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FAN-DELTA SEDIMENTATION: AN EXAMPLE FROM THE LATE JURASSIC – EARLY CRETACEOUS OF MILNE LAND, CENTRAL EAST GREENLAND

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ABSTRACT

The Hartz Fjeld Formation (Middle Volgian – Ryazanian) is interpreted as a synorogenic fan-delta complex. The lower part of the formation is characterised by coarsening upwards fan-delta sequences with marine delta destructive units. A thick lagoonal unit separates these sequences from the upper part of the formation in which fan-delta deposition resumed in a lateral position and fan plain sands are intercalated within bay muds. A distinction is made between fan-delta deposition, dominated by sheetflood and streamflood processes, and short-headed stream delta deposition in which flow is confined in stable channels.

INTRODUCTION

The late Jurassic and early Cretaceous clastic sequence in Milne Land is located near the western edge of the central East Greenland Mesozoic basin (fig. 1). The sediments were first observed by Hartz (1896), and subsequently studied by Rosenkrantz (1929). Aldinger (1935) mapped the eastern part of the outcrop in detail and made the first sedimentological observations on the East Greenland Mesozoic. More recently the remaining outcrops have been mapped (Håkansson, Birkelund, Heinberg & Willumsen, 1971). In the summer of 1974 the present authors paid a short visit to the eastern part of the outcrop to study the sedimentology of the Hartz Fjeld Formation. The Hartz Fjeld Formation is the final unit of a late Jurassic basin fill. This succession resulted from increasing tectonic activity, and the formation may be regarded as a synorogenic phase of the Kimmerian orogeny, deposited simultaneously with coarse breccias of the Lindemans Bugt Formation in Wollaston Forland, north-east Greenland (Maync, 1947; Surlyk & Clemmensen, 1975).

STRATIGRAPHY

The lithostratigraphy of the Milne Land Mesozoic has not yet been formalised (Håkansson et al., 1971), although certain formation names used by Surlyk (in press) will be adopted here. The Hartz Fjeld Formation rests on the Kap Leslie Formation (= Glauconite Series of Håkansson et al., 1971), which consists of richly fossiliferous shelf siltstones and sandstones of Middle Volgian age (Callomon, 1961; Håkansson et al., 1971). On Kronen and at the north end of Hartz Fjeld, the basal Hartz Fjeld sandstone rests with erosional unconformity on fossiliferous glauconitic sandstones. Towards the south 30 m of shale with ammonites (Konkretionshorizont α^1 of Aldinger, 1935) is found above this unit, and the base of the Hartz Fjeld Formation is ill-defined, occurring within micaceous siltstones (see fig. 4).

Owing to the very sparse and poorly preserved ammonite fauna, the biostratigraphy of the Hartz Fjeld Formation is poorly known. We have informally divided the formation into a lower section (fig. 2) and an upper section (fig. 5), with 28 m of very poorly exposed shales separating them. Limited material collected by Aldinger (1935) and Donovan (1964) from the lower section includes *Laugeites groenlandicus* (Spath) from the *Lingula* Bed (unit 7). This indicates a Middle Volgian age (Håkansson et al., 1971; Surlyk, 1973). *Laugeites* has also been found, as high as unit 8, whilst 25 m higher at the base of unit 12, the occurrence of *Tollia groenlandica* (Spath) was interpreted by Donovan (1964) as indicating an Upper Ryazanian or Lower Valanginian age. This evidence suggests the presence of a disconformity at the Jurassic – Cretaceous boundary in the south. Further to the north the thicker, sandier succession may be more complete, but the absence of ammonites precludes any definite conclusions. The age of the central shale and the upper section remain unknown due to a complete lack of macrofauna. The Hartz Fjeld Formation is in part a correlative of the Raukelv Formation in southern Jameson Land – a similar succession of siltstones and mega crossbedded delta front sandstones transported by southerly or southeasterly flowing palaeocurrents (Surlyk, 1973; in press; Surlyk, Callomon, Bromley & Birkelund, 1973). However the considerable difficulty

