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Lithostratigraphy, sedimentary evolution and sequence stratigraphy of the Upper Proterozoic Lyell Land Group (Eleonore Bay Supergroup) of East and North-East Greenland

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Cover
View of the Lyell Land Group on the southern shores of Lyell Land and the snow-capped Berzelius Bjerg seen from Scoresby Land. The basal formation of the Lyell Land Group (Kempe Fjord Formation) is not exposed, and most of the overlying Sandertop Formation is covered by scree to the left (west). The rest of the group is well exposed and shows the pale weathering Berzelius Bjerg Formation, followed by the grey to brownish red weathering Kap Alfred Formation. The Vibeke Sø Formation forms a conspicuous pale unit in the centre of the picture and is overlain by the reddish Skjoldungebræ Formation. The top of the group is formed by the yellowish weathering Teufelsschloss Formation. The Lyell Land Group is overlain by grey, red and pale weathering mainly carbonate rocks of the Ymer Ø and Andrée Land Groups. Mountain summit is approximately 1900 m. For geological annotation see Fig. 7.

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Abstract

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The Late Proterozoic Lyell Land Group is an approximately 3 km thick succession of siliciclastic shelf deposits, within the upper part of the Eleonore Bay Supergroup. It is widely exposed in the region between Ardencaple Fjord in the north and Canning Land in the south. In this paper the seven formations named by Sønderholm & Tirsgaard (1993) are formally described. These are from base to top: the Kempe Fjord Formation (400–600 m thick), the Sandertop Formation (200–405 m thick), the Berzelius Bjerg Formation (250–450 m thick), the Kap Alfred Formation (500–640 m thick), the Vibeke Sø Formation (290–325 m thick), the Skjoldungebræ Formation (205–240 m thick) and the Teufelsschloss Formation (35–110 m thick).

Five facies associations have been recognised. Outer shelf deposits dominated by dark green, brown to dark red mudstones with thin sandstone lenses are mainly found in the Sandertop, Kap Alfred and Skjoldungebræ Formations. Storm- and wave-dominated inner shelf deposits comprising fine-grained sandstones and dark heterolithic mudstones are common in the Sandertop, Kap Alfred, Vibeke Sø and Skjoldungebræ Formations and are also found in southern outcrops of the Teufelsschloss Formation. Tidally influenced shoreface deposits form stacks of laterally extensive sandstone bodies separated by heterolithic mudstones and are only found in the middle part of the Kap Alfred Formation. Storm- and wave-dominated shoreface deposits comprise highly mature, thick and laterally very extensive sandstone bodies of which a few may be traced for distances exceeding 150 km. This association is present in several intervals within all formations of the Lyell Land Group. Tidally dominated coastal plain deposits consist of stacked sandstone sheets forming laterally extensive, multistorey units separated by heterolithic mudstones and sandstones. These sediments form part of the Kempe Fjord and Berzelius Bjerg Formations and are also found in northern outcrops of the Teufelsschloss Formation. Evidence from palaeocurrent data combined with regional lithological variations suggest a consistent general N–S coastline with the basin deepening in an eastward direction. Deflection of geostrophic currents suggest a palaeolatitude on the southern hemisphere.

The deposits of the Lyell Land Group are subdivided into four, large-scale sequences which overall show the same general sedimentary evolution through time reflecting large-scale, cyclic changes in relative sea-level. The sequences vary in thickness from 400–1000 m and are all readily traceable 300 km parallel and 100 km perpendicular to inferred palaeocoastline. The development of all sequences indicates that major regional translation of facies are related to large-scale forced regressions. Sequence stratigraphic considerations suggest that correlation of formations of the Lyell Land Group with units of the Petermann Bjerg Group some 75 km to the west may be very difficult to carry out.

