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Triassic rift sedimentation and palaeogeography of central East Greenland

by

Lars B. Clemmensen

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Abstract

The majority of the investigated Triassic (upper(?) Scythian – Rhaetian) rocks apparently formed in continental environments comprising alluvial fans, braided rivers, aeolian deserts, flood plains, saline playa lakes and freshwater shallow lakes. In the Middle Triassic a brief but widespread marine transgression affected large parts of the basin and resulted in the deposition of barrier limestones and lagoonal mudstones. Details of sedimentary structures, bed types, facies sequences and vertical and lateral variations are discussed for each of these environments. Special emphasis is given to the remarkable variety of lacustrine facies associations.

The Triassic sediments probably accumulated in a N-S trending rift valley. This fault controlled depositional basin apparently formed in connection with overall rifting of the 'Laurasian' megacontinent. Tectonic movements along N-S trending fault lines appear to have been an important control on the thickness and nature of the Triassic facies, and the basal alluvial fan sediments formed simultaneously with or slightly after tectonic uplift of the borderlands.

The climate throughout the Middle-Late Triassic period was warm and subtropical with alternating dry and wet seasons. The basin was under the influence of dominant north-east trade winds (winter) and less common south-east trade winds (summer). The vertical succession of climate-sensitive rocks further suggests a gradual shift towards increased humidity during the Middle-Late Triassic times. This climate trend is explained by a northwards continental drift of the area.

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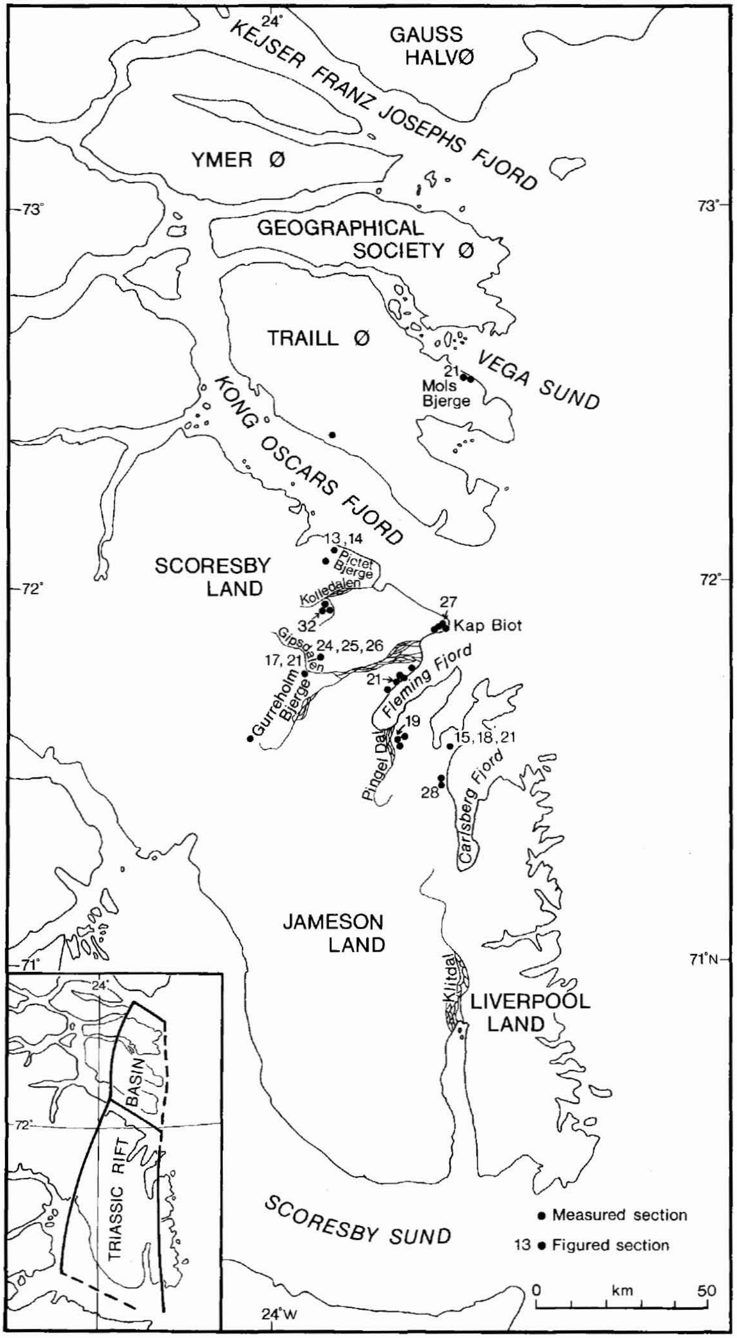


Fig. 1. The investigated area in East Greenland with inset showing the approximate maximum size of the Triassic rift basin, which is divided into a southern (Jameson Land Basin) and a northern basin by the cross fault in Kong Oscars Fjord.

INTRODUCTION

The sedimentary facies, facies associations and depositional environments of the mainly continental Scythian–Rhaetian (Triassic) rift sediments of central East Greenland (fig. 1) form the subject of this paper. The Triassic sediments are very well exposed and offer an excellent opportunity to study lateral and vertical facies trends. The sedimentological field-work was carried out in 1975 and 1976 as a continuation of earlier stratigraphical studies by Perch-Nielsen *et al.* (1974).

The Triassic sediments were deposited in a N–S trending rift valley occasionally transgressed by the sea. Strong rifting and deposition of syntectonic fluvial conglomerates took place in the Early and Late Triassic. The effects of these early rifting pulses have also been documented in North-Western Europe (Ziegler, 1978), and the rifting can be linked with the incipient break-up of the Triassic megacontinent in the North Atlantic region.

PREVIOUS INVESTIGATIONS

The Triassic sediments in the area were first described in 1900 by O. Nordenskjöld and N. Hartz (see Nordenskjöld, 1909). Since then many authors have added to the knowledge of the Triassic sediments in the area. Previous work has been summarized e.g. by Noe-Nygaard (1934), Putallaz (1961), Grasmück & Trümpy (1969) and Perch-Nielsen *et al.* (1974) and will not be repeated here. Only papers that have contributed significantly to the understanding of the Triassic environments of deposition are mentioned.

Stauber (1942) made a comprehensive study of the Triassic rocks between Scoresby Sund and Kejser Franz Josephs Fjord, and he divided the Triassic into a basal marine unit, a middle continental unit and an overlying brackish-marine unit. Stauber gave a very detailed description of the lithology and many of the sedimentary structures of the sediments involved.

Grasmück & Trümpy (1969) gave an excellent description of the Triassic rocks around Fleming Fjord and subdivided the sediments into a basal marine formation, a middle continental formation with marine incursions, and an overlying marine formation.

Perch-Nielsen *et al.* (1972, 1974) erected a formal lithostratigraphy for the Triassic sediments in central East Greenland and described some of the characteristic sedimentary structures. The interpretations of Perch-Nielsen *et al.* (1972,

1974) of the Triassic sedimentary environments are in close agreement with the views of Stauber (1942) and Grasmück & Trümpy (1969).

The rocks discussed in the present paper correspond to the Pingo Dal, Gipsdalen and Fleming Fjord Formations of upper (?) Scythian – Rhaetian age of Perch-Nielsen *et al.* (1974). Some of the results obtained during the present investigation of the sedimentary facies, environments of deposition and stratigraphy of upper Lower – Upper Triassic and overlying Rhaetian – Liassic sediments have been published by Clemmensen (1976, 1977, 1978a, b, 1979) and Clemmensen & Andreasen (1976).

GEOLOGICAL SETTING

According to Vischer (1943) and Haller (1971) the continental margin of central East Greenland was strongly faulted along tectonic lineaments trending roughly N–S in Post-Devonian times. During the Carboniferous and the Early Permian coarse clastic material was repeatedly transported into the continental basin after tectonic uplift (Perch-Nielsen *et al.*, 1972). In the Late Permian, shallow marine conditions were established and continued until the Early Triassic (late (?) Scythian) when coarse-grained continental sediments again were transported into the basin after renewed upheaval of the borderlands. After deposition of relatively fine-grained continental and subordinate marine sediments in Middle and early Late Triassic times, coarse-grained continental sediments were once more shed into the basin towards the end of the Triassic mainly from a western source area. After a short period of non-deposition in Early Rhaetian (Perch-Nielsen *et al.*, 1974) the continental red-beds disappeared and the Scoresby Land area came under the gradual influence of a Rhaetian–Liassic transgression (see Clemmensen, 1976).

Sediments of the upper Lower – Upper Triassic Pingo Dal, Gipsdalen and Fleming Fjord Formations crop out between Scoresby Sund (lat. 70°25′) and Vega Sund (lat. 72°35′). The Triassic rocks on Geographical Society Ø have not been studied by the author but according to the descriptions of Stauber (1942) and Donovan (1953) these rocks probably mainly belong to the Lower Triassic Wordie Creek Formation. The area in question is naturally divided by the Kong Oscars Fjord into: (1) a southern area with Jameson Land and Scoresby Land (named the Jameson Land Basin) where the Triassic sequence is completely developed and very well exposed, and overlain by Rhaetian – Liassic sediments, and (2) a northern area with Traill Ø and Geographical Society Ø, where the Triassic is dominated by the Wordie Creek Formation, but where the Gipsdalen or parts of the Fleming Fjord Formations locally appear. In this northern area the Triassic rocks are overlain by the mainly Middle Jurassic Pelion Member.

There is evidence to suggest that Kejser Franz Josephs Fjord was the site of a major cross-fault in Early and Middle Jurassic (Surlyk, 1977) and it appears reasonable to conclude that the same was the case in late Early, Middle and Late Triassic times. If so, a large N–S trending tectonic basin is apparent, here named the Central East Greenland Basin, demarcated to the west by the post-Devonian fault lineaments (Vischer, 1943; Haller, 1971), to the north by the hypothetical cross-fault zone in Kejser Franz Josephs Fjord and to the east more or less by the Liverpool Land High (Surlyk, 1977; Clemmensen, 1978b) and its northward prolongation (fig. 1).

STRATIGRAPHICAL FRAMEWORK

The upper Lower to Upper Triassic sediments (Pingo Dal, Gipsdalen and Fleming Fjord Formations) of central East Greenland are composed of an up to *c.* 1200 m thick sequence of red, variegated or greyish conglomerates, sandstones, mudstones, evaporites and dolostones of continental origin associated with subordinate shallow-marine greyish calcarenites and black mudstones. The sediments in question overlie the wholly marine Wordie Creek Formation (fig. 2).

The recent field-work by the author in Jameson Land and Scoresby Land has made it desirable to introduce some changes in the stratigraphical scheme of Perch-Nielsen *et al.* (1974). A revised stratigraphical scheme for the Triassic rocks in the Jameson Land Basin is accordingly presented in fig. 2 (see also Clemmensen, 1977); this scheme will serve as a base for the following discussion of Triassic sedimentary environments.

APPROXIMATE AGE	JAMESON LAND AND SCORESBY LAND					TRAILL Ø
	GROUP	SUBGROUP	FORMATION	MEMBER	BEDS	MEMBER
RHAETIAN / NORIAN?	Scoresby Land	Kap Biot	Fleming Fjord	Ørsted Dal	*Tait Bjerg	S Ørsted Dal N
CARNIAN?				Malmros Klint		S ?Malmros Klint N
LADINIAN?				Edderfugledal	*Pingel Dal *Sporfjeld	Edderfugledal
			▲ Gipsdalen	▲ Kap Seaforth		Kap Seaforth
ANISIAN?				*Kolledalen / ▲ Solfaldsdal	*Gråklint	*Vega Sund
SCYTHIAN U		Nordenskiöld Bjerg	▲ Pingo Dal	▲ Paradigmabjerg / Klitdal Rødstaken		Paradigmabjerg
SCYTHIAN L			Wordie Creek			*Ødepas *Svinhufvuds Bjerge

* New unit ▲ Redefined unit ☐ Undivided |||||| Hiatus

Fig. 2. Lithostratigraphical subdivision of the Triassic rocks in Jameson Land and Scoresby Land, and on Traill Ø.

Investigations on Traill Ø have resulted in the establishment of a new stratigraphic scheme for the Triassic on this island (Clemmensen, 1977). All four Triassic formations originally defined only within the Jameson Land Basin by Perch-Nielsen *et al.* (1974) have been recognized on Traill Ø and three new members are established (fig. 2). Formal designation of new or redefined members and formations in both areas will be presented elsewhere (Clemmensen, in prep.).

Fossils are very scarce within the upper three Triassic formations apart from the fossiliferous limestones in the Gipsdalen Formation (the Gråklint Beds, fig. 2) and the age of the formations can therefore only be established within very broad terms. Perch-Nielsen *et al.* (1974) suggest the Pingo Dal Formation to be of upper Scythian age, the Gipsdalen Formation to be of Anisian? Ladinian? age and the Fleming Fjord Formation to be of Ladinian? to Rhaetian age.

Stratigraphical correlations within the central East Greenland Basin are accordingly based on the presence of characteristic facies associations and lithological markers. The base of the brackish-marine Rhaetian–Liassic Kap Stewart Formation has here been selected as the best approximation to a time-marker and the stratigraphical correlations in figs 3 and 4 have been constructed on this assumption. The restricted marine Gråklint Beds, though possibly somewhat diachronous,

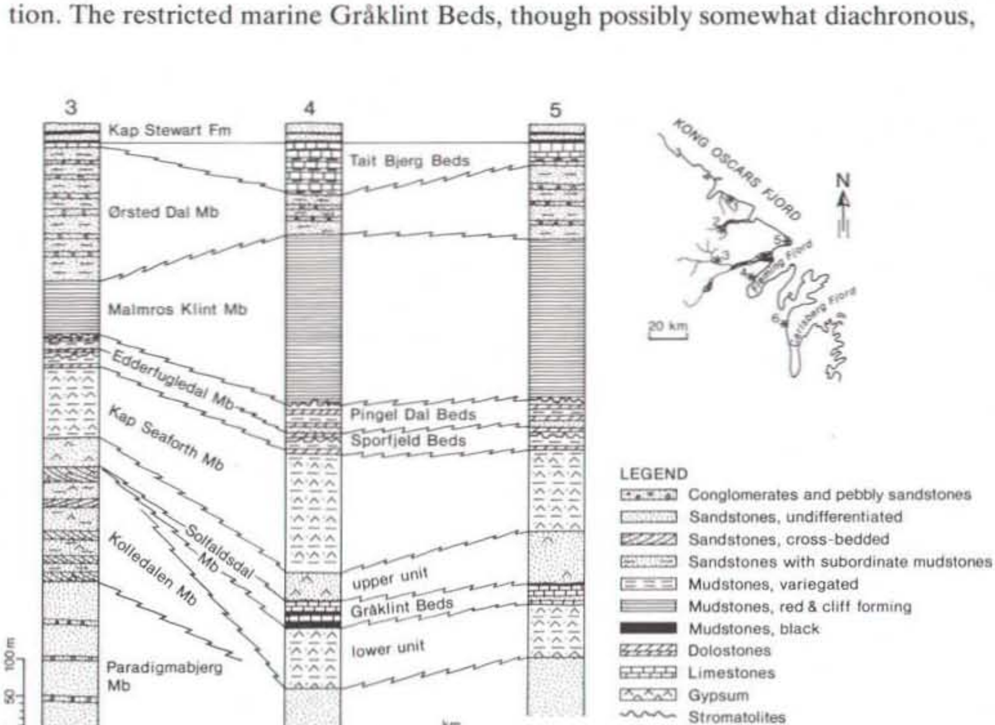


Fig. 3. Stratigraphic framework of Middle and Upper Triassic rocks in Scoresby Land and Jameson Land. The base of the Rhaetian–Liassic Kap Stewart Formation is used as a horizontal level in conformity with Audley-Charles' (1970) correlation of the Triassic in Britain.

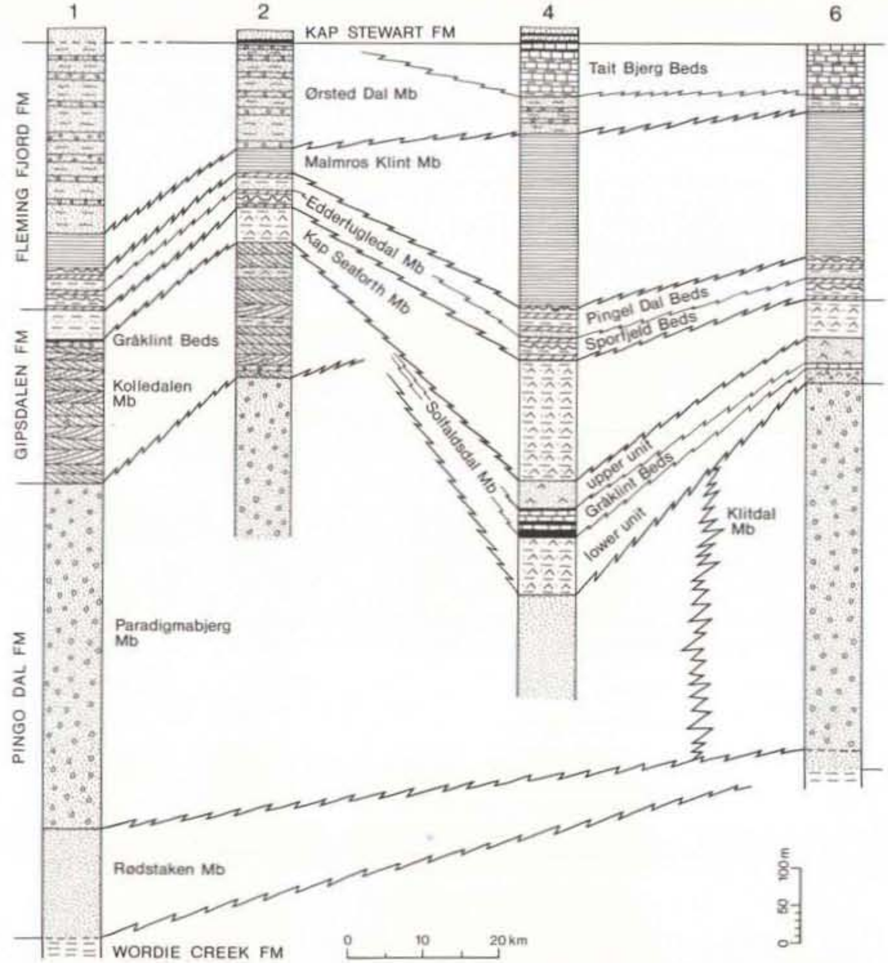


Fig. 4. Stratigraphic framework of Lower – Upper Triassic rocks in Scoresby Land and Jameson Land. The base of the Rhaetian–Liassic Kap Stewart Formation has been selected as a horizontal level. For explanation of sedimentary units and location of individual logs see fig. 3.

are an excellent field marker in large parts of the basin, and serve as the only sound correlation possibility within the Gipsdalen Formation (fig. 5).

SEDIMENTARY STRUCTURES AND DEPOSITIONAL PROCESSES

All the primary sedimentary structures encountered in the field have been recorded on graphic logs and classified according to the scheme in fig. 6. The classifi-

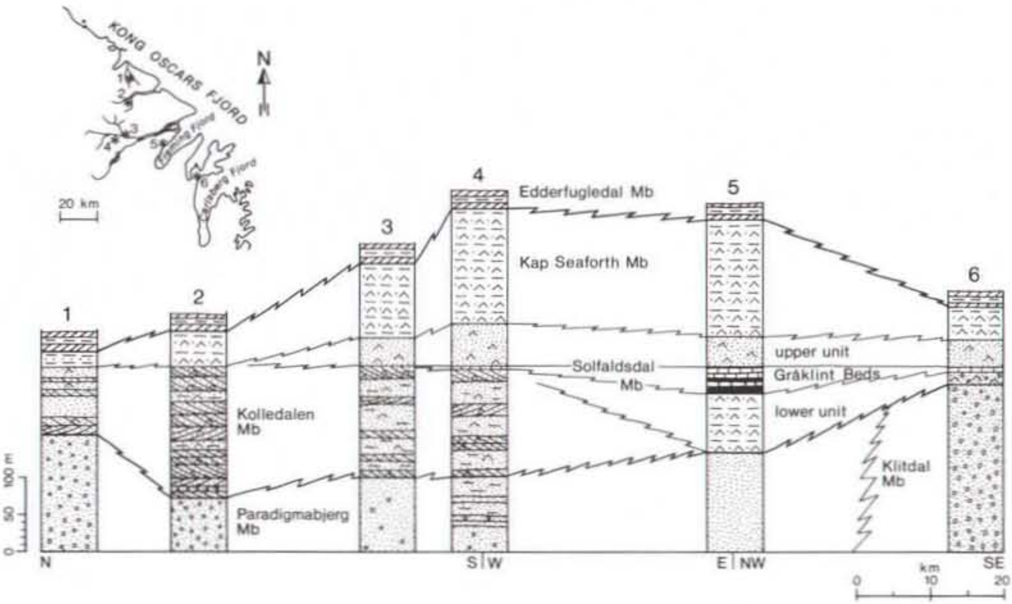


Fig. 5. Stratigraphic framework of the Middle Triassic Gipsdalen Formation in Scoresby Land and Jameson Land. The top of the Gråklint Beds has been used as a horizontal level. For explanation of sedimentary units see fig. 3.

cation of the sedimentary structures are in most respects in agreement with Reineck & Singh (1973). The only new term introduced here is undulatory lamination, which covers various structures in fine sand and silt consisting of straight laminae with a wavy or undulatory appearance.

In figs 7, 8, 9 examples of some of the most common and environmentally most significant Triassic structures are shown and interpreted in terms of depositional processes. Both wind, wave and current-formed structures occur.

The relationship between sedimentary structures and the energy level during deposition has been dealt with by various authors (e.g. Allen, 1970a). Here it is sufficient to state:

1. Low-energy wave-action creating wave ripple lamination is the most important depositional mechanism within the basin; high-energy wave-action played only a minor role.

2. Powerful river currents operating in both lower and upper flow regimes were active from time to time during the infill of the basin.

3. Strong winds affected the basin during several intervals in the Middle Triassic and heaped the sand into large dunes.

Fig. 6. Legend used in the field classification of the Triassic rocks. A few of the symbols (e.g. plant remains) do not occur in the logs figured here.