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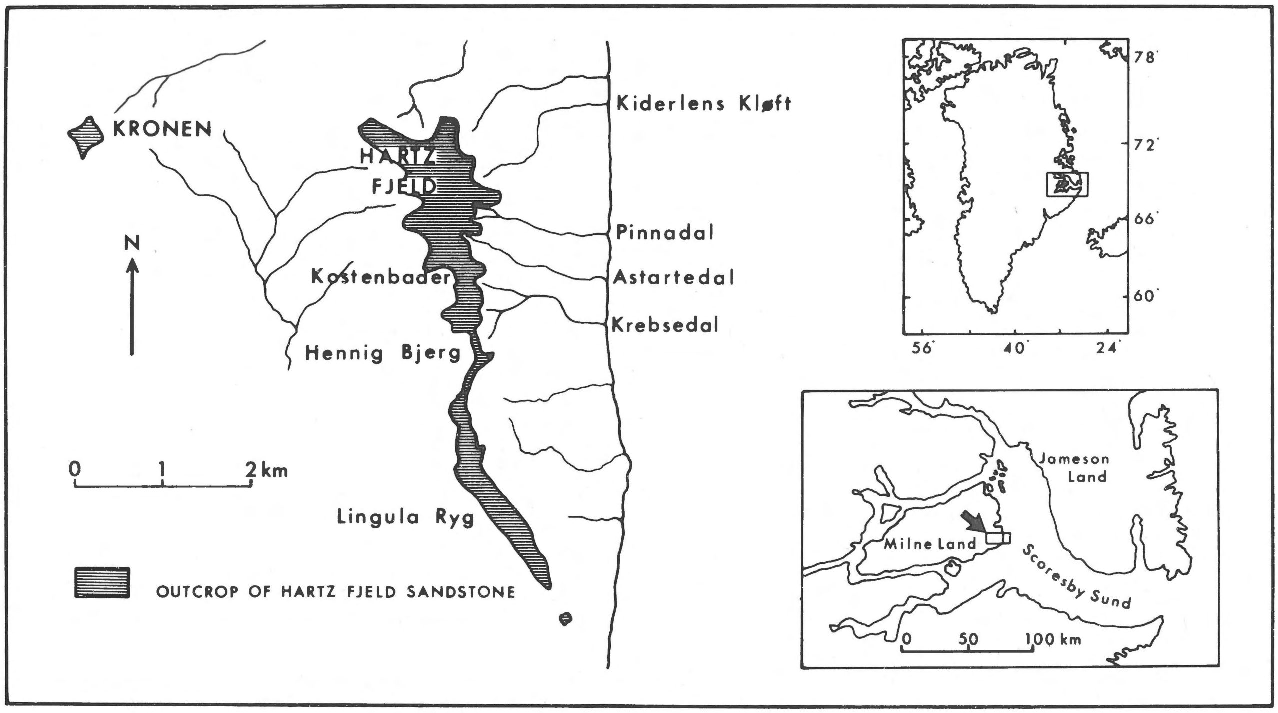

Fig. 1
Location and outcrop of the Hartz Fjeld Formation in Milne Land, central East Greenland (after Håkansson et. al. 1971).

in correlating between these two areas only 60 km apart attests to the marked tectonic activity in the Jameson Land basin at this time.

LOWER SECTION

A complete section through the Hartz Fjeld Formation was measured between Kiderlen Kløft and Pinna Dal where it totals 296 m in thickness (fig. 1). The lower section at this locality is 192 m thick and has been divided into 22 units (fig. 2). Four facies may be distinguished:

Facies 1: Reworked pebbly sandstone

Two end members may be differentiated:

Subfacies 1a is a thin-bedded, often highly ferruginous coarse-grained sandstone with pockets rich in mica, carbonaceous material or quartz pebbles. Logs and occasional rootlet horizons are also found.

Subfacies 1b is a medium to coarse-grained sandstone with a few glauconite and pebble rich lenses. It weathers to an irregular nodular texture, sometimes preserving *Thalassinoides* burrows infilled with finer grained sandstone and mudstone.

The thickness of facies 1 varies from 10 cm to 1 m.

Facies 2: Siltstones and fine-grained sandstones

Subfacies 2a: Micaceous siltstone. This facies is a predominantly shaly, micaceous siltstone which is often structureless except where mudstone and siltstone are found as discrete bands or lenses. On a small scale bedding appears to be parallel laminated, but in detail very low-angle (less than 5°) trough cross-bedding is developed with troughs up to 15 cm deep and less than 2 m across. Bioturbation has locally disturbed the mudstone – siltstone alternations and a few burrows of *Gyrochorte* were observed. Body fossils are generally absent, but where preserved indicate a fully marine environment with *Pleuromya* sp., other infaunal suspension feeding bivalves and occasional ammonites. Fossiliferous horizons were noted by the present authors at the base of unit 7 which is equivalent to Aldinger's (1935) *Lingula* Bed. However the true *Lingula* Bed to the south of Hartz Fjeld is a fine to medium-grained sandstone and does not belong in this facies. Also the base of unit 8 is a condensed glauconitic horizon which yielded *Buchia fisheriana* (d'Orbigny) (identified by Mr. S.R.A. Kelly) and a fragmentary *Laugeites* sp.

Subfacies 2b: Low-angle cross-bedded sandstone. Occurring with a sharpbased, erosive contact, are further very low-angle (less than 5°) cross-bedded sandstones forming cosets up to 1 m thick. The lithology is distinctive in that it contains little mica and silt within the well sorted fine to medium-grained sandstone. The scale of the cross-bedding is smaller than in subfacies 2a with troughs up to 1 m across and foreset angles between 5° and 10°, although definite bands of interbedded parallel laminated sandstone also occur. There are no biogenic structures.

Facies 3: Medium-grained sandstones

Subfacies 3a: Homogeneous sandstone. This facies covers sandstones which gradationally coarsen upwards from siltstone to medium-grained sandstone over a thickness of several metres. Mica content is variable, being most abundant towards the base which may be gradational with subfacies 2a. The apparently massive nature of this subfacies is a field characteristic, although there may be faint indications of micro cross-lamination and tabular cross-sets up to 15 cm high. Carbonaceous material is commonly dispersed within the sandstone as irregular wisps and indeterminate burrow-like forms. Since this was only a reconnaisance study, detailed petrographic work has not been undertaken. However in general the sandstones are strongly quartzose and moderately to well sorted.