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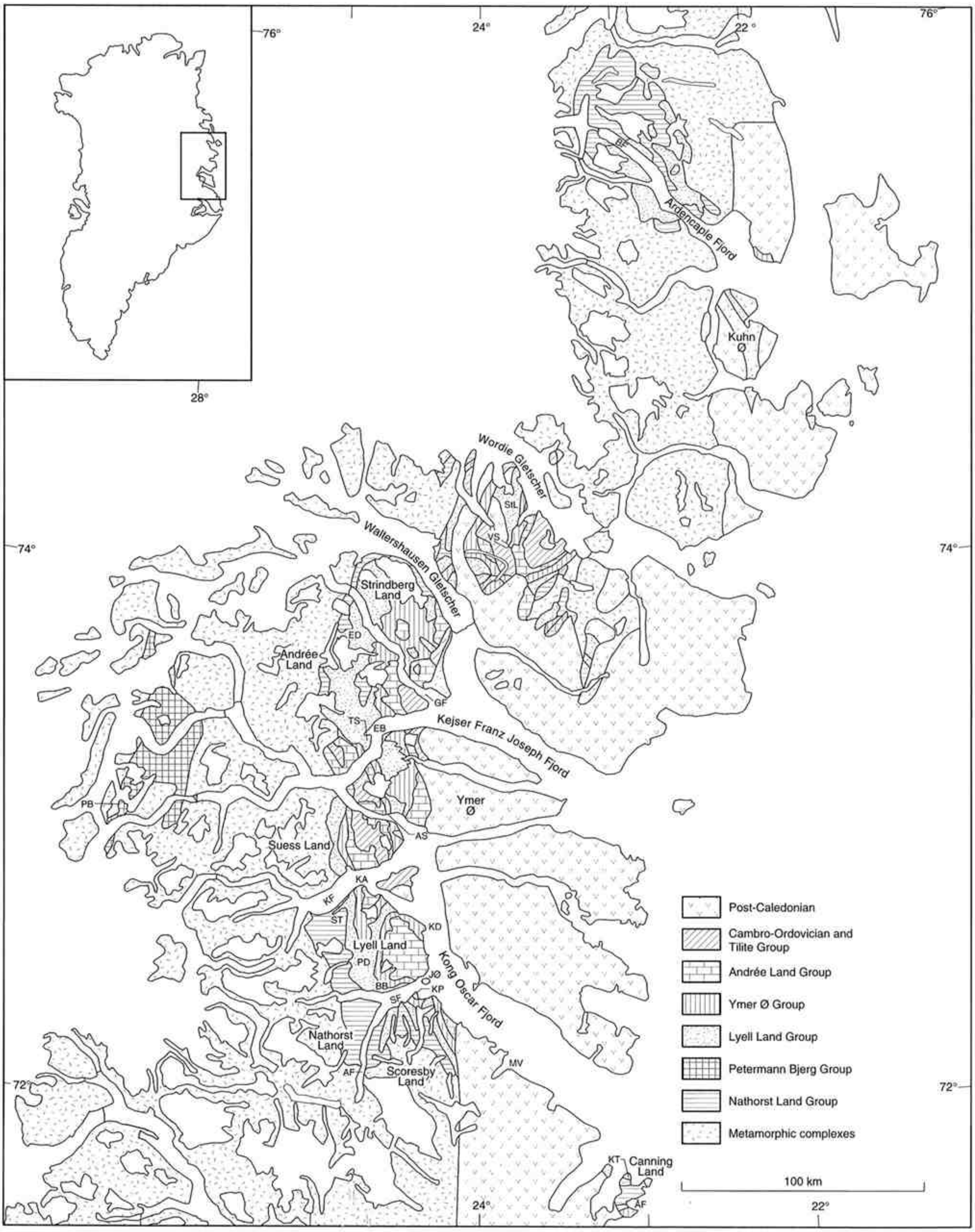

Fig. 1. Simplified geological map showing the distribution of the Eleonore Bay Supergroup outcrops in East and North-East Greenland with geographical place names used in the text from north to south: BF: Bredefjord, StL: Steno Land, VS: Vibeke Sø, ED: Eremitdal, GF: Geologfjord, EB: Eleonore Bugt, TS: Teufelsschloss, PB: Petermann Bjerg, AS: Antarctic Sund, KA: Kap Alfred, KF: Kempe Fjord, ST: Sandertoppene, KD: Kap Dufva, PD: Polhelm Dal, BB: Berzelius Bjerg, SF: Segelsällskapet Fjord, JØ: Jägmästarens Ø, KP: Kap Peterséns, AF: Alpefjord, MV: Mesters Vig, KT: Kap Tyrrell, ÅF: Ålborg Fjord. The 'central fjord zone' coincides with the Eleonore Bay Supergroup outcrop area between Waltershausen Gletscher and Alpefjord. Modified from Sønderholm & Tirsgaard (1993).