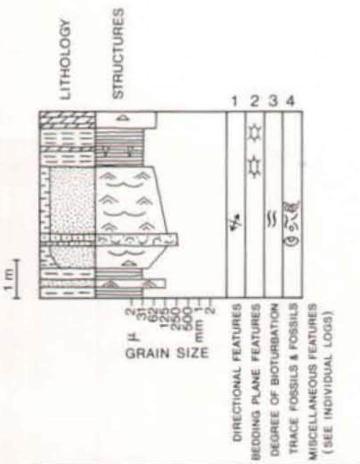
GUIDE TO READING OF SEDIMENTOLOGICAL LOGS

LITHOLOGY

- mudstone
- sandy mudstone
- interlaminated mudstone & sandstone
- sandstone
- muddy sandstone
- calcareous sandstone
- pebbly sandstone
- conglomerate
- dolomitic siltstone
- dolomitic sandstone
- limestone
- limestone, quartz-rich
- stromatolitic limestone
- oolitic limestone
- gypsum

1
- cross-lamination
- wave ripples, direction of oscillation
- cross-bedding
- imbrication
- strike of longitudinal cross-bedding
- stromatolite elongation
- *Rusophycus* orientation
- sole lineations

2
- polygonal desiccation cracks
- rocksalt pseudomorphs



3
- weakly bioturbated
- moderately bioturbated
- strongly bioturbated

4
- *Pelecypodichnus*
- *Rusophycus* = (*Cruziana*)
- *Cruziana* = (*Isopodichnus*)
- *Fuersichnus*
- small Fodinichnia & "worm trails"
- large feeding burrows, mainly *Steinichnus* & *Scoyenia*
- vertical tubes, mainly *Skolithos*
- escape structures
- conchostracans
- gastropods
- *Myalina*
- *Myophoria*
- ?*Anodontophora*
- vertebrate remains
- plant remains

STRUCTURES

Mudstones
- structureless
- horizontal lamination

Heteroliths
- lenticular lamination
- flaser lamination
- undulatory lamination

Sandstones
- structureless
- horizontal lamination
- wave ripple lamination
- current ripple lamination
- climbing ripple lamination
- adhesion ripple lamination
- planar cross-bedding
- trough cross-bedding
- longitudinal cross-bedding
- antidune cross-bedding
- undulatory lamination
- irregular lamination

Conglomerates
- structureless
- horizontal bedding
- imbrication
- cross-bedding

ADDITIONAL STRUCTURES

- convoluted bedding
- ?algal limestone lumps
- stromatoid clasts
- intraclasts
- edgewise breccia
- vertical cracks
- shell concentrations
- gypsum, dolomitic limestone nodules
- caliche horizon

FIELD EXAMPLE

PINGEL DAL BEDS
CARLSBERG FJORD

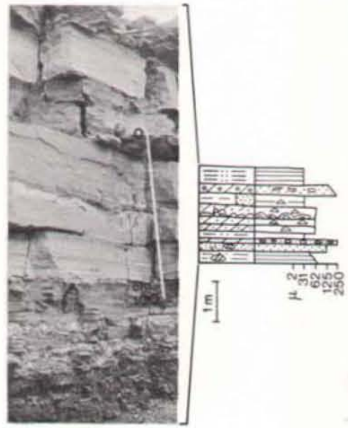
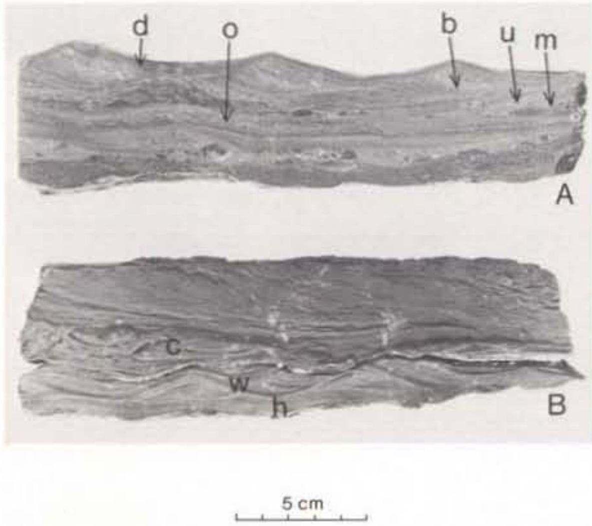


Fig. 7. Large-scale aeolian cross-bedding probably formed by migration of barchanoid dunes in two directions. The lowermost set (H = *c* 6 m) dips towards the north with a maximum inclination of *c* 35 degrees. Bounding surfaces and internal unconformities in the uppermost set are indicated. For scale see geologist at the left bottom. Kolledalen Member, Gurreholm Bjerge.

Fig. 8. Various units with pebble sandstone (s) and unsorted conglomerates (c) of stream flood origin. Note the cross-bedding in the sandstones formed by westward migrating fluvial sandbars and megaripples. Klitdal Member, northern Carlsberg Fjord.

Fig. 9. Sedimentary structures formed by wave action. A. Wave ripple lamination. Note the symmetrical form of the uppermost ripples and the characteristic features of the cross lamination such as: draping (d), bundled upbuilding of foresets (b), occurrence of undulating very low angle cross lamination (u), and local existence of opposed foresets (o). Small dark areas are probably mainly mud pebbles (m). B. Wave ripple lamination partly deformed by synsedimentary liquefaction in extreme cases forming well-developed convolute lamination (c). Note the bidirectional bundled upbuilding of the wave ripple laminae (w), the perfect symmetrical form of the ripples in question, and the occurrence of horizontal lamination (h). For diagnostic criteria of wave ripple lamination see also de Raaf *et al.* (1977). Malmros Klint Member, Carlsberg Fjord. Ripple height 1 cm.



A final very important feature obtained from the sedimentary structures is the direction of transport. The following results can be mentioned:

1. Apart from the Gråklint Beds all the current-formed structures have formed from unimodal flowing, mainly fluviatile currents (fig. 10). This means that there is no convincing evidence of tidal current transport of these sediments.
2. All the wind-formed dunes were probably formed during the interaction of two wind systems, a dominant north-eastern wind and a less frequent south-eastern wind (see Clemmensen, 1978a).
3. Measurements of wave ripple crests (fig. 11) suggest that most of the wave ripple crestlines were orientated perpendicular to the dominant wind direction(s).

The definition of sedimentary facies includes colour, lithology, grain size, sedimentary structures and palaeocurrents, chemical properties, trace and body fossils. In the Triassic sequences studied the number of facies is immense. Even if one excludes colour (which is a highly variable and very significant feature in the field) as well as type and degree of bioturbation and use crude grain size limits 52 facies are distinguished (fig. 12). Crucial or environmentally significant facies or small-scale facies sequences are treated in the description of the facies associations.

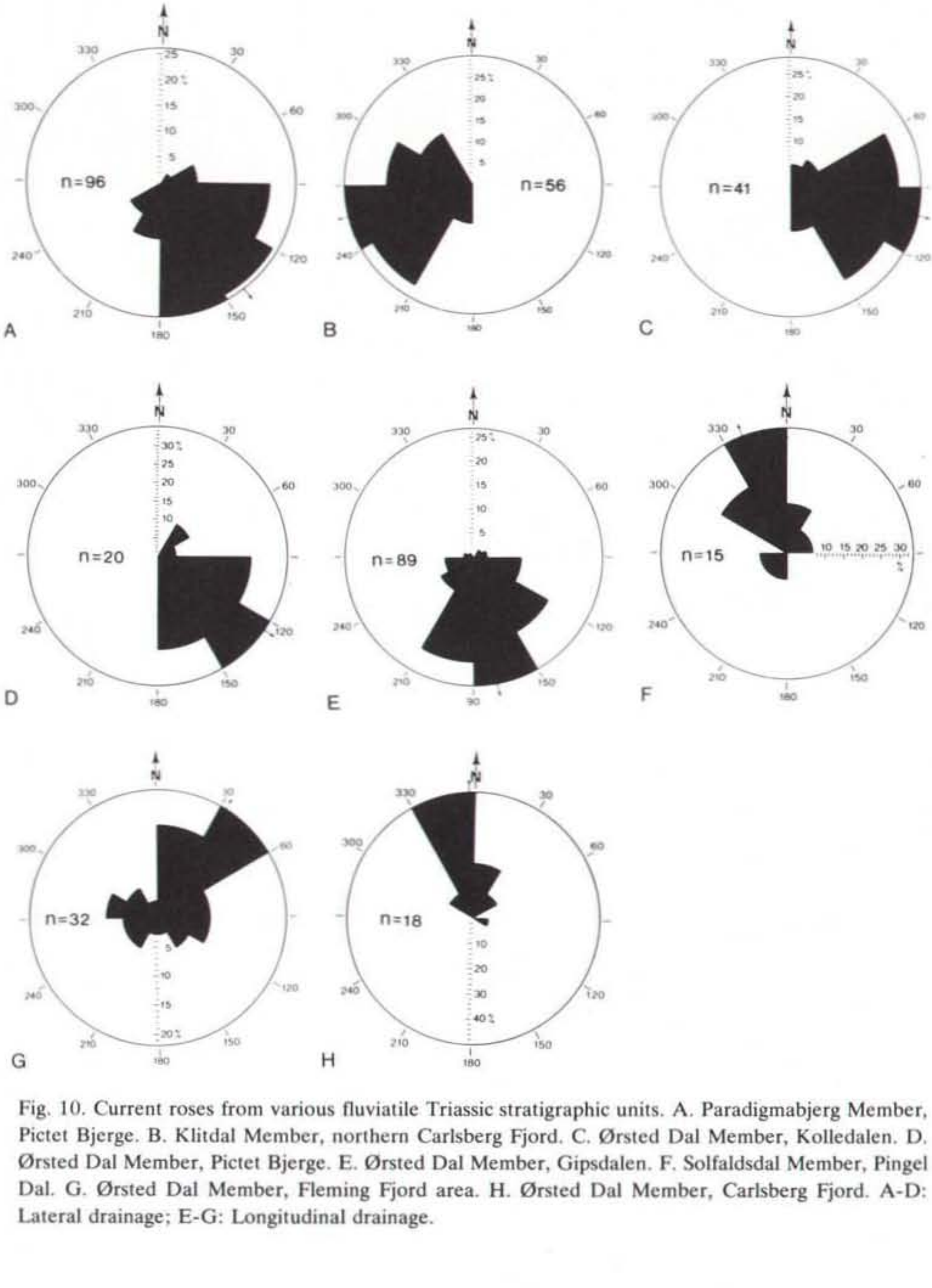


Fig. 10. Current roses from various fluviatile Triassic stratigraphic units. A. Paradigmabjerg Member, Pictet Bjerge. B. Klitdal Member, northern Carlsberg Fjord. C. Ørsted Dal Member, Kolledalen. D. Ørsted Dal Member, Pictet Bjerge. E. Ørsted Dal Member, Gipsdalen. F. Solfaldsdal Member, Pingel Dal. G. Ørsted Dal Member, Fleming Fjord area. H. Ørsted Dal Member, Carlsberg Fjord. A-D: Lateral drainage; E-G: Longitudinal drainage.

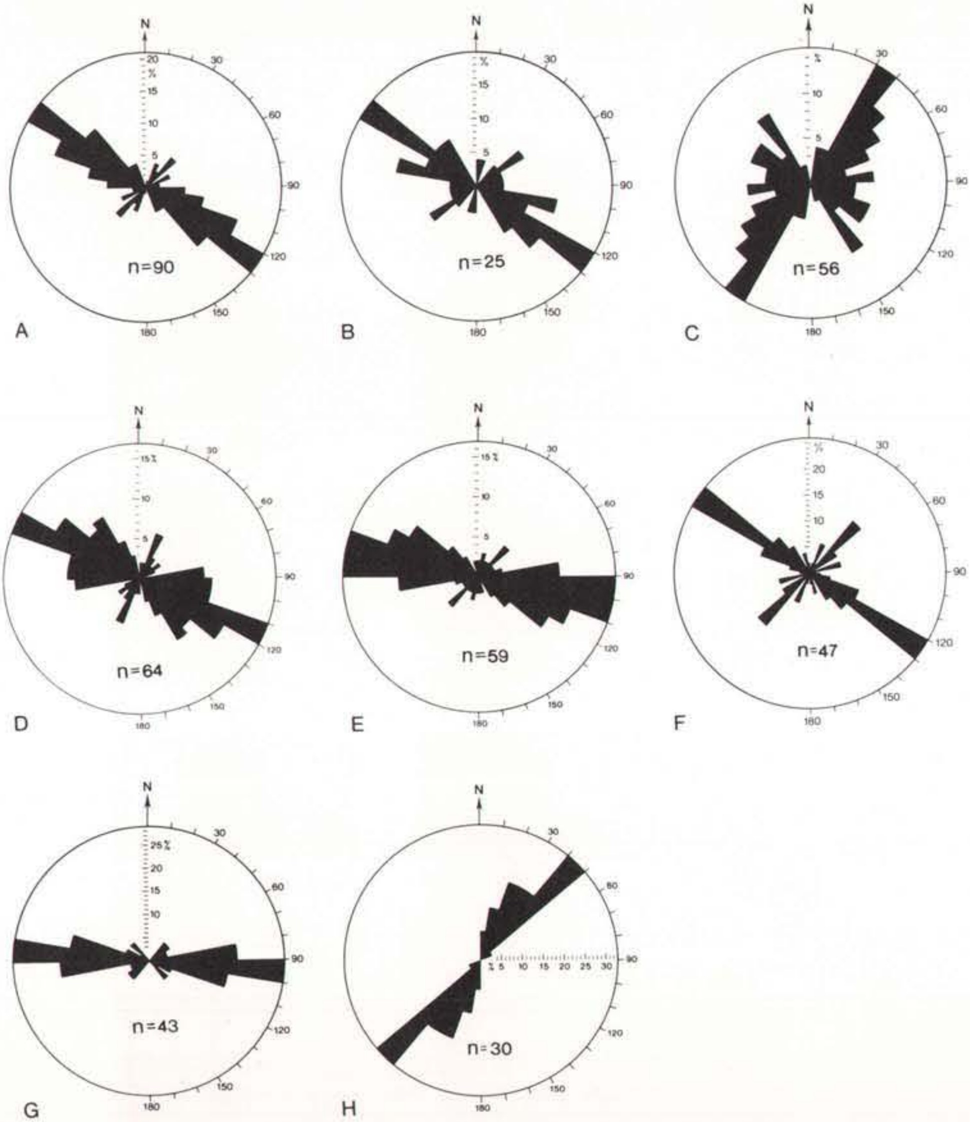


Fig. 11. Orientation of wave ripples (A-G) and elongated stromatolites (H) in various lacustrine Triassic stratigraphic units. A. Edderfugledal Member, Kap Biot. B. Edderfugledal Member, Fleming Fjord. C. Edderfugledal Member, Kolledalen. E. Edderfugledal Member, Gipsdalen. F. Malmros Klint Member, Kap Biot. G. Ørsted Dal Member, whole basin. H. Edderfugledal Member, eastern part of basin.

TRIAS EAST GREENLAND

PINGO DAL, GIPSDALEN AND FLEMING FJORD FORMATIONS

MAIN SEDIMENTARY FACIES	INTERPRETATION	Rodstaken Mb	Paradigmabjerg Mb	Klitdal Mb	Kolledalen Mb	Vega Sund Mb	Gråklint Beds	Solfaldsdal Mb upper part	Kap Seaforth Mb	Sporfjeld Beds	Pingel Dal Beds	Malmros Klint Mb	Ørsted Dal Mb basal part	Tait Bjerg Beds
Structureless conglomerate	Fluvial stream-floods, debris flows		X	X										
Horizontally bedded conglomerate	Fluvial stream-floods, upper plane bed		X	X										
Imbricated conglomerate	Fluvial streams, rolling transport of clasts		x	x										
Cross-bedded conglomerate	Fluvial streams, bars and megaripples		X	X										
Structureless pebbly sandstone	Fluvial streams, debris flows	X	X	X									X	
Horizontally laminated pebbly sandstone	Fluvial streams, upper plane bed	X	X	X									X	
Cross-bedded pebbly sandstone	Fluvial streams, bars and megaripples	X	X	X									X	
Structureless sandstone	?Debris flows, ?liquefaction, ?bioturbation, ?diagenesis	X	X	X	X	X	x	X	X	X	X	X	X	x
Horizontally laminated sandstone	Fluvial stream or wave action, upper plane bed	X	X	X			X	X	x	x	x	X	X	x
Horizontally laminated, well-sorted, medium sandstone	Wind action, sheet deposits		x		X	X		x	X					
Wave ripple laminated sandstone	Wave oscillation, low-energy shallow water	X	x		x		X	X	X	x	X	X	X	x
Current ripple laminated sandstone	Fluvial streams, low-energy	X	X	X	x		X	X	x	x	x	X	X	x
Climbing ripple laminated sandstone	Fluvial streams, low-energy, high aggradation	X	x					X				x	X	
Adhesion ripple laminated sandstone	Wind action, transport over a damp surface				X	X			X					
Large-scale planar cross-bedded sandstone	Fluvial streams, bars and straight-crested megaripples	X	X	X	x			X				x	X	
Large-scale planar cross-bedded, well-sorted, sandstone	Wind action, small barchanoid dunes				X	x		x	X					
Large-scale trough cross-bedded sandstone	Fluvial streams, linguoid megaripples	X	X	X	x			X				x	X	
Giant-scale planar cross-bedded sandstone	Wind action, large barchanoid dunes		X		X									
Giant-scale trough cross-bedded sandstone	Wind action, large dunes				X									
Giant-scale wedge-shaped cross-bedded sandstone	Wind action, large barchanoid dunes				X			X						
Longitudinal cross-bedded sandstone	Fluvial streams, point-bars	x	x									x	X	
Antidune cross-bedded sandstone	Fluvial streams, rapid flow											x		
Undulatory laminated sandstone	Low-energy stream or wave action, high aggradation										X	X		
Irregularly laminated sandstone	Diagenesis				x	x		X	X					
Lenticularly laminated heterolith	Intermittent low-energy stream or wave action (high mud/sand ratio)	x	x					x			X	X	x	
Flaser laminated heterolith	Intermittent low-energy stream or wave action (low mud/sand ratio)	x	x					x			X	X	x	
Undulatory laminated heterolith	Low-energy stream or wave action, high aggradation	x	x					x			X	X	x	
Structureless mudstone	?Rapid deposition, ?liquefaction, ?bioturbation, ?diagenesis	X	X	x	x		x	X	X	X	X	X	X	X
Horizontally laminated mudstone	Settling from suspension, lower plane bed	X	X	x	x		X	X	X	X	X	X	X	X
Structureless limestone	Low-energy precipitation, or deposition of carbonate grains						X							X
Horizontally laminated limestone	Shallow marine stream or wave action, upper plane bed						X							
Wave ripple laminated limestone	Shallow marine low-energy wave oscillation						x							
Large-scale cross-bedded limestone	Shallow marine stream or wave-action, bars and megaripples						X							
Stromatolitic limestone	Algal mats in shallow water, low terrigenous influx						x			X	X	x		
Oncolitic limestone	Rolled algal mats in wave agitated shallow water									X	X		x	
Oolitic limestone	$CaCO_3$ precipitation in wave agitated shallow water									X	X			
Shelly limestone (coquina)	Shell accumulation in high-energy shallow water						X				X			
Limestone with brecciated horizons	Penecontemporaneous disruption											X		X
Structureless dolostone	Shallow water deposition, penecontemporaneous dolomitization								x	X	X			x
Horizontally laminated dolostone	Shallow high-energy deposition, penecontemporaneous dolomitization									X	X			
Wave ripple laminated dolostone	Shallow wave-influenced deposition, penecontemporaneous dolomitization									X	X			
Current ripple laminated dolostone	Shallow current-influenced deposition, penecontemporaneous dolomitization									x	x			
Structureless gypsum sand	Wind action, sheet deposition				x				X					
Ripple laminated gypsum sand	Wind action, low-energy bedforms				x									
Large-scale cross-bedded gypsum sand	Wind action, small barchanoid dunes				X				X					
Layers with massive or nodular gypsum	Evaporative concentration, subaerial exposure				X			X	X					
Gypsum-cemented beds	Evaporative concentration, subaerial exposure				X	X		X	X	x				
Layers with rock salt pseudomorphs	Evaporative concentration, subaerial exposure								X	x				
Layers with polygonal mud-cracks	Subaerial exposure, desiccation	X	X	X	x	x	x	X	X	X	X	X	X	X
Layers with ?syneresis cracks	Spontaneous subaquatic dewatering										x	X		
Layers with intraformational clasts	Subaerial exposure, desiccation, erosion by water	X	X	X				X		X	X	X	X	X
Layers with vertebrates ("bone-beds")	Lag deposit						x					x		X

X = common x = rare

FACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS

Sequences of genetically interrelated facies can commonly be related to specific environments of deposition. In order to interpret the Triassic environments of depositon the rock sequences have been divided into 13 facies associations (in the sense of Collinson, 1969). Each facies association corresponds to one or, in a single case, two well-defined stratigraphic units. The facies associations and their stratigraphical nomenclature are listed below:

1. Red cross-bedded sandstone association – Rødstaken Member.
2. Reddish or greyish conglomeratic sandstone association – Paradigmabjerg Member.
3. Pink conglomeratic sandstone association – Klitdal Member.
4. Yellowish cross-bedded gypsum-bearing sandstone association – Kolledalen Member.
5. Yellowish horizontally laminated gypsum-bearing sandstone association – Vega Sund Member.
6. Grey limestone and black mudstone association – Gråklint Beds.
7. Red gypsum-bearing sandstone association – upper Solfaldsdal Member.
8. Variegated gypsum-bearing sandstone-mudstone association – lower Solfaldsdal Member and Kap Seaforth Member.
9. Yellowish stromatolitic limestone-dolostone association – Sporfjeld Beds.
10. Variegated sandstone-mudstone-stromatolitic limestone association – Pingel Dal Beds.
11. Red mudstone association – Malmros Klint Member.
12. Red mudstone-grey sandstone association – basal Ørsted Dal Member.
13. Light-coloured carbonate rock association – Tait Bjerg Beds.

In the following the associations are described and interpreted in ascending stratigraphic order.

1. Red cross-bedded sandstone association

General

This facies association is characteristic of the Rødstaken Member. It occurs in the western, northern and north-eastern part of the Jameson Land Basin. The association will not be dealt with in detail here as the unit was only briefly studied at one locality. At Pictet Bjerge locality the facies association was non-fossiliferous and non-bioturbated. This taken together with the fact that the association occurs between the fully marine Wordie Creek

Fig. 12. Triassic (upper(?) Scythian – Rhaetian) sedimentary facies, and depositional processes.

