High angle, planar, faults were also seen, in some cases, which appear to have pre-dated the cementing of the rock (Fig. 21). We have also noted 'jumbled' beds, in which fractured blocks of strata with haphazard orientation occupy sets (10–40 cm thick) which are concordant with the surrounding strata. Both these features occur most commonly in well-sorted sandstones with large (2–5 m) sets of cross-strata.

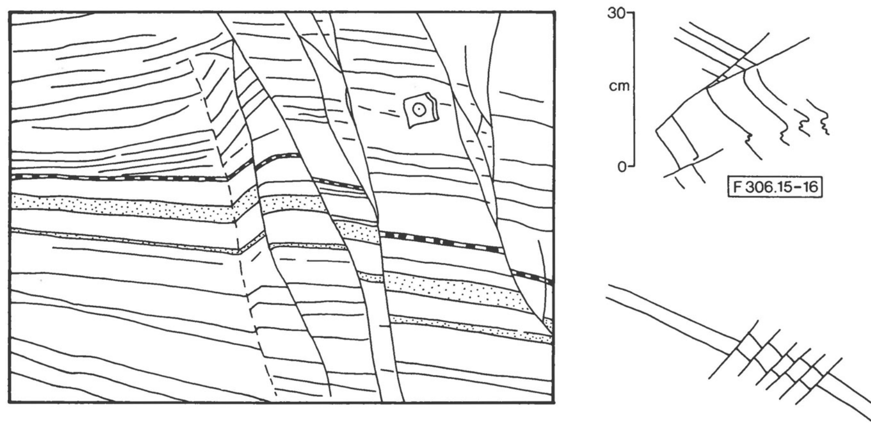


Figure 21. Penecontemporaneous fractures in sandstones. Left-hand sketch is from the central area. Right-hand sketches are both from probably aeolian sandstones, Fladedal, western area. Scale is correct for all three sketches.

In the siltstone groups (4E (grey-co., m. slst.-asym. rip., flat), 5B (red-co., m. slst.-asym. rip., flat), 4C (grey-m., co. slst.-flat)), there are small-scale reverse faults deforming folded strata of grey siltstone in sets 10 to 15 cm thick (Fig. 22). These are similar to 'schuppen' structures in the oilshale of the Green River Formation (BRADLEY, 1931, p. 24).

One example was seen of a tilted block of strata (70 cm high), which we presume formed by inter-stratal sliding of large fracture fragments (Pl. 22).

Mudcrack Deformation

One example was seen in which strata were folded in sympathy with underlying mudcracks.

In other examples, sediment filled mudcracks had suffered folding along their vertical dimension, presumably during general compaction.

Fluid Release Structures

A few examples were noted of pipes or fissures extending upwards through and deforming overlying strata (Plate 23).

Importance of Pore-water Pressure and Grain size

Granular sediment will deform by shearing when one of the stress components acting on the sediment exceeds a critical value. This critical value will be smaller if the internal friction due to grain packing and grain contacts is reduced by a rise in the pore-water pressure. In other words, a rise in local pore-water pressure will tend to trigger soft sediment deformation.

Variations in pore-water pressure will tend to be propagated more rapidly in coarser-grained sediments (Table 14). Unless coarser sediments

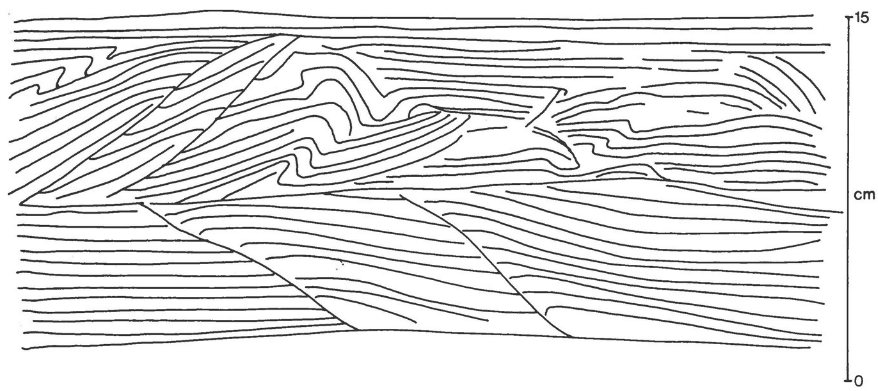


Figure 22. Syn-sedimentary small-scale thrusts in finely laminated siltstone, Kap Franklin, eastern area, Østreplateau Member.

Table 14. *Pore-water velocities in various sediments* (TOLMAN, 1937, p. 219)

	Average flow velocity (ft. per day) for 1% hydraulic gradient
Soil and clay	0.001
Silt, fine sand......................	0.04
Fine to medium sand	1.03
Medium to coarse sand, sandy gravel..	6.33
Gravel...........................	25.00
Coarse gravel......................	110.00

are confined below finer-grained material, variations in pressure will be dissipated and high pore-pressures will not be sustained.

We can, therefore, postulate two different situations. In the first of these, high pore pressures are maintained by a layer of finer-grained material. In this situation local shear failure of the sediment might be readily caused by some external stress influence. In the second case, where sediment near the surface is not confined by a layer of fine-grained material, high pore pressures are not likely to develop, but local stress changes might cause deformation, particularly where linked in finer-grained sediments with slow adjustment of pore-water. These local surface stress changes are more likely to be large in environments of sand or gravel deposition.

In our Greenland rocks, we frequently found deformations beneath finer-grained sandstones, or siltstone beds and partings, showing that these bodies assist in the maintenance of high-pore pressures in the under-lying sediment. For example, in the central area, in sample group 2C (red-m., co. sst.-trough X), complex fold deformations in medium sandstones have been noted immediately beneath lenticular siltstone bodies.

In the various sandstone sample groups of the central area, the modal grain sizes of deformed beds are of either fine or medium sand grade. 2 to 15% of beds are affected by deformation. In the western area, the modal grain sizes of deformation in the different groups are also fine and medium sand grade, the same as the modes of the groups as a whole. A similar range was found in the eastern area, where it was noted that the modes for deformation and the modes for all beds, tend to be the same, except in the siltstone beds where the deformed beds tend to be the coarser ones, in which grain cohesion was relatively low.

The cusps which are frequently found in folded strata are often surrounded by a region in which stratification is absent. The relatively gentle folding or "wrinkling", described above, must represent less violent variation of pore-water pressure.

Other Processes Causing Deformation

Increase in pore-water pressure may lower the frictional resistance to deformation in a granular sediment, but it will not, by itself, result in deformation unless there are large enough differences between the principal stress components.

Failure will tend to be by fracture at superficial levels, and by local granular liquefaction and folding at deeper levels.

The following appear to be the main relevant mechanisms for producing these differences.

Increase of Stress due to Deposition

Deposition of further material on the lee side of a dune may eventually load the surface to the extent that shear failure will take place. This produces the avalanching that is the normal method of building cross-strata (ALLEN, 1968a). Under the special conditions of a rain-wetted aeolian dune-slope, it may also produce fracture failure and a jumble of sediment blocks may result (GLENNIE, 1970, Fig. 91). RETTGER (1935, p. 286) showed that a dry sediment is more likely to fracture than a subaqueous one under some conditions. We have seen these jumbled beds in Greenland (Plate 24).

The movement of bed forms (dunes and ripples) over a sediment surface will produce periodic variation in the vertical load on that surface. Some idea of the size and rate of movement of bed forms in a major river (Brahmaputra) is conveyed by the data of Table 15.

The sorts of rates cited here, which occur at time of flood, are sufficient to hinder dissipation of the high pore-water pressures generated particularly in finer-grained sands. We have examined a model of an advancing large sand body and shown by application of slope stability analysis that failure is very likely to take place within it.

Table 15. *Flood movement of bed-forms, Brahmaputra*
(COLEMAN, 1969. Table VI, p. 199)

Bedform	'Mega-ripples'	'Dunes'	'Sand-waves'
Height-range	1–5 ft.	5–25 ft.	25–50 ft.
max. movement/24 hours	810 ft.	520 ft.	2100 ft.
average movement/24 hours	400 ft.	220 ft.	670 ft.

We suggest that this method is an important one in generating the folded cuspate lamination and the wrinkled lamination.

Over a period of time and accumulating of sediment, vertical stresses due to loading will increase. Inhomogeneity in the sediment will lead to differential compaction, and the possibility of shear failure. Load is clearly the cause of the mudcrack deformation, two examples of which have been noted in Greenland.

Increase of Stress due to Current Drag

Moving water applies a shear-stress to its bed. If this bed is granular, then the stress may be sufficient to cause movement of the grains as bed-load. This may be the cause of the oversteepening of cross-strata which is a rather rare form in East Greenland. This mechanism was cited by ROBSON (1956) and COLEMAN (1969), but disputed by JONES (1962), who favoured gravity collapse triggered by seismic shocks.

Lowering of Stress due to Removal of Water or Sediment

Rapid draw-down of water level, with waning flood, would deprive dune slip-faces and channel banks of lateral support, and failure of the sediment would be caused by residual high pore-pressures; HARMS *et al.* (1963) and COLEMAN (1969) have described bank failures due to this process.

We have observed shear planes on the upper parts of the lee faces of dunes, on the tidal sand bar near the life-boat station at Wells-next-the-Sea, Norfolk, England. These dunes were linguoid, about 0.4 m high. The fracture surfaces ran parallel to, and slightly below, the tops of the slip-faces, for distances of 10 m, and were overlain by slides of sand.

We suggest that these planes form when the lateral confining stresses are removed due, in the Wells case, to falling tide level. In simple experiments with a tank similar shear planes were formed in a sand bank by rapid draw-down of water level. Failure seems more likely in fine sand than in medium or coarse sand, because of the very rapid dissipation of pore-water pressure in the coarser material.

Removal of sediment by erosion could presumably have a similar effect.

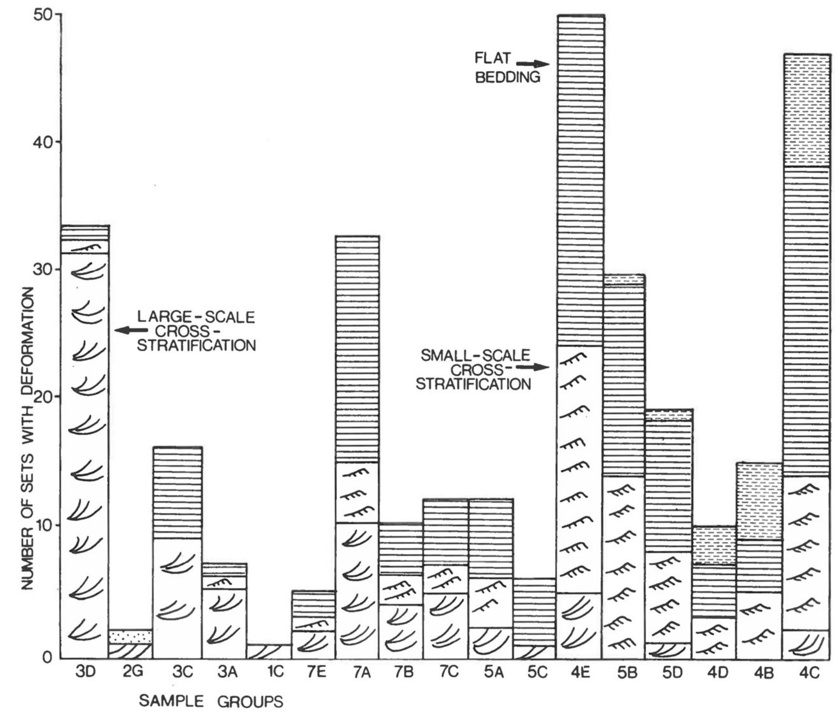


Figure 23. Occurrence of deformation in sets of different internal structure in each sample group. Data come from the eastern area.

Variation of Stress caused by Seismic Activity

Many records exist of fluctuations of well-level due to earthquakes (eg. Tolman, 1937, p. 337). These fluctuations imply fluctuations in pore-water pressure which might trigger soft-sediment deformation.

The accelerations of the vibrating sediment pile during the passage of earthquake shock waves will, in themselves, vary the stress field acting on the sediments. This may be sufficient to cause deformation in some places.

The processes may have been of major importance in deforming the East Greenland sediments.

Air Heave

Fluctuations of water level may trap air in sediment. We have no evidence that this mechanism was of importance in East Greenland.

Deformation and Primary structures

In our discussion of mechanisms, we have stressed the importance of the movement of bed forms, and the deformation of bed forms during fluctuation of water level.

In the eastern area, statistics were assembled showing the relationship between deformation and the internal structure deformed in the various

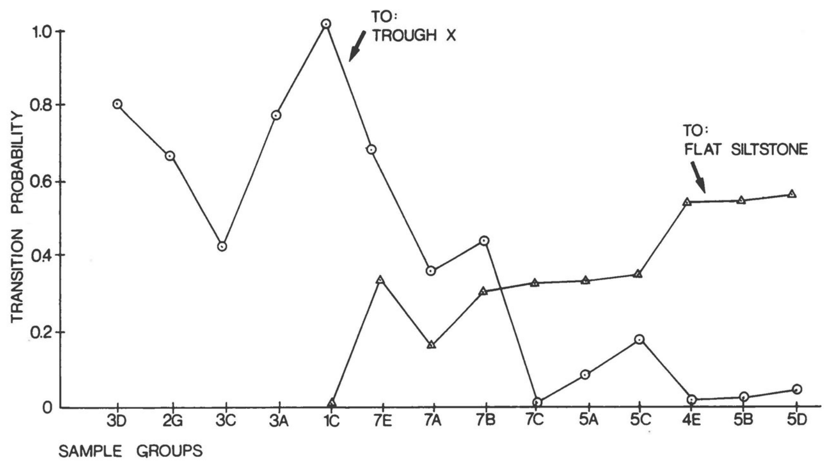


Figure 24. Probabilities of transitions *from* deformed stratification *to* cross-stratification or *to* flat-bedded siltstone.

groups (Fig. 23). These show no clear pattern, although the amount of deformed small-scale cross-stratification in the siltstone groups is noteworthy. This association does not imply that all the deformation, in these cases mainly small-scale "convolution" (SANDERS, 1960), results from current drag. It merely shows that the small-scale cross-stratification and the deformation tend to form in the same granular material.

In the western area, a statistical study was made of the association between cross-stratification, flat-bedded sandstone and deformation. It was found that there was no significant difference between the occurrence of deformation in the two primary structures.

In both the western and eastern areas, transition probability studies indicate that most deformed sets are overlain by bed-load deposits (large and small-scale cross-stratification, flat-bedded sandstones). This is consistent with our suggestion of the importance of bed shear and differential bed-loading. However (Fig. 24), in the siltstone groups, deformed strata tend to be overlain by flat-bedded siltstones. In these cases the flat siltstones may have formed an impermeable cap under which high pore-water pressures may have been generated.

4. FAUNA, FLORA AND TRACE FOSSILS

Fauna and Flora

In this section we describe the occurrence of the various fossils and discuss their environmental significance. We leave their stratigraphical implications to the detailed regional-stratigraphical papers which are to follow.

Vertebrates

A review of the famous Devonian vertebrate faunas of East Greenland has been provided by JARVIK (1961, p. 197–204).

Vertebrates of the Eastern Area

Published sources and our observations show that the following taxonomic groups are numerically important.

Crossopterygians, small:	*Gyroptychius* *Glyptolepis* Small osteolepids
Crossopterygians, large:	Porolepiformes
Antiarchs:	*Asterolepis säve-söderberghi*
Arthrodires:	Coccosteomorphs

We collected 177 specimens over three years in this region, (Table 16), mostly from screes. We recognise the following assemblages:

1) *Antiarchs and arthrodires*, fragments 5–10 cm across, in sandstone sets of siltstone samples 5C (red-co. slst., v. f. sst.-flat, asym. rip.) 5D (red-co., m. slst.-flat, asym. rip.).

2) *Small crossopterygians*, fragments c. 1 cm across, in siltstone sets of siltstone sample groups (4C (grey-m., co. slst.-flat), 4E (grey-co., m. slst.-asym. rip., flat), 5B (red-co., m. slst.-asym. rip., flat)).

3) *Mixed 1) and 2)*, in thin cherty limestone at base of Randbøl Conglomerate. (BÜTLER, 1954, p. 24).

Table 16. *Vertebrates in mark-sense data, eastern area*

Sample group	No. 10m units	%No. 10m + vert.	No. of vertebr. records	Colour	Modal grain size
4B	15	7	1	Grey	Csilt
4C	33	15	9	Grey	Msilt
4D	18	5	2	Grey	C,Msilt
4E	27	15	6	Grey	F,Csilt
5B	16	6	1	Grey	Csilt
5C	20	20	5	Red+Gr.	Fsand
5D	28	7	2	Red+Gr.	VF/Msand

Only 4 of the 177 specimens show bones articulated together (scales of *Gyroptychius*) so skeletal disintegration was general before fossilisation. In the siltstone sequences, the general distinction between the antiarch-arthrodire assemblage and the small crossopterygian assemblage suggests that they preferred to live in different environments.

Vertebrates of the Western Area

Vertebrate fossils are rare amongst the sandstones and conglomerates of the western area, compared with the other areas. Disaggregated bones of the crossopterygian *Glyptolepis*, and the antiarch *Asterolepis* were found by us in two of the intervals of limestone and siltstone in the Ella Ø Conglomerate.

Vertebrates of the Central Area – Kap Graah Group

Three principal genera characterise the Kap Graah Group: *Phyllolepis*; *Holoptychius*; *Bothriolepis*. In addition to these at least one dipnoan genus is present *(Nielsenia)*, and possibly a second (*Soederberghia*): the shark *Cladodus* is known only from its teeth (cf. STENSIÖ, 1948, p. 534); JARVIK (1961) reported the presence of acanthodian scales. Our data on the distribution of the main genera in the groups are given in Table 17.

Table 17. *In-situ vertebrates in sample groups, Kap Graah Group*

		5A	7D	1B	7E	3A	2E	3D
Bothriolepis	sst	1	–	T	1	–	–	–
	sl	1	–	–	–	–	–	1
Holoptychius	sst	1	2	1	–	1	–	1
	sl	1	–	–	–	–	–	1
Phyllolepis	sst	1	–	–	–	–	1	–
	sl	–	1	–	–	–	–	–
Dipnoans	sst	1	–	–	–	–	–	–
	sl	–	–	–	–	–	–	–

All records are shown and fossils in sandstone (sst) are distinguished from those in siltstone (sl). (T, possible tracks).

Almost all *Bothriolepis* pieces are by isolated trunk plates or pectoral fin bones, generally in association with *Phyllolepis* and *Holoptychius*. Only in one instance was a semi-complete carcass collected, infilled with sandstone, with the pectoral bones still attached, but the head missing.

Phyllolepis bones are moderately common (STENSIÖ, 1934, 1936, 1939). Three new localities were found by our expeditions. At all of these, *Phyllolepis* was accompanied by *Bothriolepis* and *Holoptychius*. Most of the bones occur singly, in fine and very-fine grained sandstone, or in siltstone. STENSIÖ (1936, plate 24), figured a block containing numerous moderately complete specimens, but such occurrences are rare.

The crossopterygian *Holoptychius* (STENSIÖ, 1931; JARVIK, 1950) is the commonest fossil in the Kap Graah Group. Detached cycloidal scales are of the types called *H. nobilissimus* and *H. giganteus* (WOODWARD, 1900; HEINTZ, 1930, 1932). Only three fossils were collected by us in

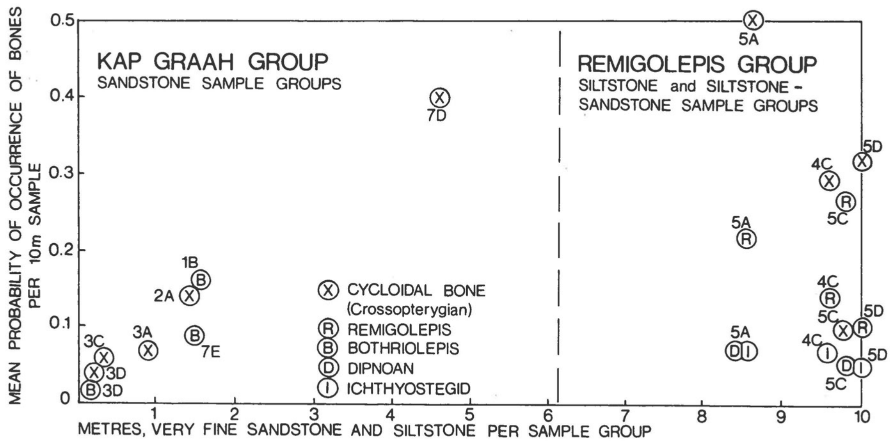


Figure 25. Probability of occurrence of vertebrates in the various sample groups, central area.

which bones are in contact (an almost complete fish, a cranial roof and a group of snout bones).