Subfacies 3b: Mud-based trough cross-bedded sandstone. This subfacies varies in grain size from fine to medium sandstone and is cross-bedded in troughs and scours up to 1 m across which commonly show laminated carbonaceous mudstone at the base. This mudstone also defines small slump and load structures as well as indeterminate burrow forms.

Subfacies 3c: Pebbly trough cross-bedded sandstone. The scale of the trough cross-bedding is larger than in subfacies 3b, with some troughs up to 1.5 m across and 0.3 m deep. The principal difference is that pebbly lags characterise the base of many troughs and form small-scale fining upwards set units. Sideritic concretions and discontinuous mudstone bands also occur, and vertical *Planolites*-like burrows are locally common.

Subfacies 3d: Large-scale tabular cross-bedded sandstone. Within units 1, 2 and 16 are fine to medium grained sandstones occurring in tabular cross-sets from 1-10 m in height. The foresets are usually planar or slightly concave in cross section and are asymptotically based with dips up to 21°. Individual foresets are up to 30 cm thick and are defined by laminae rich in mica and carbonaceous material. Internally they may be graded or inversely graded and show small-scale trough and scour intrasets. Bioturbation is locally visible, whilst at the northern end of Hartz Fjeld, roots descend from many foresets.

Facies 4: Pebbly sandstone

At the top of most of the 22 units of the lower section is a rather massive pebbly sandstone or conglomerate. Small-scale trough cross-bedding overlain by parallel lamination was found in several cases. Sideritic mudflakes are occasionally present, whilst towards the top of this facies beds up to 0.5 m thick grade upwards from conglomerate to sandstone.

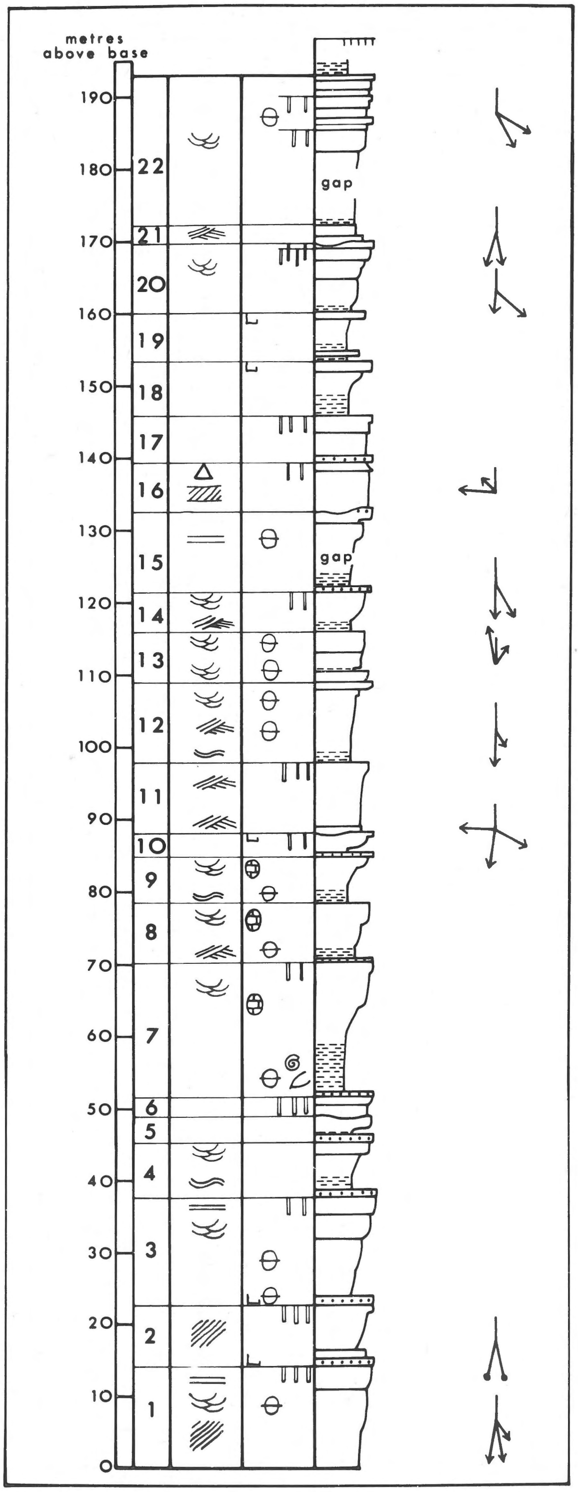

Fig.2
Lower section of the Hartz Fjeld Formation with palaeocurrent data (crossbed dips).