Formation, which it overlies with a transitional contact, and the unquestionable continental Paradigmabjerg Member probably indicates deposition in a fluvial coastal plain environment.

Facies

Description. The association displays only rarely clear cut fining upwards cyclothems and consists dominantly of superimposed beds of medium, moderately well sorted, reddish sandstones. The sandstones commonly display cross-bedding, which typically is of low angle semi-planar or trough formed appearance. Rare horizons with horizontal lamination, convolute bedding or wave ripples appear. Intraformational mud pebbles are common.

Interpretation. The almost total lack of facies differentiation and well-developed fining upwards cyclothems indicates that the fluvial sub-environments were only poorly developed. It is tentatively suggested that this can be explained by depositon in shallow braided or low-sinuosity non-braided rivers without well-established meander belts operating in a subsiding flood plain environment.

Facies trends

As the association has only been studied at one locality, the lateral facies variations are unknown. The association shows a marked coarsening upwards trend on a large scale, and towards the top of the unit coarse sandstones and pebbly sandstones become gradually more common. The contact to the conglomeratic sandstones of the overlying Paradigmabjerg Member is gradual.

Similar coarsening upwards sequences in alluvial sediments have been described from the ?Permo-Triassic in Scotland (Steel & Wilson, 1975; Steel *et al.*, 1977). In this case the sequences were explained by rapid subsidence of the basin floor followed by aggradation and progradation of proximal alluvial facies over distal ones. The coarsening upwards trend in the Rødstaken Member is in agreement with these ideas interpreted as a progradational alluvial flood plain sequence formed after tectonic uplift of the borderlands and relative subsidence of the basin floor. Palaeocurrent evidence indicates a regional palaeoslope towards the north or the north-east during deposition of the flood plain sediments.

As a conclusion it is suggested that the facies association was deposited in a fluvial coastal plain situation during a relatively high and with time increasing clastic supply.

2. Reddish or greyish conglomeratic sandstone association

General

This facies association (figs 13, 14) is typical of the Paradigmabjerg Member. It occurs in the north-eastern, northern and western part of the Jameson Land Basin, and on north-eastern Traill Ø. The association shows features generally considered as indicative of deposition

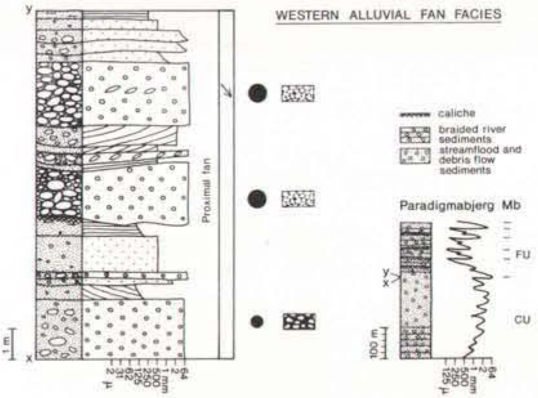


Fig. 13. Sedimentary log of the Paradigmabjerg Member, Pictet Bjerge. The sedimentary log is accompanied by a generalized stratigraphic log showing sedimentary environment and mean grain size trends. Maximum pebble size 30 cm. See figs 6 and 15 for explanation of symbols.

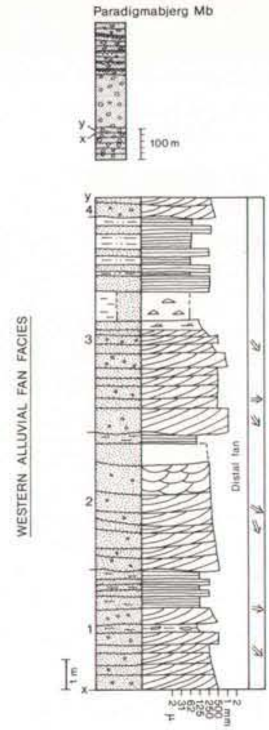


Fig. 14. Sedimentary log of the Paradigmabjerg Member, Pictet Bjerge. The sequence can be divided into four fining upwards cyclothems of braided river origin. Maximum pebble size 1–2 cm.

in a continental environment. The association is oxidized and displays fresh water trace fossils; many beds contain incipient caliche horizons, and large-scale cross-bedded aeolian sandstones are locally encountered; bedding planes show desiccation cracks and sedimentary structures reveal a unimodal palaeocurrent pattern.

Facies sequences

Three types of small-scale sequences are distinguished. One constitutes regular alternations of poorly sorted conglomerates or pebbly sandstones and sandstones (A), the second is composed of clast supported conglomerates and sandstones (B) and the last of well developed fining upwards cyclothems of complex (C_1) or simple (C_2) types. Sequences A, B and C_1 are interpreted as alluvial fan deposits because of their coarse-grained nature, whereas the fine-grained fining upwards cyclothems (C_2) are interpreted as flood plain deposits.

A – *Description*. The coarse facies consists of structureless poorly sorted conglomerates or pebbly sandstones of sheet-like character. The facies as generally matrix supported with a matrix of poorly sorted sand. The clasts are subangular to subrounded granites, gneisses or quartzites and locally some intraformational mud pebbles. The conglomerates are ungraded or commonly normally graded; pebble segregation is 30–50 or 50–70 (see Clifton, 1973).

The fine facies is composed of laterally persistent, moderately to poorly sorted, fine to coarse sandstones. In the coarser varieties scattered pebbles are common. Apart from rare low-angle cross-bedding the sandstones appear to be structureless. In the fine-grained varieties desiccation cracks and incipient caliche may occur. Vertical to horizontal cylindrical burrows with an ordered wall structure (probably *Steinichnus*) are common in these fine-grained sandstones. Both facies contain much feldspar and should be classified as arkoses.

A –*Interpretation*. The poor sorting, the characteristic lack of sedimentary structures and the lateral persistency of the conglomerates probably indicate deposition mainly from debris flows in a proximal alluvial fan environment (e.g. Steel, 1974a). The sandstones probably formed during high stages of flood-water after deposition of the debris flows. Periods of non deposition in an arid climate are indicated by the incipient caliche horizons.

B – *Description*. These sequences consist of alternating conglomerates and sandstones. In contrast to the former these are commonly pebble supported and have a better sorted sand fraction. The conglomerates furthermore possess an erosive channelled base and interfinger with sandstones. The clasts are generally well rounded granites, gneisses or quartzites with a maximum length between *c* 5 and *c* 20 cm. Imbrication as well as large scale cross-bedding are locally developed but the clasts are commonly subhorizontal to randomly orientated. The associated sandstones are fine to coarse, often pebbly, and commonly show low angle cross-bedding. Rare incipient caliche horizons occur in the most fine-grained sandstones. A high feldspar content is common in the sediments.

B – *Interpretation*. The channelled base and the well ordered appearance of the conglomerates as well as the cross-bedding in the sandstones and a few of the conglomerates strongly suggest deposition by stream floods in the present context of an alluvial fan environment (cf. Steel, 1974a).

C – *Description*. The fining upwards cyclothems can be divided into complex (C_1) and simple (C_2). The complex ones consist of several units of medium often pebbly large-scale, cross-bedded sandstone overlain by structureless or horizontally laminated fine often muddy, sandstones. The cross-bedding is of the high angle and semi-planar or trough formed types and show commonly decreasing set height upwards.

The simple (C_2) cyclothems consist of a fairly regular alternation of fine sandstones with a channelled base and locally with longitudinal cross-bedding and siltstones with current ripple lamination or wave ripple laminated. Intraformational clasts are numerous in the sandstones, whereas the siltstones display bedding planes with polygonal cracks. *Steinichnus* or similar burrows are quite common in the siltstones.

C – *Interpretation*. The complex (C_1) cyclothems were deposited in an alluvial fan situation and the fining upwards, the abundance of large-scale trough cross-bedding and erosional surfaces suggest a shallow braided river origin (e.g. Williams & Rust, 1969; Steel, 1974a).

The simple (C_2) fining upwards sequences are interpreted as flood plain deposits and possibly resulted from a fluvial system which had an established meander belt. Within the context of this general meandering river interpretation the basal sandstones are thought to record the channel or point bar deposits, whereas the siltstones are interpreted as overbank deposits. The absence of caliche probably indicates the existence of only relatively short periods of subaerial exposure in a distal flood plain situation.

Facies trends

The coarse alluvial fan deposits (sequences A, B and C_1) along the western margin of the basin grades into the fine flood plain deposits (sequences C_2) in the centre of the basin. The palaeocurrent evidence (fig. 10) suggests that the fans dispersed east or southwards from a N–S or NNE–SSW trending highland. Only few palaeocurrent directions were obtained in the flood plain deposits, but the few data available suggest flood plain construction down a northerly palaeoslope almost at right angless to the fan palaeoslopes. Within the marginal alluvial fan association one major coarsening upwards and five major fining upwards sequences have been distinguished (fig. 13).

The major coarsening upwards alluvial fan sequence is here interpreted in agreement with the ideas of Steel & Wilson (1975), as a result of an increasing rate of uplift of the source area, or an increasing rate of subsidence of the basin. The fining upwards fan sequences on the other hand most probably indicate basin margin faulting of gradually decreasing intensity. Within this general pattern of increasing or decreasing basin margin faulting the alluvial fan sequence at Pictet Bjerge has been divided into proximal or distal (fig. 13). Proximal fan sediments are characterized by coarse debris flows and minor coarse stream-flood deposits and show an absence of caliche horizons. The distal fan sediments typically are composed of either braided stream deposits or rather fine-grained debris flow and stream-flood deposits with incipient caliche horizons in the fine sandstones.

In summary the association is regarded as alluvial fan and flood plain deposits formed in association with tectonic uplift in a western source area.

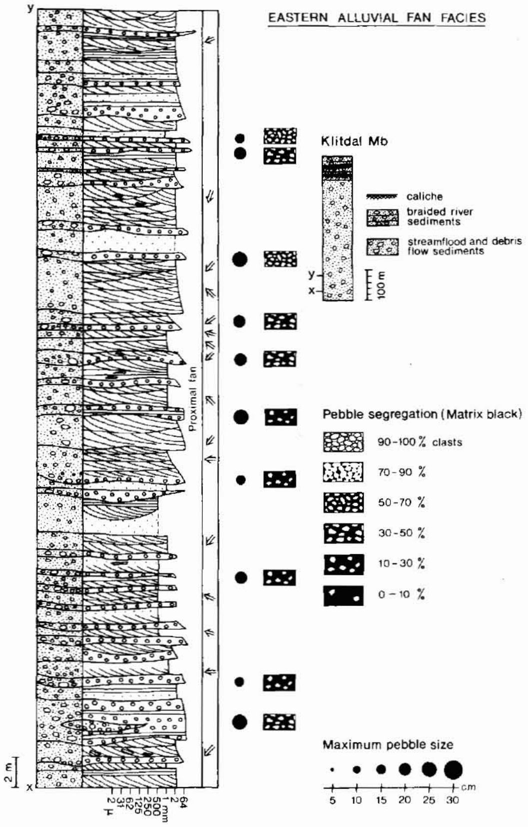
3. **Pink conglomeratic sandstone association**

General

This association (fig. 15) of sediments characterizes the Klitdal Member and occurs at the south-eastern border of the basin in Jameson Land. The coarse-grained nature of the sediments, the evidence of deposition during oxidizing conditions and the lack of marine fossils indicate deposition in a continental environment.

Facies sequences

Two different sequences could be distinguished within this association. One consists of couplets of conglomerates and cross-bedded pebbly sandstone (A), the other constitutes fining upwards cyclothems commonly initiated by pebbly sandstone and capped by incipient caliche horizons (B). The coarse-grained nature of the sequences suggests an alluvial fan – braided river origin.



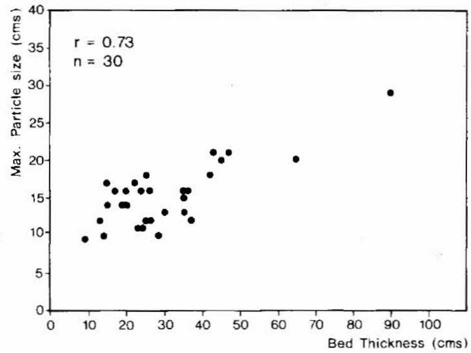


Fig. 16. Maximum pebble size/bed thickness diagram for stream flood conglomerates. Klitdal Member, northern Carlsberg Fjord.

◀

Fig. 15. Sedimentary log of the Klitdal Member, northern Carlsberg Fjord. Note the characteristic association of massive conglomerates and overlying cross-bedded pebble sandstones probably representing a stream flood unit.

A – *Description*. The conglomerates can be described as matrix supported, non-imbricated and unstratified sediments (fig. 8). The clasts, which are enclosed in a coarse sandy or fine gravelly matrix, are subrounded porphyrites, granites, gneisses and quartzites with a maximum length up to *c.* 40 cm. The pebble segregation of the conglomerates typically lies between 30–50 og 50–70 (cf. Clifton, 1973, fig. 15). Most of the conglomerates are normally graded in terms of decreasing clast size upwards within a bed. The conglomerates are confined to broad (5–30 m) and shallow (10–50 cm) channels and are laterally replaced by sandstones. Measurements of bed thickness – maximum pebble size relationships in 30 beds (cf. Steel, 1974a) showed a relatively low correlation between the two factors (r = 0.73, see fig. 16). The sandstones associated with the conglomerates are medium to coarse and contain scattered pebbles. A striking feature in the field is the abundant occurrence of pink feldspar in the sandstones and conglomerates. The feldspar may become the dominant constituent of the rocks. The sandstones display prominent semi-planar and low angle (10–20°) cross-bedding (see figs 8, 15). The height of the sets commonly lie between 10 and 70 cm, but some reach *c.* 2 m. Also the sandstones are confined to broad shallow channels.

A – *Interpretation*. Both the conglomerates and the sandstones are interpreted as stream-flood deposits. The partial correlation between bed thickness and maximum pebble size in the conglomerates should according to Steel (1974a) be characteristic of stream-flood action. The cross-stratification, channelled base and lateral impersistence of the beds support the suggested interpretation (cf. Steel, 1974a). The sediments were channelled across the fan surface and deposited during decrease of the stream velocity either as graded conglomerates or as pebbly cross-bedded sandstones. The cross-bedding resulted from bar and megaripple migration.

B – *Description*. The fining upwards cyclothems are initiated by pebbly coarse sandstones with large-scale semi-planar cross-bedding. Then follows medium large-scale, or at the top locally small-scale, horizontally laminated fine sandstone or siltstone. Incipient caliche as well as rare chert horizons are encountered at the top of the sequences. At one place a 0.2 m thick jasper horizon was encountered.

B – *Interpretation*. The fining upwards cyclothems are interpreted as braided stream deposits (e.g. Williams & Rust, 1969). Periods of non-deposition in an arid climate is indicated by the incipient caliche, the chert nodules, and the jasper horizon. Caliche forms today commonly on the margin of alluvial fans in an arid or semiarid climate (e.g. Bull, 1972), and has also been reported from similar Triassic braided stream deposits in the eastern United States (Hubert, 1977). Also chert and jasper are known to form in continental settings during a warm and dry climate (e.g. the Tertiary silcretes of the Lake Eyre Basin, Australia; Twindale, 1972).

Facies trends

The discussed association is confined to the south-easternmost part of the Jameson Land Basin and it gradually wedges out (i.e. within *c.* 25 km) towards the west, where the association is replaced by finer-grained flood plain deposits of the former association (Paradigmabjerg Member).

Palaeocurrent data (fig. 10) and clast composition indicate the existence of an easterly source area composed of granitic and volcanic highlands. The present Liverpool Land area and its possible northwards extension served as an active source area during deposition of these sediments. With time tectonic activity in the borderland decreased as indicated by the upwards change from proximal to distal fan sediments (fig. 15). The proximal fan sediments are composed of conglomerates and pebbly sandstones of stream-flood origin, whereas the fining upwards braided stream cyclothems with caliche compose the distal fan environment.

The association appears to be a north-south trending belt of coalescing alluvial fans formed in connection with tectonic uplift of an eastern source area.

4. **Yellowish cross-bedded gypsum-bearing sandstone association**

General

These sediments (fig. 17) characterize the Kolledalen Member and occur in the western and northern part of the Jameson Land Basin. The total lack of marine fossils in the association and the type and scale of the encountered cross-bedding in the sandstones indicate an aeolian origin (Clemmensen, 1978a). Associated sediments include alluvial fan, sabkha and shallow lake deposits.

Facies

Four facies were distinguished by Clemmensen (1978a) within this facies association in the Kolledalen area:

A. Structureless or horizontally laminated sandy siltstone.
B. Horizontally laminated or ripple laminated sandstone.
C. Giant- or large-scale cross-bedded sandstone.
D. Conglomerates and pebbly sandstones.

An additional facies sequence has been added after further studies in the central part of the basin:

E. Interbedded well-sorted sandstones and silty sandstones with mud pebbles.

As the first four facies were described in detail by Clemmensen (1978a), only their most characteristic features are listed below. The sandstone – silty sandstone sequences will be described in some detail.

A – *Description*. Red sandy micaceous and locally gypsum-bearing siltstones commonly with horizontal lamination. Gypsum generally occurs as nodules within the sediment.

A – *Interpretation*. The sediments are interpreted as shallow water, presumably lacustrine deposits (Clemmensen, 1978a).

B – *Description*. Very fine to fine light yellowish, reddish or variegated sandstones with gypsum nodules. Sedimentary structures include horizontal, current ripple, and adhesion ripple lamination.

B – *Interpretation*. The depositional environment is interpreted as an inland sabkha (Clemmensen, 1978a).

C – *Description*. Planar or more rarely wedge-shaped or trough cross-bedded, commonly gypsum-bearing, sandstones (sets up to *c.* 6 m; fig. 7) associated with minor planar or wedge-shaped cross-bedded gypsum sand (sets between 10 cm and 1 m). Rare asymmetrical wind ripples appear along the foreset slopes of the gypsum-bearing sandstones. The gypsum occurs either as a cement or as centimetre-large scattered nodules.

C – *Interpretation*. The sandstones are interpreted as barchanoid dunes and were presumably deposited during alternating periods of north-north-east and south-south-east trade winds (Clemmensen, 1978a). The gypsum was concentrated by evaporitive pumping.

D – *Description*. Various subfacies of pebbly sandstones and conglomerates. Rare gypsum nodules occur. Sedimentary structures include cross-bedding and imbrication.

D – *Interpretation*. The sediments are interpreted as alluvial fan deposits (Clemmensen, 1978a). The gypsum formed by precipitation from continental ground-water during evaporative pumping.

E – *Description*. The sequence consists of two different facies (fig. 17). One constitutes reddish gypsum-bearing fine-medium, silty sandstones. The sandstones are generally only moderately well sorted. They possess erosive basis and display horizontal lamination or rare trough formed cross-bedding. Mud pebbles occur along the erosive base, scattered throughout the sediment or along the foresets. These sandstones are relatively hard owing to

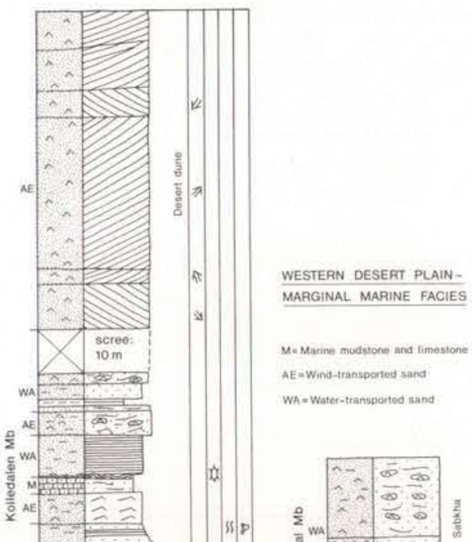


Fig. 17. Sedimentary log of the uppermost Kolledalen Member at Gurreholm Bjerge. Gk = Gråklint Beds.

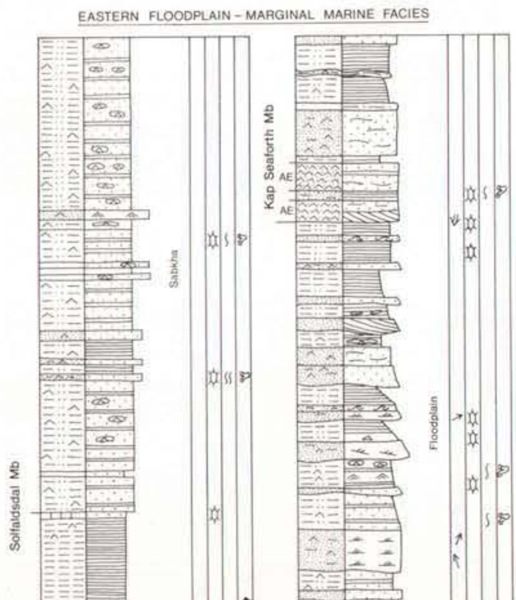


Fig. 18. Sedimentary log of the Gråklint Beds, uppermost Solfaldsdal Member and Kap Seaforth Member, northern Carlsberg Fjord.

cementation by carbonate. The second facies in the cyclothem is represented by better sorted gypsum-bearing 'clean' and 'soft' sandstones displaying horizontal lamination or planar cross-bedding. The two facies occur randomly interbedded.

E – *Interpretation*. The sequence is interpreted as a wadi sequence in a desert climate. During arid periods sand was blown into small dunes, but after heavy rains in the uplands much of the aeolian sand became reworked and redeposited by short-lived wadi floods. The sequence here discussed shows many similarities to the wadi sequences from the Recent deserts described by Glennie (1970). One point of similarity among others is that the aeolian sandstones in both examples stay rather soft owing to lack of lithification, whereas the water-laid sandstones become lithified by carbonate. The gypsum within the sediments was concentrated by evaporative pumping, and sulphur isotope data indicate that sulphide from the weathering of mudstones was a major component of the source sulphur (cf. Clemmensen, Holser & Winter, in press).

Facies trends

The association only occurs in the western and northern part of the Jameson Land Basin. Closest to the north-western margin of the basin dune sandstones dominate and are here intercalated with and underlain by alluvial fan sediments (Clemmensen, 1978a). Towards the south-east dune sandstones become less common at the same time as reddish sabkha or flood plain sediments increase in importance. At the very south-eastern limit of the dune sandstone field, the association interfingers with and is overlain by thin limestones and dark mudstones of the restricted marine Gråklint Beds (fig. 5).