Introduction

The Late Proterozoic Lyell Land Group is an approximately 3 km thick succession of siliciclastic shelf deposits, widely exposed in the region between Ardencaple Fjord and Scoresby Land (Fig. 1). It forms part of the more than 16 km thick Eleonore Bay Supergroup (Fig. 2; Sønderholm & Tirsgaard, 1993), in which it overlies an approximately 11 km thick succession of mainly siliciclastic deposits, constituting the Nathorst Land Group. It is overlain by the 1 km thick Ymer Ø Group and 1.5 km thick Andrée Land Group, both consisting predominantly of carbonate platform sediments (Fig. 2). Although dating is poor, the deposits of the Eleonore Bay Supergroup are generally considered to have been laid down during a time period of approximately 200–300 Ma, covering the Late Proterozoic Riphean and Sturtian Epochs (Sønderholm & Tirsgaard, 1993). Together with the overlying Tillite Group and the Cambro-Ordovician succession, the Eleonore Bay Supergroup constitutes a relatively continuous depositional record, which reflects the disintegration and subsequent accretion of a supercontinent in connection with the opening and closing of the Iapetus Ocean (Sønderholm & Tirsgaard, 1993). It has previously been suggested that the Eleonore Bay Supergroup, including the Lyell Land Group, was laid down along a passive continental margin of the Iapetus Ocean (e.g. Harland & Gayer, 1972; Caby & Bertrand-Sarfati, 1988).

Aspects of the sedimentology of the Eleonore Bay Supergroup, including the Lyell Land Group have recently been described by Sønderholm *et al.* (1989), Sønderholm & Tirsgaard (1990), Sønderholm & Tirsgaard (1993) and Tirsgaard (1993), but more comprehensive basinwide studies of the siliciclastic deposits of the Eleonore Bay Supergroup have not previously been published. This paper presents a sedimentological analysis of the Lyell Land Group and includes descriptions and interpretations of a range of depositional environments within the group. From the distribution of the sedimentary environments in time and space, a model of the depositional evolution of the group is suggested. Although biostratigraphic data are missing, the model uses basic sequence stratigraphic principles in order to define the major events in the basin evolution, which reflect basinwide reorganisation of the palaeogeography.

The Lyell Land Group was formally defined by Sønderholm & Tirsgaard (1993) and corresponds to the 'Quartzit Serie' and the lower part of the 'Bunte Serie' of Teichert (1933) and to the 'Quartzit Serie' of Katz (1952), Eha (1953), Fränkl (1953a, b) and Sommer (1957a, b). Sønderholm & Tirsgaard (1993) provided a comprehensive review of the Eleonore Bay Supergroup including the Lyell Land Group along with a historical review and a more detailed lithostratigraphic description. They subdivided the Lyell Land Group into seven formations mappable throughout the area of exposure; formations were defined in a generalised sedimentological log and in the terrain (Sønderholm & Tirsgaard,