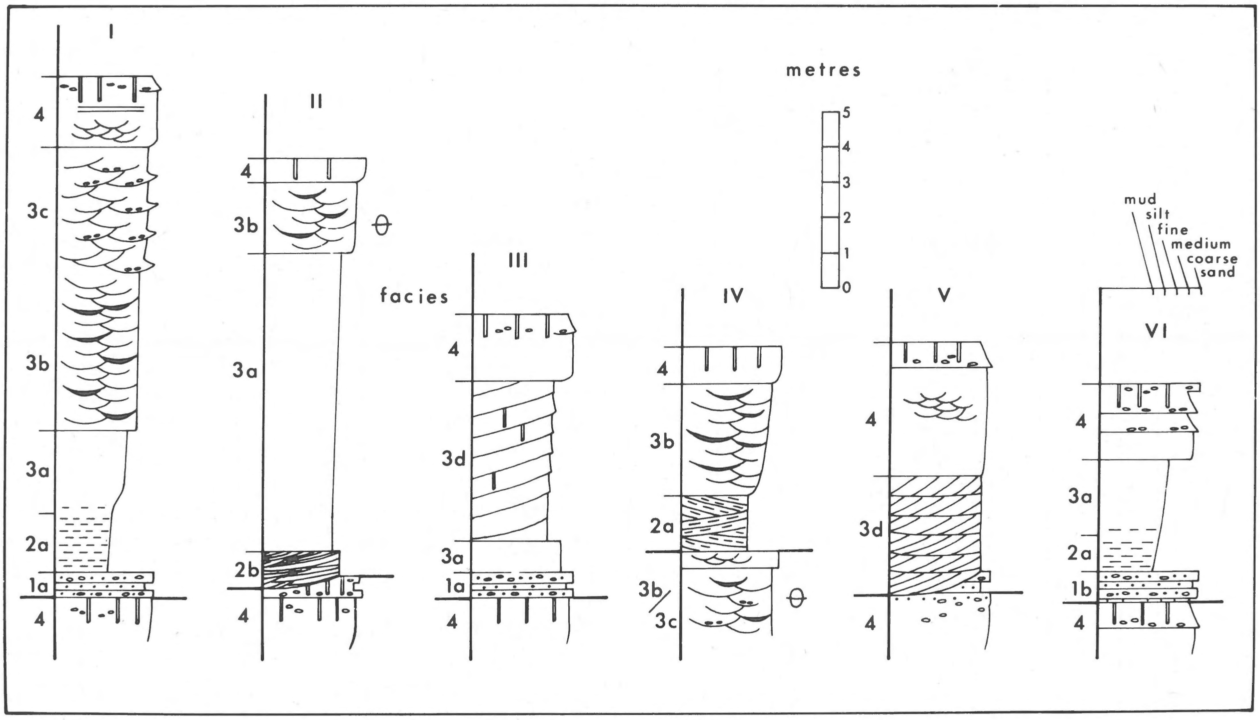

Fig. 3
Sequences illustrating the association of facies types in the lower section.

Roots characteristically descend up to 90 cm from the top surface, and these are later shown to be important in environmental interpretation. The thickness of facies 4 rarely exceeds 2 m.

Sequential arrangement

Fig. 3 shows the six most typical sequence types illustrating various facies associations. With only slight variations sequence type 1 characterises 11 out of the 22 units in the lower section. The only major divergence from these sequence types is unit 1 (fig. 4). The latter shows considerable variation both in its thickness, which decreases from 42 m at the northern end of Hartz Fjeld to less than 5 m south of Pinna Dal, and also in its internal morphology which becomes more complex towards the north. In the south the base of the unit is marked by continuing siltstone deposition, whilst only 2 km further north medium-grained sandstones of subfacies 3d show a sharp erosional base. Roots permeate many horizons within unit 1 in the northerly outcrops on Hartz Fjeld and Kronen, but are not present south of Pinna Dal (figs. 1 and 4).

Interpretation

As indicated by the occasional marine fossils and ubiquitous root marks, the lower part of the Hartz Fjeld Formation was deposited close to sea level. The coarsening upward nature of the sequences together with the strongly unidirectional southerly flowing palaeocurrents suggests some form of fluvially-dominated delta system.

However these sequences show several rather unusual aspects. Firstly, the upper part of the sequences consists of medium to coarse-grained or even conglomeratic sandstone. Secondly they average only 10 m in thickness and apart from unit 1 show a tabular geometry. Thirdly, no true channel sands with strongly down cutting basal contacts were seen. These observations suggest that the sand bodies were rather the product of braided river type deposition, yet the more shaly beds are frequently marine. Perhaps the most applicable model in this case is the fan-delta. The fan-delta concept was introduced by Holmes (1965) for alluvial fans which prograde directly into a standing body of water. This is a common feature in glaciated and mountainous areas, but he also illustrates the East and West Lyn rivers in south-west England building out a fan-delta into the sea. The most comprehensive picture of a fan-delta is presented by McGowen (1970) who describes the Gum Hollow fan-delta prograding out into the shallow lagoon of Nueces Bay, Texas.

In these examples the fan-deltas are supplied by short, high gradient streams with small drainage areas. These streams are able to transport bedload sand and gravel. Flow over the fan surface is unconfined giving rise to sheetflood