Palaeowind directions (n=150) were collected at five localities. At each locality there was a dominant palaeowind from the north or north-east and a less frequent wind from the south or south-east (cf. Clemmensen, 1978a).

The general trend – alluvial fan – desert dunes – sabkha/floodplains – shows that we are dealing with a retrogradational sequence in a continental basin. Strong winds shifted large barchanoid dunes either towards south-west or towards north-west; thus there was an effective transport of dune sand in a western direction, and the dune field was bordered towards the west by alluvial fan sediments. Towards the end of this continental period a marine transgression was gradually established and marine limestones spread towards the centre of the basin.

5. **Yellowish horizontally laminated gypsum-bearing sandstone association**

General

This facies association characterizes the Vega Sund Member of north-eastern Traill Ø. The total absence of marine fossils and the stratigraphical position above the fluvial Paradigmabjerg Member suggest a continental origin.

Facies

Description. The association is composed almost solely of horizontally laminated or structureless poorly lithified light yellowish sandstones. Close inspection of the structureless sandstones showed the local existence of poorly developed adhesion ripple lamination. Large-scale southwards facing planar cross-bedding (H = 20–50 cm) are also encountered locally. The non-micaceous sandstones are generally well sorted and commonly weakly cemented with gypsum. The content of gypsum decreases upwards.

Interpretation. Horizontally laminated sand may form in various sedimentary environments by fluvial currents (e.g. Picard & High, 1973), by wave action (e.g. Reineck, 1963; Clifton, 1969) or by wind action (e.g. Glennie, 1970). In the present case it is suggested that the sandstones are of aeolian origin. This interpretation is supported by the non-micaceous and well-sorted appearance of the sandstones, the lack of fossils and the local occurrence of adhesion ripple lamination. In the light of this interpretation the large-scale cross-bedding is suggested as representing small southwards migrating dunes. Horizontally laminated aeolian sandstone, which dominates the sequences, should according to Glennie (1970) be characteristic of interdune areas characterized by a combination of rapid deposition, high wind velocities and fairly uniform grain size of the transported sand.

Facies trends

The association gradually overlies red fluvial mudstones and associated pebbly sandstones of the Paradigmabjerg Member. In the transitional zone reddish or greyish sandstones with feeding burrows and desiccation cracks are common. Upwards the sandstones show a gradual change to better lithified greyish wave rippled sandstones. The association has only been found at one locality and lateral variations in the facies picture are therefore unknown.

The vertical trend is interpreted in terms of a continental basin, where gradual subsidence causes aeolian sheet sandstones of the centre to overlie fluvial sediments closer to the basin margin. With time a marine transgression gradually encroaches on the aeolian sediments and a shallow bay is eventually formed.

6. **Grey limestone and black mudstone association**

General

The association (fig. 18) is characteristic of the Gråklint Beds. The main occurrence of this association is the north-eastern part of the Jameson Land Basin. The sediments gradually wedge out towards the south, west and north-west. In contrast to the rest of the sequence the association contains a relatively abundant fauna mainly of restricted marine origin, and the association seems therefore to represent a marine interlude in the otherwise continental sequence (Grasmück & Trümpy, 1969).

Facies

The association is typically composed of the following facies: (A) black or dark grey mudstones and limestones, (B) more or less sandy calcarenites, (C) calcareous quartz sandstones.

A – *Description*. The black mudstones (terrigenous claystones and fine siltstones) and limestones (lime-mudstones or wackestones) are organic-rich and commonly bituminous; the limestones have commonly been recrystallized partly to sparry calcite. They occur mostly in thin horizons (*c*. 10–50 cm) but locally form small sequences up to a few metres thick (fig. 18). The mudstones mostly occur alone, but in some cases the two rock types form interbedded sequences. The mudstones generally display horizontal lamination and bedding planes are frequently plastered with conchostracan shells. The limestones, which may contain *c*. 10% terrigenous silt or fine sand, are commonly massive and frequently contain small marine bivalves. The bivalves occur in thin layers or lenses in random position.

A – *Interpretation*. The black mudstones are thought to represent a lagoonal environment; the well-developed horizontal lamination and the absence of biogenic structures suggest stagnant water and reducing conditions at the sediment-water interface. The conchostracan shells could have been introduced by ephemeral streams. The black limestones probably also originated in a lagoonal environment but during more marine influence as indicated by the fauna.

B – *Description*. The calcarenites of this facies dominate the sequence at the type locality at Gråklint, where they constitute a 14 m thick grey cliff forming unit. The petrography of the rocks are already described in some detail by Grasmück & Trümpy (1969). They typically constitute somewhat porous limestone (wackestones and packstones) composed of rolled and slightly incrustated shell fragments. The shells have been affected by diagenetic recrystallization and are mostly indeterminable, but at some horizons various marine bivalves have been recognized. Terrigenous clastic grains (quartz and feldspar) occur in varying number, in some cases being so frequent that the limestones almost pass into calcareous sandstones. Massive limestones are not as common as stated by Grasmück & Trümpy (1969). Most of the rocks display horizontal lamination of large-scale cross-bedding (planar and trough formed; bi- og polymodal orientation). A special type of cross-bedding consists of rather large (set height up to *c*. 1 m) accretion units with low angle sets (*c*. 10°) inclined towards the north-east. Rare centimetre-thin greyish and poorly laminated stromatolitic limestones occur in association with the calcarenites.

B – *Interpretation*. The horizontally laminated and cross-bedded calcarenites are interpreted as high-energy shoreline sediments; the sedimentary structures of the facies are comparable to those along the Oregon coast (Clifton *et al.*, 1971). The relatively steep north-eastward dipping beach foresets seen locally in the upper part of the association suggest the existence of shoreline bars facing an open sea with storm waves towards the north-east (cf. Warme, 1971; Reineck & Singh, 1973).

C – *Description.* The calcareous light greyish sandstones are fine- to medium-grained and display a wealth of sedimentary structures indicative of very shallow water and frequent subaerial exposure such as: capped-off wave ripples, double crested wave ripples, interfering wave ripple systems, desiccation cracks and intraformational mud pebbles. A few flaser bedded sandstones with NW–SE bimodal dipping small-scale current cross lamination could indicate tidal influence. Marine bivalves are relatively rare.

C – *Interpretation*. The sandstones presumably originated in a very shallow marine environment characterized by a relatively high supply of clastic terrigenous material.

Facies trends

The association contrasts with the rest of the associations by showing great lateral variations in thickness, facies and sequential pattern. Relatively thick sequences of calcarenites occur in the central Fleming Fjord area and the unit decreases in thickness towards the margins of the basin. In the north-eastern region around Kap Biot the calcareous sandstones are very common and occur in association with calcarenites and black mudstones and limestones. Elsewhere in the Jameson Land Basin black mudstones and limestones dominate the sequence. Towards the north on Traill Ø calcareous sandstones with wave ripples again become dominant.

The complex facies pattern seems to fit well with a marine origin. Extensive limestone beach barriers were probably developed in the central Fleming Fjord area and interfingered towards south and west with lagoonal mudstones and limestones. Towards the north-east the shoreline limestones merged into a very shallow marine shelf, which frequently became subaerially exposed. The increase of clastic terrigenous material towards the north-east could indicate temporary erosion of an eastern source area presumably the northward extension of the Liverpool Land high.

In conclusion the association represents various lagoonal, high-energy shoreline and shallow marine sediments deposited during a brief marine transgression of the land-locked basin. As judged from the facies relationship, the sea which invaded the basin probably lay to the north-east.

7. **Red gypsum-bearing sandstone association**

General

This association (figs 18, 19) characterizes the uppermost clastic terrigenous part of the Solfaldsdal Member, i.e. the portion above the Gråklint Beds. The sediments occur in the north-eastern and central part of the Jameson Land Basin. The evidence of deposition during oxidizing conditions (red coloration), the total lack of marine fossils, and the occurrence of continental trace fossils, rare aeolian sediments, numerous desiccation cracks and penecontemporaneous gypsum nodules suggest an alluvial environment.

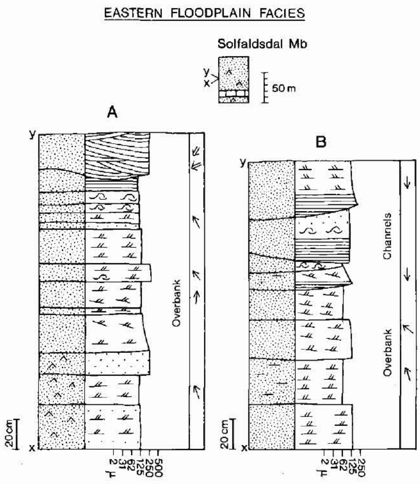


Fig. 19. Red fluviatile sediments of the uppermost Solfaldsdal Member, Pingel Dal. Note the large scatter of palaeocurrent directions probably due to the existence of meandering rivers.

Sequences and facies

Two characteristic facies sequences can be distinguished within this member. One constitutes regular alternations between current cross-stratified sandstones and siltstones (A). The second one is composed of relatively thick sequences of apparently randomly interbedded wave rippled fine sandstones and siltstones (B). Both types are locally associated with horizontally laminated or planar cross-bedded medium sandstones.

A – *Description*. The basal facies of this sequence is typically composed of fine to medium micaceous sandstone with small-scale current ripple lamination (commonly of climbing attitude), large-scale trough cross-bedding or locally longitudinal cross-bedding and horizontal lamination. The lower contact of the sandstones is weakly erosive. The overlying facies is darker red than the underlying sandstones and constitutes siltstones being massive, horizontally laminated or current ripple laminated (commonly with an angle of climb generally between 5 and 10 degrees). Wave ripples are locally encountered. The upper part of the siltstones display ubiquitous desiccation cracks and may show convoluted bedding. Both the sandstones and especially the siltstones fine upwards and the cyclothems constitute an example of fining upwards. Some examples of these cyclothems are shown in figs 18 and 19. Gypsum in the form of cement or nodules (scattered or lined in well defined horizons) occur in both the sandstones and in the siltstones, but are most common in the latter. The associated horizontally laminated or planar cross-bedded non-micaceous sandstones are well sorted and rather soft in contrast to the better lithified surrounding sediments. They, too, are cemented with gypsum, but contain no trace fossils in contrast to the above facies, which possess *Steinichnus* or similar burrows.

A – *Interpretation*. The general feature of the fining upwards cyclothems are similar to the alluvial fining upwards cyclothems of Allen (1965, 1970b), and a flood plain origin is therefore suggested for the sediments. Cornstone (fossil caliche), which is common in such cyclothems in the Devonian (Allen, 1965) and Triassic (Steel, 1974b) of Great Britain is, however, lacking here. This presumably indicates that discharge was relatively continuous. During periods of exposure (most likely in the order of weeks to months) only gypsum nodules could form, whereas there was not sufficient time for the development of caliche profiles, which according to Allen (1965) and Steel (1974b) often requires hundreds or thousands of years.

Within the context of the general flood plain interpretation the sandstones are thought to record point bar deposits (trough cross-bedded or longitudinal cross-bedded sandstones), basal levee deposits or basal overbank deposits (horizontally laminated and current ripple laminated sandstones). The siltstones probably represent the most fine-grained overbank sediments deposited after heavy floods upon the basal sandy overbank deposits. The flood plain was presumably characterized by meandering rivers that moved and shifted their position rapidly as suggested by the great palaeocurrent variance (figs 10 and 19) and the variety of preserved fluvial subenvironments.

It is suggested that the well sorted horizontally laminated or cross-bedded sandstones represent aeolian deposits, eroded from the fluvial sands and redistributed by wind during periods of exposure. Similar flood plain sequences with aeolian deposits have been recorded both from the recent (e.g. Reineck & Singh, 1973, p. 237) and from other Triassic sequences (Thompson, 1969; Steel, 1974a).

B – *Description*. The sequence consists of up to 70 m of weakly gypsiferous micaceous fine sandstones and siltstones. The facies occur in layers betwen *c.* 10 and 100 cm thick and display a random pattern of interbedding. Wave ripples and desiccation cracks are ubiquitous on bedding planes; internally the sediments are mostly horizontally laminated or massive. Both facies are rich in trace fossils, and *Steinichnus* or similar burrows dominate. Well sorted non-micaceous horizontally laminated sandstones with gypsum cement also occur in this sequence.

B – *Interpretation*. The sediments were laid down in a continental environment, where periods of sand or silt deposition in shallow water alternated with periods of wave reworking, prolonged exposure and occasional wind activity. The transitional zones between distal flood plains and adjacent playa lakes seem to be the best environmental fit. Periodically the playa mudflat was affected by wind activity as suggested by the existence of well sorted non-micaceous sandstones.

Facies trends

The association lies rather abruptly upon the shallow marine – lagoonal limestones and dark mudstones of the Gråklint Beds. This seems to indicate a renewed closure of the Jameson Land Basin probably in combination with minor tectonic uplift in the eastern source area.

The flood plain sequences (A) appear to be confined to the marginal and ?southern parts of the basin, whereas the playa mudflat sediments are confined to the northern and central parts of the basin. Palaeocurrent evidence in the flood plain sediments is relatively meagre, but the data obtained (fig. 10) indicate fluvial transport down a northerly palaeoslope. This northerly palaeoslope seems to fit with the restriction of the playa mudflat sediments to the northern part of the basin.

In summary it is suggested that the marginal and southern flood plains merge into a northern very shallow and ephemeral playa lake.

8. Variegated gypsum-bearing sandstone-mudstone association

General

The sediments are characteristic of the lowest part of the Solfaldsdal Member, i.e. the portion below the Gråklint Beds, and of the Kap Seaforth Member. The lower unit in the Solfaldsdal Member is restricted to the eastern part of the Jameson Land Basin, whereas the Kap Seaforth Member occurs in large parts of the Jameson Land Basin and also on north-eastern Traill Ø (fig. 20). The total lack of marine fossils, the well developed cyclicity and the frequent occurrence of aeolian sediments make it likely that these sediments accumulated in large playa lakes as suggested by Clemmensen & Andreasen (1976) and Clemmensen (1977, 1978a). Recent investigations of sulphur isotope ratios in the gypsum have given results highly indicative of a non-marine origin (Clemmensen *et al.*, in press). In

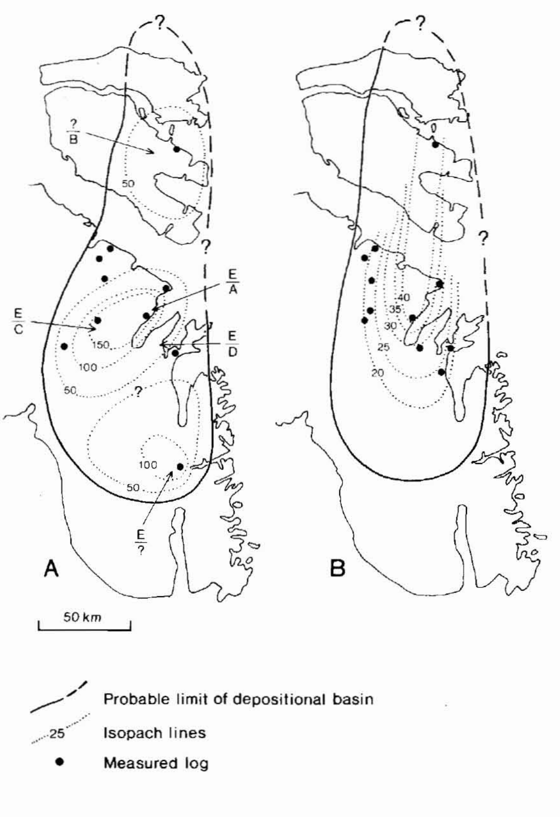


Fig. 20. Probable basin configuration during deposition of the Middle Triassic (Ladinian?) Kap Seaforth Member (A) and the overlying Middle Triassic (Ladinian?) Sporfjeld Beds (B). All numbers are in metres; capital letters refer to cyclothem types described in the text.

the following account only the well exposed cycles of the Kap Seaforth Member will be discussed in some detail; the poorly exposed sediments of the lower Solfaldsdal Member have only been studied briefly at a few localities.

Cyclothems

The general aspect of this association is the occurrence of gypsum-bearing sandstone-mudstone cycles. These gypsiferous cycles seem, however, restricted to three depocentres within the basin, and outside these sites of maximum sedimentation only thin sequences of non-gypsiferous and non-cyclic sediments occur (fig. 20). In the lower and middle part of the Kap Seaforth Member four (A, B, C, D) types of cyclothems, each characteristically developed only within a restricted area, have been observed. In the upper part of the unit a fifth (E) type occurs, and these cycles appear to be more uniformly developed throughout the basin.

A – *Description*. These cyclothems (Fleming Fjord type, fig. 21) consist of four facies: (1) variegated mudstone; (2) greenish mudstone and sandstones; (3) dark red massive sandstone and (4) rare light red cross-bedded sandstone (Clemmensen, 1978a). A total of 30 cycles were observed within 48 m. Facies 2, 3 and 4 are gypsiferous to a varying degree. A sequential analysis using the method advocated by Selley (1970) to construct data arrays and facies relation diagrams shows that three different facies couplets occur more commonly than expected assuming that the facies were randomly arranged (fig. 22). These are common alternations between variegated mudstone (1) and red massive sandstone (3); common alternations between greenish mudstone and sandstone (2) and red massive sandstone (3), and rare alternations between the two red sandstone facies, i.e. 3 and 4.

A – *Interpretation*. The cyclothems were probably deposited in fluctuating lakes during a warm and semiarid climate (Clemmensen, 1977, 1978a). The red sandstones of facies 3 and 4 represent aeolian influenced lake margin and the aeolian sand flat environment respectively, whereas the muddy sediments of facies 1 and 2 were laid down in shallow lacustrine water.

B – *Description*. These cyclothems (Mols Bjerge type, fig. 21) possess a simple symmetrical motif and consist of alternations of light yellowish, fine-medium sandstones and dark grey, muddy, very fine sandstones. A total of 24 cycles were observed within 21 m. The yellowish sandstones are massive, horizontally laminated or rarely cross-bedded. A few beds contain planar cross-bedding facing southwards. The dark very fine sandstones are most commonly horizontally laminated. The yellowish sandstones, which vary in thickness from less than 10 cm to more than 1 m, are commonly gypsum cemented, whereas the dark fine sandstones only rarely show signs of gypsum. Desiccation cracks and rare small feeding burrows have been observed at a few bedding planes in the transition zones between the two facies.

B – *Interpretation*. The sedimentary features of these cycles suggest deposition in a fluctuating environment subject to frequent subaerial exposure (gypsum, desiccation cracks). However, the lack of diagnostic structures in both facies makes it difficult to decide on actual

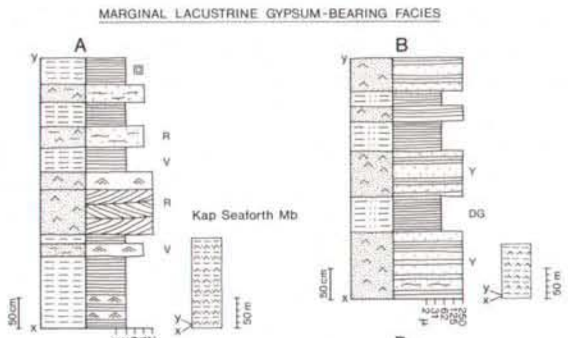


Fig. 21. Variegated cyclic sequences of lacustrine origin in the Kap Seaforth Member. A. Fleming Fjord type, measured at Fleming Fjord. B. Mols Bjerge type, measured at the northern slope of this mountain. C. Gipsdalen type, measured at Gurreholm Bjerge. D. Carlsberg Fjord type, measured at northern Carlsberg Fjord. Y = yellow; R = red; GR = green; BR = brown; V= variegated; LG = light grey; DG = dark grey.

processes of deposition. The well sorted appearance of the yellowish sandstones could, however, argue for an aeolian origin especially when the aeolian depositional conditions of the underlying association, as well as the common evidence of wind activity elsewhere in this association are taken into consideration. Thus the light yellowish sandstones are interpreted as thin aeolian sheet sands subject to later modification by aqueous processes and finally overlain by dark fine lacustrine sandstones during a transgressive period.

C – *Description*. This third type of cyclothems (Gipsdalen type, fig. 21) consists of three facies: (1) dark greyish or more rarely variegated sandy mudstone, (2) light yellowish gypsiferous well sorted medium sandstone and (3) rather pure gypsum beds with a varying but in general relatively small (*c.* 10–25%) quartz sand content. Within 7 m 10 cycles could be defined with cycles varying in thickness from *c.* 25 cm to *c.* 1.5 m. Apart from poorly developed horizontal lamination in most of the mudstones no well defined sedimentary structures could be detected in the field. The sandstones, however, commonly showed an irregular lamination (adhesion ripples or more likely deformation structures caused by gypsum growth). A sequential analysis (fig. 22) showed the cycles to consist of upwards transitions from gypsiferous sandstone (2) via gypsum (3) to mudstone (1). The base of the cycles appears to be defined by the sandstones, which commonly lie rather abruptly upon the mudstones. The mudstone facies occasionally also show signs of grain size fining upwards.

C – *Interpretation*. The well sorted yellowish sandstones are interpreted as aeolian. This interpretation is substantiated by the fact that these sandstones are lithologically identical to the more convincing large-scale cross-bedded yellowish aeolian sandstones in the underlying association (association 4). The gypsum formed in a lake margin environment characterized by some aeolian influence and intense evaporation of shallow lake water and/or terrestrial ground water, and the mudstones finally formed in shallow low energy lacustrine water.

D – *Description*. These cyclothems (Carlsbjerg Fjord type, fig. 21) differ from the former three mainly in two respects. Firstly brownish dolomitic siltstones appear in these cycles, of which the other components are gypsiferous horizontally laminated mudstones, gypsiferous reddish or greenish massive sandstones and rather pure gypsum layers. Secondly the cycles display various degrees of post-depositional disturbance. The disturbances show all transitions from gently folded bedding with discontinuous, or nearly so, layers to 'chaotic bedding' characterized by unorientated slabs of gypsum and dolomitic siltstones in a 'matrix' of unsorted muddy sandstone. Rare desiccation cracks and a few small feeding burrows have been observed in some of the sandstone-mudstone transitions.