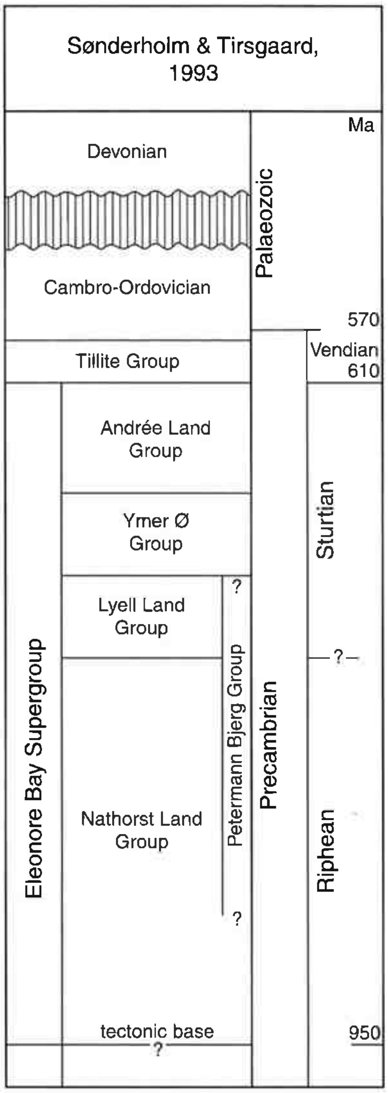

Fig. 2. Lithostratigraphic subdivision of the Eleonore Bay Supergroup after Sønderholm & Tirsgaard (1993).

1993, figs 9, 17–21, 23) but no formal descriptions of the formations were given. In the first section of this paper, these seven formations are formally defined and described in detail. The subdivision and the formation names are identical to those published by Sønderholm & Tirsgaard (1993).

Terminology

In the lithological descriptions of the Lyell Land Group, only basic grain size terms are used, e.g. 'sandstone' is used in preference to 'quartzite' and 'mudstone' instead of 'shale'. Nomenclature of the various stratigraphic units follows that of Sønderholm & Tirsgaard (1993).

There exists no universally accepted subdivision of shelves and shelf environments, or any general consensus on terminology, with consequent ambiguity. Tillman (1985) for instance, subdivides the shelf into shoreface, inner shelf, middle shelf and outer shelf zones, while Reading & Collinson (1996) use the terms shoreface, offshore-transition and offshore zones. Walker & Plint (1992) simply use a twofold subdivision applying the terms shoreface and offshore zone.

In this paper, the shelf is subdivided into three zones: outer shelf, inner shelf and shoreface. Landward of the shoreface lies the coastal plain. The outer shelf lies below storm wave base, and deposition is here dominated by suspension fall-out. The inner shelf lies between the fair-weather wave base and the storm wave base and is characterised by an interaction of oscillatory movements and uni- or bi-directional currents. The shoreface is here defined as that part of the shelf above the fair-weather wave base and therefore is almost constantly influenced by oscillatory wave movements and also includes foreshore deposits. The coastal plain is defined as the extensive, very gently sloping area between the shoreface and the nearest elevated land. It is influenced by marine processes, but it is not dominated by wave activity and may periodically be subaerially exposed and subjected to alluvial processes.

Lithostratigraphy

Lyell Land Group

Sønderholm & Tirsgaard (1993)

History. The Lyell Land Group was defined by Sønderholm & Tirsgaard (1993) as part of the general lithostratigraphic revision of the Eleonore Bay Supergroup. It corresponds to the 'Quartzit Serie' ('bed groups 1–6') as defined by Teichert (1933), and later described in more detail by Katz (1952), Eha (1953), Fränkl (1953a, b), Sommer (1957a, b), Haller (1971), Caby (1972), Caby & Bertrand-Sarfati (1988), Sønderholm *et al.* (1989) and Sønderholm & Tirsgaard (1990). It likewise corresponds to the Agardhsbjerg Formation (Fig. 3; Katz, 1961).

Name. After Lyell Land, where the group is extensively exposed and well preserved (Fig. 1).

Type area. Lyell Land, from Kap Alfred in the north to Berzelius Bjerg in south (Figs 1, 4).

Thickness. The group reaches a maximum thickness of 2800 m in northern Lyell Land around Kap Alfred (Figs 4, 5). In the rest of the central fjord zone, the total thickness is between 2000 and 2500 m (Katz, 1952; Fränkl, 1953a, b). A similar thickness has been reported from the area between Waltershausen Gletscher and Wordie Gletscher (Fig. 1; Haller, 1971; Sønderholm *et al.*, 1989). At least 1500 m are exposed in the

Bredefjord–Ardencaple Fjord area (Sommer, 1957b), and a minimum of 750 m is found in Canning Land (Fig. 1; Sønderholm & Tirsgaard, 1993, figs 12, 19).