We collected dipnoan rib bones at two localities in the Kap Graah Group.

In Fig. 25 we have plotted the occurrence of various types of bones in the different sample groups against their proportion of siltstone (with very fine sandstone). There is a tendency for bones to be more abundant in finer grained sample groups. This may reflect original abundance, because it seems reasonable to suppose that the vertebrates would be more numerous in slack water, and in environments with stable silt banks that would be preferentially vegetated.

Vertebrates of the Central Area – Mt. Celsius Supergroup

In the Mt. Celsius Supergroup, bones of the antiarch *Remigolepis* are common. They were found by us in twenty-one 10 m samples in the *Remigolepis* Group (Table 18). They are commoner in sandstones and intraformational conglomerates than in siltstones. They most commonly occur with *Holoptychius*. *Remigolepis* appears to be absent where coarser, (medium sandstone) sediments are locally abundant, and this suggests that they were unable to thrive in an environment of greater stream power. Like *Bothriolepis*, *Remigolepis* was a mud-consuming fish.

Holoptychius occurs through the Mt. Celsius Supergroup, as high as the *Grönlandaspis* Group at the top of the Mt. Celsius Supergroup. Cycloidal scales are much more common than head bones. We identified one specimen of the rhizodontid *Eusthenodon wängsjöi* (JARVIK, 1952).

Dipnoans are represented by *Soederberghia*, *Oervigia*, and *Jarvikia* (LEHMAN, 1959). We have recognised them only from cranial fragments, centra and rib bones; the cycloidal bones that covered their trunks are

Table 18. *In situ vertebrates in sample groups, Mount Celsius Supergroup*

		4C	4E	5D	5C	5A	7D	3C	2A
Remigolepis	sst	1	–	4	9	3	1	–	–
	sl	1	–	–	1	1	–	–	–
Holoptychius	sst	7	1	8	4	5	–	1	1
	sl	1	–	3	1	2	–	–	–
Ichthyostegids	sst	2	–	–	–	–	–	–	–
	sl	–	–	1	–	–	–	–	–
Dipnoans	sst	–	–	–	1	–	–	–	–
	sl	–	–	2	1	–	–	–	–
Grönlandaspis		? sandstones of 3A, 3C, 3D							

See Table 17 for abbreviations.

similar to those of *Holoptychius*, and so the true abundance of the dipnoans is difficult to assess. Jarvik (1961, p. 198) describes dipnoan bones as 'fairly common' in the *Remigolepis* Group.

Amphibia, the earliest known anywhere, occur in the *Remigolepis* Group of the Mt. Celsius Supergroup. About 250 specimens have been found (Jarvik, 1952; Säve-Söderbergh, 1932b). The genera *Ichthyostega*, *Ichthyostegopsis*, and *Acanthostega* have been distinguished. We found Ichthyostegid bones at three localities. In each case they consisted of cranial roof fragments and in one case, limb bones and single cranial bones were also present. At each locality, these bones were mixed with bones of *Holoptychius* and *Remigolepis*. Like *Remigolepis* the amphibians have not been found in the coarser-grained *Grönlandaspis* Group, above the *Remigolepis* Group. They do not appear to have lived in the higher-power environments.

The arthrodire *Grönlandapis* is known only from single plates (Heintz, 1930, 1932; Stensiö, 1934, 1939; Miles, 1964). It is restricted to the *Grönlandaspis* Group of the upper Mt. Celsius Supergroup. We found it in-situ once only, but we suggest that it is probably characteristic of sandstone sample groups 3A (grey-f., m. sst.-trough X), 3C (grey-m., f. sst.-flat, trough X), and 3D (grey-m., co. sst.-trough X) at this stratigraphic level.

On Fig. 25 we have plotted the occurrence of vertebrate fragments *in situ* according to sample group, vertebrate type and siltstone (with very fine sandstone) content of the sample group. It is notable that crossopterygian and *Remigolepis* remains are more common than in the more sandy Kap Graah Group. It is also notable that dipnoans and amphibians are rare. In the absence of other bones, dipnoan scales would have been classified as holoptychiid (crossopterygian), so the rareness of dipnoan records probably merely reflects this misidentification.

Laboratory survey of *Remigolepis* Group collections

In order to examine the immediate matrix of the bones, as opposed to the general sedimentary association, we carried out a systematic examination of 1800 bones in our collections from the *Remigolepis* Group (Mt. Celsius Supergroup). We used a standard form to record the nature of the bones, their association with other bones, their state, the nature of the matrix and any special features of it. These data were then transferred onto computer tape, and analysed by simple programs.

Almost all the bones were disarticulated (single), and most of them were moderately well-preserved, with their surface ornamentation intact. Although fracturing, *in situ* during compaction, is sometimes apparent, almost all the bones wholly-contained in a hand specimen were entire; bone breakage during river transport was apparently rare.

In order to study the hydro-dynamic significance of the presence of the bones, we defined eight groups on taxonomic and size/shape grounds:

(A) Teeth and tusks of crossopterygians and amphibians (3 % of total) probably shed as a result of growth processes (SCHULZE, 1969).

(B) Elongate and flat shoulder girdle and jaw bones, forming 7 % of total collection. Examination of well preserved dipnoans and crossopterygians in museum collections shows that shoulder girdle bones begin to separate soon after death.

In situ compaction fracturing of these bones tends to occur: clavicle stems are almost invariably broken.

(C) A group of very varied bones of about the same size and thickness (up to 2 mm)—includes cranial roof, cheek, palate and opercular bones of dipnoans, crossopterygians, amphibians, and the ventral median bone of *Remigolepis* (rare). 12 % of the bones were allocated to this group.

(D) Cycloidal scales of crossopterygians—form 41 % of bones collected.

(E) Rib and limb bones of dipnoans and amphibia. This forms about 2 % of all bones, and most of the records are from one large collection of dipnoan fragments.

(F) Comprises small, flat and slightly curved pectoral and skull bones of *Remigolepis* (7 % of total). These bones were found mainly in siltstones, and in several collections showed a tendency to occur with large *Remigolepis* trunk bones. Because of this range of size, we suggest that these assemblages must have been rapidly buried.

(G) Contains the strongly concave median dorsal plates of *Remigolepis*. These formed only 2 % of the bones collected. 80 % of them were deposited with the concave face downward, suggesting that they were turned into this stable position by current action.

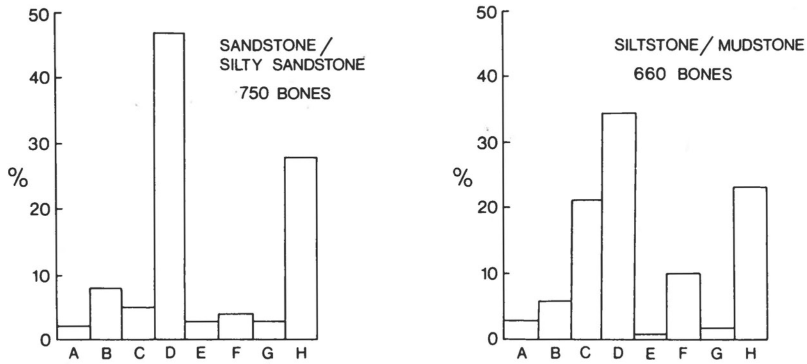


Figure 26. Summary of distribution of the bone groups in sandstone/siltstone lithologies; *Remigolepis* Group, central area. Letters A–H refer to bone types, defined in the text.

(H) All the trunk bones of *Remigolepis*, except the median plates (groups C and G). This formed about 28% of the total. These large antiarch bones often occur at the base of sandstone beds, with intraformational conglomerates—smaller and lighter bones, such as those of groups (C) and (D), tend to occur higher in the bed, in cross-stratified sandstone.

We also had to classify some bones as indeterminate.

Figure 26 shows the occurrence of the eight groups of different bone types of specimens of sandstone and of siltstone matrix. The proportions of bone types are very similar in the two grain size ranges. The only difference apparent is that the small, thin bone categories (C and F) may be more abundant in the siltstones.

Our analysis of the mutual associations of bones in hand specimen produced some generalisations. (Fig. 27). Antiarch debris (F, G, H) appears to be more associated with other antiarch debris than with crossopterygian bones, and vice-versa. In some cases, current sorting may have been responsible for this segregation, whereas, in other cases, the segregated material appears to result from local burial of a number of fish of one type. An example of this local burial mechanism is the association of bones of groups (H) and (F).

Allen and others (1968) described a British Lower Devonian occurrence of channel sandstones in which the faunas are mixed and strongly water-sorted. These faunas contrast with faunas of their overbank flood deposits, which consist of bones of a single species and these bones may not be size-sorted.

Some of the East Greenland collections show the same pattern.

A collection from medium sandstones, thought to be channel, bedload deposits (Upper *Remigolepis* Group, N.E. Celsius Bjerg), consists only of large trunk plates of *Remigolepis*, with large siltstone fragments. Obviously this was current sorted.

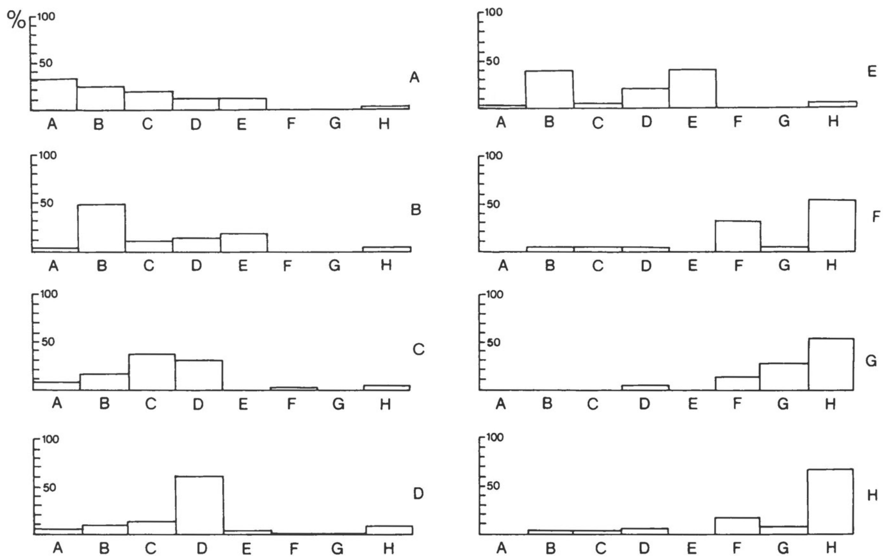


Figure 27. Associations between bone types A–H (%), in fossiliferous rock samples from the central area.

Bones from our Agda Dal locality (sample group 5A (red-co. slst., v. f. sst.-asym. rip.)) were collected both from cross-stratified sandstones and from siltstones. In the sandstones, probably channel deposits, the assemblage was size-sorted, consisting of *Holoptychiid* plates, ribs of a dipnoan, and small plates of *Bothriolepis*; the bones from the overbank siltstones, were also derived from a number of genera, but exhibited much greater size variation.

A large collection of dipnoan bones of various shapes and sizes, was obtained from a generally overbank sequence of interbedded siltstones and sandstones, on N. Celsius Bjerg. No other genera were associated so the fauna appears to be of the unmixed sort, typical of overbank areas. However it does show alignment of long axes of the bones, by current action. A collection of *Holoptychiid* bones from siltstones of sample group 5C (red-co. slst., v. f. sst.-flat, asym. rip.) contained, similarly, bones of no other genus.

One of the distinctive features of many ancient lacustrine deposits, is that fish tend to be preserved in them more or less entire (eg. BRADLEY, 1948; DINELEY & WILLIAMS, 1968; GREINER, 1962; RAYNER, 1963; see also ZANGERL & RICHARDSON, 1963). This often appears to have resulted from anaerobic conditions at and near the bottom of the lake, in addition to anaerobic conditions within the sediment. Complete carcasses are not a characteristic of any part of the East Greenland Devonian succession and this supports the idea that the siltstone intervals were deposited by floods or in aerobic short-lived lakes rather than in long-lived lakes. In the

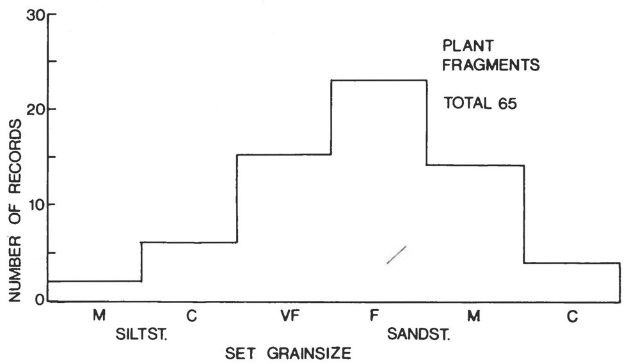


Figure 28. Grain-sizes of sets with plant fragments, eastern area.

above discussion, we have cited many examples of current mixing and sorting of bones. We would add that, in a fluvial environment, although mixing and sorting may have occurred between death and first burial of the animal, mixing and sorting may also have occurred after its first burial during reworking of sediment.

Plants

There are scattered references to plant remains in the literature of the East Greenland Devonian. WITZIG (1951) described and figures *Archaeopteris* from the *Remigolepis* Group (Mt. Celsius Supergroup) on Celsius Bjerg.

Dr. K. C. ALLEN, University of Bristol, was a member of one of our expeditions, and is working on the macro- and microfloras he collected (ALLEN, 1972).

In the eastern area, ALLEN (personal communication) reports *Thursophyton milleri*, *Drepanophycus*, *Milleria* sp., tracheids, cuticular fragments and spores. Carbonaceous impressions of parts of plant stems, commonly 5 to 20 mm wide, are locally abundant on stratification surfaces, especially in grey fine sandstone sample groups (7A (grey-f., v. f. sst.-trough X, flat)) (Table 19). More rarely plant fragments were seen as casts in red clay, especially in fine sandstone (Figure 28), and 90 percent of records were from non-red rocks. The presence of a few fragments in grey flat-bedded siltstones (4C (grey-m., co. slst.-flat)) indicates drifting of low-density plant stems into quiet, standing bodies of water. In grey very fine sandstones, finely comminuted plant fragments are often associated with a high concentration of mica flakes. Larger fragments up to 90 cm long, were recorded from grey fine sandstones; the largest, flattened stems, however, were found in the Inderdalen Formation in green siltstone, and measured 10 cm wide by at least 2 metres long.

In the western area (Kap Kolthoff Supergroup), ALLEN (personal communication) reports *Svalbardia* in addition to microfloras (ALLEN,

Table 19. *Plants in mark-sense data – eastern area*

Sample groups	No. 10m units	Fragments		Rootlets	
		%No. 10m units	No. of records	%No. 10m units	No. of records
2A	10	0	0	20	5
3C	26	27	13	0	0
3D	37	11	5	0	0
4C	33	12	6	0	0
4F	8	25	6	12	2
5A	38	3	1	10	4
5C	20	0	5	40	19
5D	28	20	0	4	1
7A	25	48	19	16	4
7B	14	21	4	0	0
7C	12	25	3	0	0
$7D_2$	6	0	0	50	12
7E	12	8	3	0	0

1972). Large stem imprints, frequently with fragments of thick carbonaceous material, are a feature of this unit. They are common in sample group 3D (grey-m., co. sst.-trough X) where they often tend to be concentrated at the base of cross-stratified sets. A similar concentration in the present-day deposits of the Brahmaputra River is reported by COLEMAN (1969, p. 210).

In the central area (Kap Graah Group and Mt. Celsius Supergroup), ALLEN (personal communication) has reported microspores and megaspores (ALLEN, 1972). Almost all the large plant materials seen were stem casts or impressions. Table 20 indicates the sample groups in which these fragments were recorded. With the exceptions of the leaf imprints noted above, and a concentration of *Calamites*-like stems found at Obrutschews Bjerg in sample group 4C (grey-co. slst.-flat), all the material was found in sandstones. Longitudinally striated stems up to 1 m in length are very common in the *Grönlandaspis* Group (sample groups 3A (grey-f., m. sst.-trough X) and 3D (grey-m., co. sst.-trough X)). They were referred by SÄVE-SÖDERBERGH (1934, p. 44, after HALLE) to "*Knorria*".

Trace Fossils

We found many different kinds of trace fossils in the East Greenland Devonian strata. We shall describe these area by area.

Trace Fossils of the Eastern Area

(a) 'Rootlets': These are trace fossils probably indicating the former presence of plant roots in the sediment. They consist of irregular tubular structures, up to 5 mm wide and 2 to 10 cm long, transgressing lamination at high angles, and sometimes with branching offshoots. In red sediment,

Table 20. *Plant remains in the sample groups, central area*

Sample group	Modal grain size of sediment with plants	Mean probability of occurrence of plants in 10m interval	% occuring in: Sandstone	Siltstone	Number collected
4C	sl	< 0.1	–	100	1
4E	ms	0.4	100	–	2
5D	fs	0.2	75	25	4
5C	vfs–fs	0.1	100	–	2
5A	vfs	0.2	100	–	3
7B	fs	0.2	100	–	1
3C	ms	0.1	100	–	1
1C	–	–	–	–	–
2A	fs	0.1	100	–	1
7D	vfs	0.3	100	–	2
2G	–	–	–	–	–
1B	–	–	–	–	–
7E	–	–	–	–	–
3A	vfs–fs	0.2	100	–	3
2B	–	–	–	–	–
2C	–	–	–	–	–
2E	–	–	–	–	–
3D	ms	0.3	100	–	14
2F	–	–	–	–	–

they are often green or blue-grey. In grey rocks, the tubes may be infilled with red clay. 68% of all records occur in red sediment; the remainder often have a distinctive 'leached' appearance. Rootlets occur modally in very fine sandstone (Figure 29). They are most abundant in sample groups 7 D_2 (grey-v. f., co. sst.-trough X, flat), 5 C (red-co. slst., v. f. sst.-flat, asym. rip.), 2 A (red-m., f. sst.-trough X, flat) and 4 F (grey-co. slst., co. sst.-flat, asym. rip.), which are also notably richer in carbonate concretions than other groups. In the red silt sample group 5 C (red-co. slst. v. f. sst.-flat, asym. rip.), for example, rootlets occur commonly in lens-shaped sets of very fine sandstone, 5 to 40 cm thick, associated with numerous burrows and carbonate concretions. These features, together with the 'leached' appearance of such sets, suggest long pauses in sedimentation in shallow channels, during which soil-forming processes were active.

(b) Bioturbation: This term is applied to all sets in which original lamination was more or less completely disrupted by burrowing activity, and is the most commonly recorded type (Table 21).

(c) Large Burrows: In less completely bioturbated sets, these trace fossils are a common characteristic of finer-grained sample groups (Table 21). They consist of long straight or sinuous tubes, unbranched,

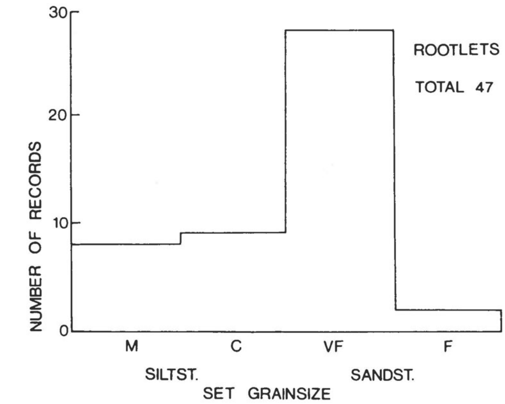


Figure 29. Grain-sizes of sets with rootlets, eastern area.