D – *Interpretation*. The cycles originated in a shallow lacustrine environment characterized by fluctuating water level. Lake margin aeolian influenced sandflats passed into lakeshore

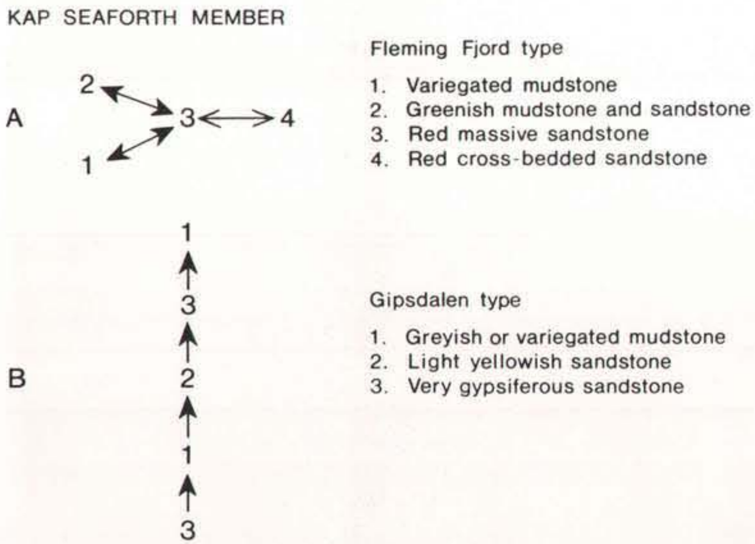


Fig. 22. Sequence analysis of two sections within the Kap Seaforth Member. A. Facies relationships in the Fleming Fjord type. B. Facies relationships in the Gipsdalen type. Thick arrows denote transitions occurring three times or more frequently than expected had the facies arrangement been random.

evaporitic zones and finally into shallow lacustrine mudstones. According to degree of evaporation dolomite or gypsum formed in the lakeshore sediments. Observations by Grasmück & Trümpy (1969) suggest that the disturbance of the gypsum-rich layers took place in the Tertiary.

E – *Description*. These cyclothems (Gurreholm type, fig. 20) are already described by Stauber (1942) and are characteristically composed of three facies: (1) dark bluish grey siltstones and muddy fine sandstones, (2) light grey gypsum rich fine-medium sandstones and (3) rarer relatively pure gypsum layers (fig. 20). Typical cycles (0.5–1 m) constitute symmetrical alternations between dark siltstones and light grey gypsum rich sandstones with occasional intervening thin gypsum layers (0.1–0.2 m). The siltstones and some of the sandstones display horizontal lamination, but in general the degree of exposure and the fact that many of the cycles suffer from post-depositional deformation ('chaotic bedding') does not allow detailed studies of sedimentary structures. Most of the dark siltstones contain some microscopic organic matter.

E – *Interpretation*. Stauber (1942) interpreted these cycles as lagoonal. The interpretation here favoured differs from the one of Stauber (1942) mainly in two respects. Firstly the gypsum is thought to be of continental origin, and most of it probably formed in subaerially exposed sabkha flats by evaporative pumping. A large part of the gypsum crusts were eroded, transported and redeposited by wind action. Locally small gypsum dunes formed. Elsewhere gypsum precipitated directly from saline ponds. Secondly the clastic sediments are thought to be both water-borne (fluvial sheet floods) and wind-borne, and not only river-borne as proposed by Stauber (1942). Pure aeolian sediments can probably be seen in the light grey, relatively well sorted fine-medium sandstones.

Thus there was probably a shallow to moderately deep lacustrine water body where the dark siltstones were deposited. This lake frequently shrank and lake shore sand or aeolian sand was deposited.

Facies trends

The cyclothems discussed above show the following vertical and lateral relationships:

(1) Type A, B, C and D are confined to the lower and middle part of the association; type E to the upper part. At most localities there is a gradual upwards transition from cyclothems such as A or C to E (fig. 20).

(2) The cyclothems in the lower and middle part of the association are of restricted geographical extension. Several cyclothems occur in the same depocentre, e.g. type A, C and D in the Fleming Fjord – Gipsdalen depocentre (fig. 20).

(3) The E cyclothems are in contrast to the rest uniformly developed in the Fleming Fjord – Gipsdalen depocentre. Similar cycles appear to exist in the Klitdal depocentre (Perch-Nielsen *et al.*, 1974, fig. 16). In the Mols Bjerge depocentre, these cycles, however, are not developed (fig. 20).

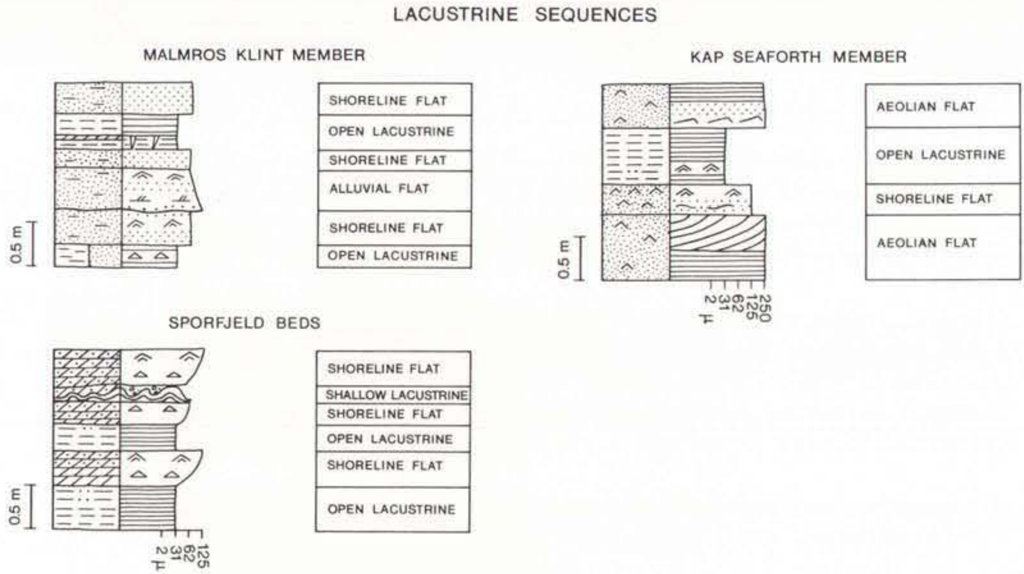


Fig. 23. Generalized lacustrine sequence based on facies analysis of the sediments in the Kap Seaforth Member, Sporfjeld Beds (Edderfugledal Member) and the Malmros Klint Member.

The lateral trends e.g. within the Fleming Fjord – Gipsdalen depocentre (lake) show that different cyclothems were deposited simultaneously in various parts of the lake. The C cyclothems (Gipsdalen type) in the western part of the lake are dominated by light yellow aeolian sheet sands, in the eastern part of the depocentre variegated muddy sandstones are common and red aeolian sandstones rare within the A and D cyclothems. These differences could reflect either provenance or palaeoenvironmental factors such as wind. Wind is here considered to have been a significant factor, and assuming the existence of alternating north-east and south-east palaeowinds (Clemmensen, 1978a) the aeolian sands would be shifted westwards. According to Tanner (1965) the palest aeolian sands are those that have moved the greatest distance from the source. This was apparently also the case here where the palest sands occur downwind.

The upward trend from e.g. cyclothems A and C to E is thought to reflect a gradual deepening of the lakes. This is suggested by the gradual upwards disppearance of unmodified aeolian sandstones (especially well seen in the C-E transitions) and by the fact that desiccation cracks are lacking in the E cyclothems.

In summary it can be stated with some confidence that the cyclothems originated in fluctuating playa lakes. According to variations in source areas, shoreline orientation with respect to palaeowinds and average lake depth slightly different lake cyclothems developed. The general cyclothem (fig. 23) can be described as an upwards transition from (1) aeolian sheet sand via (2) aeolian influenced lake shore sand to (3) open lacustrine siltstone. Gypsum became concentrated in the aeolian and lake shore sandstones by evaporative pumping.

9. Yellowish stromatolitic limestone-dolostone association

General

The sediments (fig. 24) are characteristic of the Sporfjeld Beds, which occur in Jameson Land, Scoresby Land and on north-eastern Traill Ø (fig. 20). The occurrence of non-marine trace and body fossils, of sedimentary structures indicative of shallow water and frequent subaerial exposure, and of a cyclic pattern of sedimentation led Clemmensen (1978b) to suggest a lacustrine origin for the association.

Cyclothems

The characteristic aspect of the association is similar to the underlying association of the Kap Seaforth Member with the existence of well developed cyclicity (Clemmensen, 1978b). In the lower part of the association dolostone-mudstone cyclothems (A) dominate; towards the top dolostone-mudstone cyclothems with common stromatolitic limestones and/or oolitic flat pebble conglomerates (B) appear.

A – *Description*. These simple cyclothems consist of regular alternations between yellow dolostone and greenish mudstone. The dolostones are sandy and commonly massive. Calcite filled vugs may represent cavities left by solution of gypsum nodules and rare pseudomorphs after 'swallow-tail' gypsum twins have likewise been observed. Halite crystal casts occur occasionally. The mudstones are mainly restricted to the silt fraction and are horizontally laminated or massive. There is a gradual contact between mudstones and overlying dolostones. Fossils have not been observed in this lowermost portion of the association, and trace fossils are very rare.

A – *Interpretation*. The cyclic sediments were interpreted by Clemmensen (1978b) as deposits of a fluctuating lake. The green mudstone represents the open lacustrine stage, whereas the dolostone formed in a marginal lacustrine carbonate mudflat environment. The dolomite is probably early diagenetic and formed by pene-contemporaneous alteration of primary calcite mud by evaporative pumping (cf. Wolfbauer & Surdam, 1974).

B – *Description*. These cyclothems are characterized by the income of stromatolitic limestone and oolitic flat pebble conglomerates (fig. 24) (Clemmensen, 1978b). In these cyclothems the dolostones are more sandy and display various sedimentary structures such as wave ripples, desiccation cracks and bioturbation. Halite crystal casts and rare radiating crystal moulds similar to the trona moulds of the Green River Formation (Eugster & Hardie, 1975) occur.

B – *Interpretation*. The cyclothems are interpreted in terms of a fluctuating lake. Whereas the flat pebble conglomerates formed during high energy wave action as beach lags or as local accumulations, the stromatolites possibly formed in shallow nearshore lacustrine water during periods of relative lake stability.

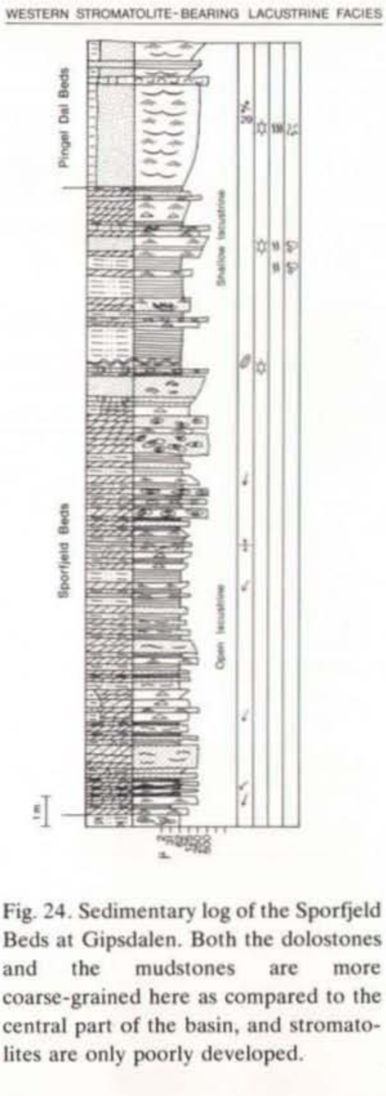


Fig. 24. Sedimentary log of the Sporfjeld Beds at Gipsdalen. Both the dolostones and the mudstones are more coarse-grained here as compared to the central part of the basin, and stromatolites are only poorly developed.

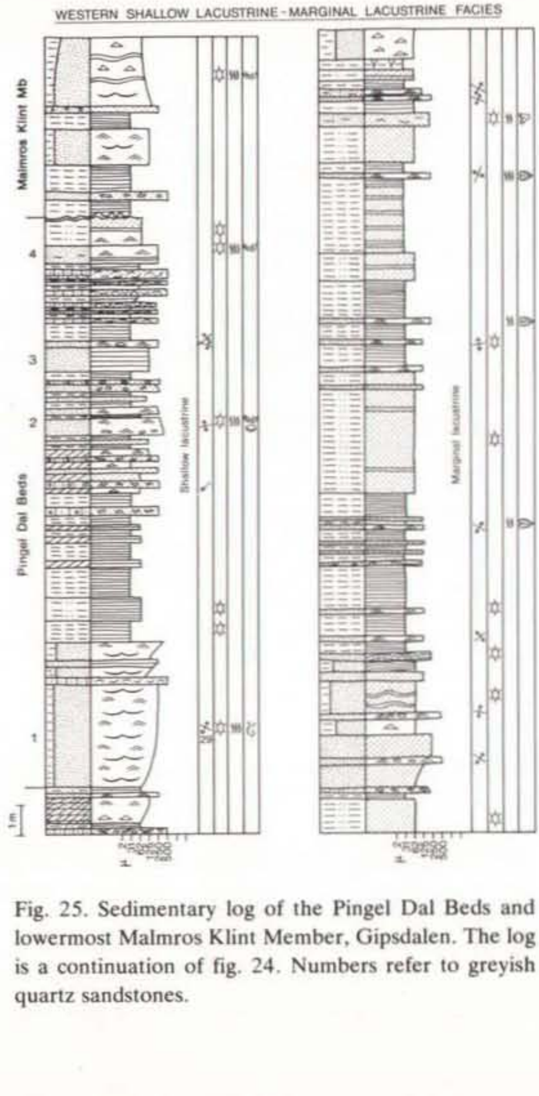


Fig. 25. Sedimentary log of the Pingel Dal Beds and lowermost Malmros Klint Member, Gipsdalen. The log is a continuation of fig. 24. Numbers refer to greyish quartz sandstones.

Facies trends

The upwards increase in sand content and grain size of the dolostones and the fact that these dolostones in the upper half display frequent wave ripples and desiccation cracks seems to indicate a shallowing of the lake accompanied by an increased supply of classic material.

The upwards decrease in gypsum or halite crystal casts and the increased biogenic activity could indicate a general lowering of lake salinity. The development of stromatolitic limestones only in the upper part of the sequence would then confine the formation of these structures to fairly low salinity conditions. This observation contrasts with the general opinion from marine environments expressed by several authors (e.g. Logan *et al.*, 1974; Hoffman, 1976) that the development and preservation of stromatolites are favoured by fairly high salinities.

As a conclusion it is suggested that the association was deposited in a moderately deep to fairly shallow lake with lake salinity decreasing during time from fairly high to within the lower brackish regime. The lake margin environments consisted of carbonate mudflats, which were dolomitized penecontemporaneously in the warm and semiarid climate.

10. **Variegated sandstone-mudstone-stromatolitic limestone association**

General

This association (fig. 25) makes up the Pingel Dal Beds, which have the same geographical distribution as the Sporfjeld Beds. The faunal and sedimentological evidence support a lacustrine environment perhaps subject to rare marine flooding (Clemmensen, 1978b).

Cyclothems

The basic cycles constitute alternations between greenish mudstone and yellowish dolostone commonly with intervening stromatolites or flat pebble conglomerates (A and B cyclothems), but commonly other cycles occur. These consist of alternations between stromatolitic limestone and reddish sandstone or mudstone (C), or couplets of: greenish mudstone and wave rippled sandstone (D), wave rippled sandstone and reddish sandstone and mudstone (E) and greenish mudstone and reddish sandstone or mudstone (F). Only the additional cyclothems C, D, E and F will be briefly described and interpreted below.

C – *Description*. The stromatolites associated with the reddish sandstones or mudstones are yellow weathering, thin (2–5 cm) poorly laminated beds. In extreme cases no lamination can be detected and the stromatolites are only identified by their colour and undulatory upper surface. The reddish sandstone and mudstone are massive, horizontally laminated or show wave ripple lamination. Desiccation cracks are common.

C – *Interpretation*. These cycles probably indicate a fluctuating marginal lacustrine environment (cf. Clemmensen, 1978b). The reddish sediments were probably introduced from nearby alluvial plains during flooding. The stromatolites presumably developed in standing water during minor lake transgressions.

D – *Description*. The cyclothems consist of alternations between green mudstone and greyish fine-medium wave ripple quartz sandstone. Desiccation cracks are common in the sandstones, which are described in some detail by Clemmensen (1978b).

D – *Interpretation*. The green mudstone is interpreted as open lacustrine, whereas the quartz sandstones probably originated on lacustrine shoreline sandflats (Clemmensen, 1978b). The intimate association between the two facies is interpreted in terms of a fluctuating lake level.

E – *Description*. The facies involved in these cyclothems constitute fine and muddy reddish grey quartz sandstones with flaser lamination and darker red sandy siltstones commonly of rather massive nature. In extreme cases it may be difficult to differentiate between the two facies of the cyclothem.

E – *Interpretation*. It appears likely that the cyclothems originated in a marginal lacustrine environment where periods of fluvial flooding and deposition of the red siltstones alternated with periods of lake transgression and wave reworking forming the better sorted, greyish red, fine sandstones.

F – *Description*. These final cyclothems show an alternation between red and greenish mudstones and fine sandstones. The facies are almost identical to those previously described above from other cycles.

F – *Interpretation*. The association of alluvial mudflat sediments (the reddish mudstones and fine sandstones) and the open lacustrine green mudstones suggest a lake margin environment characterized by relatively sudden transgression.

Facies trends

The characteristic feature of this association is the occurrence of greyish shoreline quartz sandstone and reddish alluvial mudflat sediments. The quartz sandstones are coarse-grained and thick (*c*. 4–5 m) below and gradually decrease in thickness and grain size upwards, simultaneously developing a reddish tint. The reddish sediments are rare in the lower portion of the unit and become very dominant towards the top. These sediments furthermore can be shown to be more common in the north-eastern part of the basin.

The income of marginal lacustrine facies is in this association mainly interpreted as a result of intermittent tectonic uplift towards the north (Clemmensen, 1978b). The rejuvenated source area shed more clastic detritus into the basin and quartz sandstones originated in shoreline environments. Coupled with this trend of increased clastic supply, possibly reinforced by increased erosion of the borderlands during a more humid climate, the topographic gradient of the basin gradually diminished. As a result the reddish alluvial mudflat sediments prograded intermittently into the basin.

The upwards increase in freshwater biogenic activity could indicate a gradual change of lake salinity to nearly fresh, and increased climatic humidity is a possible explanation.

Thus one should probably visualize the depositional environment as a fluctuating shallow lake. Lake salinities were low (fresh to slightly brackish), and clastic lake margin environments were well developed.

11. **Red mudstone association**

General

This association (figs 25, 26, 27, 28), which is characteristic of the Malmros Klint Member, is a red-bed sequence that crops out in a very spectacular way in north-eastern

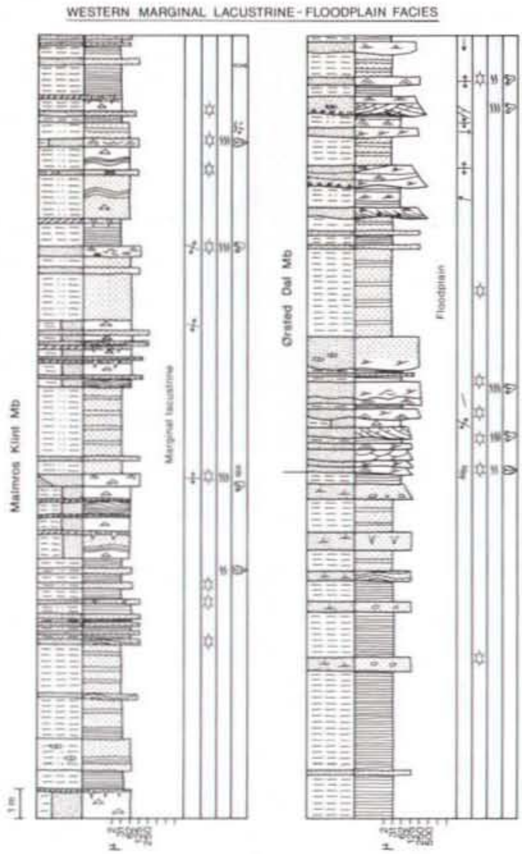


Fig. 26. Sedimentary log of the red-beds of the Malmros Klint Member and lowermost Ørsted Dal Member, Gipsdalen. The log is a continuation of fig. 25.

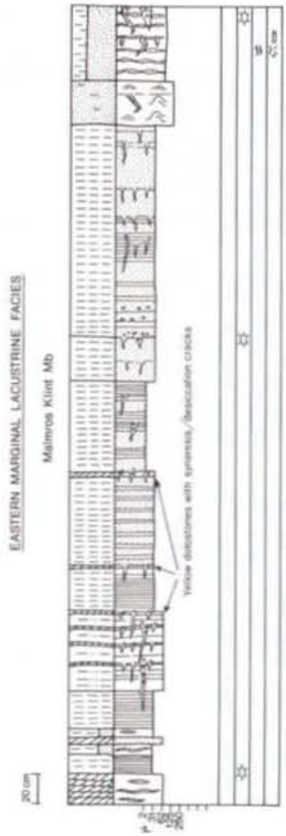


Fig. 27. Detailed sedimentary log of the Malmros Klint Member at Kap Biot. Note the frequent occurrence of thin dolomitic marlstones as well as the common long slender crinkled shrinkage cracks.

Jameson Land and Scoresby Land. The continental lacustrine origin of the association is given by the absence of marine fauna, by the cyclic bedding and sedimentary features (evidence of aquatic deposition, lateral persistent beds, lack of tidal scour) and especially by the presence of a very diverse freshwater trace fossil assemblage (Clemmensen, 1979).