Distribution. The group is widely distributed in the area between Wordie Gletscher and the central part of Scoresby Land (cf. Bengaard, 1992). The lower and central parts of the group are widely exposed in the Bredefjord–Ardencaple Fjord region (Fig. 1). On Kuhn Ø (Fig. 1), a 650 m thick succession of sandstones and mudstones of Precambrian age is present. This succession is probably best referred to the lower part of the Lyell Land Group, but may, alternatively, belong to the underlying Nathorst Land Group (Sønderholm & Tirsgaard, 1993). The group is also represented on Canning Land (Caby, 1972; Caby & Bertrand-Sarfati, 1988; Sønderholm & Tirsgaard, 1993) but outcrops are generally poor and tectonised which often results in exposures with a restricted and non-diagnostic stratigraphy. However, the upper part of the group is well exposed in an approximately 750 m thick succession in northern Canning Land around Kap Tyrrell. Caby (1972) reported that the lower part of the group ('bed-groups 1–2/?3') is present around Ålborg Fjord (Fig. 1), but an unequivocal distinction between sandstone and mudstone units within the Lyell Land Group and the underlying Nathorst Land Group is difficult in this area.

Dominant lithology. The group consists of alternating units of white to purple weathering, fine- to medium-grained sandstones, and dark green, brownish or dark red silty mudstones and heterolithic mudstones. The

Katz, 1952; Eha, 1953; Fränkl, 1953aa, b; Sommer, 1957a, b		Katz, 1961		Sønderholm & Tirsgaard 1993; this paper	
Quartzite Series	bed-group 6	Agardhsbjerg Formation	Member 5	Lyell Land Group	Teufelsschloss Formation
	bed-group 5		Member 4		Skjoldungebræ Formation
	bed-group 4				Vibeke Sø Formation
	bed-group 3		Member 3		Kap Alfred Formation
	bed-group 2		Member 2		Berzelius Bjerg Formation
	bed-group 1		Member 1		Sandertop Formation
					Kempe Fjord Formation

Fig. 3. The subdivision of the Lyell Land Group into seven formations compared with the older, informal subdivisions.

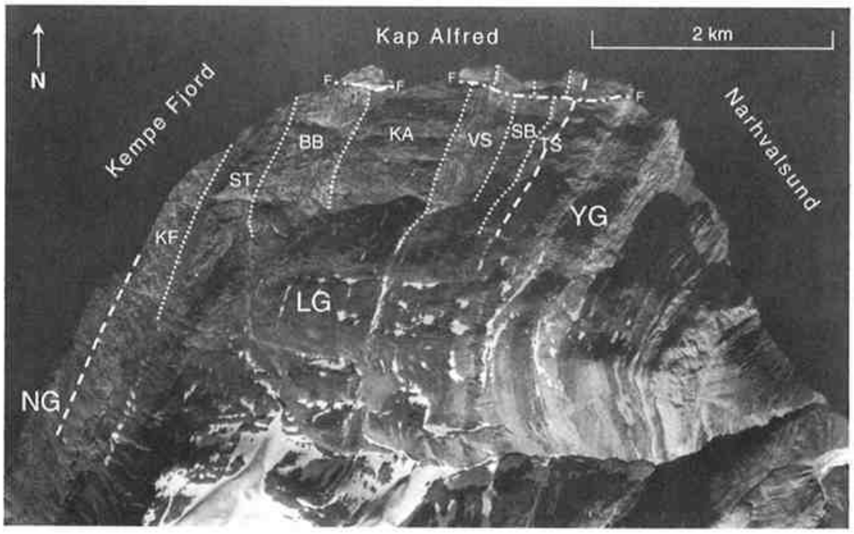

Fig. 4. Aerial photograph of the northern part of Lyell Land. The coastal section along Kempe Fjord around Kap Alfred provides the best continuous exposures of the Lyell Land Group (LG) and includes the type locality of the Kempe Fjord Formation (KF), the Sandertop Formation (ST) and the Kap Alfred Formation (KA) together with well exposed reference sections of the Berzelius Bjerg Formation (BB), the Vibeke Sø Formation (VS), the Skjoldungebræ Formation (SB) and the Teufelsschloss Formation (TS).
NG: Nathorst Land Group, YG: Ymer Ø Group, F: fault.
Photo: Kort- og Matrikelstyrelsen, Denmark, route 888 K-3713 (1985).