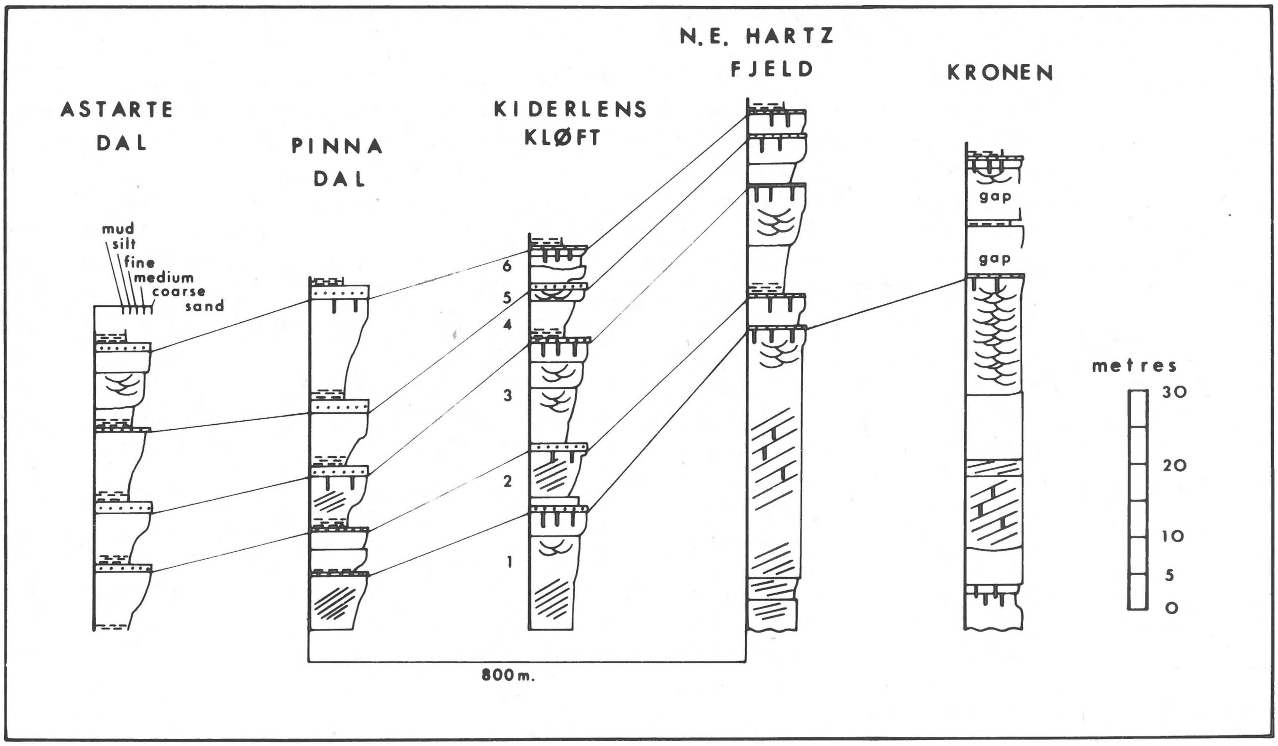

Fig. 4
Sections through units 1-6 of the Hartz Fjeld Formation, showing north-south lateral variation.

and streamflood processes rather than confined stream flow. Hence a network of regularly shifting braided streams traverses the fan plain. With the steep gradient the pro-delta slope is often steep giving rise to rapid lateral facies changes, limited progradation and hence repetitive, vertically stacked sequences. Lobate extensions of the fan-delta are built out during periods of heavy rain and subsequently abandoned, whereupon marine reworking and swash bar development may occur (McGowen, 1970).

In interpreting the lower part of the Hartz Fjeld Formation it is necessary to consider unit 1 separately. It rests on the richly fossiliferous glauconitic sands and siltstones of the Kap Leslie Formation which were laid down in an open marine inner shelf environment. In the north of the area (Hartz Fjeld, Kronen) thin homogeneous sandstones with rootlets mark the base of unit 1 and show an erosional contact. To the south these beds are overlapped by a 40 m wedge-shaped sand body which built out southwards with an upper surface gradient of 4-5°. Very large scale foresets up to 10 m high with rootlets are common in the lower part of the body, whilst trough cross-bedding is the dominant structure in the upper part. Similar sandstones have been interpreted as deltaic by McKenzie (1965) and Collinson (1968), but these are now considered to represent the deposits of large transverse bars similar to those described from the Brahmaputra River by Coleman (1969). Thus unit 1 seems to represent a thick series of fluvial channel bar sands which filled up the underlying shelf to near or slightly above sea-level, forming the framework for subsequent fan-delta development. Following unit 1 lateral variation in bed thickness became much less pronounced, although slightly thicker sequences with roots are found in the northern sections. The sequences appear as an alternating succession of dark shales and light sands which Aldinger (1935) argued could be generated by the migration of beach cusps, but many lines of evidence suggest the proximity of a fluvial supply system. In the common sequence type 1, facies 1 indicates shallow marine conditions whilst active progradation of the fan-delta commenced with facies 2 siltstones. Their presence between shallow marine delta destructive units and fan-delta plain deposits suggests that these siltstones were deposited in the pro-fan-delta environment. The presence of parallel and low-angle cross-lamination attests to the strong current velocities and therefore marked fluvial influence on this environment – a feature also emphasised by McGowen (1970).

Thereafter depositional energy levels increased slowly and a gradation is seen up unto the medium-grained sandstones of facies 3. Indications of strong current activity are first seen in subfacies 3b – however the currents were probably of short duration since the troughs and minor scours were often filled with laminated carbonaceous mudstone. In the Gum Hollow fan-delta dark grey mud forms 20% of the sediment in the braided fan plain channels. It accumulates both as a result of buoyant outflow in active channels and mud drapes in abandoned channels. Locally subfacies 3a and 3b become heavily bioturbated with some ripple cross-lamination. This probably reflects wind and tide reworking of abandoned channels in the distal fan area.