Table 21. *Trace Fossils, excluding rootlets, eastern area.*

Sample groups	No. 10m	%No. 10m	Bturb	Lge Bur	Sml Bur	Grv Bse	Arthr track	Aver-Fac-prof thick, m	Modal Color	Modal grain size	Modal Structure
1A	2	50	–	–	1	–	–	1.33	Red	VFsd	Flat
1B	2	0	–	–	–	–	–	–	–	–	–
1C	7	0	–	–	–	–	–	–	–	–	–
1D	1	0	–	–	–	–	–	–	–	–	–
2A	10	20	2	–	–	–	–	0.13	Red	VFsd	X/F
2B	2	50	1	–	–	–	–	0.07	Red	Fsd	Flat
2C	1	0	–	–	–	–	–	–	–	–	–
2F	1	0	–	–	–	–	–	–	–	–	–
2G	8	25	4	–	–	–	–	0.32	Red	Fsd	Flat
3A	13	23	3	–	–	–	1	0.27	Grey	Fsd	Flat
3C	26	4	1	–	–	–	–	0.10	Red	Csilt	Flat
3D	37	5	4	–	–	–	–	0.09	Grey	Fsand	Flat
4B	15	73	29	–	12	2	–	1.93	Grey	Csilt	Flat
4C	33	76	79	12	7	2	–	1.51	Grey	Csilt	Flat
4D	18	50	50	2	2	4	–	2.29	Grey	Csilt	Flat
4E	27	78	66	6	6	1	1	1.00	Grey	Csilt	Flat
4F	8	12	1	–	–	–	–	0.24	R/G	Csilt	Lent
4G	7	14	1	–	–	–	–	0.06	Grey	VFsd	Flat
5A	38	61	55	10	3	1	1	0.78	Red	Csilt	Flat
5B	16	75	56	15	2	–	1	1.45	Red	Csilt	Flat
5C	20	85	39	44	9	–	–	2.27	Red	VFsd	Flat
5D	28	86	98	22	10	5	1	2.38	Red	Csilt	Flat
7A	25	24	6	6	–	–	2	0.16	Grey	VFsd	Flat
7B	14	14	2	–	–	–	–	0.16	Grey	Csilt	F/ASR
7C	12	25	3	2	1	–	–	0.12	Grey	Fsd	Flat
$7D_1$	3	0	–	–	–	–	–	–	–	–	–
$7D_2$	6	66	7	3	–	–	–	0.98	Grey	VFsd	Flat
7E	12	22	3	–	–	–	–	0.17	R/G	VFsd	Flat
8	3	0	–	–	–	–	–	–	–	–	–

Second column gives % of this number with trace fossils. The following column headings refer to headings in text. 'Aver-Fac-prof thick, m.' refers to thickness of sediment that contains trace fossils in 10 m. sample.

4 to 10 mm in diameter, and up to 36 cm long. They sometimes show a meniscus filling of laminae of very fine sandstone or silt 1 mm thick alternating with thinner clay laminae. The burrows frequently run horizontally through a set (Plate 25); elsewhere they are oblique to vertical, appearing as circular pits, or knobs, on surfaces. McKee (1954, Plate 11B) figured similar 'worm trails' from the Moenkopi Formation (Triassic) and Daley (1968, Fig. 12a) records slightly smaller burrows of this type from a lacustrine horizon in the Bembridge Marls (Oligocene), referring them to Seilacher's (1964) Fodinichnia group—deposit feeders. Friend found them in the Devonian of Spitsbergen.

(d) Small Burrows: Virtually restricted to siltstone facies (sample groups 4, 5), these have the same external shape and range in orientation as the larger burrows, but are 1 and 2 mm in diameter and up to 20 mm long. No internal structure can be seen in the filling, but in some cases there is a marked concentration of mica flakes at the margins of the burrow.

(e) Grooved Bases: A distinctive trace fossil was observed on the base of certain coarse siltstone sets mainly in non-red siltstone sample groups (4B (grey-co., m. slst.-lent., flat), 4C (grey-m., co. slst.-flat), 4D (grey-co., m. slst.-flat), 4E (grey-co., m. slst.-asym. rip., flat), and 5D (red-co., m. slst.-flat, asym. rip.)). It appears as a group of relatively straight, unbranched, randomly oriented casts 2 mm wide by 10 mm long, with rounded ends (Plate 26). Hand specimens, when sectioned normal to the bedding, show a high degree of bioturbation internally. The burrows therefore tend to be U-shaped, with the bottoms of the 'U' preserved at the interface with the underlying sediment. Sediment in the burrows appears to be depleted in the clay fraction compared to surrounding lamination.

(f) Miscellaneous: One case of clustered branching burrows, each 3 mm wide and up to 10 cm long, was recorded on the base of a red very fine sandstone set (in 5C (red-co. slst., v. f. sst.-flat, asym. rip.)). Clustered burrows were also seen in 4E (grey-co., m. slst.-asym. rip., flat). In sample group 5B (red-co., m. slst.-asym. rip., flat), one instance was sketched

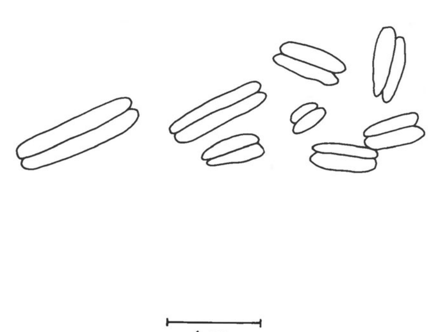


Fig. 30. Resting traces? Inderdalen Formation, Rødedal, eastern area.

Table 22. *Trace Fossils and Primary Structures, eastern area*

Sample group	No. of Flat sets	No. of Flat + trace	No. of AsRip sets	No. of AsRip + tr. f	%Flat + trace f.	%AsRipples + trace f.
4E	491	52	375	25	10.6	6.7
5A	220	23	141	15	10.4	10.6
5B	332	41	214	29	12.4	13.6
5C	236	55	71	17	23.4	24.0
5D	345	56	241	44	16.2	18.3

(Fig. 30) of bilobate 'coffee-bean' shaped structures 3 mm wide by 5 to 11 mm long with a median groove, preserved as casts on the base of a fine sandstone set. They resemble forms described as *Rusophycus* HALL and *Isopodichnus* BORNEMANN', in HÄNTZSCHEL (1962), and may have been resting traces (*Cubichnia* – SEILACHER, 1964) of arthropods.

(g) Arthropod tracks: These trails (*Repichnia*; SEILACHER, 1964) were observed seven times *in situ*, in a variety of finer-grained facies. They consist of two parallel, equal and equidistant rows of impressions on the sediment surface, 7 to 15 mm apart (Plate 27). The impressions are straight, 1 to 2 mm long, slant consistently outwards from the axis of each row, and recur at intervals of 2 to 4 mm along the row. Impressions in one row are offset from those of the other. Sometimes a median groove is preserved between the two rows, and in one case, remains are found of a further row exterior to and in step with one of the main rows. The median groove is presumably caused by dragging a telson. These marks are best preserved in red fine silt veneers, but were also recognised on laminae within grey flat-bedded sandstone. McKEE (1954, Plate 12A) records similar tracks from the Moenkopi Formation. FRIEND observed such tracks in the Devonian of Spitsbergen. There are some similarities to *Ichnispica* sp. LINCK and *Platyo- nychus latipes* PENN (LESSERTISSEUR, 1955, Plate 5, Fig. 1; Plate 3, Fig. 10).

(h) Associations: Trace fossils occur modally in grain sizes ranging from coarse silt to fine sandstone, depending on sample group. In the silt sample groups (4C (grey-m., co. slst.-flat), 5C (red-co. slst., v. f.sst.-flat, asym. rip.)) for example, trace fossils occur dominantly in sets one Wentworth grade coarser than the mode for the sample group; the activity of deposit-feeders in removing finer clay fractions from the sediment results in an apparent coarsening of the horizon, especially at the top of a set. In the sandstone sample groups (2A (red-m., f. sst.-troughX, flat), 2G (red-m., f. sst.-troughX, flat), 3C (grey-m., f. sst.-troughX, flat), 3D (grey-m., co. sst.-troughX), 7A (grey-f., v. f. sst.-troughX, flat), 7B (grey-f., v. f. sst.-flat, troughX), 7E (grey-f. sst.-

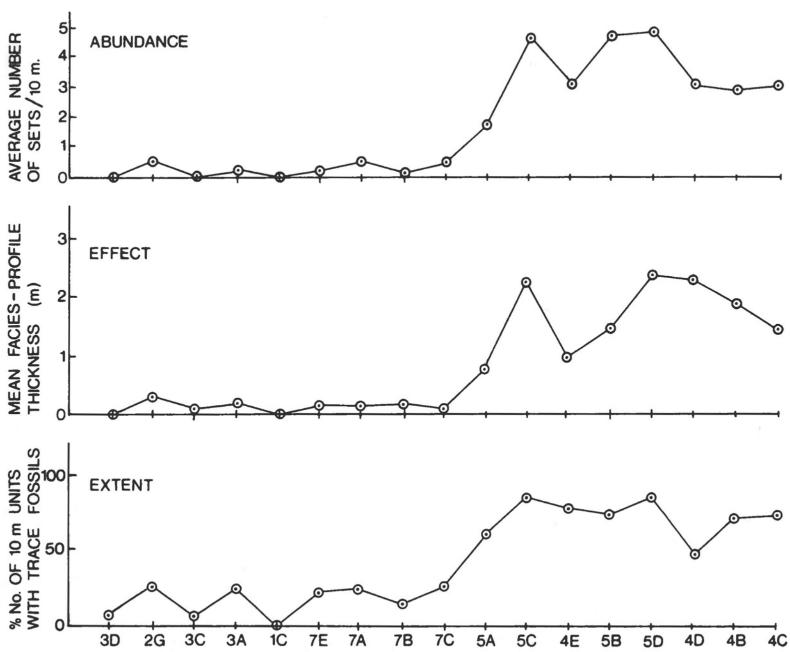


Figure 31. Trace fossils in the various sample groups, eastern area.

trough X)) organisms apparently preferred to live and feed in sediment of finer grade than the mode for each sample group. The colour of the sets containing trace fossils is normally the same as the mode for each sample group. There is no statistical preference (χ^2) for red sediments, except in 5 D (red-co., m. slst.-flat, asym. rip.). Trace fossils occur dominantly in flat-bedded sets and those with small-scale cross-stratification (ripples) which contain trace fossils are not significantly different in red silt sample groups (Table 22), but in 4 E (grey-co., m. slst.-asym. rip., flat), trace fossils show a slight preference for flat-bedding, rather than ripple sets (significant at the 95 % level).

(i) Distribution between sample groups: Figure 31 indicates that trace fossils are widespread, abundant, and affect an appreciable thickness of sediment only in silt sample groups (4, 5). Moreover, the mean facies profile thickness affected tends to increase with increasing thickness of flat-bedded siltstone (Figure 32), so that within these groups, those sample groups which contain greater thickness of asymmetrical ripples (5 A (red-co. slst., v. f. sst.-asym. rip.), 5 B (red-co., m. slst.-asym. rip., flat), 4 E (grey-co., m. slst.-asym. rip., flat) are less affected by trace fossils than those (5 C (red-co. slst., v. f. sst.-flat, asym. rip.), 5 D (red-co., m. slst.-flat, asym. rip.), 4 D (grey-co., m. slst.-flat)) with more flat-bedded siltstones. The organisms presumably preferred living and eating in environments where deposition was largely from suspension.

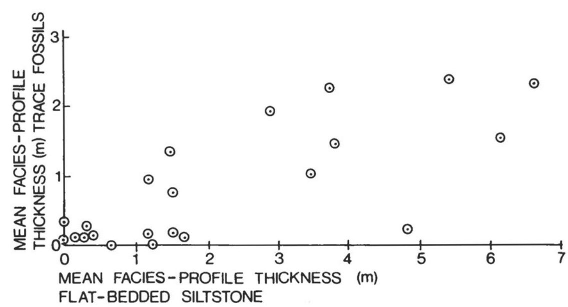


Figure 32. Trace fossils and flat-bedded siltstone, eastern area.

Trace Fossils of Western Area

During work on the mainly sandy sediments of the western area, only 144 beds contained trace fossils out of a total of 14,700.

(a) Burrows: Single parallel-sided tubes were seen cutting through the sediment; they range from 4 cm to 30 cm in length and from 0.3 cm to 2 cm in width. They are oriented approximately normal to the bedding and although not straight, no branches were observed. The tubes have been infilled with sand which ranges in grain size from very fine to coarse sand. In one example there was a concentration of coarse rhombohedral crystals of calcite lining the base of the tube. The contents of the tubes are, in general, homogeneous but, in one case, there was a thin red medium silt layer between the margin of the tube and the core of fine red sand. The form of these trace fossils may compare with *Planolites montanes* (HÄNTZSCHEL, 1962, p. W210; SEILACHER, 1964, p. 306).

The tubes occur modally in fine sand and flat-bedding, and they often cut through the plane lamination without disturbing the bedding. However there are units in which the lower part of the bed has not been disturbed, but in the higher part, small-scale cross-lamination has been destroyed and the bed altered to a green colour. The green colouration is associated with carbonate concretion horizons.

The geometry of sand bodies containing tubes is not known in many cases. However, in two exposures, the tubes occurred in a lens of asymmetrical ripples lying on top of a large cross-stratified coset. The lens was topped by a horizontal plane mudcracked horizon, which itself was cut by tubes. The ripples were filling a small channel formed during low flood stage. It appears that the animal formed the burrows (a worm according to HÄNTZSCHEL (1962), p. W210) after the filling of the small channel and after desiccation.

In a second type of exposure, long tubes cut through a lens infilled with flat-bedding. On the surface of the unit are pellets, 1 cm across, composed of fine- to medium-sand. On other surfaces small vermiform traces of animal activity are preserved.

(b) Complex Burrows: A single example of complex burrows was found. They are very plant-like in appearance, with parallel sided tubes approximately 2 mm thick which branch downwards but do not anastomose or cross each other. They have been filled with red fine silt and occur in a red coarse silt horizon with asymmetrical ripples. No carbonaceous matter was observed and the tubes crosscut the laminae at about 30° to the horizontal. All plant-like material observed in other localities is either carbonaceous or stained green, and so we suggest that this is an invertebrate burrow, like *Chondrites* (Häntzschel, 1962, p. W187), rather than a plant trace.

(c) Rootlets: The term 'rootlet' is used to describe almost vertical zones of reduction approximately 1 cm thick, which start at the upper surface of the bed and bifurcate downwards, but do not anastomose. They contain a central core which does not appear to be carbonaceous or parallel sided. They occur modally in very fine sand and asymmetrical ripples (Table 23) and frequently destroy and reduce the otherwise red small-scale cross-lamination.

Tubes and rootlets are not found in the same horizon. Rootlets are associated with finer-grained lenses or ripples at the top of sequences of cosets of cross-bedding.

(d) Small Burrows (escape structures): Small parallel-sided tubes, approximately 1 cm long and less than 0.5 cm wide, were sometimes found in flat bedded horizons oriented normal to the lamination in the 'flat beds with cross-stratification' association. These cut a single lamina, the edges of which dip inwards towards the tubes, and are distributed randomly within the bed. They tend to be infilled with pale red sand of the same grain size as the rest of the bed and are most clearly observed cross-cutting darker red laminae. None have been seen on the bedding surface.

Table 23. *The association between trace fossils and colour, grain size and internal structures, western area*

	Red	Green	csl	vfss	fss	mss	css
Burrows	59	3	3	13	40	6	
Roots	16		1	10	1		
Escape structures	37				25	3	

	Flat	Asr	Sym	Xbed	Conc.
Tubes	29	4		2	1
Roots	6	6	2		
Escape structures	30			2	

Columns in sequence are: red, green, coarse siltstone, very fine-, fine-, medium-, coarse-sandstone, flat bedding, asymmetrical ripples, symmetrical ripples, cross-stratification, concretions.

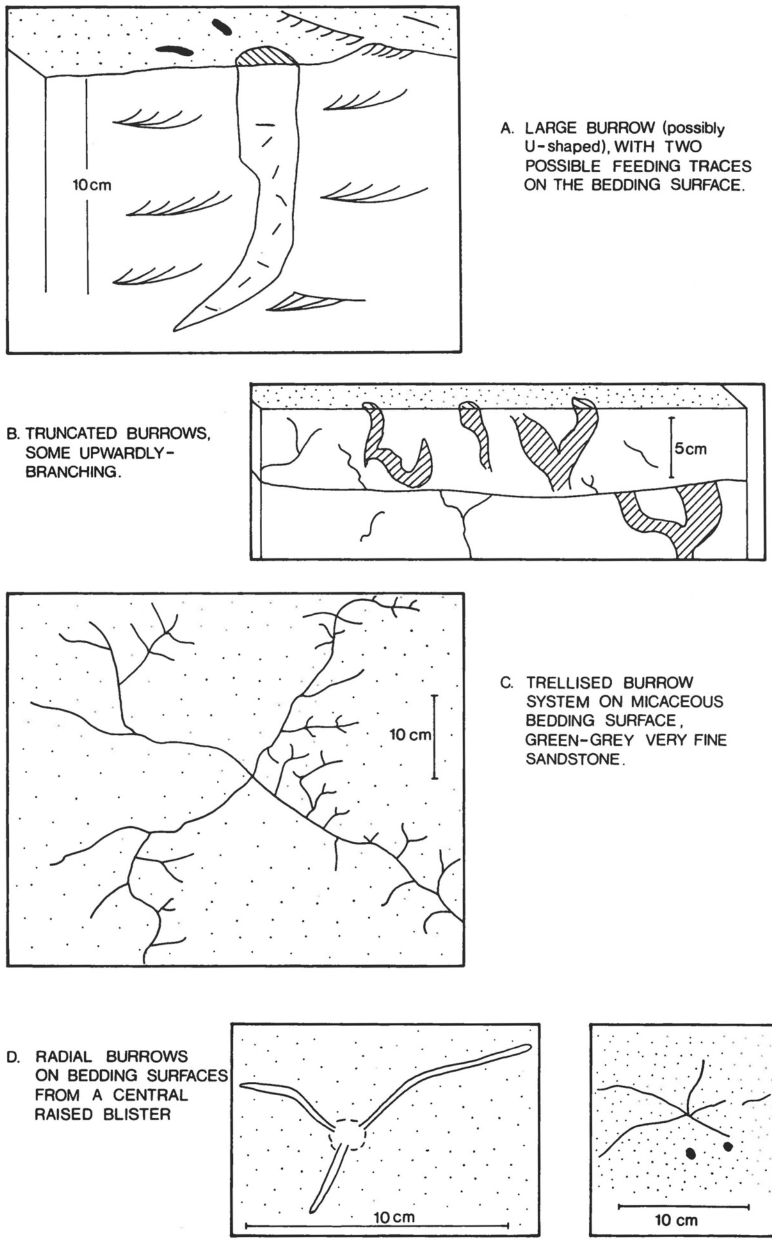


Figure 33. Trace fossils in very fine sandstones of sample group 5A (*Remigolepis* Group), S.W. Celsius Bjerg, central area.

We thought that these were formed by something excaping through the lamina just after deposition of that lamina and during deposition of the bed. This something may have been an animal (HALLAM, pers. comm., 1969) or water or gaseous emission.

(e) Trace Fossils in Sample Groups: It is found that the structures and grain size with which the various trace fossils are associated are similar in each sample group. Burrows are most abundant in sample groups 1B (red-f. sst.-trough X), 1A (red-f. sst.-flat), and 2D (red-m., sst.-flat, trough X), and roots in sample groups 7E (grey-f., m. sst.-flat, trough X), 5A (red-v. f. sst.-flat, asym. rip.), and 2A (red grey-m., f. sst.-trough X) but escape structures are found in sample groups 1A (red-f. sst.-flat), 1B (red-f. sst.-trough X) and 2G (red-m. sst.-trough X, flat). Sample groups 7E (grey-f., m. sst.-flat, trough X) and 3C (grey-m., sst.-trough X) contain few escape structures and burrows but they both have abundant flat-bedding and up to 1.7 metres of ripples in a 10 metre unit. All sample groups with a mean thickness of asym metrical ripples of more than 0.4 m, (except 8 (red-v. f. sst.-flat) and 7D (grey-co. sst.-troughX) contain rootlets.

It appears that, although there is an association between sample group and particular types of trace fossils, there is a further factor, such as the location of that sample group within the fluvial system or the mean annual level of the water table.