Facies and cyclothems

Also this association is characterized by the presence of cyclic sedimentation. In contrast to the underlying associations, however, this is not easily seen in the field because of the

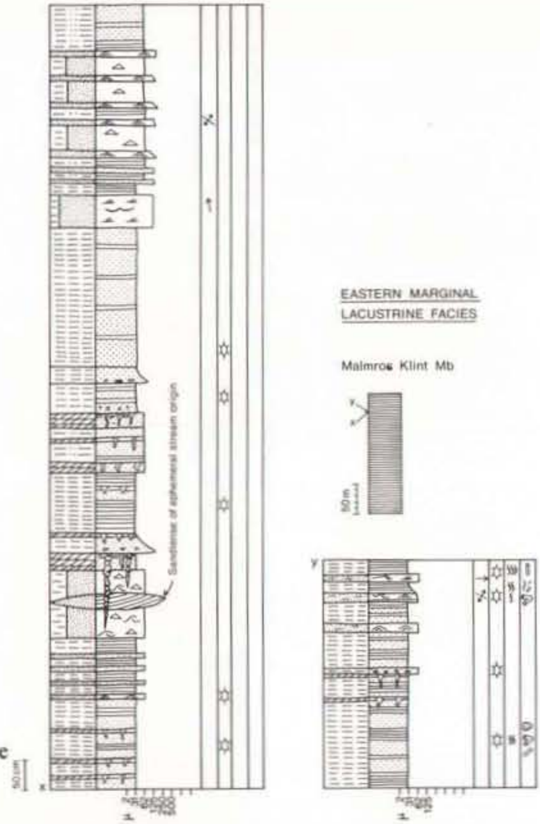


Fig. 28. Detailed sedimentary log of the Malmros Klint Member, Carlsberg Fjord.

rather uniform grain size and colour of the facies involved. Close inspection of well exposed sequences has made it possible to distinguish two slightly different associations of cyclothems (A and B), which are described and interpreted below.

A – *Description*. These cyclothems consist of four main facies: (1) Greyish red fine or coarse siltstone which is lenticularly and horizontally laminated. A general rule is that the coarsest subfacies show lenticular, while the finest only display horizontal lamination; (2) brownish red generally structureless coarse siltstone or fine sandstone occasionally with wave ripple lamination (fig. 9) or current ripple lamination; (3) reddish grey (often with a yellowish overprint) weakly erosive, massive, current rippled or wave rippled muddy sandstones and (4) reddish grey strongly bioturbated flaser and lenticularly bedded muddy sandstones. The burrows are endichnial and relatively numerous in contrast to the former facies where the biogenic structures occur scattered and are found mainly in hyporelief.

All the main facies show intensively mud-cracked upper bedding plane surfaces (fig. 29). In vertical faces the same rocks show numerous horizons with long slender crumbled shrinkage crack casts (fig. 30). Cracks may reach lengths of more than one metre, but commonly lie between a few centimetres and *c.* 25 cm.

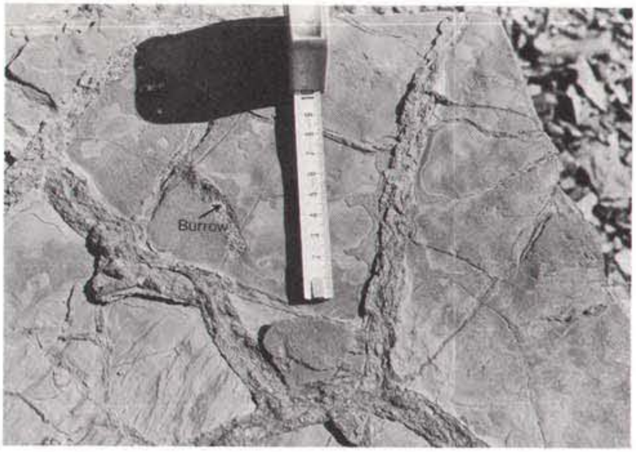


Fig. 29. Several generations of polygonal mud cracks with evidence of multiple filling. The mud cracks probably formed during subaerial exposure. Malmros Klint Member, Carlsberg Fjord.

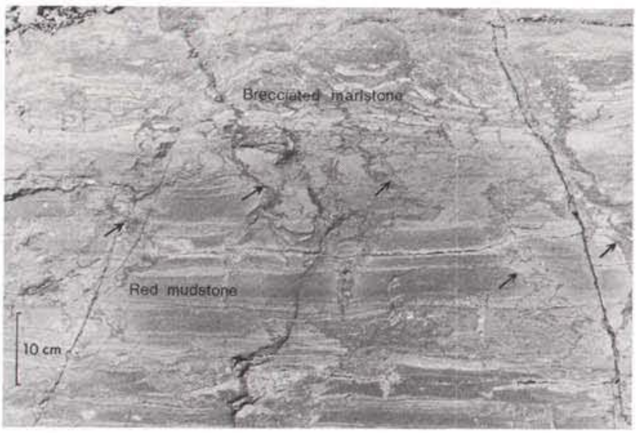


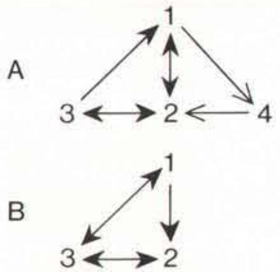
Fig. 30. Red sandy mudstones with a thin brecciated light coloured dolomitic marlstone. The whole sequence is disrupted by numerous slender crinkled cracks (outlined by arrows). These cracks probably formed during the combined effect of desiccation during subaerial exposure and syneresis. Malmros Klint Member, Fleming Fjord.

Three of the facies (4, 2 and 1) are intimately associated with yellowish or brownish weathering, strongly disrupted or even brecciated, centimetre thin, dolomitic marlstones (fig. 30). Other associated facies include rare horizons with centimetre large mud pebbles, large sand lenses with inclined bedding (fig. 28) and horizons with graded layers and antidune structures.

An analysis of recurrent facies at Kap Biot showed that the lower portion of the association contains 102 cyclothems of somewhat varying nature within 125 m. The analysis furthermore shows (fig. 31) that symmetrical alternations between facies 1 and 2 and between facies 2 and 3 in combination with upwards transitions from facies 3 to 1, from 1 to 4 and from facies 4 to 2 constitute the statistical significant cyclothems.

A – *Interpretation*. A crucial point in the interpretation of the cycles is the origin of the impressive mud cracks. Were they formed by desiccation in a subaerially exposed environment (sun cracks), or were they formed subaqueously by syneresis (White, 1961; Burst, 1965).

MALMROS KLINT MEMBER



C

	N	n	%
1	71	25	35
2	73	10	14
3	0	0	0
4	4	3	75

1. Greyish red laminated siltstone
2. Brownish red massive siltstone
3. Red ripple-laminated muddy sandstone
4. Red bioturbated muddy sandstone

Fig. 31. Facies relationship diagrams depicting facies transitions within the lacustrine Malmros Klint Member at Kap Biot: A. Corrected facies relationship diagram, lower part of the member. B. Corrected facies relationship diagram, upper part of the member. C. Table illustrating the number of times (n) each facies (1–4) is associated with the dolomitic marlstone.

In the present examples bedding planes most commonly display regular and well developed polygons of the sun crack type, and the cracks locally show evidence of multiple filling (fig. 29). Most cracks were filled from above, but others were injected, at least to some degree from below. This accounts especially for the cracks associated with the thin dolomitic marl layers (fig. 30). It is therefore suggested that many of the cracks, and especially the long ones, had a complex history of generation. Most were probably initiated as sun cracks with infilling from above, slightly later, however, salinity changes or initial compaction caused dewatering of the mud (syneresis) and many cracks turned into a stage of upward moving fluid and sediment.

Syneresis cracks appear to be common in ancient lacustrine rocks (see Van Houten, 1964; Picard & High, 1972; Donovan & Forster, 1972; Clemmey, 1978), whereas sun cracks just indicate subaerial exposure. The complex cracks in the discussed rocks therefore seem to indicate that we had a lacustrine environment characterized by frequent subaerial exposure and with common synsedimentary dewatering of individual beds.

The greyish red mudstones of facies 1 probably originated in a relatively open lacustrine environment where settling of mud from suspension only was affected by weak intermittent wave action. Progradation of lake shoreline flats caused the reddish brown massive or wave rippled fine sandstones (facies 2) to overlie the mudstones. When progradation continued, facies 3 sandstones of distal alluvial mudplain origin topped the cycles. Rare, strongly bioturbated flaser and lenticularly laminated sediments of facies 4 probably originated in a shoreline environment during transgressive phases. The thin dolomitic marlstones are interpreted as open lacustrine chemical precipitates. Practically identical marlstones have been described from Upper Triassic lacustrine rocks in North America (Van Houten, 1964). The associated facies with mud pebbles, antidune structures etc. indicate periods of flash flooding.

The total lack of gypsum, halite etc. and the frequent occurrence of freshwater trace fossils indicate that the lake was fresh to only slightly brackish.

Thus, the cyclothems probably formed in a large featureless lake subject to frequent shoreline oscillations and flash flooding during periods of subaerial exposure.

B – *Description*. These cyclothems consist of the same facies as the former ones, but facies 4 (bioturbated fine sandstones) is missing. Another point of significance is that the facies 3 is on the average more coarse-grained than in the former cyclothems. Rare associated facies include medium-grained erosive sandstones displaying large-scale low angle cross-bedding of longitudinal type. The facies relationship diagram in fig. 31 indicates that cyclothems consist of symmetrical alternations of facies 1 and facies 3, of facies 2 and facies 3 as well as upward transitions from facies 1 to 2. The frequent occurrence of facies 3 light grey sandstones in these cyclothems shows up clearly at a distance giving the sequences a striped appearance. This contrasts with the former cyclothems which are less easy to depict at a distance in the field.

B – *Interpretation*. Compared to the former A cyclothems the B cyclothems show the following points of difference:

1. Less frequent occurrence of aquatic lacustrine sediments (facies 1).
2. More frequent occurrence of shoreline (facies 2) and especially alluvial flood plain facies (facies 3).
3. A relatively more coarse-grained nature of the flood plain sandstones.

This suggests that the cyclothems depict shoreline fluctuations in a more marginal and more fluvially influenced part of the lake.

Facies trends

In a vertical sequence the B cyclothems always overlie the A cyclothems. Thus within the fluctuating lacustrine environment there was a clear tendency of gradual progradation. In other words the lake was gradually infilled, causing shoreline flat and alluvial flood plain facies to dominate towards the top of the facies association. This clear-cut overall coarsening upwards trend could be tectonically or climatically induced or most likely a combination of both.

The first hypothesis involves gradual rejuvenation of source area relief and a corresponding increased erosion rate causing the flood plain to prograde over the lacustrine sediments. The second hypothesis explains the observed time trend of sedimentation by assuming a decrease in aridity through time. An increased annual precipitation (increased length of rainy season) would probably produce an increased annual run-off. If the plant cover in spite of this change was still negligible owing to the overall semiarid climate, the net result would probably be an increased sediment yield to the basin. During such a climatic change the lake shoreline would tend to prograde assuming that subsidence was fairly constant. Tectonic rejuvenation of source areas is here favoured as a dominant control because of the general setting of the Triassic sediments in a rift basin, but climatic control may well have been important as well.

In lateral respect the association displays a pronounced thinning from more than 200 m thick lacustrine mudstones in the east to thin (40–60 m) sandy siltstones towards the west. Furthermore, there is evidence to suggest that the upper half of the eastern lacustrine siltstone association can be correlated with fluvially more coarse-grained deposits of the basal part of the overlying association (fig. 3). This lateral trend seems to indicate that the western source area was the major one during deposition of these two associations and that clastic material was mainly carried into the lake basin from western source areas.

12. **Red mudstone – grey sandstone association**

General

This association (figs 26, 32) is characteristic of the basal clastic portion of the Ørsted Dal Member, which occurs in Jameson Land, Scoresby Land and on south-eastern Traill Ø. Lack of marine fossils and evidence of oxidation (red coloration) and subaerial exposure, existence of continental trace fossils and occurrence of alluvial fining upwards sequences indicate deposition in a fluvially dominated continental regime.

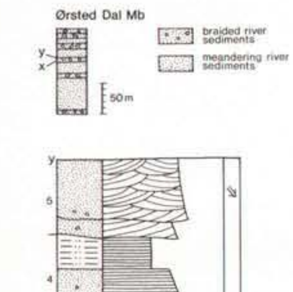


Fig. 32. Sedimentary log of greyish pebbly sandstones and red mudstones of the Ørsted Dal Member, Kolledalen. The sequence can be divided into five fining upwards cyclothems. Maximum pebble size varies from 6–12 cm in the lower part to 2–3 cm in the upper part.

Facies and cyclothems

The association is characterized by two main facies: (1) red or more rarely greenish or variegated mudstones and (2) fine-coarse sandstones with various types of ripple lamination and large-scale cross-bedding as well as horizontal lamination.

The sandstones commonly possess erosive lower surfaces and as a general rule show a fining upwards grain size. If two or more sandstones are superimposed, the lower one is almost always the coarsest one. The mudstones always overlie the sandstones, and well-developed fining upwards cycles are therefore the result. On the basis of the sandstones grain size, thickness, internal sedimentary structures and sandstone-mudstone ratio two well defined (A, B) cyclothems can be distinguished, which are described below. Gradational types exist between these two end members.

A – *Description*. These cyclothems constitute small-scale fining upwards sequences (commonly from less than 1 m to a few metres) with the following general features:

1. Relatively fine grain size of the sandstones (observations at Gipsdalen indicate a variation in mean grain size between 125 μ and 500 μ).
2. Relatively thin sandstones (measurements at Gipsdalen indicate thicknesses between 15 cm and 100 cm with a mean of 46.5 cm).
3. Sandstones display longitudinal cross-bedding, and intraformational mud pebbles dominate over extraformational clasts.
4. The mudstone-sandstone ratio is relatively high (1.41 at Gipsdalen, where 40 m of the exposure was measured in detail).

Whereas the mudstones are horizontally laminated, the sandstones contain a wealth of physical sedimentary structures: longitudinal cross-bedding, large-scale trough cross-bedding, current ripple lamination (commonly of climbing attitude), wave ripple lamination (mostly concentrated in the upper portion of the sandstones), convoluted bedding, groove marks and flute marks. The sandstones show distinct pinching out and/or swelling in lateral respect; interbedded mudstones may commonly wedge out and over- and underlying sandstones then join to one amalgamated sandstone. Desiccation cracks (sun-cracks) are common in the mudstones and continental freshwater trace fossils are numerous in both mudstones and sandstones.

A – *Interpretation*. The general features of the fining upwards sequences indicate a flood plain origin (e.g. Allen, 1965, 1970b), and the occurrence of longitudinal cross-bedding suggests the existence of point bars in high-sinuosity meandering rivers (Moody-Stuart, 1966). The observed point-bar cross-bedding is quite similar, apart from scale, to those described from the Miocene of Spain (Puigdefábregas, 1973) and show intimate interbedding between small-scale current ripple lamination and large-scale low angle accretional sets. The topping mudstones are interpreted as overbank deposits. The general lack of caliche (only rare calcite nodules occur) indicates that discharge was relatively continuous. Wave ripples and sun cracks, on the other hand, indicate that periods of transportation and sedimentation were followed by ponding, stagnation and finally subaerial exposure.

B – *Description*. In these cyclothems the following characteristic features could normally be observed:

1. Relatively coarse grain size of the sandstones (observations at Gipsdalen show a variation in mean grain size between 250 μ and 2000 μ).
2. Relatively thick sandstones (at Gipsdalen between 15 and 310 cm with a mean of 97 cm).
3. The lack of longitudinal cross-bedding and the dominance of extraformational clasts over intraformational ones.
4. The mudstone-sandstone ratio is relatively low (0.51 at Gipsdalen, where 15 m of these cyclothems were measured in detail).

The mudstones of these sequences are practically identical to those in the A cyclothems. The sandstones, on the other hand, mainly show intricate trough-formed (channel-fill) cross-bedding, very difficult to measure with respect to palaeocurrent directions. Associated structures in the lower parts of the sandstones include horizontal lamination (and associated streaming lineation) and planar, large-scale cross-bedding. The upper part of the sandstones display common, small-scale, current ripple lamination and more rarely wave ripple lamination. The basis of the sandstones is distinctly erosive and often lined with quartzite pebbles between a few centimetres and 10 cm long. Laterally the sandstones pinch and swell, but individual sandstone horizons may occasionally be traced for several hundreds of metres.

B– *Interpretation*. The frequent erosion surfaces, the cross stratified channel fills, the pebbles and overall large grain size and the relative rarity of mudstones suggest deposition by powerful river currents. Lack of longitudinal cross-bedding, which is considered diagnostic of meandering rivers (e.g. Moody-Stuart, 1966) and comparison with published recent and ancient braided river sequences (e.g. Doeglas, 1962; Williams & Rust, 1969; Coleman, 1969; Steel, 1974a; Harms *et al.*, 1975 and Steel *et al.*, 1977) make a distal braided river situation for the present cyclothems the most likely. Lack of caliche suggests relatively continuous discharge, but desiccation cracks in the mudstones (overbank deposits) point towards frequent exposure of these finer sediments. Periods of stagnation, even within the channels, are shown by the wave rippled sandstone horizons.

Facies trends

In a vertical respect the B cyclothems always follow on top of the A cyclothems. Thus distal braided river deposits prograded with time over the meandering flood plain systems. This trend could have two different causes: tectonic rejuvenation of source areas or climatic changes or both. The marked upwards increase in grain size and the income of extraformational pebbles suggest that tectonic rejuvenation must have played a role. A climatic shift towards more humid conditions, which is apparent at the end of the Triassic, would increase the annual run-off, but it is uncertain whether this also would result in an increased sediment yield to the basin.

In lateral respect the association shows a pronounced grain size decrease and corresponding thinning towards the east, where the lacustrine siltstones of the underlying association in contrast are very thickly developed (fig. 3). Furthermore, the B cyclothems have only been observed in the uppermost part of the association in the western part of the basin. A major source area towards the west seems to be the best interpretation of this lateral trend; the eastern source probably only shed minor material into the basin. Palaeocurrent analyses are consistent with this interpretation as they indicate (fig. 10) eastern (or locally southern) transport in the western part of the basin, whereas palaeocurrents in the eastern half of the basin were towards north.

Thus it appears as if there was an actively eroded western source area from where rivers were directed eastwards into the basin. The central and eastern part of the basin was occupied by lacustrine or with time distal flood plain sediments. The upwards trend from flood plain to braided rivers (western half of the basin) or from lacustrine to flood plain (eastern half of the basin) could be partly climatically controlled, though source area rejuvenation probably acted as a dominant control.

13. **Light-coloured carbonate rock association**

General

This association, which characterizes the Tait Bjerg Beds, constitutes the uppermost unit of the mainly continental Triassic sequence. The sediments occur in the south-eastern part of the Jameson Land Basin, and wedge out towards the north-east. The stratigraphical occurrence between fluviatile red-beds of the lowermost Ørsted Dal Member and the Rhaetian–Liassic deltaic sediments of the Kap Stewart Formation (Clemmensen, 1976), as well as faunal evidence (freshwater bivalves, ostracods and vertebrate remains including scales of a marine fish in the topmost beds) suggest deposition in a flood plain environment eventually transgressed by the sea.

Facies and sequences

The association can be divided into a lower unit with red or variegated red-beds and impure limestones (A) and an upper unit with thin dark mudstones, yellowish dolomitic limestones and fossiliferous conglomeratic limestones (B).

A – *Description*. The red or variegated mudstones and sandstones of these sequences are identical to those occurring in the underlying association (the Ørsted Dal Member). The mudstones are dominantly horizontally laminated and display desiccation features. The associated rare sandstones are fine to medium, display fining upwards and contain mud pebbles along their lower contacts. The greyish or variegated limestones, which are embedded in the variegated mudstones, weather out with a characteristic crumbly surface and are more resistant than the surrounding mudstones. The micritic limestones contain much silty terrigenous matter and are structureless apart from common intervals with spar-filled open space structures. The open space structures include centimetre-large vugs and cracks. No fossils were found in these limestones.

A – *Interpretation*. The general aspects of the sequence suggest a distal flood plain origin and the cycles can be viewed as fluviatile fining upwards cyclothems initiated by thin crevasse splay(?) sandstones and topped by flood plain mudstones and shallow lake limestones.

B – *Description*. The yellowish dolomitic limestones and dark mudstones of these units are already described by Grasmück & Trümpy (1969). The dark mudstones are thin (a few to 10–20 cm) and often contain large freshwater bivalves. The associated dolomitic limestones vary in thickness between a few decimetres and more than one metre. They also show horizons with a brecciated or fragmented appearance and bedding planes may display desiccation cracks. Terrigenous quartz grains occur in varying amounts. The limestones contain plant remains, freshwater bivalves and small gastropods. Intimately associated with the limestones are limestone conglomerates with worn vertebrate fragments, and scales and teeth. The fossils occur randomly orientated in association with quartz grains, rock fragments and limestone pebbles. The various clasts vary in size between coarse sand and fine gravel, whereas the vertebrate fragments may reach several centimetres in length. Phosphorite is a common constituent of the 'bone-beds' and occurs as rounded intraclast or as a brownish matrix, in the latter case in association with calcite. In general appearance the 'bone-beds' compare closely to the Rhaetic bone-beds of England (Greensmith *et al.,* 1971; and own observations).

B – *Interpretation*. The plant remains, freshwater bivalves and vertebrate remains (? amphibians) suggest a continental environment favourable for the preservation of materials introduced by streams from surrounding areas. The scales of a marine fish on the other hand indicate periods of marine influence. The occurrence of intraformational clasts and relatively large quartz grains and rock fragments in the 'bone-beds' suggest erosion of earlier deposits, and the high percentage of vertebrate remains in the same facies suggest repeated reworking in an environment with a low terrigenous influx. The environment should perhaps be viewed as a distal flood plain with carbonate lakes that were affected by brief but frequent marine transgressions.

Facies trends

There is a gradual transition between the underlying flood plain deposits of the Ørsted Dal Member and the flood plain carbonate lake sediments represented by the A cyclothems. These continental A sequences are again gradually overlain by the partly marine B sequences with dolomitic limestones, dark mudstones and fossiliferous bone-beds. The coarse-grained deltaic deposits of the Kap Stewart Formation follow on top of the B cyclothems.

Both sequences in the Tait Bjerg Beds have their maximum development along the eastern margin of the basin and wedge out towards the west. The eastern part of the basin appears therefore to have been the site of the greatest subsidence at this period, and the sea, which invaded the basin, probably lay to the east (cf. Clemmensen, 1976).

Thus the association seems to represent a shift from strictly continental to lagoonal conditions.