Following above subfacies 3b in sequence type 1 is the pebbly, trough cross-bedded sandstone (subfacies 3c) which shows indications of more continuous strong current activity with the trough-fills fining upwards from basal pebbly lags. The absence of mud laminae together with large quartz grains and mudflakes suggests deposition within the main active channel system of the fan-delta. The flat, laterally extensive form of the deposits and their character are both consistent with braided stream deposits; the lack of channel morphologies may be explained by shifting, unconfined flow on the fan plain.

At the top of nearly all sequences is a homogeneous, pebbly sandstone with roots (facies 4). The coarse-grained nature of this facies could indicate washing out of dunes under upper flow regime sheetflood conditions. At this point active sedimentation ceased and during the net rise in sea level *Equisetites* colonised the very shallow water on top of the former fan This change may have been due to subsidence of an abandoned fan-delta lobe, but the sheet-like geometry of the sequences and regional tectonic conditions suggest that rapid basinal subsidence was probably responsible. This fan-delta destructive phase culminated in the formation of the erosion surface separating facies 4 from facies 1 of the overlying sequence. This surface, which frequently shows a ferruginous crust could represent a soil level on top of the old fan-delta, but many equally indicate shoreface ravinement during transgression. Above it the conglomerates of facies 1 were formed during continuing delta destruction, with the low-angle cross-laminated sands of subfacies 2b representing local swash bar development as at Gum Hollow (McGowen, 1970).

It is probable that water depth rarely exceeded 10 m – i.e. the average thickness of the sequences less the subaerial relief of the fan plain (cf. Klein, 1974.

UPPER SECTION

Fig. 5 shows the top 11 units of the Hartz Fjeld Formation. Unit 23 is very poorly exposed and not shown in the log – only a few metres of carbonaceous, micaceous, silty mudstone with thin rippled sandstone bands were seen at the top, and these are referred to subfacies 2c (see below).

Subfacies 2c: Alternating shale and sandstone. This subfacies is one of alternating carbonaceous, micaceous mud-

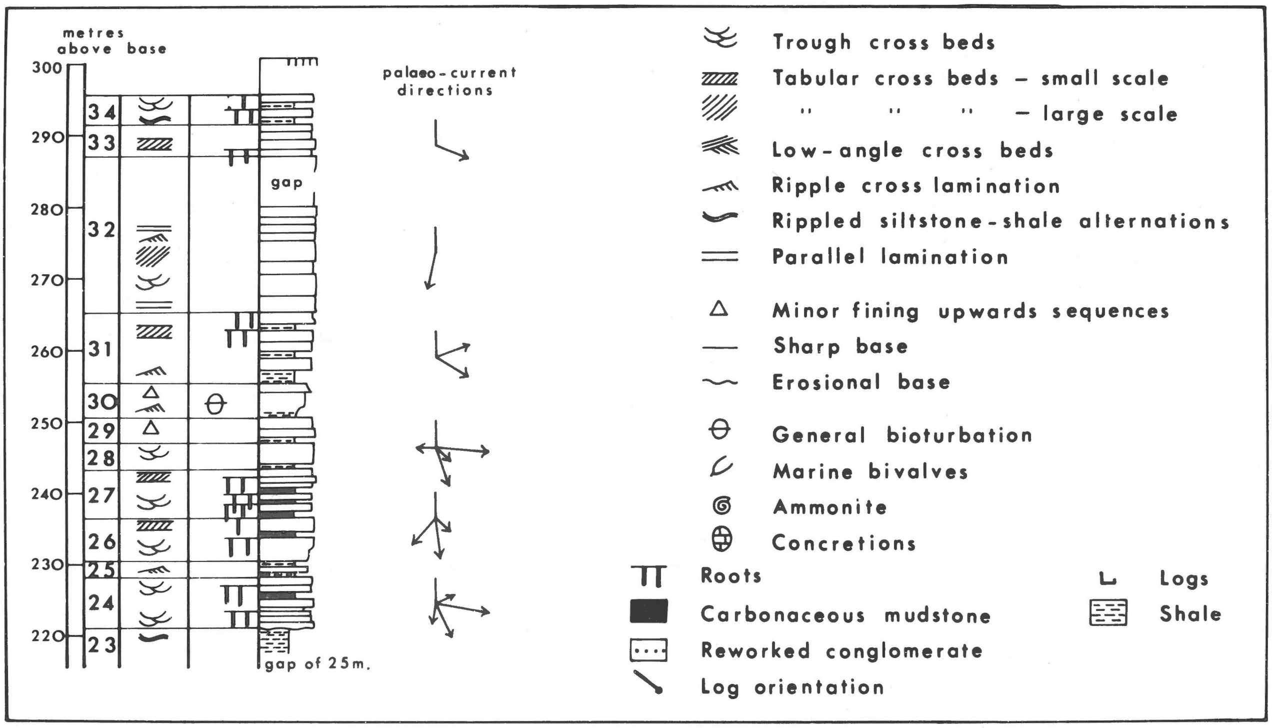

Fig. 5
Upper section of the Hartz Fjeld Formation with palaeocurrent data (crossbed dips).

stone and fine to medium-grained sandstones, showing a variety of lenticular, flaser and wavy bedding. More continuous sandstone bands up to 30 cm thick show wave rippled tops. The subfacies may be either mud or sand dominated.