Trace Fossils of Central Area

(a) Burrows: These are numerous in sample group 5A (red-co. slst., v. f. sst.-asym. rip.) in the *Remigolepis* Group, and are illustrated in Figure 33. Sketch (A) represents a burrow, probably of a worm, around which impressions are radially disposed. The fill of these burrows is usually structureless, often with a lining of darker sediment; burrows may branch, as sketch (B) shows, and almost invariably the branching is upwardly-directed (in contrast to plant root systems). Diagram (C) illustrates a complex network preserved on a bedding surface, inferred to be a burrow system (possibly of a *Chondrites*-like organism). The branches never cross or anastomose, other than at the central point. Sketch (D) represents a much simpler structure, with radial traces from a central raised blister.

(b) Tracks: Plate 28, illustrates two sets of tracks from a locality near the Kap Graah peninsula, topographically about 100 m below ORVIN's locality with *Bothriolepis*, *Holoptychius*, and *Phyllolepis*. Figure 34 is a scaled diagram of the paired imprints, and Figure 35 is a measured section (classified in sample group 1B (red-f. sst.-trough X, flat)) encompassing the bedding surface on which they are preserved.

Limited palaeocurrent data obtained adjacent to the bedding surface suggest that the current flow over the sand surface may have been almost parallel to the straight stretches of the tracks.

In our consideration of the origin of these tracks, we have benefited from discussions with Miss A. ANDERSON, B.P.I. (Palaeontology), Uni-

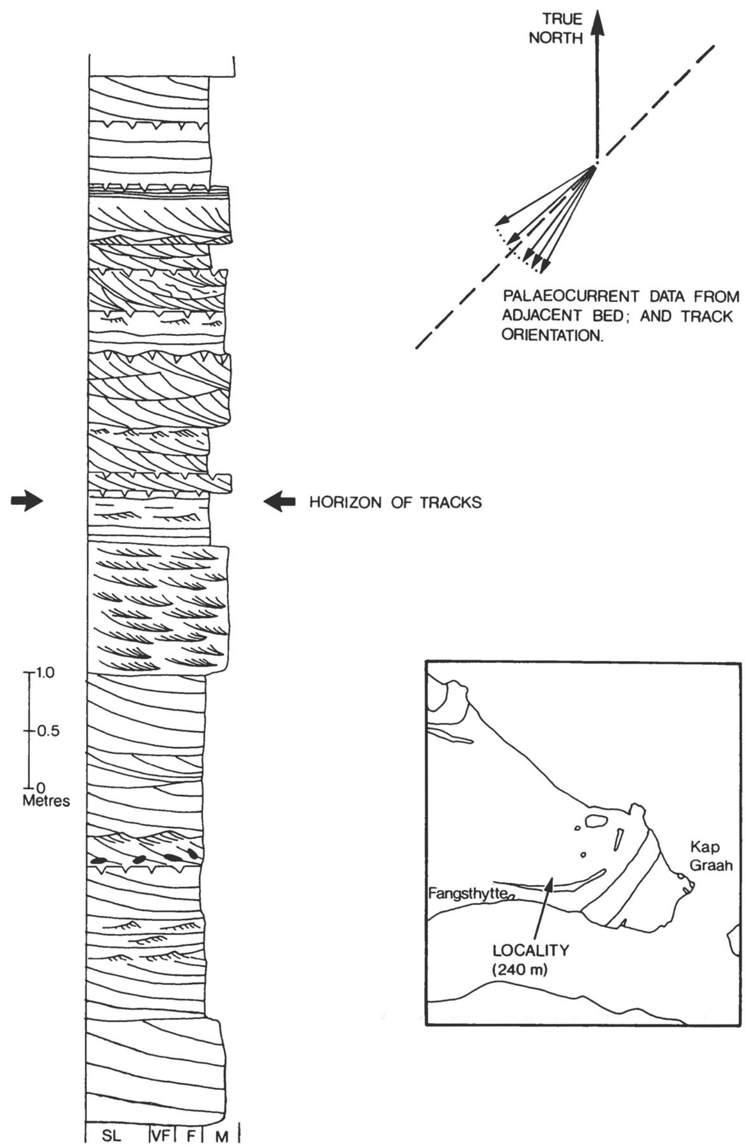
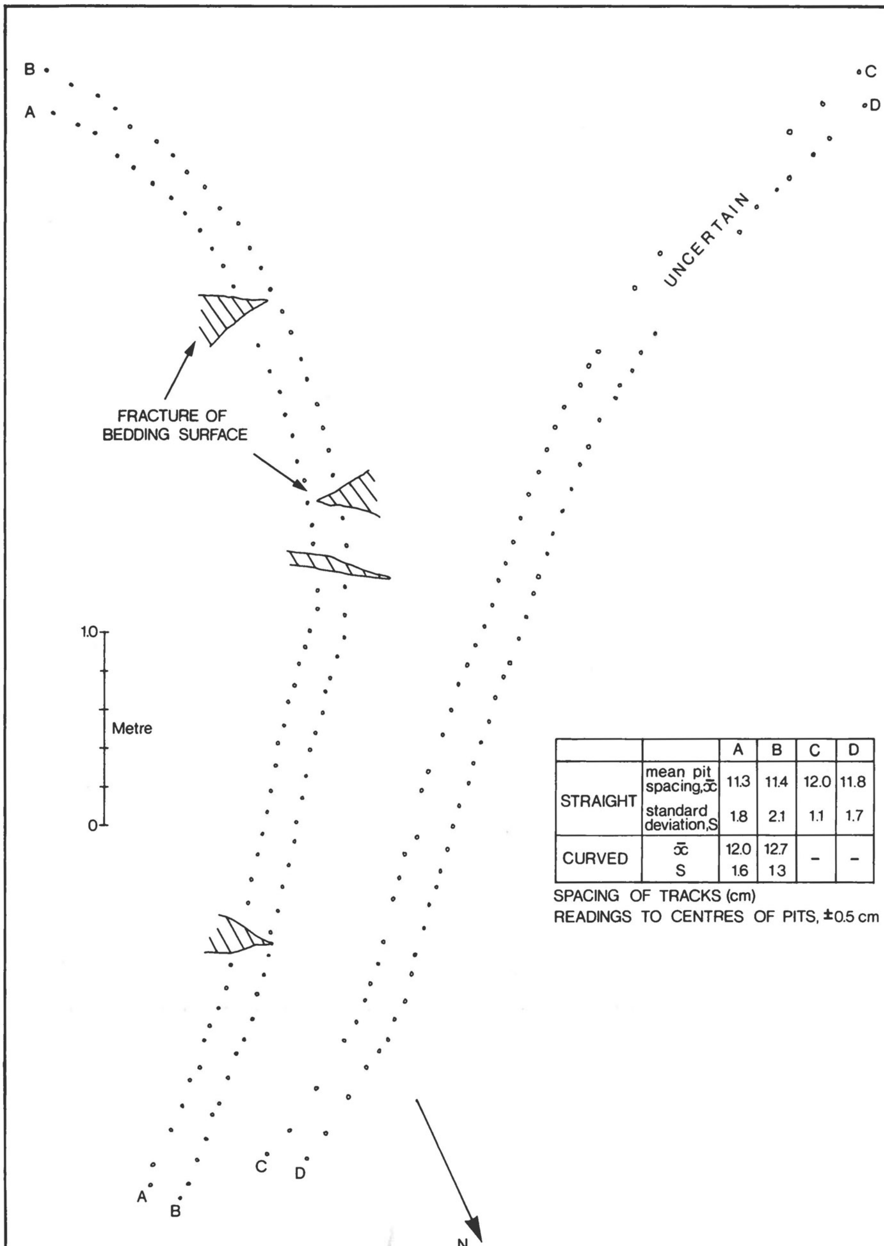


Figure 34. Measured section at the locality of the tracks (inset), classified in sample group 1B, Kap Graah, Kap Graah Group.

versity of Witwatersrand, Johannesburg. We shall mention three groups of organisms which might have left these tracks.

The tracks might have been made by an early tetrapod amphibian. The early ichthyostegid tetrapods, known so far only from Greenland, came from the stratigraphical unit above the Kap Graah Group in which these tracks were found. If these tracks were tetrapod, alternate prints in each row might have been made by the same foot. Otherwise, if each impression was the result of placing of a front foot, and then overprinting



		A	B	C	D
STRAIGHT	mean pit spacing, $\bar{x}$	11.3	11.4	12.0	11.8
	standard deviation, S	1.8	2.1	1.1	1.7
CURVED	$\bar{x}$	12.0	12.7	-	-
	S	1.6	13		

Fig. 35. Paired tracks, from a sandstone bedding surface, Kap Graah Group, near Kap Graah.

by the back foot, evidence of dragging or overlapping of the two prints would be expected. Overlapping and dragging are seen in some Upper Devonian prints recently reported from Australia and thought to be tetrapod (Warren & Wakefield, 1972). The regularity, and lack of

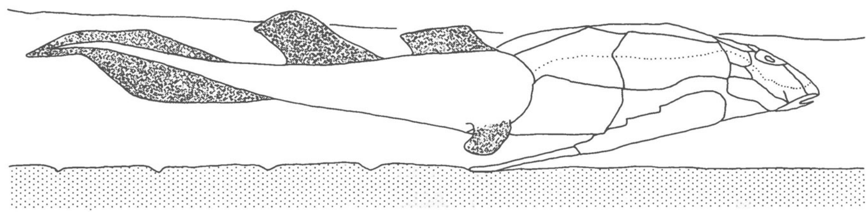


Fig. 36. A possible mode of origin for the paired tracks. Restoration of *Bothriolepis* based on that of STENSIÖ (1948).

overprinting suggest to us that these tracks were not formed by tetrapods.

Miss ANDERSON rather favours an invertebrate origin, and likens the prints to those left by arthropods in the Ordovician and Silurian of South Africa. She also draws attention to the sort of prints left by the many-legged terrestrial arthropod *Peripatus* (MANTON, 1950). She points out, however, that the size of our Greenland prints is surprisingly great, and we would add that no fossils of such large arthropods are known from fresh-water strata of Devonian age.

We suggest that these tracks may be *Bothriolepis* fin marks. It is difficult to visualise *Holoptychius*, with its relatively short, rayed fins making marks of this sort. The fact that the imprints are paired rather than alternating suggests that the fins were used together, while an antiarch rested between movements of its tail (Figure 36). *Bothriolepis* was a mud browsing herbivore (DENISON, 1941), and this mode of movement may have been characteristic, as is the case with some modern fish.

Specimens of *Bothriolepis* with trunk lengths of up to 36 cm have been described (STENSIÖ, 1948, p. 536), and these lengths are consistent with the track dimensions. The breadth of each track is virtually constant, but the longitudinal spacing of the pits does vary slightly; in track B, (Figure 35), the mean pit separation is increased by 0.5 cm on the outside of the curve, and decreased on the inside (track A).

Unfortunately the pits were not well-enough preserved to allow their depth variation to be studied, nor could the temporal relationship between the tracks and the mudcracks on the bedding surface be determined with certainty. However we think that if *Bothriolepis* made these tracks, the individuals must have been in water. The "lungs" of *Bothriolepis* reported by DENISON (1941), have been disputed by STENSIÖ (1948, p. 168) and by MYERS (1942), who interpret them as casts of the gill chamber. Also, the pectoral fins were not of solid bone, and may not have been capable of supporting the full weight of the fish.

In addition to the tracks, other similar but non-linear impressions occur on the bedding surface area, and these may be resting marks. Using very well preserved material, Dr. R. S. MILES has shown us how

Bothriolepis fins could "lock" in a forward position, so as to support the fish on the substrate.

Table 24. *Modal grain size per structure per sample group, eastern area*

	Flat Sandstone	Large Xstrat.	Asym. Ripples	Flat Silt
1C	F sand	F sand	F, VF sand	C silt
2A	F sand	M sand	VF sand	C silt
2G	F sand	M sand	F, M sand	–
3A	F sand	M sand	F sand	C silt
3C	F sand	M sand	VF sand	C silt
3D	M sand	M sand	VF sand	C silt
4B	–	–	VF sand	C silt
4C	–	–	C silt	M silt
4D	VF sand	–	C silt	C silt
4E	VF sand	VF sand	C silt	M silt
4F	–	C sand	F sand	C silt
4G	VF sand	–	VF sand	C silt
5A	VF sand	VF sand	C silt	M silt
5B	VF sand	–	C silt	M silt
5C	VF sand	VF sand	VF sand	C silt
5D	VF sand	VF, M sand	C silt	M silt
7A	F sand	F sand	VF sand	C silt
7B	F sand	F sand	VF sand	C silt
7C	VF sand	F sand	VF sand	C silt
7E	F sand	F sand	VF sand	C silt

Table 25. *Modal grainsize per structure per sample group, central area*

	Flat Sandstone	Large X.strat.	Small X.strat.
1B	F sand	F sand	F sand
1C	F sand	F sand	–
2A	F sand	F, M sand	F saud
2B	F sand	M sand	F sand
2C	F, M sand	F, M sand	F sand, C silt
2E	M sand	M sand	F sand, C silt
2F	F, M sand	M, C sand	–
2G	F, M sand	M sand	F, M sand
3A	F sand	F, M sand	F sand
3C	F, M sand	M sand	F sand
3D	F sand	M, C sand	C silt, VF sand
4E	F, M sand	F sand	VF sand
5A	VF sand	VF sand	VF sand
5C	VF sand	VF sand	VF sand
5D	VF, F sand	F, VF sand	C silt
7B	F sand	F sand	–
7D	VF sand	F sand	C silt
7E	F sand	F sand	VF sand

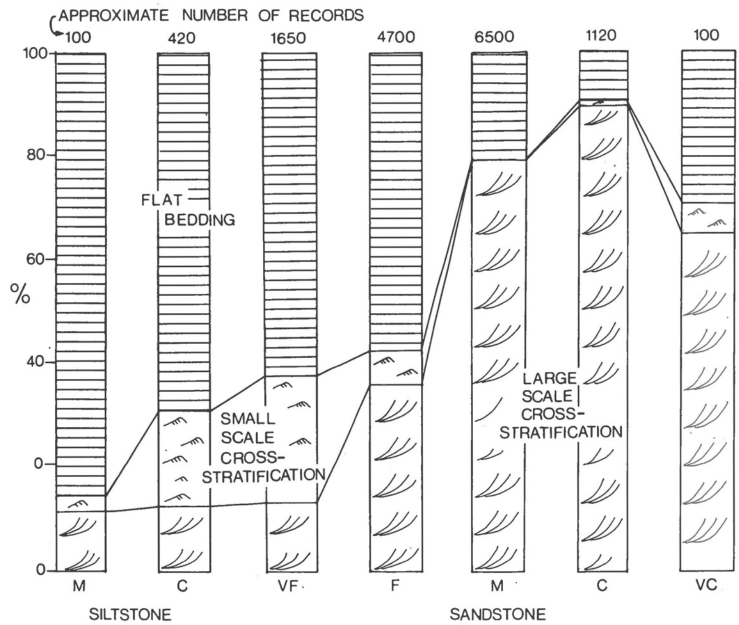


Figure 37. The association between grain-size and internal structure, western area.

5. LOCAL ASSOCIATIONS OF STRUCTURE, GRAIN SIZE AND THICKNESS

Summary of the Associations between Grain Size and Structure

Each of the common primary internal structures was formed in sediments of a range of different grain sizes. For each structure we have determined the commonest grain size, and we have given these determinations in the descriptions of the individual structures. In this section we summarise these data (Tables 24 and 25).

Generalising we find that in the various sample groups,

Large Cross-stratification (if present) is modally coarser grained than, or the same grade, as *flat sandstone bedding* (if present).

Flat sandstone bedding (if present) is modally coarser grained than, or the same grade as *asymmetrical ripples* (if present).

Summary of the Proportions of Structures in Different Grain Sizes

We find a range of internal structures in sets composed of sediment of each grain size.

Our data here are summarised in Figs 37 and 38 (western and eastern areas respectively). These two independent collections of observations, in rocks of differing facies, show some clear similarities.

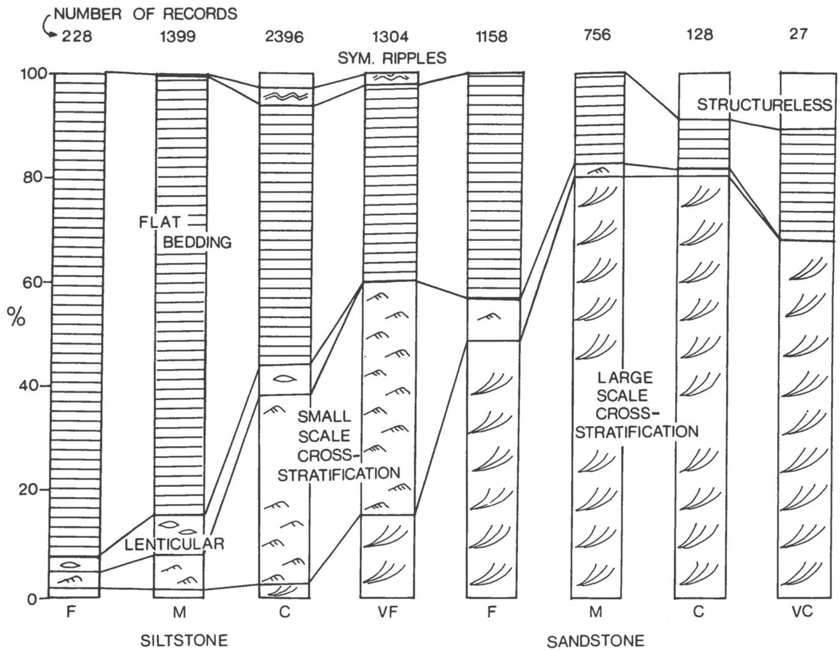


Figure 38. The association between grain-size and internal structure, eastern area.

Large-scale cross-stratification is commonest in medium and coarse sandstones, becoming less common in very coarse sandstones, finest sandstones and siltstones. *Small-scale cross-stratification* is commonest in coarse siltstones and very fine sandstones. *Flat-bedding* is most abundant in the siltstones, and becomes progressively rarer with increasing coarseness of sandstone, until the very coarse grade is reached, where the proportion increases again.

A similar pattern was found by FRIEND (1965) using a much smaller number of observations from Devonian fluvial sediments in Spitsbergen. ALLEN (1969b, p. 14) pointed out that the complementary amounts of large and small-scale cross-bedding are similar to the ranges of stream-power at which experimental dunes and ripples are stable, at the different grain sizes.

These plots include data from all the sample groups recorded.

In Fig. 39 we present data for one sample group (3 D (grey-m., co. sst.-trough X)) in the eastern area. The pattern of structure development is the same as it is for the more variable data.

Transitions from One Structure to Another

One Step Transitions

We have gathered statistics on the number of transitions from one structure to another, which occur up our logged sections.

These statistics were first assembled in the form of a transition tally

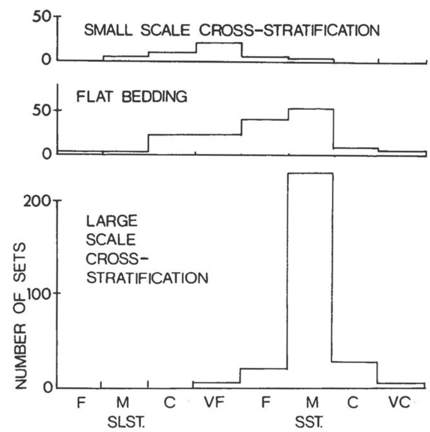


Figure 39. The association between grain-size and structure, sample group 3D, eastern area.