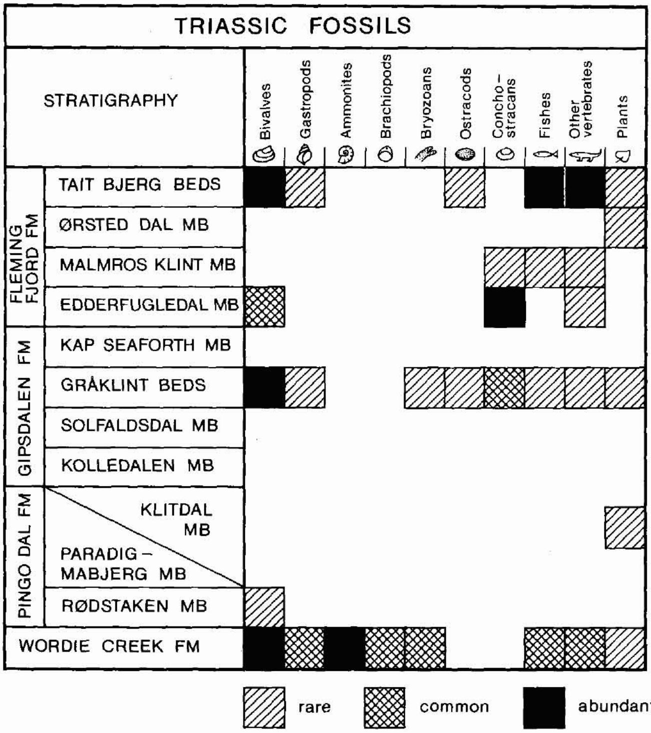


Fig 33. The stratigraphical occurrence of Triassic fossils. Based on Grasmück & Trümpy (1969), Perch-Nielsen *et al.* (1974), Birkelund & Perch-Nielsen (1976) and own observations.

TRACE AND BODY FOSSILS

Body fossils are rare and have only been located in the Rødstaken Member, the Gråklint Beds, the Edderfugledal Member, the Malmros Klint Member and the Tait Bjerg Beds (fig. 33). In contrast to the underlying marine Wordie Creek Formation (see e.g. Trümpy, 1969), the Middle–Upper Triassic fauna, which has been described by Trümpy (1961), Grasmück & Trümpy (1969), Defretin-Lefranc (1969), Perch-Nielsen *et al.* (1974) and Clemmensen (1978b), is characterized by the complete absence of ammonites.

The rarity of body fossils stands in marked contrast to the wealth of trace fossils. Some of these trace fossils were already observed and illustrated by Stauber (1942), but he misinterpreted most of them as physical surface markings. More recently the non-marine Triassic trace fossils have been described by Bromley & Asgaard (1972, 1979), Perch-Nielsen *et al.* (1972) and Clemmensen (1977, 1978b). The dominant non-marine trace fossils of the Pingo Dal, Gipsdalen and Fleming Fjord Formations have been compiled in fig. 34.

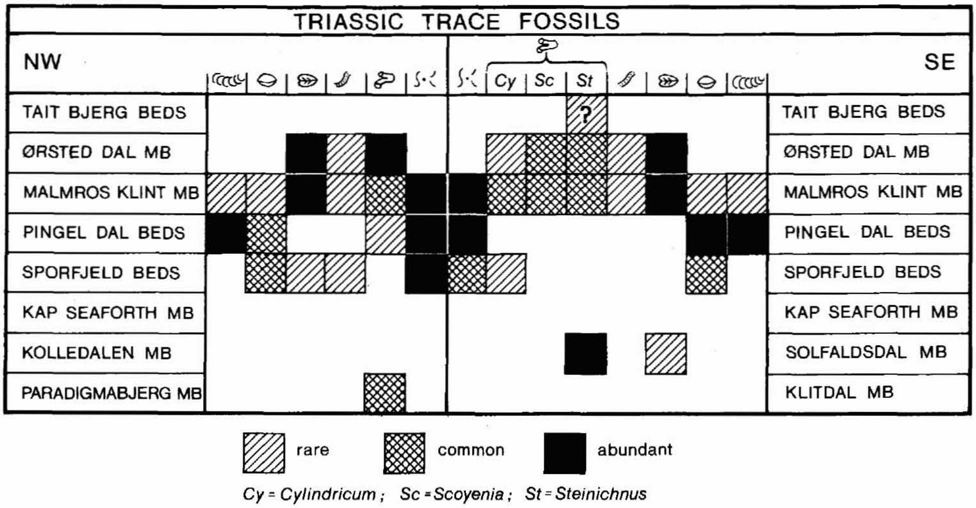


Fig. 34. The stratigraphical occurrence of trace fossils in the upper(?) Scythian – lower Rhaetian Triassic sequence in Jameson Land and Scoresby Land.

VERTICAL AND LATERAL SUCCESSIONS OF ENVIRONMENTS

Description. The depositional environments and their lateral and vertical trends are best known in the Jameson Land Basin due to continuous and often superb exposures. In contrast Traill Ø only possesses incomplete and fragmentary exposures, and the environmental framework is accordingly less well known. The following description is therefore based only on observations in the Jameson Land Basin (fig. 35).

In the western part of the basin the continental sequence is initiated by alluvial fan and braided river conglomerates and sandstones of the Paradigmabjerg Member. Locally this member can be divided into one coarsening upwards and five fining upwards megasequences. The coarse-grained alluvial deposits interfinger with and are overlain by aeolian dune sandstones of the Kolledalen Member. These aeolian sandstones are again overlain by a rather thin lacustrine sequence, namely the gypsum bearing Kap Seaforth Member, the Edderfugledal Member with stromatolites and the Malmros Klint Member with red silt and sandstones. The lacustrine red-beds of the latter member grade upwards into the more coarse-grained fluvial red-beds of the Ørsted Dal Member. Also the Ørsted Dal Member constitutes a coarsening upwards sequence. The fluvial sediments are capped by a thin sequence dominated by lake or lagoonal carbonates of the Tait Bjerg Beds.

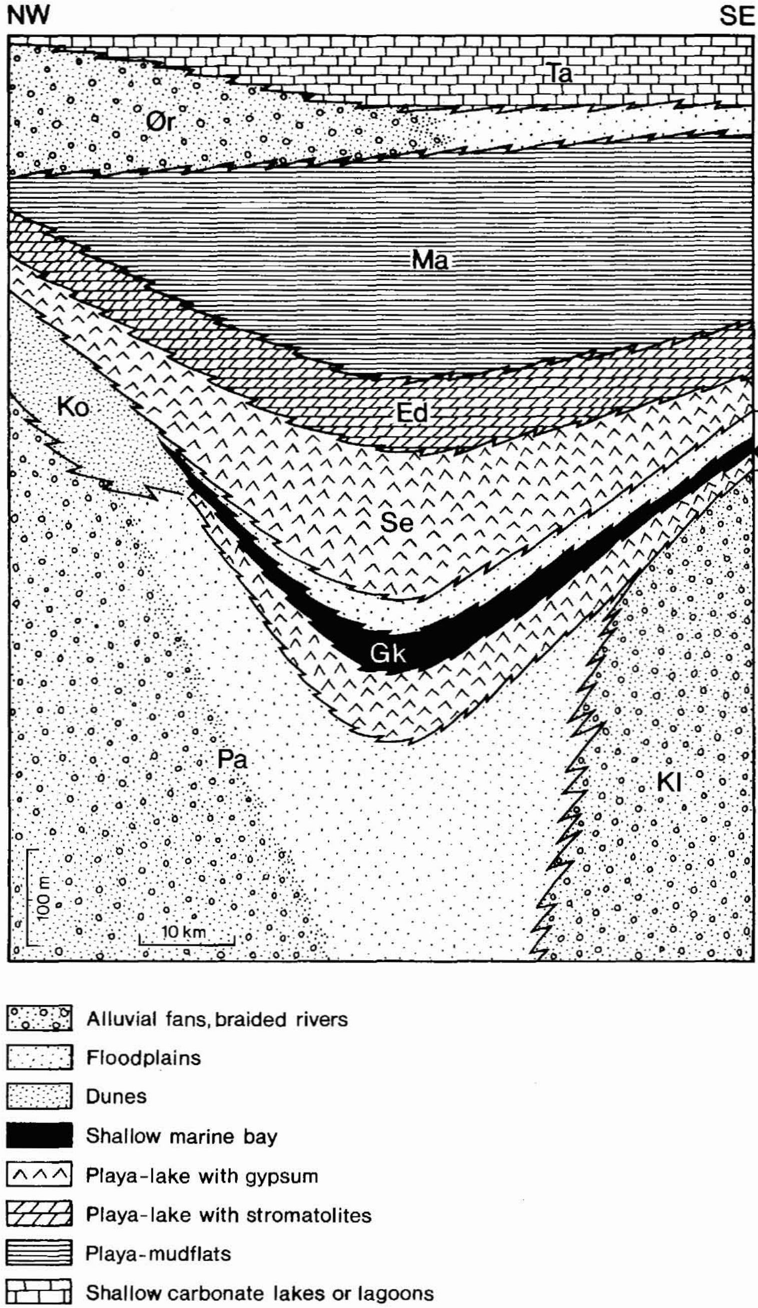


Fig. 35. Vertical and lateral succession of Triassic depositional environments, Jameson Land Basin. Kl = Klitdal Member; Pa = Paradigmabjerg Member; Ko = Kolledalen Member; So = Solfaldsdal Member; Gk = Gråklint Beds; Se = Kap Seaforth Member; Ed = Edderfugledal Member; Ma = Malmros Klint Member; Ør = basal clastic part of Ørsted Dal Member; Ta = Tait Bjerg Beds.

In the eastern part of the basin a rather similar sequence is developed. Thus basal coarse-grained alluvial fan deposits (Klitdal Member) are overlain by lacustrine sediments (Solfaldsdal, Kap Seaforth, Edderfugledal, and Malmros Klint Members) and fluvial sandstones (Ørsted Dal Member), and the sequence is again topped by lake or lagoonal carbonates of the Tait Bjerg Beds. In contrast to the western part of the basin the lacustrine sediments here are interbedded with shallow marine limestones of the Gråklint Beds. Further points of dissimilarity are the development of thick lacustrine rocks (especially well seen in the eastward thickening of the Malmros Klint Member), the thin and fine-grained appearance of the Ørsted Dal Member and the increased thickness of the Tait Bjerg Beds towards the south-east.

In the central part of the basin the sequence is initiated by fluvial sandstones of the Pardigmabjerg Member, while conglomerates are lacking. Otherwise the sequence is rather similar to that encountered along the eastern margin of the basin.

Interpretation. Following tectonic uplift of both western and eastern uplands alluvial fan sediments were shed laterally into the basin. With time these coarse-grained marginal sediments were gradually overlapped by finer-grained flood plain, aeolian, lacustrine and shallow marine rocks (fig. 35). This transgressive or retrogradational trend is probably related to sourceward retreat of the borderland scarps and their adjacent alluvial fans (cf. Bull, 1972, p. 77).

The sudden appearance of marine sediments on top of the aeolian or lacustrine sediments appears to indicate temporary subsidence of the eastern borderland, just as the abrupt income of flood plain sediments above the marine rocks would seem to indicate renewed uplift of this borderland. It is suggested that the sea, which invaded the basin, lay to the north-east.

The upper thick lacustrine sequence is overlain by fluvial deposits. This part of the succession can therefore be regarded as regressive and it appears as if tectonic uplift of the borderlands again took place. This time, however, mainly the western borderland shed sediment into the basin.

BASIN CONFIGURATION, SEDIMENTARY TECTONICS AND PALAEOGEOGRAPHY

The upper(?) Scythian – Rhaetian Triassic rocks of the N–S orientated central East Greenland basin forms an up to 300 km long and *c.* 75 km wide fault bounded pile of mainly continental clastic sediments with subordinate evaporites. The continental Triassic sediments are overlain by fluviatile and tidally influenced deltaic Rhaetian–Liassic rocks (Sykes, 1974; Clemmensen, 1976) which gives way to various marine Jurassic sandstones and dark mudstones (Surlyk *et al.*, 1973) of considerable thickness.

The faults that bound the Triassic basin can today be determined partly by direct field mapping, partly by indirect observations. The indirect evidence of Triassic fault activity include marked lateral facies changes towards the presumed fault lines, palaeocurrent drainage away from the fault lines or major stratigraphic unconformities.

The western fault system can today be directly mapped in the field. This N–S trending fault system was termed the post-Devonian Main Fault System by Vischer (1943) and was obviously reactivated several times during the late Palaeozoic and Mesozoic epochs. The indirect evidence of movements along these western fault lines in Early Triassic time derive from the existence of coarse-grained alluvial fan deposits (Paradigmabjerg Member) banked up against the fault systems and from palaeocurrent analyses indicating that the fans spread eastwards from a western source area. The suggestion of eastern marginal Early Triassic fault lines along the Liverpool Land massif and its probably northwards prolongation comes from indirect evidence alone, viz. the westward draining alluvial fan deposits of the Klitdal Member. In the Late Triassic time the western fault zone was once again reactivated as indicated by the eastward streaming fluvial conglomerates and pebbly sandstones of the Ørsted Dal Member.

The existence of differential movements along NW–SE running fault lines crossing the main N–S trending Triassic rift valley is suggested by various facies trends, palaeocurrent analysis and some marked sedimentary unconformities.

Thus during deposition of the Middle Triassic Edderfugledal Member a northern source area north of Kejser Franz Josephs Fjord shed coarse-grained material into the basin (Clemmensen, 1978b), and slightly later large parts of Traill Ø were even subject to general tectonic uplift as suggested by the major unconformity on north-eastern Traill Ø between the Middle Triassic Edderfugledal Member and the Middle Jurassic Pelion Member (Clemmensen, 1977; Surlyk, 1977). Finally in Rhaetian–Liassic time there is evidence to suggest tectonic uplift north of Kong Oscars Fjord (Clemmensen, 1976).

Thus it appears as if the Triassic basin was formed by subsidence along major N–S trending fault lines (fig. 36). Main rifting took place in Early Triassic time, minor rifting occurred in Late Triassic time. The Early Triassic tectonic phase is

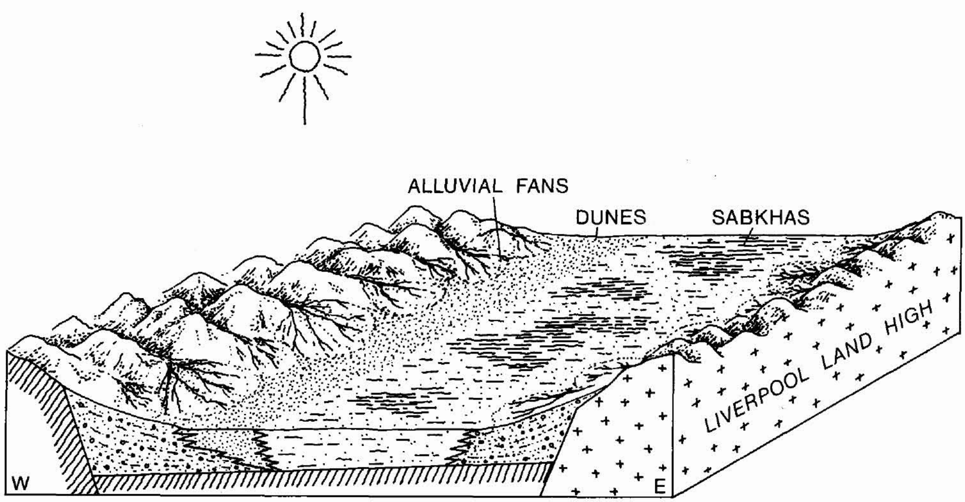


Fig. 36. Generalized palaeogeographical reconstruction of the Jameson Land Basin in late Scythian – early Anisian times. The dune sand is interbedded with minor fluvial sediments and the sabkha sediments are underlain by floodplain deposits. The fault block was probably tilted slightly towards the west. The eastern margin was relatively passive after initial upheaval. This led to the sourceward retreat of the alluvial fans eventually covering the parent fault. Vertical scale highly exaggerated.

here correlated with the Hardegsen phase of North-Western Europe, while the Late Triassic phase is included in the 'early Kimmerian phase' (cf. Ziegler, 1978). Differential movements along NW–SE running cross fault systems now hidden in the recent Kong Oscars Fjord and Kejser Franz Josephs Fjord apparently started already in the Triassic, as suggested above, and continued into the Jurassic as a dominant control on sedimentation (e.g. Surlyk, 1977). The interaction between the N–S trending Liverpool Land fault system and the Kong Oscars Fjord fault system probably formed a region of intermittent tectonic subsidence just east of Kap Biot through which marine transgression could reach the continental basin.

When viewed in the light of plate tectonics and rifting of a divergent continental margin the discussed Triassic basin can be related to early Atlantic rifting and break-up of the 'Laurasian' megacontinent. Similar early rifting phases have variously been termed the rift valley stage (Schneider, 1972), the arching stage (Lowell *et al.*, 1975), the continental rift valley stage (Kinsman, 1975) and the intracontinental rift basin stage (Selley, 1976).

According to Schneider (1972) the diagnostic sedimentary record of this stage should be a mixture of normal terrigenous material, basic and alkaline volcanic rocks, granitic conglomerates, river and lake deposits, and non-marine evaporites. Apart from the fact that volcanic rocks are totally absent in the Triassic infill of the Central East Greenland Basin the rocks in question possess the above-mentioned

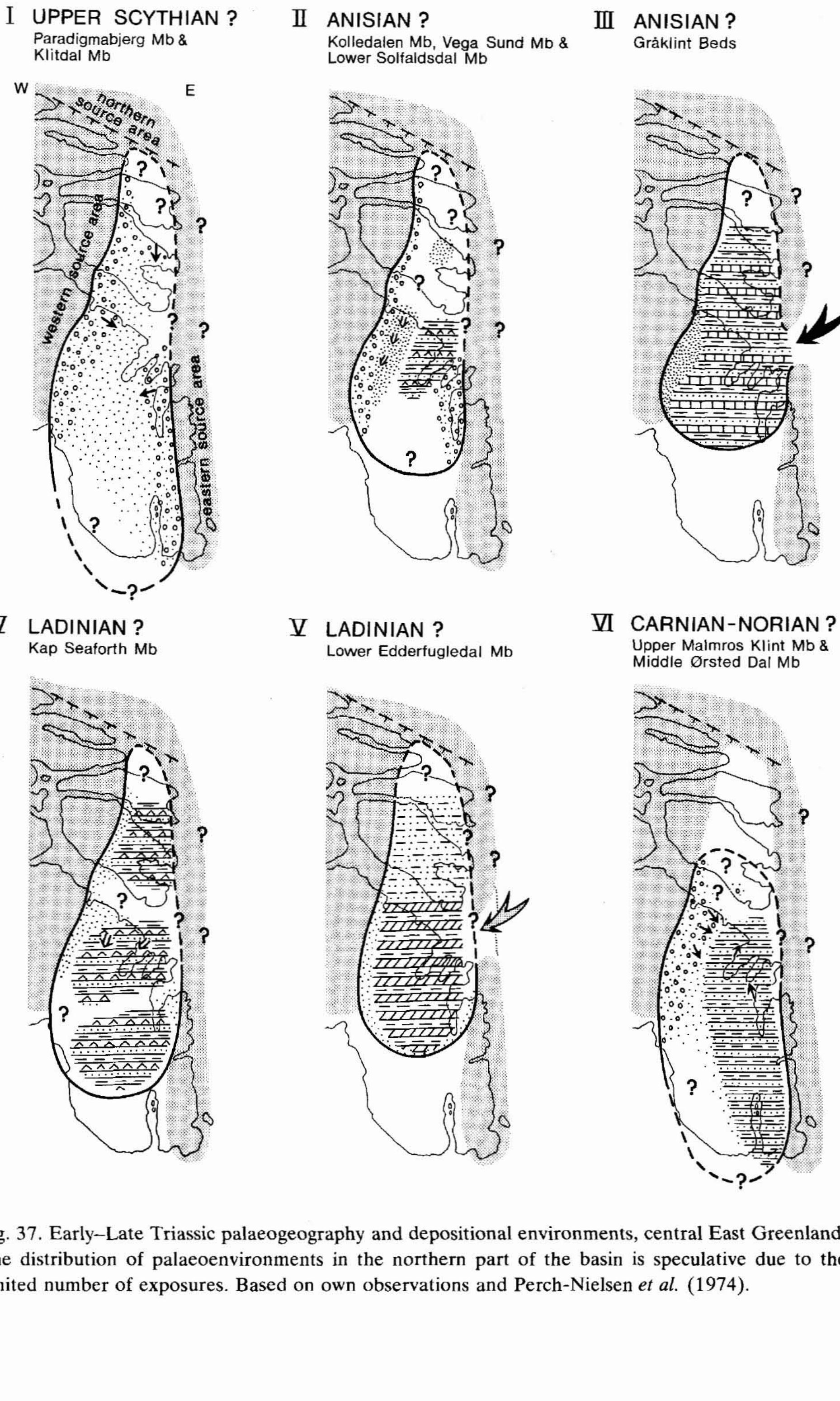


Fig. 37. Early–Late Triassic palaeogeography and depositional environments, central East Greenland. The distribution of palaeoenvironments in the northern part of the basin is speculative due to the limited number of exposures. Based on own observations and Perch-Nielsen *et al.* (1974).