thickness of the units varies between 40 and 600 m (Fig. 5). They have a distinct tabular geometry, and can be traced across most of the outcrop area, forming a characteristic lithological pattern which is recognisable from Ardencaple Fjord in the north to Scoresby Land and Canning Land in the south. The group has been subject to a high degree of recrystallisation and is locally strongly deformed, particularly in the lower part.

Fauna and geological age. Thirty-three samples from the group have been processed for acritarchs, but apart from one sample, acritarchs are scarce and poorly preserved. Based on available data, Vidal (1976, 1979) suggested a Sturtian age for the group.

Boundaries. The lower contact is placed where dark green weathering heterolithic mudstones of formation NL3 of the Nathorst Land Group are overlain by a thick succession of white weathering sandstones of the Lyell Land Group (Fig. 6). The upper contact of the group is placed where white sandstones or dark brown heterolithic mudstone deposits of the Lyell Land Group are sharply overlain by dark red or purple mudstones of the Ymer Ø Group (Fig. 7).

Subdivisions. The group was subdivided by Sønderholm & Tirsgaard (1993) into seven formations, corresponding to main sandstone and mudstone units. These comprise the Kempe Fjord Formation, the Sandertop Formation, the Berzelius Bjerg Formation, the Kap Alfred Formation, the Vibeke Sø Formation, the Skjoldungebræ Formation and the Teufelsschloss Formation (Figs 3, 5).

Correlation. The deposits of the Lyell Land Group have been suggested to be coeval with the upper part of the Petermann Bjerg Group which occurs in the nunatak region some 75 km west of the central fjord zone (Figs 1, 2; Haller, 1971). This correlation was maintained by Sønderholm & Tirsgaard (1993), but lithological patterns found in the two regions are not directly comparable and precise correlation of units is still uncertain.