Table 26. *Western Area*
The Transition Tally and Probability matrices for internal structures for all sample groups

	Mdcr	Flat	Symr	Asr	Trx	Flm	Trfs	Def
Mdcr	0	46	0	15	50	5	10	3
Flat......	74	0	16	323	1343	59	110	159
Sym......	0	17	0	3	6	2	0	4
Asr.......	12	310	5	0	163	45	10	25
Trx	25	1364	13	134	0	32	36	359
Flm	10	66	1	23	30	0	1	5
Trfs	10	59	1	9	40	1	0	2
Def	4	197	2	28	330	7	5	0
	Mdcr	**Flat**	**Symr**	**Asr**	**Trx**	**Flm**	**Trfs**	**Def**
Mdcr	0	.36	0	.12	.39	.04	.08	.02
Flat......	.04	0	.01	.16	.64	.03	.05	.07
Sym......	0	.53	0	.09	.18	.06	0	.13
Asr.......	.02	.54	.01	0	.29	.08	.02	.18
Trx	.01	.7	.01	.06	0	.02	.02	.04
Flm	.07	.49	.01	.17	.22	0	0	.04
Trfs	.08	.48	0	.07	.32	0	0	.01
Def	0	.34	0	.05	.58	.01	.01	0

matrix (eg. Table 26). We then recalculated the figure for each transition in the form of the ratio number of occurrences of lower structure. These recalculations then provide the transition probability matrix (Table 26).

In the western area sample used here (Table 26) the following one-step transitions are the most likely transitions of those that could occur. In order of decreasing likelihood:

1) Flat-bedded sandstone up to large-scale cross-stratification.
2) Large-scale cross-stratification up to flat-bedded sandstone.
3) Asymmetrical ripples up to flat-bedded sandstone.
4) Deformed strata up to large-scale cross-stratification.
5) Flat-bedded siltstone up to flat-bedded sandstone.

It is probably more valuable to consider certain transitions from sample group to sample group. An example from the eastern area is given (Fig. 40).

For the sandstone samples groups (1, 2, 3, 7) transitions from large-scale cross-stratification to flat-bedded sandstone, and back, are the most common.

For the siltstone sample groups (4, 5) transitions from asymmetrical ripples (small-scale cross-stratification) to flat-bedded siltstone, and back, are the most common.

Two Step Transitions

Whilst a transition from one structure to another is open to many hydraulic interpretations, sequences from a first structure, to a second, and then a third, may point to more specific environmental changes.

For example, experimental work has shown that, for a given grain size, the sequence:

Upper phase plane bed → dunes → ripples

occurs at decreasing values of stream power (SIMONS & RICHARDSON, 1963).

For constant slope, stream power is a function of depth, so that on a simple model (eg. ALLEN, 1963c) the sequence:

flat-bedded sandstone → large-scale cross-stratification → ripples

could result from a decrease in flow depth up the side of a stream channel.

However our data show that this sequence is not the common one.

We have calculated the combined probabilities of sequences of three structures (i, j, k). This combined probability is the product of the two individual transition probabilities (Pij × Pjk), not the mean of the two individual probabilities which was used by ALLEN (1970a, p. 304).

From the western area (Figure 41), the commonest sequences are:

Large-scale cross-stratification → flat-bedded sandstone → large-scale cross-stratification.

Large-scale cross-stratification → flat-bedded sandstone → small-scale cross-stratification.

Flat-bedded sandstone → large-scale cross-stratification → flat-bedded sandstone.

Flat-bedded sandstone → small-scale cross-stratification → flat-bedded sandstone.

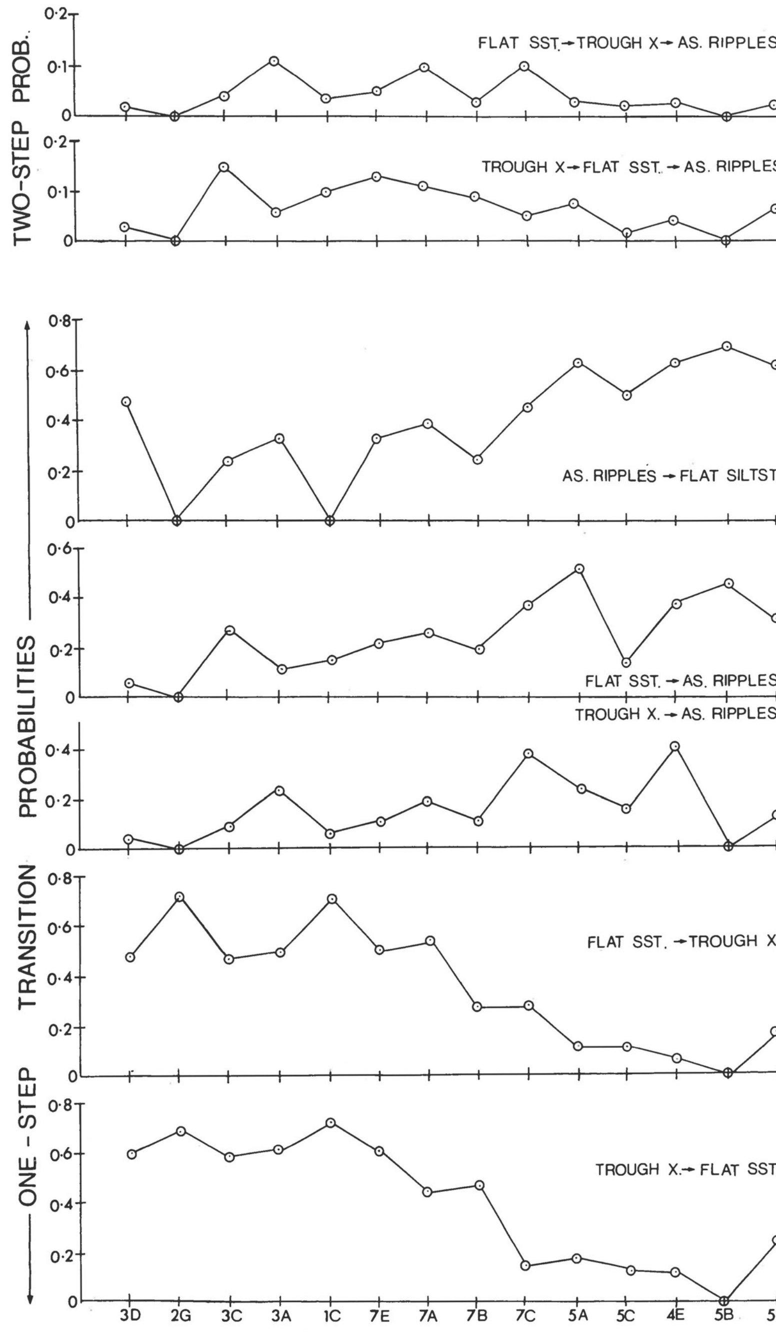


Figure 40. Primary internal structure transitions, eastern area.

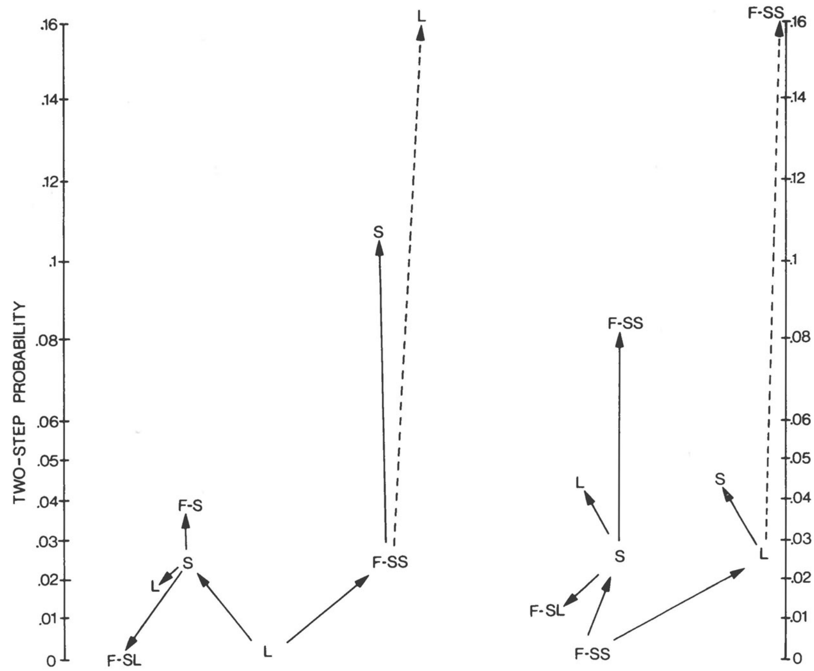


Figure 41. The cumulative probabilities for two step transitions from flat and trough cross bedding, western area. (F–SL, flat laminated siltstone; F–SS, F–S, flat bedded sandstone; L, large-scale cross-stratification; S, small-scale cross-stratification).

A study in the eastern area (Figure 40), shows that in most groups, the combined probabilities are greater for:

Large-scale cross-stratification → flat-bedded sandstone → small-scale cross-stratification,

than for:

flat-bedded sandstone → large-scale cross-stratification → small-scale cross-stratification.

Also:

Flat-bedded sandstone → small-scale cross-stratification → flat-bedded sandstone,

is more abundant than:

Large-scale cross-stratification → small-scale cross-stratification → large-scale cross-stratification.

The Significance of Flat-bedded Sandstone

We shall particularly consider, at this stage, the question of the position of flat-bedded sandstone in the sequences. This structure is abundant in association with both large- and small-scale cross-stratification. The transition probabilities do not support the suggestion, based on experimental work, that flat-bedding is characteristic of the highest power part of sedimentary sequences, separated from small-scale cross-stratification by a field of large-scale cross-stratification.

Associations between sedimentary structures and grain sizes show that in five major sample groups (2A (red-m., f. sst.-trough X, flat), 2G (red-m., f. sst.-trough X, flat), 3A (grey-f., m. sst.-trough X), 3C (grey-m., f. sst.-trough X, flat), 7C (grey-v. f., f. sst., co. slst.-flat, trough X)) the modal grain size for flat-bedded sandstone is one Wentworth grade finer than that for large-scale cross-stratification and in all other sandstone groups, the flat-bedding distribution contains a higher proportion of fine and very fine sandstone sets than does large-scale cross-stratification (eg. group 3D (grey-m., co. sst.-trough X), Figure 39). Flat beds tend to be finer-grained than cross-strata and are frequently overlain by a scoured surface, followed by cross-stratification, which marks the beginning of a new grain size-cycle.

This raises two problems: we have to account for: (a) the occurrence of upper flow regime deposition between two lower flow regime phases; and (b) grain size variation between sets.

(a) Bedform Stability Fields: The experimental data of GUY, SIMONS & RICHARDSON (1966) showed that the critical power at which upper phase plane beds are replaced by dunes is lower for fine sand (about 2 watt, in S.I. units) than for very coarse sand (about 10 watt), and the dune power stability field becomes narrower with finer sands. ALLEN (1970c), using these data and the dimensionless bed-shear stress criterion for plane bed movement derived by BAGNOLD (1966), predicted that the three stability fields should intersect in a triple point. A version of his diagram is replotted for ebuilibrium conditions in Fig. 42. HILL (1966), applying collision theory to particle movement in the bed load, came to the same conclusion: either ripples or dunes would form, if the shear stress fell below that required for plane bed movement, depending on the grain size. The triple point was predicted to occur at a grain size of 0.125 mm; on Fig. 42 it appears at about 0.135 mm. In either case, the dune phase should not be stable in grain sizes finer than fine sand. These predictions have been confirmed by the experiments of HILL *et al.* (1969) using very fine, fine and medium sand grades to determine the lower limit of plane bed stability.

Thus, the observed sequence: large-scale cross-stratification in medium sandstone → flat-bedding in fine sandstone → ripples in very fine sandstone, could represent a uniform decrease in both stream power and grain size, as shown by the dashed line on Figure 42.

(b) Grain size variation: The problem here is to explain why a given flat-bedded set consists modally of fine sand grains, when, clearly, there was enough power available for the entrainment of medium sand grains which are present in the underlying cross-strata. Mechanisms for

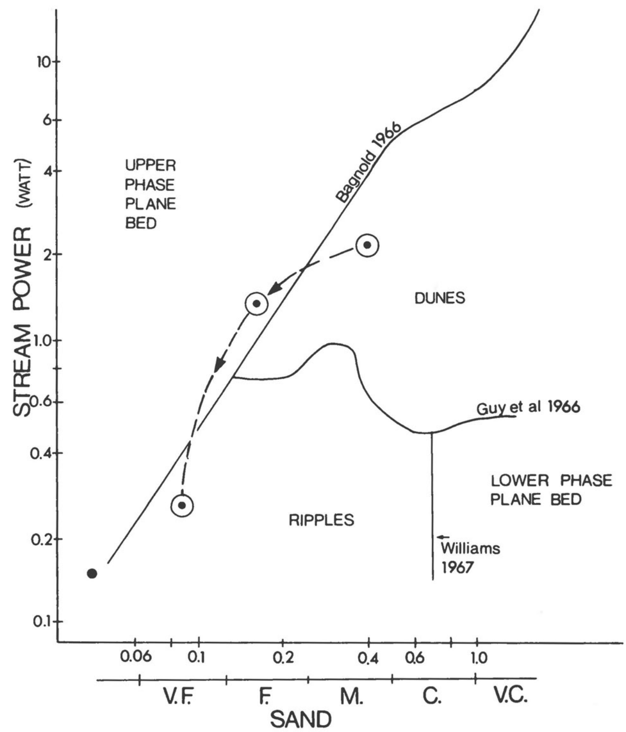


Figure 42. Bed-configuration related to power and grain size.

trapping the coarser sand grains must be involved. In a fluvial environment two such mechanisms may occur:

Bed material containing a range of grain sizes can be fractionated by suspension of the finer grades. LANE & KALINSKE (1939) showed theoretically that the ratio of concentration of a particle size in suspension to the proportion in the bed-load was a function of particle fall velocity and shear stress. BAGNOLD (1966, p. 116) predicted that much lower bed shear stress is required for the development of suspended load in fine sand than in medium sand, and that a suspended load should be present in finer grades (silt) as soon as the threshold shear stress for particle movement is exceeded. This explains why fine sand and silt, forming the largest proportion of suspended load in the channel, will become the modal grain sizes in material transported over the banks in flood, as happened at Bijou Creek (McKEE *et al.*, 1967).

A second mechanism has been proposed by ALLEN (1970a), in which bed-load particles are sorted into progressively finer grades up the side of a sediment bar in a curved channel. For the case of helicoidal secondary flow, the sorting is produced by lateral variation in magnitude of the component of bed shear stress acting tangentially up the bar surface, balanced against the component of gravitational force acting on each

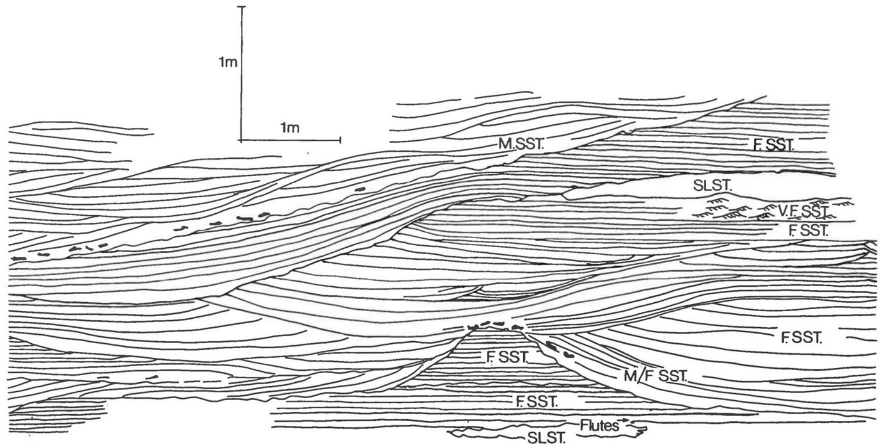


Figure 43. Bedding relations, sample group 7A, Kap Franklin, eastern area, Kap Franklin Østreplateau Member.

particle down the slope. Thus the coarsest grains occur near the talweg, where the power is at a maximum, while the finer grades are transported in shallower water on the sediment bar where the power is less. This mechanism therefore allows the decrease in both power and grain size required by the observed sequences. In particular, it explains some of the bedding relationships in Fig. 43, where trough cross-stratified fine-medium sandstone sets pass laterally and upwards into thinner sets of flat-bedded fine sandstone. The vertical sequences are explained in terms of depth of flow decreasing with time at that location, due mainly to lateral displacements of the talweg of successive channels.

Published observations of both modern rivers and other ancient fluvial deposits suggests that the occurrence of flat-bedding as a shallower water phase than trough-cross-stratification may be a widespread phenomenon. The sequence has been reported from modern point-bar deposits (McGowen & Garner, 1970, p. 94; Bernard *et al.*, 1970). Flat-bedding was restricted to channel bars in the braided streams described by Doeglas (1962), and Harms & Fahnestock (1965) observed plane bed movement over bar surfaces in shallow water, and found the resultant 'horizontal' stratification in trenches at shallow depths below the sediment surface at low stage. Harms *et al.* (1963) pointed out that the preservation potential of plane beds in the talweg was small, as with waning flow power, the succeeding dunes must scour out the underlying bed. Coleman (1969, p. 214) reported the sequence: large-scale cross-stratification → flat-bedding → ripple lamination silt, as common in crevasse-splay deposits of the levees of the Brahmaputra river. The same sequence in Carboniferous rocks was interpreted by Visher (1965) as due to the increase of Froude number to upper flow regime with decrease in depth: $F = V/(gd)$, where velocity (V) decreases less rapidly over the bar surface(g, gravitational constant; d, depth). Transition probability data from some of the sections used by ALLEN (1970a, Table 10) from the Devonian of Britain and the Catskill Mountains, also agree with the results presented here.

(c) Other effects: On the floodplain, deposition of sediment is likely to occur during the waning flow phase of a flood, so that the stability fields of the various bed configurations under equilibrium conditions may not apply in unsteady flow (ALLEN, 1970c). SIMONS & RICHARDSON (1966, p. J11) report that when power is increased, the dune phase occurs at values of stream power for which plane beds are stable when power is decreasing. The latter empirical boundary for plane beds approximately corresponds to that predicted by BAGNOLD (1966) and HILL (1966). When power declines very rapidly, there may not be enough time for dunes to build up from a plane bed (ALLEN, 1969b, p. 32; WALKER, 1965, p. 22), and flat beds may pass straight into ripples in fine or medium sandstone.

Clay in suspension increases the viscosity and density of the water, thus decreasing the effective fall velocity of the sand grains (SIMONS *et al.*, 1963). This would generate more flat-bedding than expected for a given power range and grain size.

In some cases, water temperature may have had a controlling influence. HARMS & FAHNESTOCK (1965) noted that in one reach of the Rio Grande, for similar discharges and grain sizes, plane beds in March were replaced by dunes in August, a difference of 21°C in water temperature. It is impossible to estimate the importance of this effect in the Devonian sediments.

Very shallow flow may also influence the structures. BAGNOLD (1966, p. 19) showed theoretically that when the flow depth is of the same order as the thickness of the moving bed-load carpet, the efficiency of bed-load transport is nearly three times greater than it would be for the same stream power at greater depths. Plane beds then occur where ripples would normally be expected, for a given grain size. In the braided Platte River, SMITH (1970) reported plane bed movement over the tops of transverse bars in depths less than 2.5 cm, whereas ripples formed in 3 to 8 cm depth, and dunes in deeper water. SMITH's (1971) low-angle sand-waves are probably also related to this phenomenon. Our observations in Icelandic braided streams indicate that this mechanism is important in small anabranches scoured into channel bars at low stage. A number of Devonian records of flat-bedded fine sandstone sets 10 to 15 cm thick, filling a shallow depression 2 to 3 m wide scoured into cross-stratified medium sandstone, may represent similar deposits from very shallow flow.