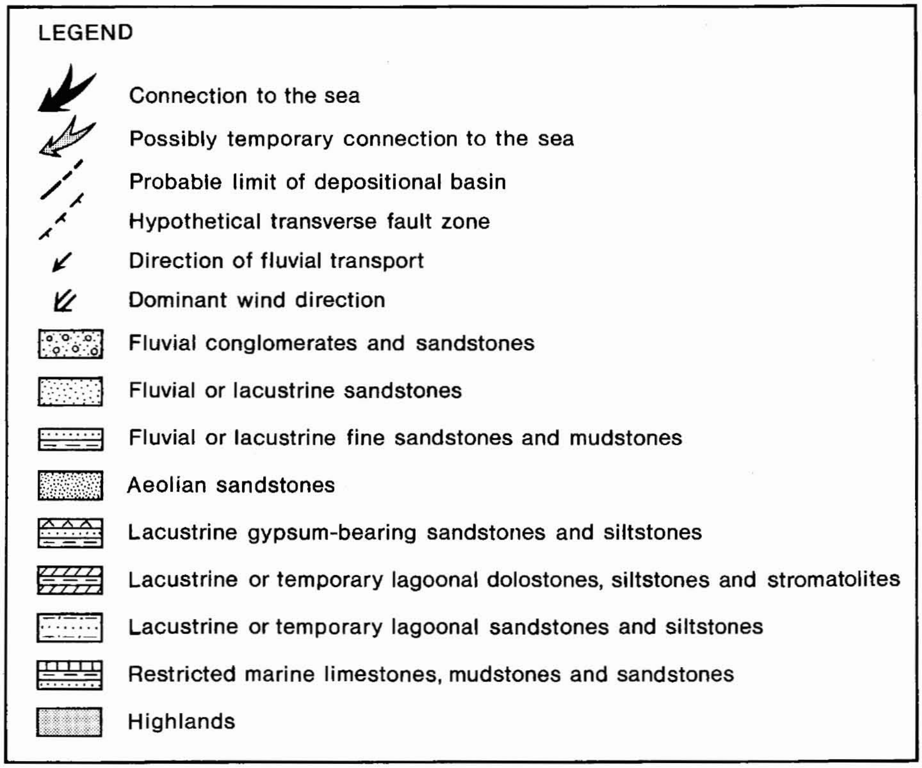


Fig. 37 cont. Legend to the palaeogeographical maps.

characteristics. In contrast to the Triassic of East Greenland the Triassic rift basin sediments of Morocco and Eastern North America do contain volcanic rocks (Mattis, 1977; Van Houten, 1977).

Now having discussed the basin configuration and tectonic setting it is attempted to delineate the changing palaeogeographical pictures of the basin through Triassic times. A series of palaeogeographical maps have therefore been constructed (fig. 37) based on tectonic, lithostratigraphic and palaeoenvironmental considerations. The stages suggested are highly tentative because of the limited biostratigraphical control.

In the following each map will be briefly described.

I Upper Scythian?

Combined with tectonic uplift of western, eastern and possibly also northern source areas a relatively long rift valley was formed probably stretching from Scoresby Sund in the south to Kejser Franz Josephs Fjord in the north. Conglomerates and sandstones of alluvial fan and braided river origin were deposited both along the western and eastern margins of the basin (fig. 36). Palaeocurrent analysis of the Paradigmabjerg and Klitdal Members indicate eastward (or locally southward) and westward palaeodrainage respectively (see also fig. 10). The centre of the basin was occupied by relatively fine-grained sandstones of flood plain origin (fig. 36).

II Anisian?

Erosion of the uplifted borderlands gradually ceased with time and the coarse-grained marginal belts of alluvial fan deposits correspondingly narrowed. The flood plain deposits in the centre of the basin gave way to aeolian dune sandstones (to the west), aeolian sheet sandstones (to the north) and a gypsiferous playa lake (to the east). Dominant aeolian wind transport was from the NNE, but frequent winds from SSE caused an effective net transport towards the west. The depositional basin probably became somewhat reduced in length in this time interval.

III Anisian?

As a result of tectonic subsidence in the region just east of Kap Biot the basin was flooded by marine water during a brief period in the Middle Triassic. Extensive beach barriers of calcareous sandstones and calcarenites were built up in the eastern part of the basin around Fleming Fjord while black lagoonal mudstones were the dominant sediment towards south and west. Towards the north on Traill Ø calcareous shoreline sandstones and associated minor black lagoonal mudstones probably were deposited during the same marine interlude. During the marine episode a sparse low diversity fauna entered the basin and colonized the eastern part of the basin around Fleming Fjord.

IV Ladinian?

After the Anisian? marine interlude continental deposition reappeared, and flood plain and lacustrine sandstones and siltstones were deposited south of Kong Oscars Fjord (north of this fjord evidence is meagre). Then very shallow gypsiferous saline playa lakes were established throughout the whole basin as shown on the map. Deposition was concentrated within three main depocentres and in the areas between these centres only thin non-gypsiferous sequences were laid down. Wind once again became a dominant control on sedimentation and NNE trade winds continued to be dominant.

V Ladinian?

With time these more or less separate gypsiferous lake systems evolved into one large lake flanked by dolomitic shoreline flats. In periods with relative lake stand stability stromatolitic limestones developed along the shorelines. Periods of minor intermittent tectonic uplift, probably towards the north, shed sandstones into the basin, which was otherwise mainly the site of accumulation of terrigenous silt and limestones. The general salinity of the lake probably decreased to fresh or slightly brackish, and a rich trace fossil assemblage and a low diversity bivalve fauna gradually developed. Possible temporary connections to the open sea via the 'tectonic gap' east of Kap Biot are suggested by the existence of sparse bivalves with marine affinity.

VI Carnian-Norian?

During this penultimate Triassic stage fluvial sandstones gradually began to approach on the freshwater lake mudflats in the central and eastern part of the basin. A climatic shift towards greater humidity in combination with tectonic uplift of the borderlands is suggested as a likely explanation to this palaeogeographical trend. Palaeocurrent analyses as indicated on the map (see also fig. 10) suggest that most of the sediments were transported into the basin from a western source area. No deposits of this stage have been found on north-eastern Traill Ø, which probably was subject to tectonic uplift in this period. In contrast, the basin seems to have been extended southwards to Scoresby Sund where red-beds of these uppermost Triassic units have been described by Birkenmajer (1976).

PALAEOCLIMATOLOGY AND PALAEOWINDS

'Climate-sensitive' rocks. The upper (?) Scythian – Lower Liassic sequence contains several sedimentary rocks normally considered as 'climate-sensitive' (cf. Briden & Irwing, 1964; Robinson, 1973). These are: aeolian sandstones (Gipsdalen Formation), evaporites (Gipsdalen Formation), dolostones (lower Fleming Fjord Formation), red-beds (Pingo Dal, Gipsdalen and Fleming Fjord Formations), deltaic sediments and coals (Kap Stewart Formation).

The vertical arrangement of the Triassic 'climate-sensitive' rocks can be summarized as follows: (1) a sequence with humidtype rocks (deltaic sediments, coals) occurs above one with aridtype rocks (aeolian sandstones, evaporites, dolostones and red-beds), and (2) within the basal arid-type sequence there is a gradual upwards decrease in numbers of rock types indicative of arid climate. Thus the basal sequence is characterized by the upwards disappearance of aeolian sandstones, evaporites, dolostones and red-beds in the mentioned order.

Starting with the Middle Triassic dune sandstones and associated evaporites (gypsum and rock salt) the sedimentary aspects of these rocks alone would suggest deposition in an arid-type climate. Comparison with present-day distribution of desert dunes and evaporites (e.g. Briden & Irving, 1964) suggests deposition in a subtropical zone. Going upwards in the Triassic sequence dune sandstones and slightly later evaporites diappear, and a unit with dolostones and red-beds develops. These latter sediments probably were deposited in a less arid but still subtropical climate zone. Still higher in the Triassic sequence only red-beds appear, and this coupled with the income of an increasing number of fluvial sandstones suggests deposition in subtropical regions subject to increasing annual precipitation. In the Rhaetian–Liassic the red-beds finally disappear and temperate humid-type coal bearing deltaic rocks are laid down.

Discussion. The vertical sequence of 'climate-sensitive' rocks indicates deposition in progressively less arid climate belts. This is explained by assuming that the basin, which was part of a large Triassic continent, gradually shifted northwards during this period from a subtropical near-equatorial position (*c*. 15–30°N) in the Middle Triassic to a temperate position (*c*. 40°N) in the Rhaetian–Liassic (cf. Robinson, 1973).

The proposed explanation is supported by palaeowind data, palaeomagnetic results and palaeogeographical reconstructions.

Measurements of the Middle Triassic dune sandstones infer (cf. Clemmensen, 1978) that there were two effective palaeowinds during this period: dominant trade winds from NNE (fig. 38) and less frequent trade winds from SSE. The rotation of Greenland since the Triassic is minor (8–10° clockwise) and do not significantly change the measured palaeowind directions. Comparison with present-day wind-belts (e.g. Glennie, 1970) and theoretical wind pattern from the Triassic (Robinson, 1973) suggests deposition up to 30°N of the palaeoequator. Measurements of wave ripple crests (fig. 11) during most of the Middle and Upper Triassic are interpreted to indicate dominant trade winds from the NNE (fig. 39) and less frequent trade winds from the SSE. The 'wave-roses' (fig. 11) offer some evidence of a shift towards more northern trade winds at the end of the Triassic epoch (fig.

AGE	STRATIGRAPHY	DEDUCED WINDS	
		EASTERN PART	WESTERN PART
Middle Triassic	Edderfugledal Mb (wave ripples)	NNE (30-40°)	NNE (10-20°)
Lower-Middle Triassic	Gipsdalen Fm (dune cross-bedding)	NE (43°)	NNE (13-22°)

Fig. 38. Deduced palaeowinds from the eastern and western part of the basin respectively in two different stratigraphic units. Winds were more northerly in the western part of the basin.

AGE	STRATIGRAPHY	n	DOMINANT MODE	DOMINANT WIND
Upper Triassic	Ørsted Dal Mb	43	90-100°	N (0-10°)
	Malmros Klint Mb	90	110-130°	NNE (20-40°)
Middle Triassic	Edderfugledal Mb	389	100-130°	NNE (10-40°)
	Kap Seaforth Mb	24	120-130°	NE (30-40°)

Fig. 39. Deduced palaeowinds throughout the Middle–Upper Triassic sequences. Based on measurements on wave ripple crest. Only dominant wind directions have been indicated. There is an upwards tendency to more northern winds, the wind shift being especially clear between the two upper members.

39). This is what one would expect in the case of a northwards moving continent gradually approaching the 'wheel-around' zone (see e.g. Bigarella, 1972) at the boundary between the trade wind belt and the western wind belt at 30–40°N.

Palaeomagnetic data of Athavale & Sharma (1974) give a Middle Triassic north pole of 49°N, 158°E indicating a Middle Triassic palaeolatitude of *c.* 30°N. This result fits very well with the results from the dune sandstones. Palaeomagnetic results, however, from the Upper Triassic lowermost Malmros Klint Member indicate a Triassic north pole of 34°N, 103°E and a palaeolatitude of *c.* 22°N during this time interval (Reeve *et al.*, 1974). These figures appear to conflict with the bulk of data and are here considered 10–12° too low.

Triassic and Early Jurassic palaeogeographical reconstructions show that East Greenland was part of a northern 'Laurasia' continent (Robinson, 1973; Smith & Briden, 1977). Estimates of palaeolatitudes shown on these maps are in very good agreement with those reached by the sedimentological reasoning above. Robinson (1973) indicates a Late Triassic palaeolatitude for the Jameson Land Basin of *c.* 35°N, and Smith & Briden (1977) indicate Early Triassic (220 m.y.) and Rhaetian (200 m.y.) palaeolatitudes of 30°N and 45°N respectively. If the latter figures are correct we had a significant northward drift (*c.* 15°) during the discussed time interval. A northward drift of this magnitude would certainly cause the Jameson Land Basin to pass through different climatic belts. Using the terminology of Robinson (1973) we can argue that the Jameson Land Basin lay at the margin of the year-round dry zone in the Middle Triassic, that the basin moved into a region in Late Triassic probably with sharply seasonal rain and that the basin was just inside the high latitude humid belt in the Rhaetian–Liassic.

After these general remarks on the Triassic palaeoclimate an attempt is made to describe in more detail the annual climate during deposition of the Middle Triassic Kap Seaforth Member.

Vectorial analyses of dune sandstones in this and the underlying Kolledalen Member have indicated the existence of common NNE trade winds and less fre-

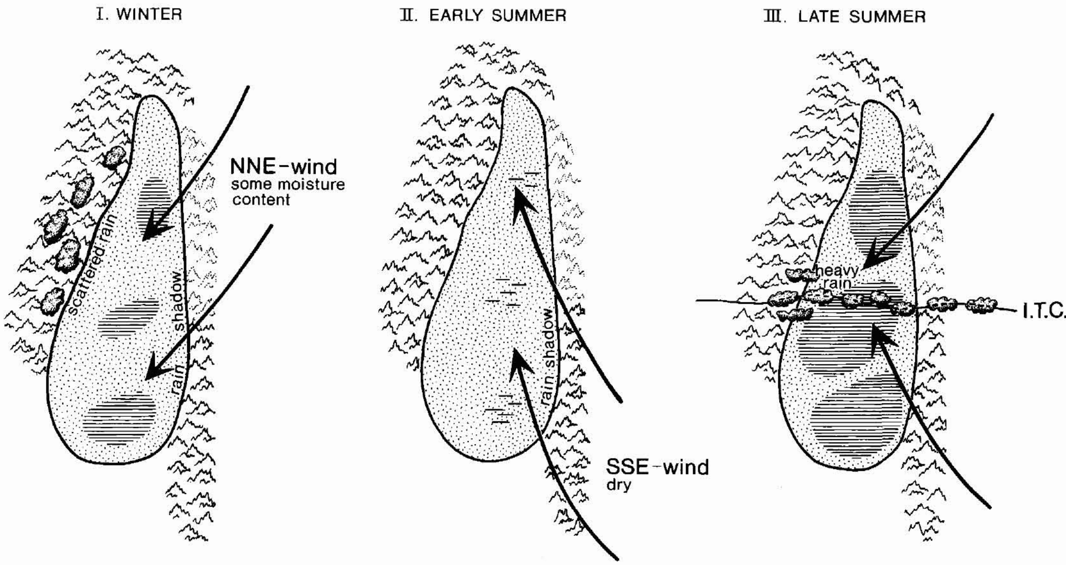


Fig. 40. Inferred palaeoclimate, palaeowinds and palaeogeography during deposition of the Middle Triassic lowermost Kap Seaforth Member. Stippled = sabkha; striped = very shallow lakes. The palaeogeography is very generalized and the figure should only be visualized as a conceptual model depicting the relationship between wind directions, amount of precipitation and approximate lake sizes. I. T. C. = Intertropical Convergence Zone.

quent SSE trade winds. These alternating trade winds were related to the yearly migration of the Intertropical Convergence Zone (I.T.C.) by Clemmensen (1978).

Thus during the Triassic winter (fig. 40) the I.T.C. lay far south of the basin, which was reached by NNE trade winds. These winds may have picked up some moisture over the nearby boreal sea and later precipitated it as scattered rain especially along the western mountain range (fig. 40). During late spring (not figured) the I.T.C. slowly bypassed the basin on its way northward. This period was probably characterized by occasional cloud-bursts. In the most of the summer situation (fig. 40) the I.T.C. zone lay north of the basin and very dry SSE trade winds reached the basin. In late summer (fig. 40) the I.T.C. zone once more crossed the basin, now on its way southwards. The I.T.C. zone is according to e.g. Robinson (1973), a zone of complex weather conditions with frequent rainfall.

ECONOMIC ASPECTS

Source rocks

Two rock units within the Triassic – Lower Jurassic sequence contain prospective source rocks. These are the black lagoonal mudstones of the Middle Triassic Gråklint Beds and the black interdistributary bay mudstones of the Rhaetian–Liassic Kap Stewart Formation (Clemmensen, 1976). Geochemical analyses of black mudstones of the Gråklint Beds indicate that this unit contains mature source rocks (T. Birkelund, pers. comm., 1977; Henderson, 1976).

Reservoir rocks

The Triassic rocks in question contain several sequences with mature or coarse-grained sandstones which could be of interest as possible potential reservoir rocks.

Thick sequences of mature aeolian sandstones (10 – *c.* 80 m) occur in the Paradigmabjerg and Kolledalen Members. Analyses of aeolian sandstones gave porosities between 4.5 and 8.9 per cent and permeabilities between 1.5 and 2.3 millidarcy. These figures are low and indicate that the primary porosity has been reduced by cementation.

Mature quartz sandstones also occur in the Rhaetian–Liassic Kap Stewart Formation, which contains up to 10 m thick shoestring delta distributary sandstones and up to 13 m thick linear barrier sands (Clemmensen, 1976). Also, in this case, however, many of the sandstones have suffered from diagenetic cementation considerably lowering the primary porosities.

Apart from the mature well-sorted quartz sandstones, arkosic relatively poorly sorted medium to coarse-grained sandstones are frequently encountered within the Triassic sequences. These are regarded less prospective as reservoir rocks as their porosity and permeability presumably are lower, but if cementation is lacking, porosity may be high enough to make these rocks potential reservoirs. Such rocks may especially be found within the fluviatile Klitdal, Paradigmabjerg and Ørsted Dal Members.

Stratigraphic traps

The potential source rocks of the Gråklint Beds occur below or adjacent to possible reservoir rocks e.g. in the aeolian sandstones of the Kolledalen Member and are overlain by impermeable lacustrine mudstones and evaporites (cf. fig. 32). The stratigraphical framework of the reservoir rocks in this sequence in East Greenland show many similarities to that of the Rotliegendes (Glennie, 1972) and the Lower Triassic Bacton Group (Brennand, 1975) of the southern North Sea, in which a large number of gas finds have been discovered (Selley, 1975; Ziegler, 1975, 1977).

The mudstones of the Rhaetian–Liassic Kap Stewart Formation may form seals over the quartz sandstones in the same formation. The depositional conditions of the Kap Stewart Formation (Sykes, 1974; Clemmensen, 1976) appear rather similar to those of the Rhaetian–Liassic oil bearing Statfjord Sands in the Viking Graben (see e.g. Selley, 1975; Ziegler, 1977).

The Triassic sequence is cut by many normal faults, the majority of which are believed to be of Tertiary age.

Copper mineralizations

Several of the Triassic facies associations contain synsedimentary – diagenetic mineralisation with copper as the most common mineral.

So far mineralizations have been observed in the following stratigraphic units: the Klitdal-Paradigmabjerg Members, the Gråklint Beds, the Kap Seaforth Member, the Pingel Dal Beds and the Malmros Klint – Ørsted Dal Members (B. Thomassen, pers. comm., 1979, and own observations).

The Klitdal–Paradigmabjerg paragenesis (Cu, Pb) is restricted to fluvial channel sandstones. Rare plant fragments and small tree logs have been found in some channels (B. Thomassen, pers. comm., 1979).

The Gråklint Beds paragenesis is of the Mississippi Valley type (B. Thomassen, pers. comm., 1979) with Pb, Zn and Cu, and occurs in both the black lagoonal mudstones and the barrier beach calcarenites.

The Kap Seaforth Member paragenesis (Cu, Pb, Zn) mainly occurs in dark lacustrine mudstones intercalated between gypsum or gypsiferous sandstone.

The Pingel Dal Beds paragenesis (Cu) is characterized by the copper minerals chalcodite-digenite, bornite and chalcopyrite (B. Thomassen, pers comm., 1979). The mineralization occurs both in grey shoreline sandstones, in dark grey open lacustrine mudstones, but especially in dolomitic shoreline flat sediments. The lateral continuity of mineralized horizons appears considerable (perhaps several tens of kilometres).

The Malmros Klint – Ørsted Dal Member paragenesis (Cu) is concentrated within various thin fluvial channel sandstones and is characterized by the frequent occurrence of native copper, which occurs in small lumps up to a few centimetres in diameter. The sedimentary facies of this unit compares closely to the cupriferous fluviatile-lacustrine rocks of the Proterozoic Grinnell Formation in Canada (Collins & Smith, 1977).

As a preliminary conclusion it is suggested that the accumulation of the synsedimentary – diagenetic copper and associated minerals is the combined result of a semiarid climate, uplifted source areas, long periods of inland drainage and a brief marine transgression. Thus the setting of the discussed sediments shows many similarities to the setting of the copper bearing Mississippian – Early Permian sediments in Eastern Canada (Poll, 1978).

CONCLUSIONS

1. The Triassic (upper(?) Scythian – Rhaetian) sediments of the central East Greenland rift basin are placed in a new lithostratigraphical framework.

2. The dominant depositional processes in the sedimentary basin were fluvial sheet flood and stream action, strong wind action and low energy intermittent wave action.

3. Thirteen main facies associations have been distinguished, each of which corresponds to a well defined sedimentary environment. The initial deposits of the upper (?) Scythian – Rhaetian sequence are coarse-grained alluvial fan deposits grading into more fine-grained flood plain sediments. Then follow aeolian dune sandstones and gypsiferous playa lake deposits which again are overlain by limestone beach barriers and lagoonal mudstones laid down during an extensive marine interlude. On top of the marine sediments appears a new sequence of apparently lacustrine origin. The basal portion of this second lacustrine sequence is gypsiferous playa lake deposits, then follow stromatolite bearing lake sediments and finally non-evaporitic red-beds of shallow lake and distal flood plain origin. The lacustrine sequence is overlain by a large-scale coarsening upwards flood plain – braid plain sequence, the topmost portion of which locally contains shallow lacustrine and lagoonal carbonates.

4. The sequences contain a relatively poor fauna of amphibians, fishes, bivalves, gastropods and conchostracans. Most of the fossils are strictly continental, but some of the bivalves are marine indicating that the basin occasionally was flooded by the sea. The Triassic trace fossils are well preserved and include a very diverse continental ichnocoenose.

5. Triassic continental or occasionally shallow marine sediments were laid down in a steady subsiding N–S orientated rift valley. The formation of this rift valley probably took place in connection with the break-up of the 'Laurasian' megacontinent. The basal alluvial fan deposits formed in direct response to tectonic uplift of eastern and western borderlands in the Early Triassic, but minor synsedimentary tectonic movements throughout the entire Middle–Late Triassic period are evident in the sedimentary record.

6. Climatic control was probably an important factor during deposition of the Triassic sediments. The vertical succession of 'climate-sensitive' rocks suggests a gradual climatic shift from semiarid to semihumid throughout the Middle–Late Triassic period. The humid-type temperate coal-bearing rocks of the Rhaetian–Liassic Kap Stewart Formation is the natural end result of this climatic trend, which

is explained by a northwards continental drift across several palaeoclimatic belts. Deduced palaeowinds indicate that the basin was characterized by alternating NNE trade winds (dominant) and SSE trade winds. With time the dominant NNE trade winds gradually became more northerly in agreement with the northward drift of the continent.

7. Although no hydrocarbon accumulations are known in the Triassic – Lower Jurassic rocks in central East Greenland, both stratigraphic intervals contain possible source rocks as well as suitable reservoir and cap rocks. Copper-lead-zinc mineralizations occur within several of the upper(?) Scythian – Rhaetian stratigraphic units and can be grouped into: 1. Fluvial sandstones with copper or copper-lead, 2. lake sediments with copper or copper-lead-zinc and 3. shallow marine limestones with lead-zinc-copper.

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