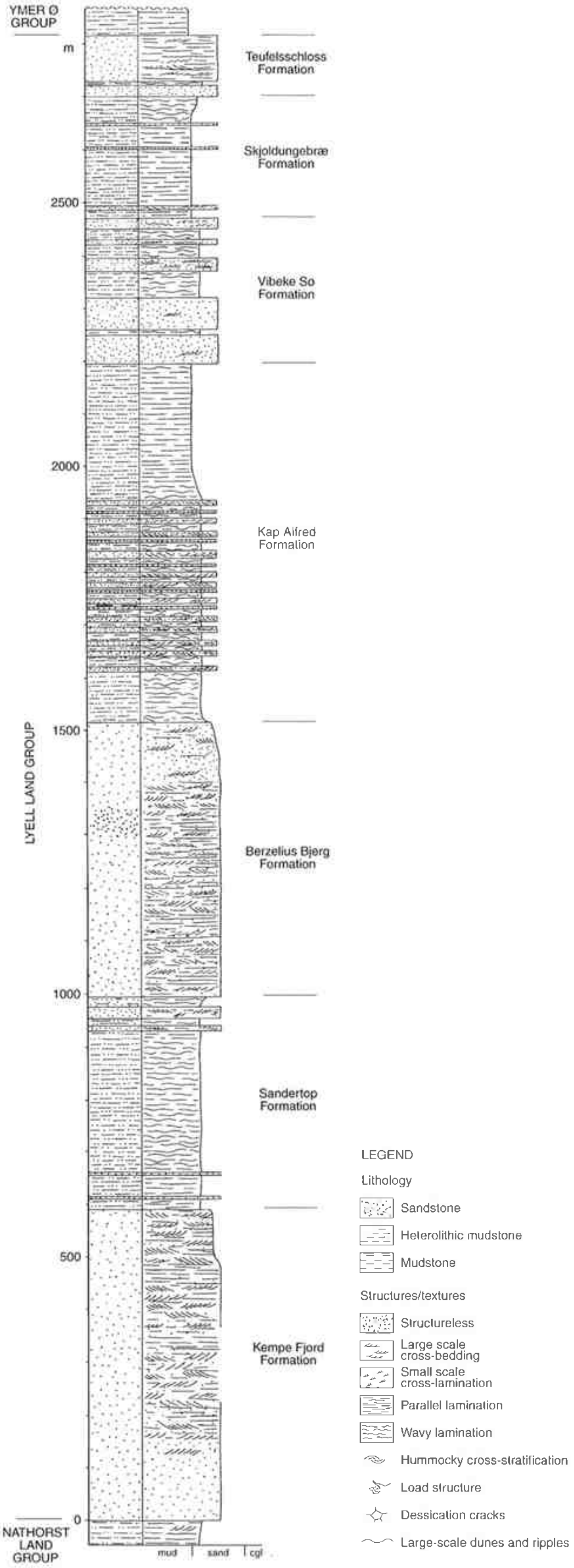

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Fig. 5. Generalised sedimentological log of the Lyell Land Group, measured at Kap Alfred (northern Lyell Land) showing the vertical development of the group and the seven formations. After Sønderholm & Tirsgaard (1993).

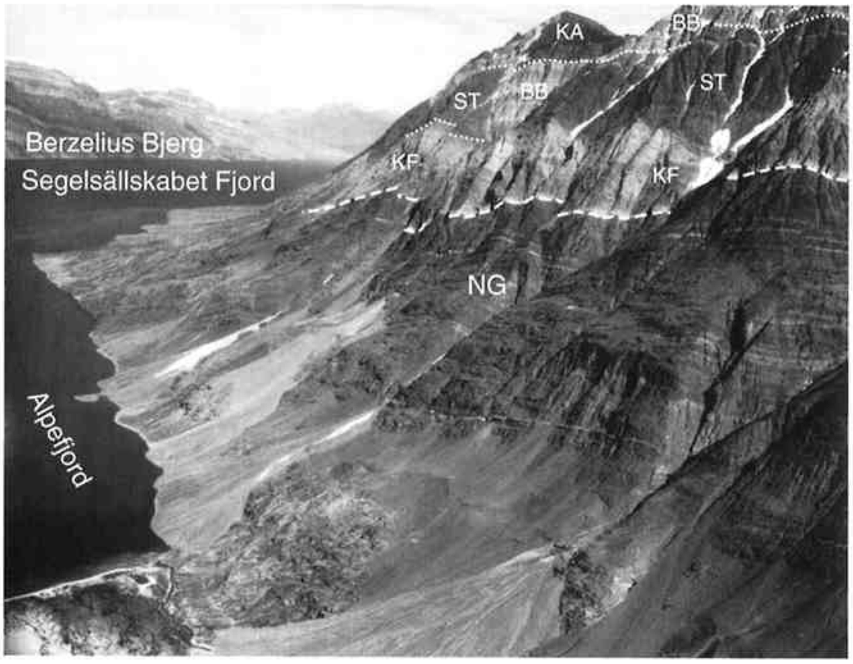


Fig. 6. Boundary between the dark mudstones and heterolithic mudstones of the Nathorst Land Group (NG) and the white sandstones at the base of the Lyell Land Group (LG) as exposed on the eastern coast of Alpefjord, KF: Kempe Fjord Formation, ST: Sandertop Formation, BB: Berzelius Bjerg Formation, KA: Kap Alfred Formation. After Sønderholm & Tirsgaard (1993).

Kempe Fjord Formation

History. The Kempe Fjord Formation was named by Sønderholm & Tirsgaard (1993) without formal description. The formation corresponds to the white or light purple weathering sandstone unit which constitutes the lower part of 'bed-group 1' of Teichert (1933), Katz (1952), Eha (1953), Fränkl (1953a, b) and Sommer (1957a, b) and the lower sandstone unit of Member 1 of the Agardhsbjerg Formation (Fig. 3; Katz, 1961).