Facies 5: Coarse-grained sandstones

Subfacies 5a: Thin sharp-based sandstones. Much of the upper section is typified by carbonaceous medium to coarse-grained sandstones with sharp bases and tops. Roots commonly descend from the top surface but may also be developed internally. The sandstones may be structureless or show small-scale tabular or trough cross-bedding. Carbonaceous mudstone and siltstone bands of subfacies 2c may be interbedded and show ripple cross-lamination.

Subfacies 5b: Thick coarsening upwards sandstones. Associated with and similar to subfacies 5a are sharp-based sandstones up to 4 m thick. They coarsen upwards from medium-grained trough cross-bedded sandstone to massive, coarse-grained sandstone with roots descending from the top surface. Thinner 2 m beds may comprise single tabular cross-sets with carbonaceous debris and roots occurring on low-angle foresets. In many respects this subfacies resembles the coarsening upwards sequences already described from the lower section.

Subfacies 5c: Coarse pebbly sandstones. Unit 32 of the upper section contains many sharp-based, very coarse-grained pebbly sandstones which are laterally extensive and vary in thickness from 0.5 to 3.5 m. Many of the sands are massive, but the thicker beds show parallel lamination with occasional small-scale tabular and trough cross-bedding. Root horizons are conspicuously absent.

Facies 6: Carbonaceous mudstones

Occurring with the coarse-grained sandstones of facies 5, and especially root horizons, are thin highly carbonaceous and pebbly siltstones.

Interpretation

Typical facies associations found in the upper section are shown in fig. 6. Following the lower section an important change occurred with deposition of the mudstone-dominated unit 23. The first sandstone with roots is developed only 1 m higher up. Only limited erosion seems to have occurred at the base of this sandstone, suggesting that at least the top of the mudstone was deposited in a very shallow water lagoon or bay.

The alternating mudstones and sandstones of subfacies 2c represent this lagoon/bay environment where a more extensive soft-bodied infauna was present, and sediment was transported in ripple trains by gentle wind, tide and wave currents. It should be noted that carbonaceous mudstones (facies 6) and root beds are absent in this subfacies. The upper section contrasts markedly with the lower section in that lithological junctions in the sandstone facies are sharp,

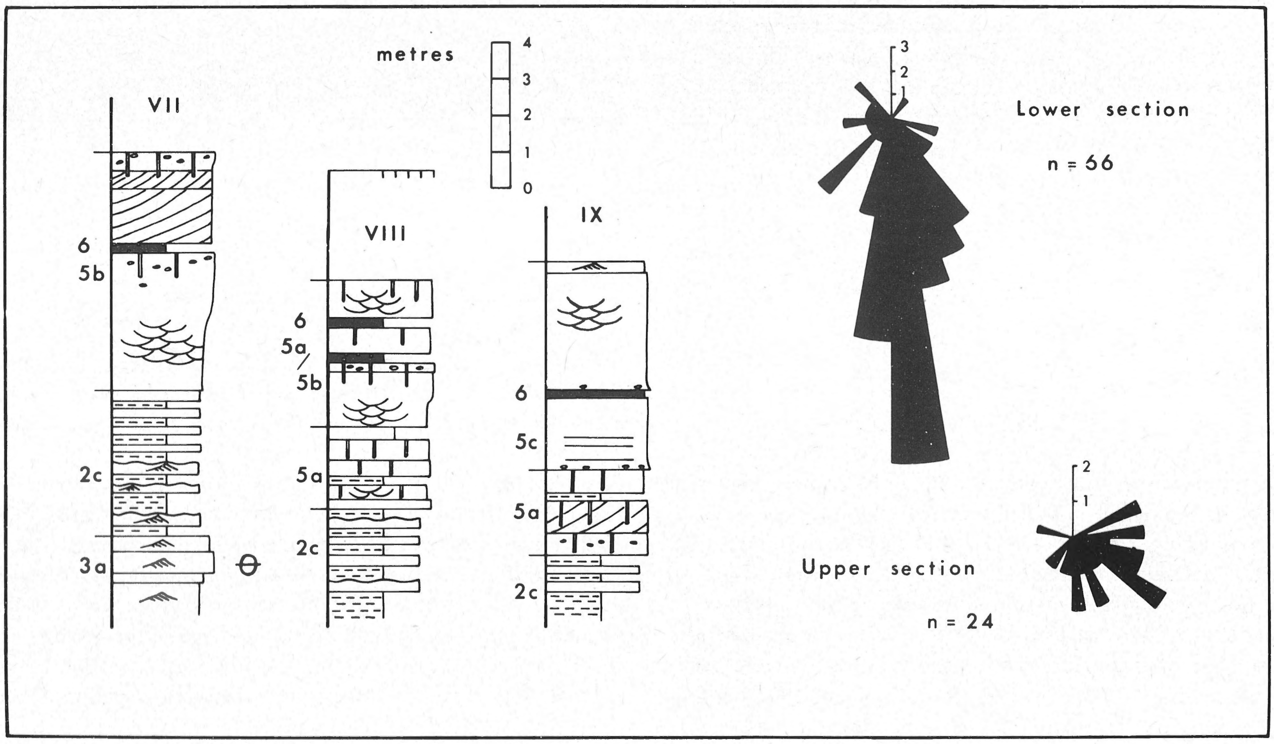

Fig. 6
Association of facies types in the upper section and summarised palaeocurrent data (crossbed dips).