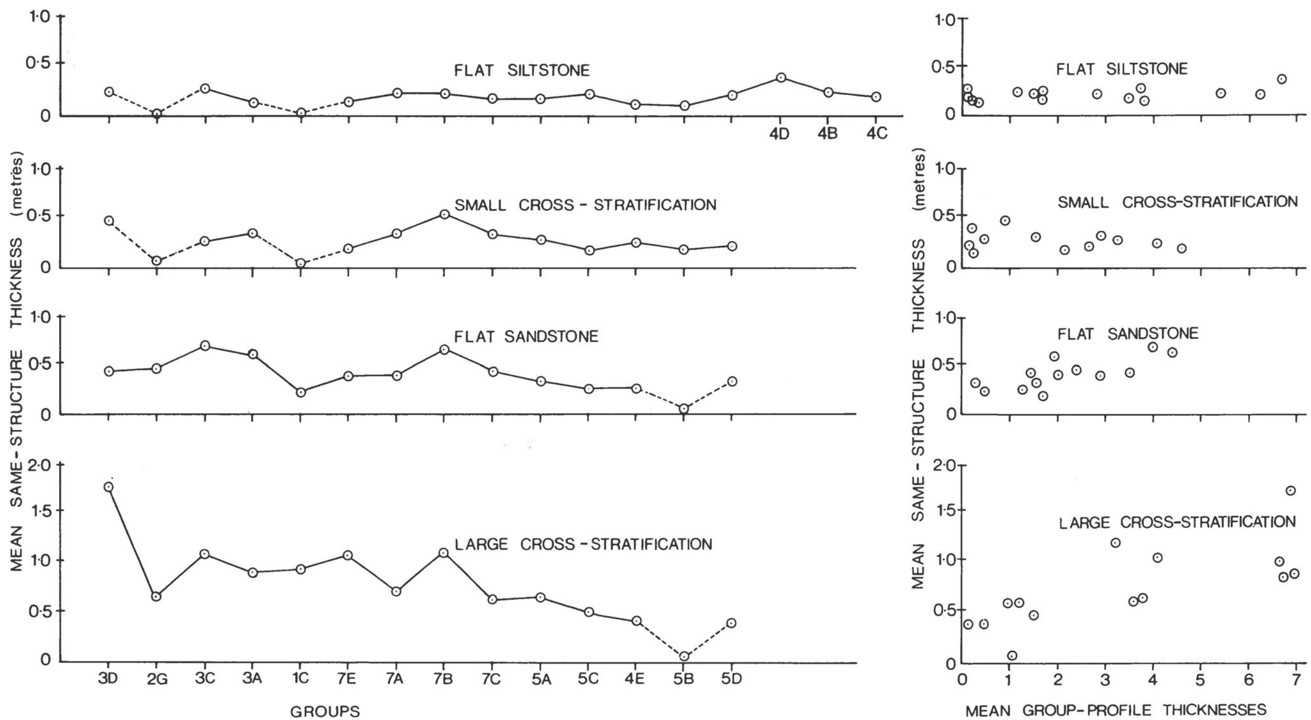


Figure 44. Same structure thicknesses for the various sample groups (left of diagram), and variation with total thicknesses per sample group of each structure (right of diagram). Data from the eastern area.

Thicknesses of Sequences of Similar Structure

We used the computer to pick our continuous vertical sequences of sets, all of the same primary internal structure. In practice these "same-structure sequences" usually correspond to the "coset" defined by McKee & Weir (1953). However, whereas their cosets terminate vertically at "original flat surfaces of erosion, non deposition, or abrupt change in character", our "same-structure sequences" only terminate at a boundary with sets of different structure.

General data for the central area showed that sequences of large-scale cross-stratification (range of arithmetic means, for different sample groups, 1.3 to 4.0 m) are usually greater than those of flat-bedded sandstones (0.15 to 0.6 m).

In many cases, we found that the thickness statistics appeared to have log-normal frequency distributions. In these cases we calculated log means. In the western area the same structure sequences for large-scale cross-stratification (log means 2.1 to 5.1 for different sample groups) are thicker than for flat-bedded sandstones (log means, 1.7 to 2.7 m), which, in turn, are thicker than for small-scale cross-stratification (log means, 1.2 to 2.8 m).

For the eastern area, mean sequence thicknesses are plotted in Figure 44 for the various sample groups. Large-scale cross-stratification sequence thicknesses tend to be smaller in groups with lower mean grain size. This is the only clear trend revealed by this analysis of the different groups ie. small-scale cross-stratification, flat-bedded sandstone and flat-bedded siltstone sequences tend to be similar in thickness whatever the group.

For this same eastern area, mean sequence thicknesses have been plotted against mean proportion of the particular structure per 10 m sample group (Fig. 44). On the whole these statistics show that groups with high proportions of flat sandstone bedding and large-scale cross-stratification, also have rather thicker individual sequences of these structures. In contrast flat-bedded siltstone and small-scale cross-stratification tend to a uniform sequence thickness (25 cm) whatever the proportion in the sample. Thus a 10 m sample group consisting dominantly of large-scale cross-stratification (eg. 3D (grey-m., co. sst.-trough X) will characterise samples in which thick (mean 1.8 m) sequences of the structure occurs. In contrast a group consisting of a high proportion of small-scale cross-stratification (eg. 4E (grey-co., m. slst.-asym. rip., flat)) characterises samples in which there is a close alternation of relatively thin sequences of the structure (30 cm) with flat-bedded siltstone (20 cm). Typical sample groups illustrate this (Fig. 44).

Each same-structure sequence can be regarded as resulting from:

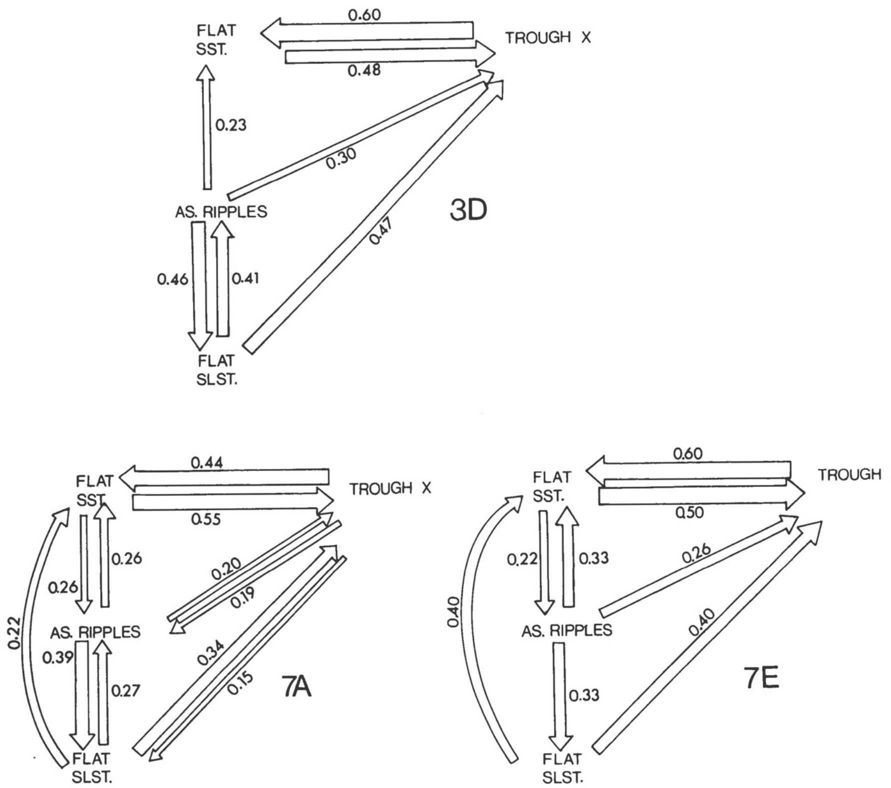


Figure 45. Transition probability arrow diagrams for three sample groups from the eastern area. In each case ripple — flat siltstone couplet is subsidiary to trough cross-stratification — flat sandstone couplet.

Table 27. The transition talley and probability matrices for grain size for all sample groups

	mslt	cslt	vfss	fss	mss	css	vcss	con
mslt......	0	4	11	12	7	7	1	0
cslt.......	4	0	81	193	104	6	0	0
vfss	12	107	0	547	118	18	2	15
fss	22	185	568	0	1104	59	6	4
mss	2	93	106	1130	0	305	8	4
css	4	2	17	48	305	0	0	1
vcss	0	0	3	3	9	3	0	1

	mslt	cslt	vfss	fss	mss	css	vcss	con
mslt......	0	.1	.27	.29	.17	.17	.02	0
cslt.......	.01	0	.21	.5	.26	.02	0	0
vfss	.01	0.13	0	.67	.14	.02	0	.02
fss	.01	.09	.28	0	.55	.03	0	0
mss	0	.06	.06	.68	0	.18	0	0
css	.01	0	.05	.13	.81	0	0	0
con.......	0	0	.22	.33	.22	.11	.11	0

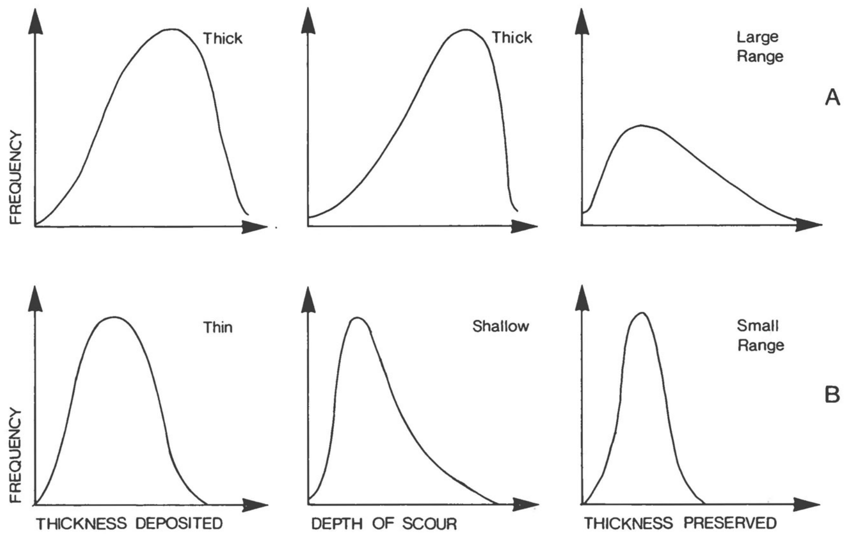


Figure 46. Hypothetical thickness distributions for small-scale cross-stratification, showing their possible derivation from different thickness distributions for deposition and for scour.

1) accumulation of a thickness of sediment,

2) removal, by scouring, if it occurred, of some of this sediment.

In the case of small-scale cross-stratification, the mean sequence thicknesses do not vary significantly from group to group. This implies either that both accumulation and scouring were more or less constant, and generally small, or that they varied in a complementary way. If they did vary in this complementary way, we might expect a greater range in the resulting sequence thicknesses eg. Fig. 46. This is not borne out by the results (Table 27); the standard deviation of small-scale cross-stratification sequence thickness in sample group 3D (grey-m., co. sst.-trough X), for example, is not significantly different from that of the much finer grained sample group 7C (grey-v. f., f. sst., co. slst.-flat, trough X). We therefore conclude that the processes affecting small-scale cross-stratification sequence thicknesses have the same magnitude in all groups: the differences between groups are largely due to the different number of sequences in the 10 m samples. This, in turn, appears to depend on the proportion of the 10 m sample not occupied by large-scale cross-stratification. There seems to be something special about the accumulation of small-scale cross-stratification that determines the thickness. The transition probability data for the sandstone groups, 3D (grey-m., co. sst.-trough X), 7A (grey-f., v. f. sst.-trough X, flat), 7E (grey-f. sst.-trough X) (Figure 45) shows that if small-scale cross-stratification (asymmetrical rippling) occurs, even though this is rare, then there is a high probability that the, also rare, flat-bedded siltstone will follow.

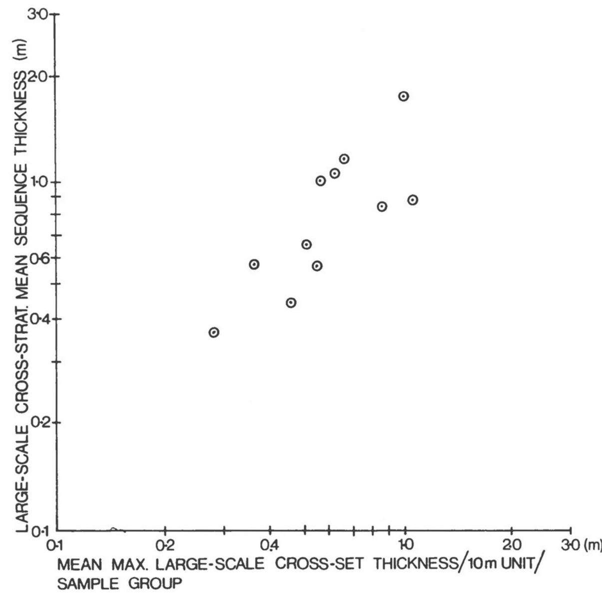


Figure 47. Variation of same structure thickness with set thickness for large-scale cross-stratification, eastern area.

It appears to us, that variation in large-scale cross-stratification sequence thickness is responsible, with grain size, for the main differences between sample groups. Mean sequence thickness increases with increase of the size of component sets, rather than with increase in their number (Figure 47, 48). We have already referred, above, to the fact that the size of sets appears to vary with the proportion of large-scale cross-stratification per 10 m sample, (Fig. 10). If maximum set thickness is a function of flow depth, sequence thickness may also be proportional to maximum flow depth. If flat-bedded sand and small-scale ripples formed in shallower water than large-scale cross-stratification, then the combined thickness of successive sequences of the three structures may approximate to the original bank-full channel depth. The association of this sequence with progressively decreasing grain size suggests that vertical grain size cycle thicknesses also ought to vary systematically between sample groups, as shown in the following section.

Patterns of Vertical Grain Size Variation

An interesting feature of the mean 10 m sample facies profiles is that the thicknesses of the various grain sizes in most sample groups are approximately normally distributed with a single mode. Two major exceptions include sample groups $7D_2$ (grey-v. f., co. sst.-trough X, flat) and 4F (grey-co. slst., co. sst.-flat, asym. rip.), in which two modes, coarse sandstone and coarse siltstone, are present, interbedded on a scale much less than 10 metres.

Table 28. *Western area*

Grain size	Log-mean of same grain size sequence thicknesses	Number of sequences
coarse siltstone	1.2 m	370
v. f. sandstone	2.3 m	521
fine sandstone	2.6 m	1991
medium sandstone	3.3 m	1871
coarse sandstone	3.1 m	290
very coarse sandstone	3.3 m	13

All the grain sizes recordable on the mark-sense form are represented in the data, but 10 metre samples consisting modally of coarse and very coarse sandstone were rarely recorded. (They classified in sample group 7 D with low communality, and are distinguished from the coarse sand-silt alternations here by the subscript $7D_1$ (grey-v. co. sst.-trough X)).

In the western area, a study was made of the thicknesses of same-grain size sequences. As with the thicknesses of same-structure sequences, these thicknesses appear to show a tendency to log normal frequency distribution, so log means are used to summarise the data (Table 28). The finer-grained sediment usually occurs in thinner sequences, but this may be a feature of the consistently sandy sedimentation of this area, and not a feature of the whole East Greenland Devonian.

A transition study was made of grain size changes in the western area. Tally and probability matrices are presented in Table 27. This work shows that

(a) medium and fine sandstone often follow each other,

(b) very fine sandstone more often succeeds a fine sandstone unit than a medium sandstone unit.

This picture was confirmed by calculating the two-step transition probabilities for all sequences starting with fine or medium sandstone. The following are the most probable (in order of decreasing probability):

(a) m. sst. → f. sst. → m. sst.

(b) f. sst. → m. sst. → f. sst.

(c) m. sst. → f. sst. → v. f. sst.

Our other main approach was to consider grain size cycles. This approach has proved useful in other Devonian fluvial areas (ALLEN, 1964b; FRIEND, 1966; ALLEN & FRIEND, 1968). However, in the great proportion of Greenland successions, distinctive cycles are rarely present.

We therefore defined a form of cyclicity, in terms of set-by-set grain size variation, as follows (ALEXANDER-MARRACK *et al.*, 1970, p. 13): a

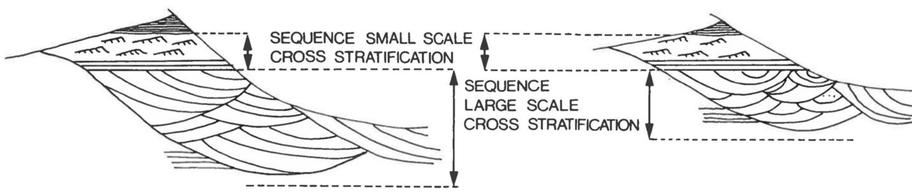


Figure 48. Schematic diagram to illustrate variation of same structure thickness with set thickness between two sample groups.

Table 29. *Grain size cycle thicknesses* (in m), *eastern area*

Facies	Mean	Log mean	Log SD	Min	Max	No.
1C	0.73	−0.308	1.17	0.10	3.05	12
2G	1.05	0.048	0.86	0.25	4.60	12
3A	1.03	0.026	0.89	0.20	4.20	27
3C	1.27	0.238	0.83	0.15	6.70	51
3D	0.96	−0.038	1.13	0.1	11.45	54
4B	0.73	−0.310	0.96	0.10	12.3	59
4C	0.47	−0.743	0.81	0.10	4.55	224
4D	0.73	−0.310	0.98	0.10	6.95	60
4E	0.48	−0.728	0.83	0.10	3.55	287
4F	0.82	−0.195	0.98	0.10	6.35	52
5A	0.64	−0.449	0.84	0.10	5.80	146
5B	0.37	−0.998	0.73	0.10	2.55	167
5C	0.59	−0.518	0.84	0.10	4.00	131
5D	0.57	−0.563	0.95	0.10	7.35	207
7A	0.91	−0.095	0.86	0.10	6.10	128
7B	0.91	−0.088	0.96	0.10	6.70	39
7C	0.67	−0.395	0.97	0.10	7.30	56
7D	0.63	−0.452	0.92	0.15	6.30	32
7E	0.96	−0.035	0.97	0.30	6.00	13

fining-up semicycle is a sequence of sets in which the grain size does not decrease upwards, while the converse is a coarsening-up semi-cycle. A cycle is defined as beginning at the initiation of an upwards-coarsening trend and ending at the next initiation of a coarsening trend (Figure 16 in No. 1 of this volume), Most cycles consist only of fining-up semicycles.

The mean cycle thickness per sample group was calculated from the results of the Fortran program "Fining-cycles". (Table 29). This thickness decreases significantly with decreasing facies profile mean grain size, reaching a minimum in the ripple-rich siltstone groups, 4E (grey-co., m. slst.-asym. rip., flat), 5B (red-co., m. slst.-asym. rip., flat) (Figure 49) and increasing again in siltstones lacking bed-load deposits (4D (grey-co., m. slst.-flat), 4B (grey-co., m. slst.-lent., flat)).

The thickness of the coarse members of the sand and silt fining-upward cycles (ALLEN, 1970a) may represent bank-full channel depth.

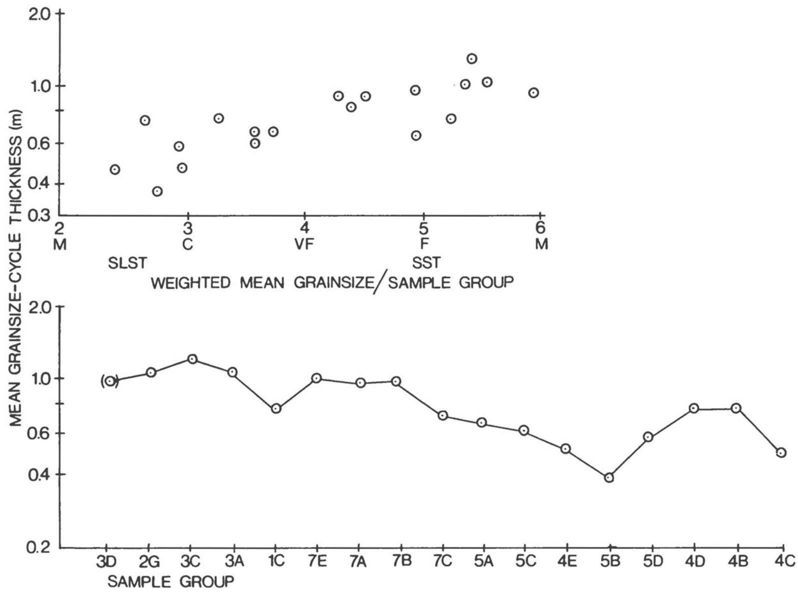


Figure 49. Variation of mean grain-size cycle thickness with mean grain-size per sample group (upper diagram), and with sample group (lower diagram).