and well defined sequences are not developed. The sharp-based sandstones with roots of subfacies 5a indicate single influxes of sand into very shallow water. Subfacies 5b represents more continuous deposition in a similar but more proximal environment. Subfacies 5c is limited to units 32-33, and the occurrence of parallel lamination in coarse-grained sands reflects deposition in the upper flow regime, possibly under sheetflood conditions. The carbonaceous mudstones of facies 6, which locally approach allochthonous coals, are associated with facies 5, but not with the interbedded shales and sandstones of subfacies 2c.

The broad facies association of the upper section reflects deposition away from the active fan-delta in a lagoon/bay area. However the sandstones of facies 5 still represent intercalations of fan-delta sediments. During flood conditions on a fan-delta flow is dominantly radial (McGowen, 1970, fig. 12B). Thus small individual lobes may build out laterally into the bay/lagoon only to be abandoned as soon as the flood subsides and unconfined radial flow is replaced by confined axial channel flow. Hence the thinnest sandstones of subfacies 5a may represent the most distal extension of such a lateral fan-delta lobe into a very shallow water lagoon. Abandonment and rapid subsidence of bay muds would allow the top surface to be quickly colonised by *Equisetites*. It is also possible that these thin sands may be crevasse splays off the main active channel system. The thicker trough cross-bedded sandstones of subfacies 5b are very similar to facies 4 in the lower section and equally may represent active channel areas of a lateral fan-delta lobe, i.e. in a more proximal position to subfacies 5a sands. It is suggested that the parallel-laminated coarse-grained sandstones of subfacies 5c may indicate the longitudinal bars in braided channels that are the dominant feature of Gum Hollow fan-delta (McGowen, 1970). The limited palaeocurrent date (fig. 6) suggests that the fan-delta may have been located slightly to the west of its earlier position, and that fan plain sands were transported laterally to the east and south-east into the bay.

DISCUSSION OF MODEL

Rifted continental margins frequently display coarsening upwards sequences in which very coarse-grained clastic facies overlay marine units. Active uplift in the source area provides heavy sediment discharge, whilst rapid, fault-controlled subsidence maintains marine conditions. In such a setting the fan-delta is an attractive model to explain such sequences. Although originally based on small features in tectonically stable areas (Holmes, 1965; McGowen, 1970), several authors have extrapolated the scale of the model and argued that thick sequences including pro-delta turbidites and mass flow deposits could also be generated (Brown, 1973; Surlyk, 1975). However the present authors feel that care should be taken to document sheetflood and streamflood processes operating in the fan plain and distal fan environments. The essentially alluvial fan nature of the sequence must be demonstrated. Other sand bodies, often formed under similar tectonic conditions, were formed by confined, channel flow processes not attributable to typical fan-delta deposition (Sykes, 1974). These latter sequences are better accommodated in the short headed stream delta model (Flores & Ferm, 1970; Flores, 1975) – they are basically normal deltaic sequences except that the steep pro-delta slope allows the generation of turbidites, whilst the high gradient supplying streams form coarse-grained delta plain facies. The difference between the two models is essentially one of hydrodynamic processes. In fan-delta deposition flow is unconfined and shallow braided channels shift across the fan surface; in short-headed stream deltas flow is confined within stable channels.

Perhaps some of the best Recent analogues to Hartz Fjeld deposition are to be found on the East Greenland coast. Braided river systems fill glaciated valleys and during spring torrential meltwaters generate widespread sheetflooding on small fan-deltas which build out into shallow, sheltered, virtually tideless seas. In particular Ryders Elv, flowing south down Klitdal to the head of Hurry Inlet in southern Jameson Land is a fine example worthy of detailed investigation.

CONCLUSIONS

1. The following sequence of events has been deduced during Hartz Fjeld Formation times (approximately Middle Volgian – Ryazanian):

a. The inner shelf environment of the underlying Kap Leslie Formation was filled by deposition of large scale fluvial bar sands in a southerly flowing channel (unit 1 of the lower section).

b. This sand body built the shelf up to sea level in the northern part of the outcrop to form the framework for a fan-delta depositional system. Coarsening upwards fan-delta sequences capped by roots were generated in the north where an alluvial fan prograded southwards into a shallow, sheltered sea.

c. In the middle of the formation enclosed bay or lagoonal conditions were established over the whole area.

d. Fan-delta deposition recommenced slightly to the west of its previous position. Radial transport on the fan surface during floods resulted in lateral transport of fan-delta sands which were intercalated within the bay/lagoon succession.

2. In coarse-grained "deltaic" sandstones, sheetflood and streamflood processes distinguish fan-delta deposits from those of short-headed stream deltas.

3. Possible analogues to Hartz Fjeld fan-delta deposition exist on the present day East Greenland coast and should be investigated.

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