We suggest that cycles, as defined by us, in the sandstone sample groups, correspond to ALLEN's coarse members, with fine members being usually aqsent. Our grain size cycles are often the same as cycles based on sequences of internal structure; exceptions occur where differences in grain size between structures are too slight to be recorded on the mark-sense form, or where fluctuctions of grain size occur within a continuous sequence of large-scale cross-stratified sets. The order of grain size cycle thickness (0.9 to 1.3 m on average) is also similar to that of the combined same-structure sequences proposed in the preceding section.

In the very common sample group, 3 D (grey-m., co. sst.-trough X), a third kind of cycle, composed of decreasingly thick sets of the same grain size and structure, is often present. Cycles of this third kind are often thinner than those defined on grain size alone or structure alone.

Extrapolating to some of the siltstone groups (5 A (red-co. slst., v. f. sst.-asym. rip.), 5 C (red-co. slst., v. f. sst.-flat, asym. rip.), 4 E (grey-co., m. slst.-asym. rip., flat), 5 B (red-co., m. slst.-asym. rip., flat)), bank-full depth appears less than in the sandstone groups; this supports previous suggestions based on set size of large-scale cross-strata and type of ripple. Where suspended load deposits become dominant (4 B (grey-co., m. slst.-lent., flat), 4 D (grey-co., m. slst.-flat), 4 C (grey-m., co. slst.-flat)), no relation between water depth and grain size cycles may be postulated.

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Færdig fra trykkeriet 28. december 1976

PLATES

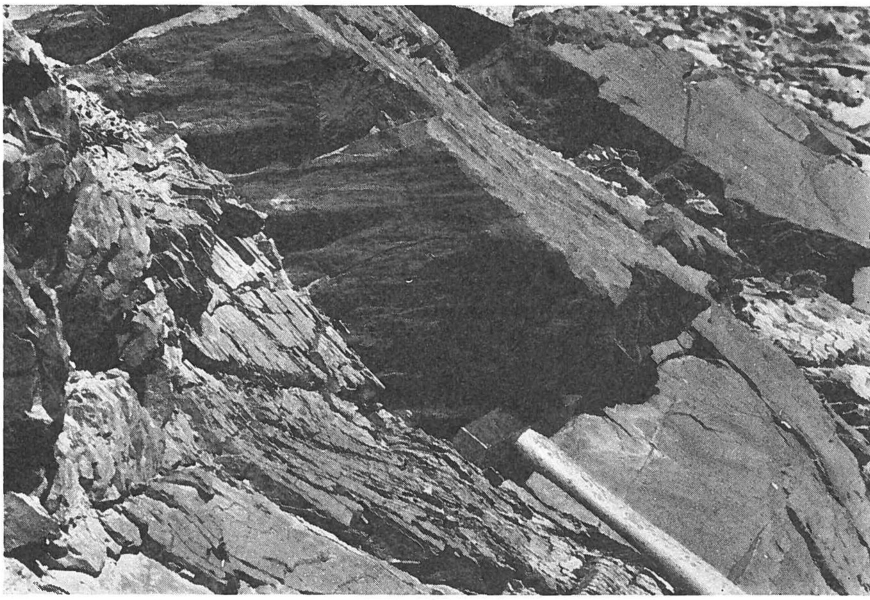

Plate 1. Flute casts; Ramsays Bjerg Red-and-green Siltstone , Agassiz Bjerg.

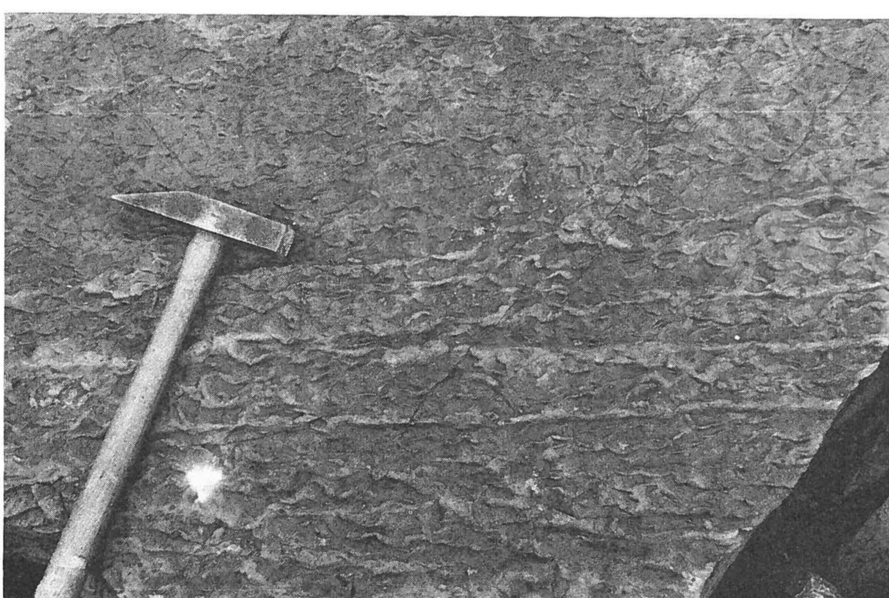

Plate 2. Crescents and other scour casts. Inderdalen Formation, Rødedal.

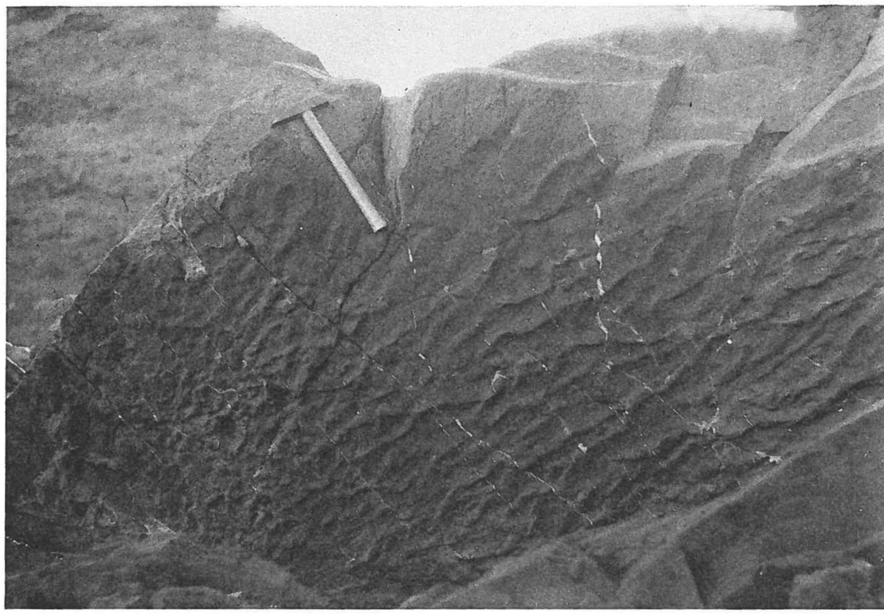

Plate 3. Welts. Vimmelskaftet Formation Red Siltstone Member, Canning Land.

Plate 4. A conglomerate unit overlying Devonian limestone. A scour approximately 10 cm deep in clearly seen. Ella Ø.

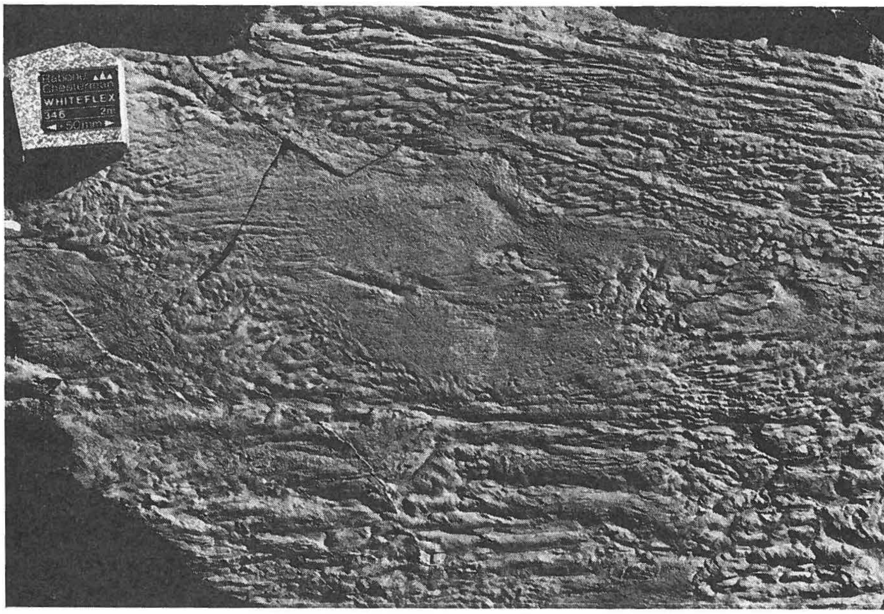

Plate 5. Squamiform scour marks, Rødedal Formation, Margrethedal.

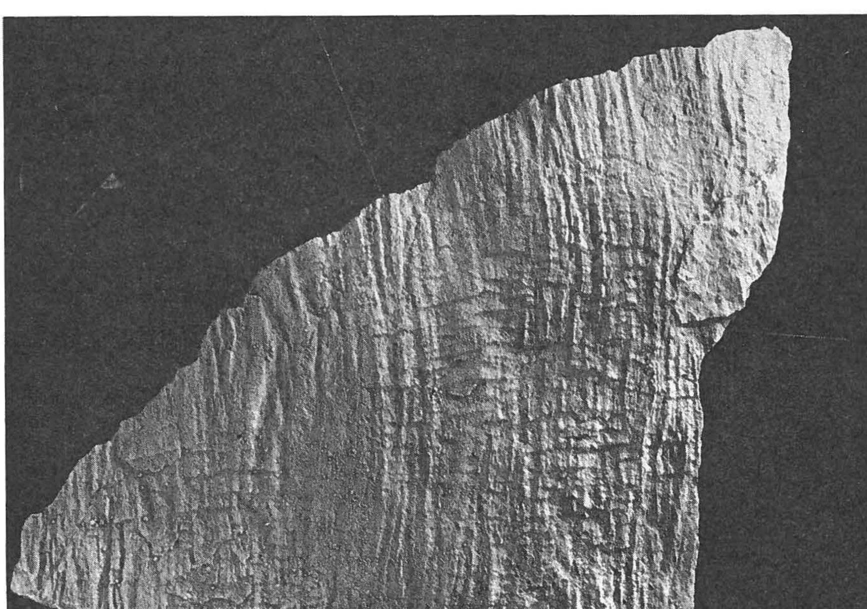

Plate 6. Shear wrinkles. Rødedal Formation, Margrethedal.

Plate 7. Groove casts. Vimmelskaftet Formation, Grey Sandstone Member, Canning Land.

Plate 8. Mudcracks. Vilddal Red-and-green banded Siltstone.

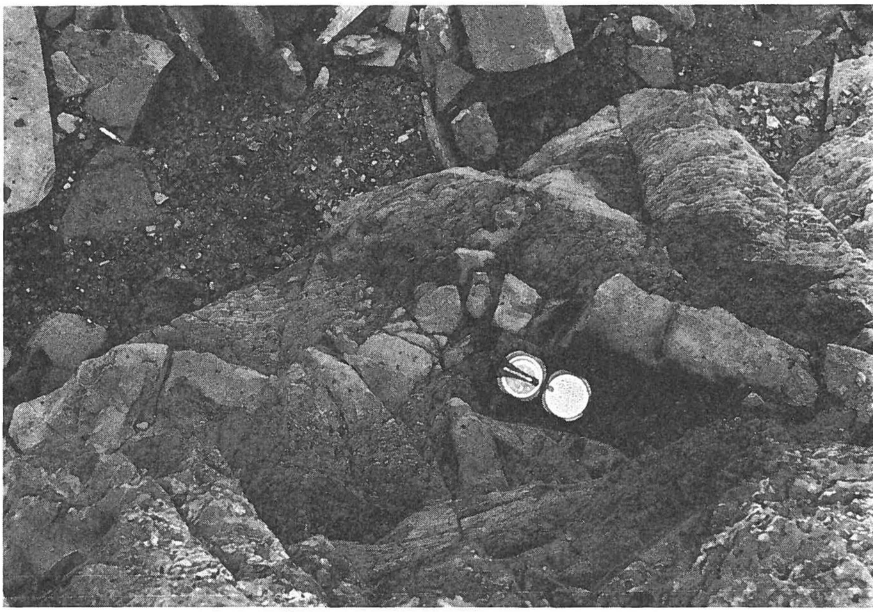

Plate 9. Sand crevices in plan view. Kap Franklin Formation, Østreplateau Grey Sandstone Member.

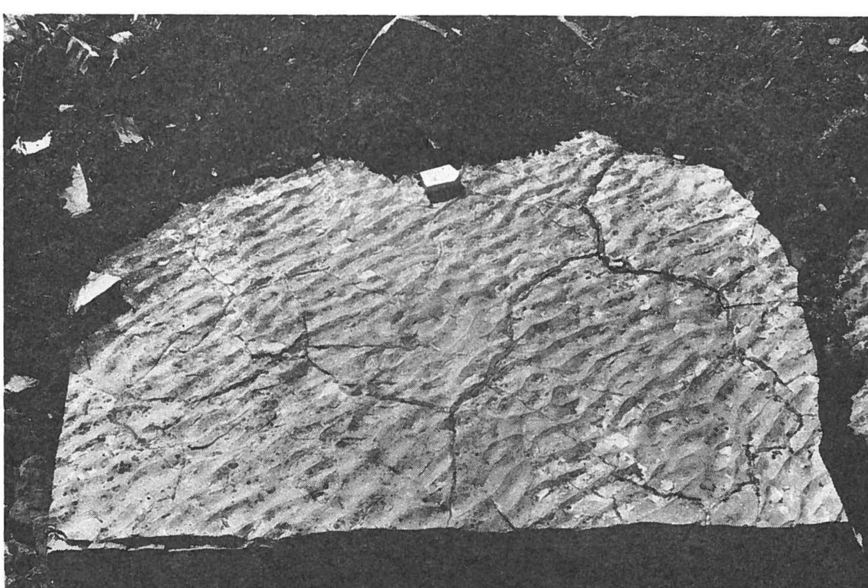

Plate 10. Narrow mudcracks. Vilddal Grey Siltstone.

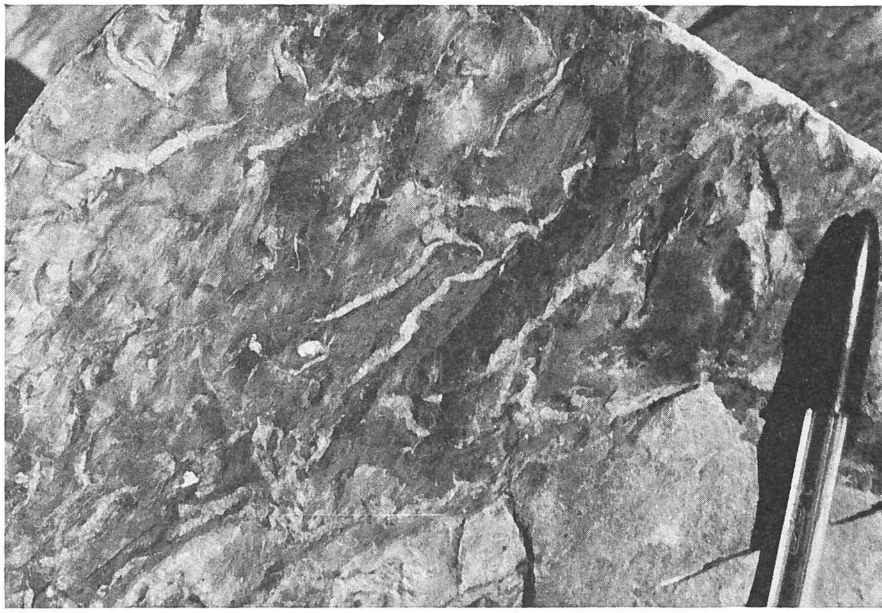

Plate 11. Crack-fill ridges, plan view. Karins Dal Grey Siltstone.

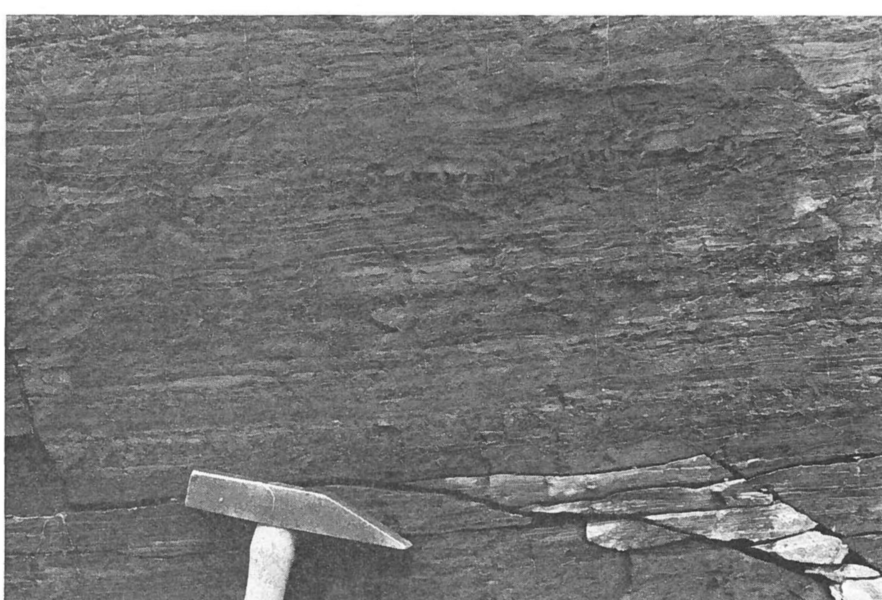

Plate 12. Crack-fill ridge lithology in section. Karins Dal Grey Siltstone.

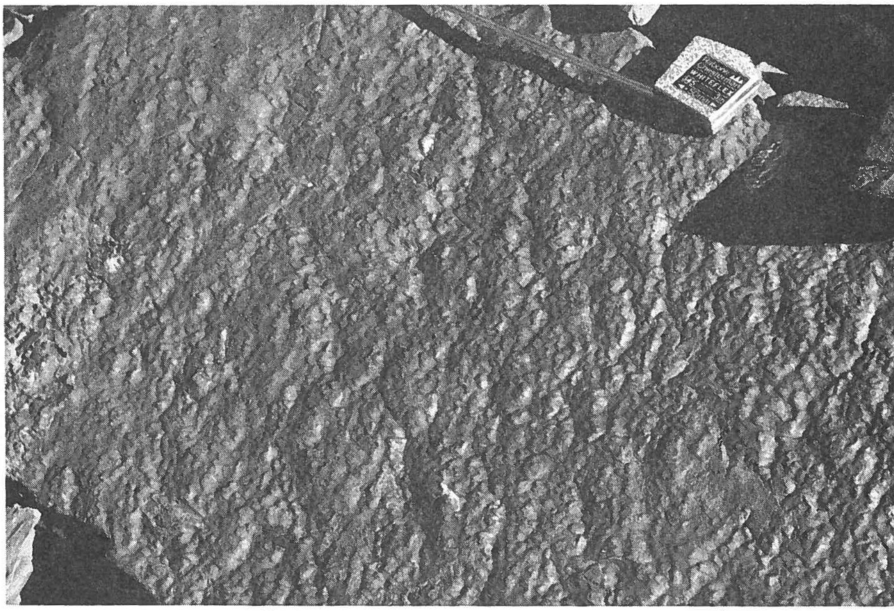

Plate 13. Dimple Structure. Vimmelskaftet Formation, Wegener Halvø.

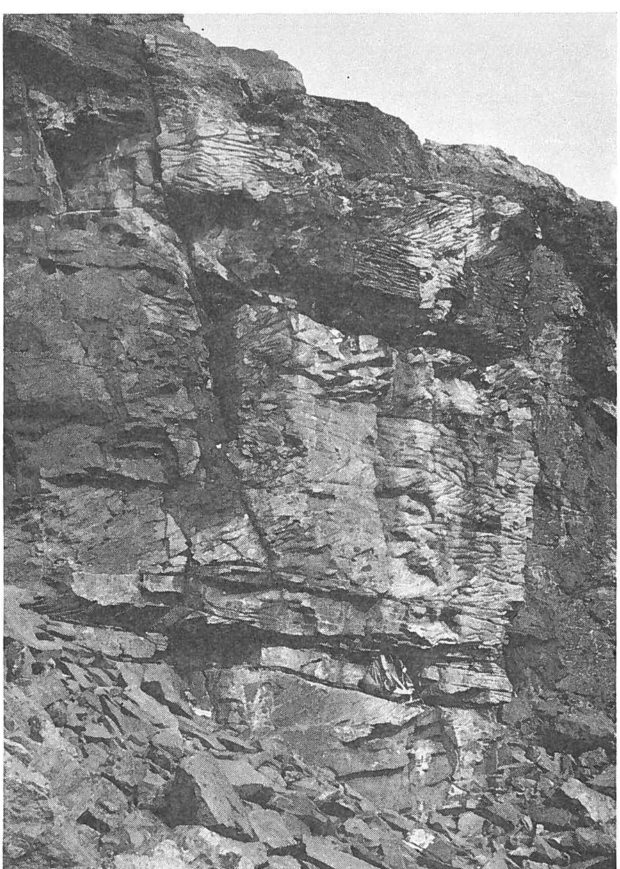

Plate 14. Type 1 (Planar) cross-stratification. Kap Franklin Formation, Saxos Bjerg Member, Kap Franklin.

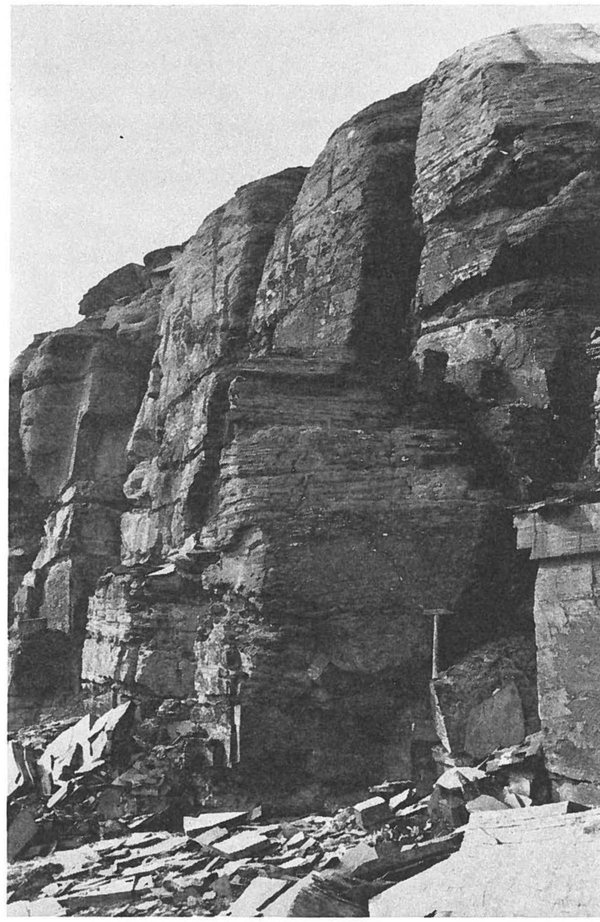

Plate 15. Type 3 cross-stratification and flat-bedded sandstone. Kap Franklin Formation, Østreplateau Grey Sandstone Member.

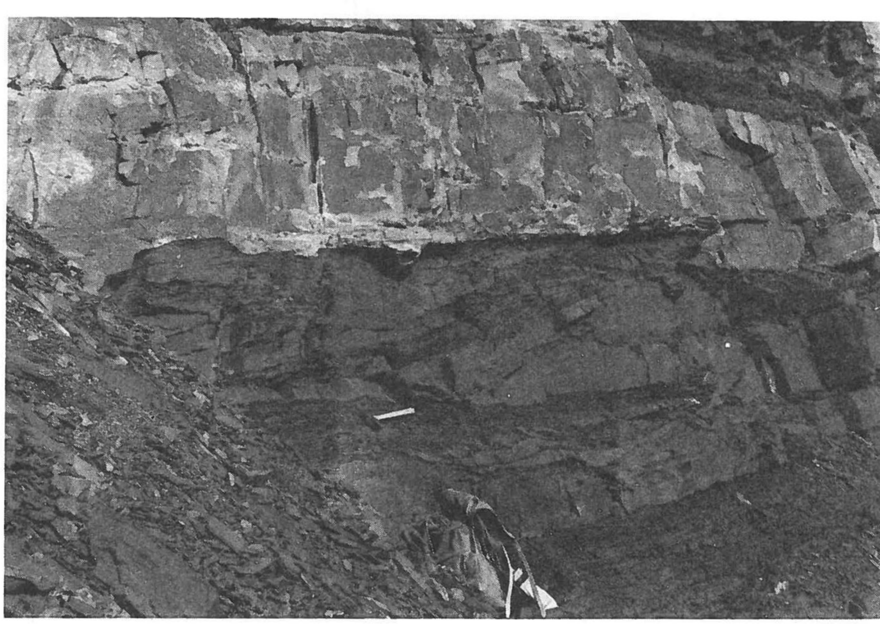

Plate 16. Type 4a cross-stratification in red very fine sandstones and siltstones. Vimmelskaftet Formation, Red Siltstone Member, Kap Brown.

Plate 17. Symmetrical Ripples with bifurcating crests. Karins Dal Grey Siltstone.

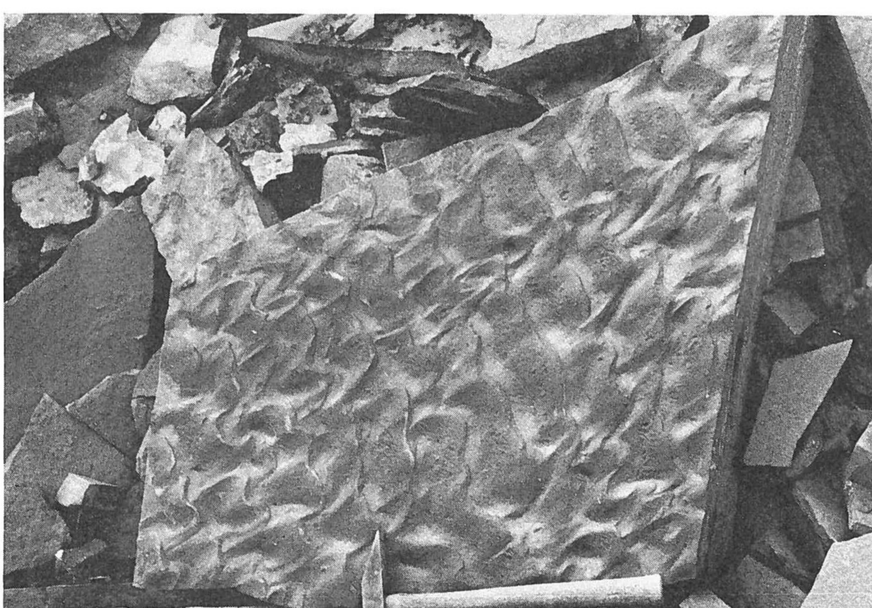

Plate 18. Linguoid ripple marks. Inderdalen Formation, Margrethedal.

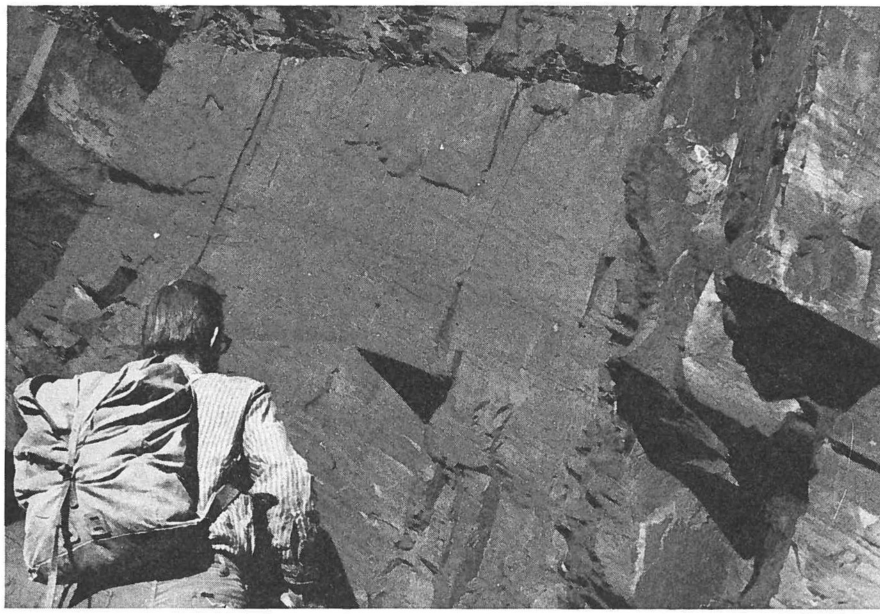

Plate 19. Several cosets with climbing ripple lamination. Vimmelskaftet Formation. Red-and-green banded Siltstone Member, Wegener Halvø.

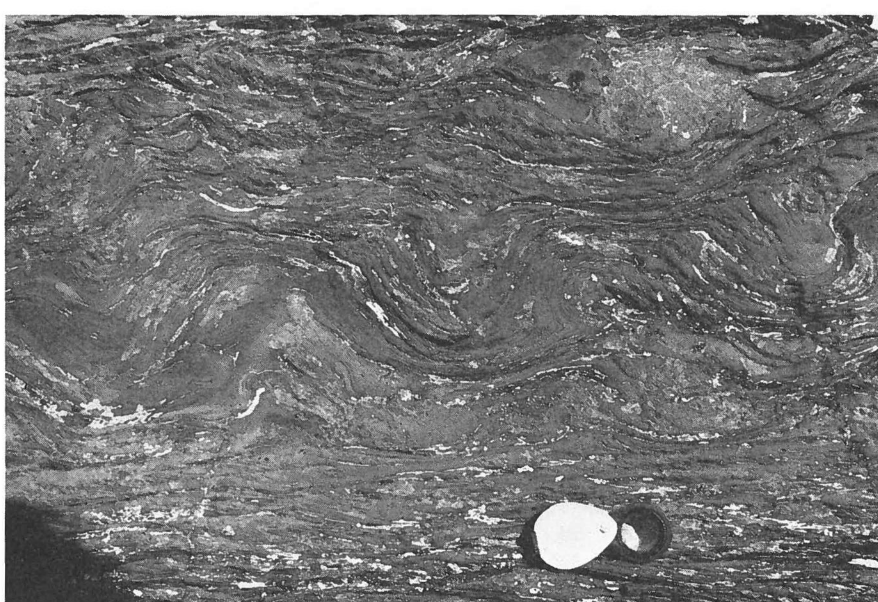

Plate 20. Convolute lamination. Vilddal Red-and-green banded Siltstone.

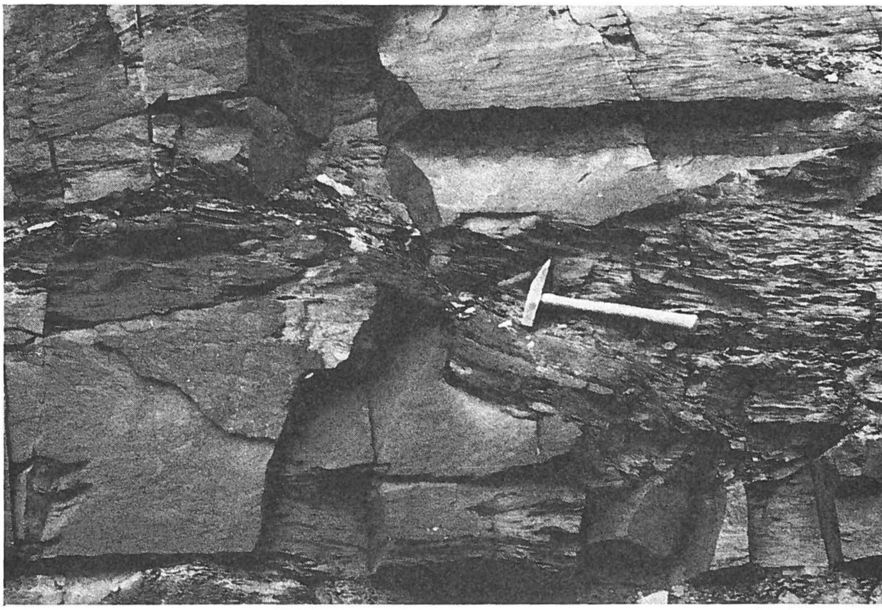

Plate 21. Bank-caving feature. Inderdalen Formation, Rødedal.

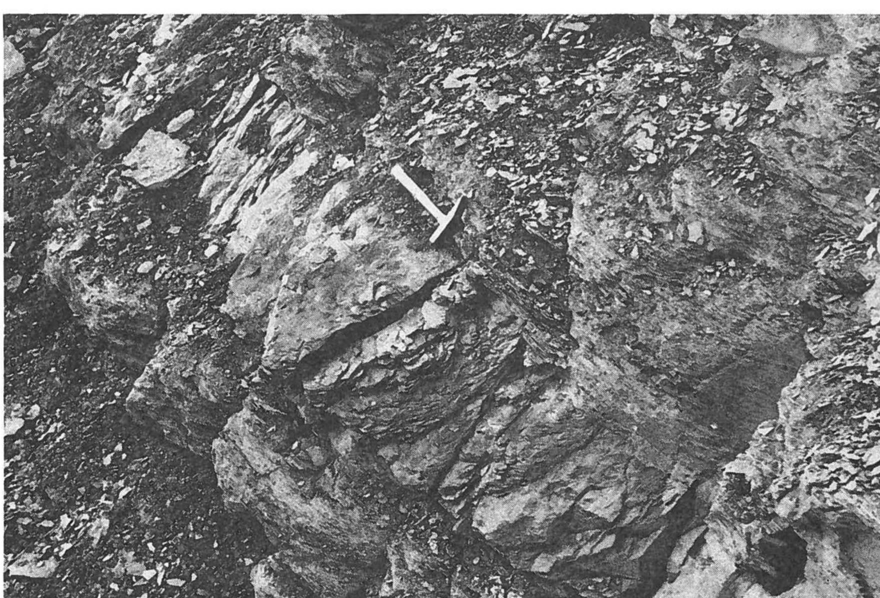

Plate 22. Tilted bedding in siltstone. Inderdalen Formation, Rødedal.

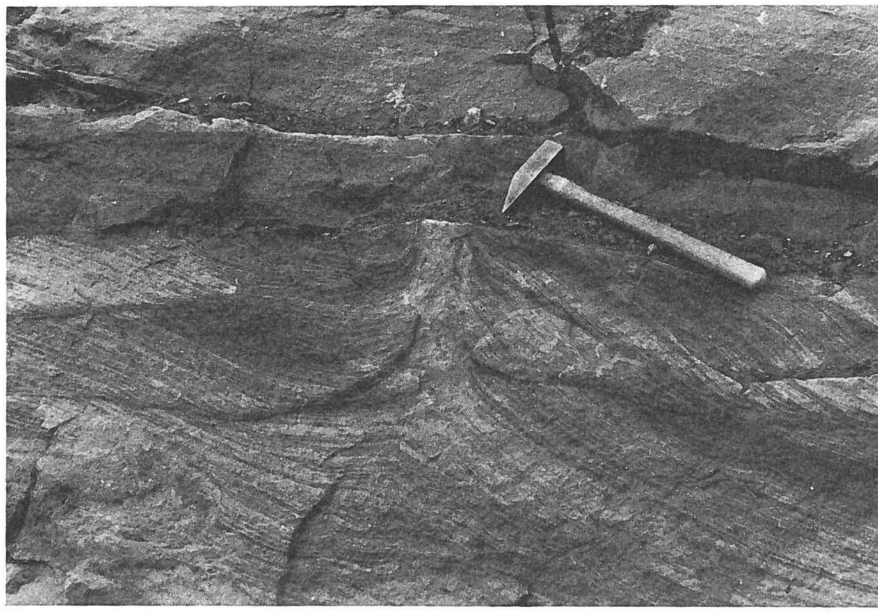

Plate 23. Deformation of overlying strata near edge of sediment-filled pipe. Kap Koltholf Supergroup. West of Zoologdalen.

Plate 24. Large-scale cross-strata, above and below 'jumbled' sequence of folded and fractured similar strata. Kap Koltkolf Supergroup. Jûluts Dal.

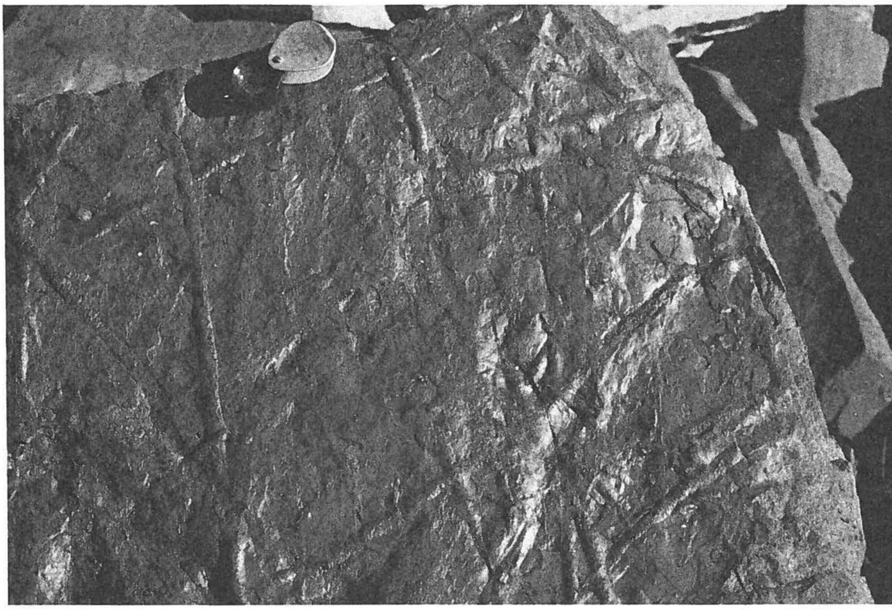

Plate 25. Large, meniscus-filled burrows. Vimmelskaftet Formation. Red-and-green banded Siltstone Member. Wegener Halvø.

Plate 26. 'Grooved Base' trace fossil. Inderdalen Formation, Inderdalen.

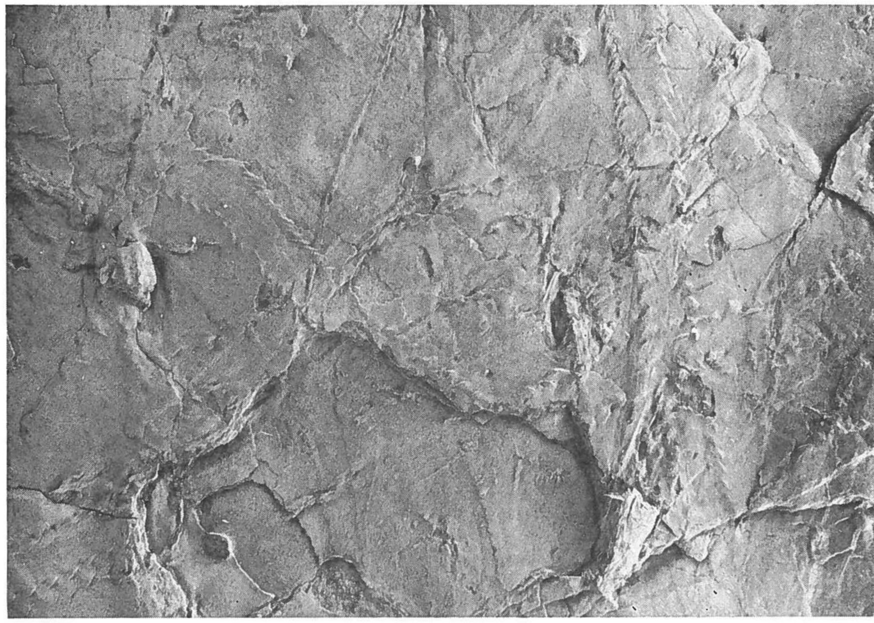

Plate 27. Arthropod tracks. Vimmelskaftet Formation, Red-and-green banded Siltstone Member, Kollen, Canning Land.

Plate 28. Two pairs of tracks on a bedding surface, Kap Graah Goup, near Kap Graah; see also Figs 34 and 35.