Name. From Kempe Fjord, the large fjord between Lyell Land and Suess Land (Fig. 1).

Type locality. The type locality is found at a well exposed coastal section immediately west of Kap Alfred in northern Lyell Land (Figs 4, 8, 9). Reference sections have not been measured in detail, but according to Katz (1961) good sections may be found in Andrée Land, around Eremitdal in the innermost part of Geologfjord (Fig. 1).

Thickness. At the type locality, the formation reaches a thickness of 585 m (Fig. 9). Similar thicknesses were reported by Katz (1952), Fränkl (1953a), Sommer (1957a) and Haller (1971) from other parts of the central fjord zone (Fig. 1), with the exception of Scoresby Land, where Fränkl (1953b) reported a thickness of only 400 m. In the Bredefjord–Ardencaple Fjord region Sommer (1957b) reported a thickness of approximately 600 m.

Distribution. The Kempe Fjord Formation is a cliff-forming, white to light brown or light purple weathering unit. It overlies dark green recessive mudstones of formation NL3 of the Nathorst Land Group (Sønderholm & Tirsgaard, 1993) and is succeeded by more brownish weathering, recessive, heterolithic mudstones of the Sandertop Formation (Figs 6, 8). The formation is widely distributed in the Bredefjord–Ardencaple Fjord area, in the region between Waltershausen Gletscher and Wordie Gletscher and in the central fjord zone, with the exception of Ymer Ø, where it is not exposed (Eha, 1953). On Kuhn Ø, at least 140 m of white sandstones are preserved; these may correspond stratigraphically to the Kempe Fjord Formation (Sønderholm & Tirsgaard, 1993), but the base of the unit is not exposed. From Canning Land, around Ålborg Fjord, Caby (1972) reported a 100 m thick sandstone unit with an unexposed base, which he tentatively correlated with the basal part of 'bed-group 1' (Kempe Fjord Formation). Correlations in this area are, however, problematic and the unit may be part of overlying formations in the Lyell Land Group or the underlying Nathorst Land Group.

Lithology. The Kempe Fjord Formation consists of white

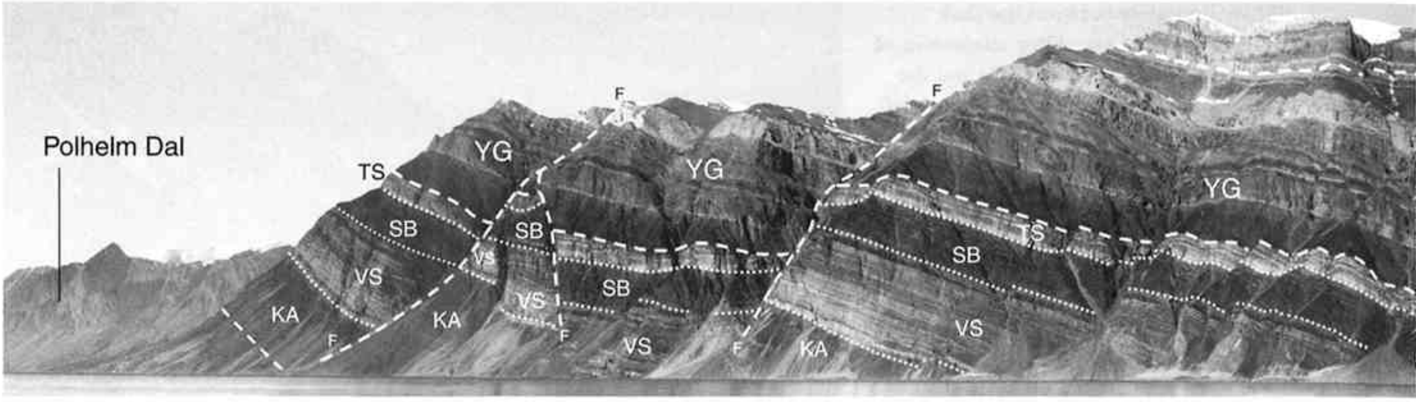


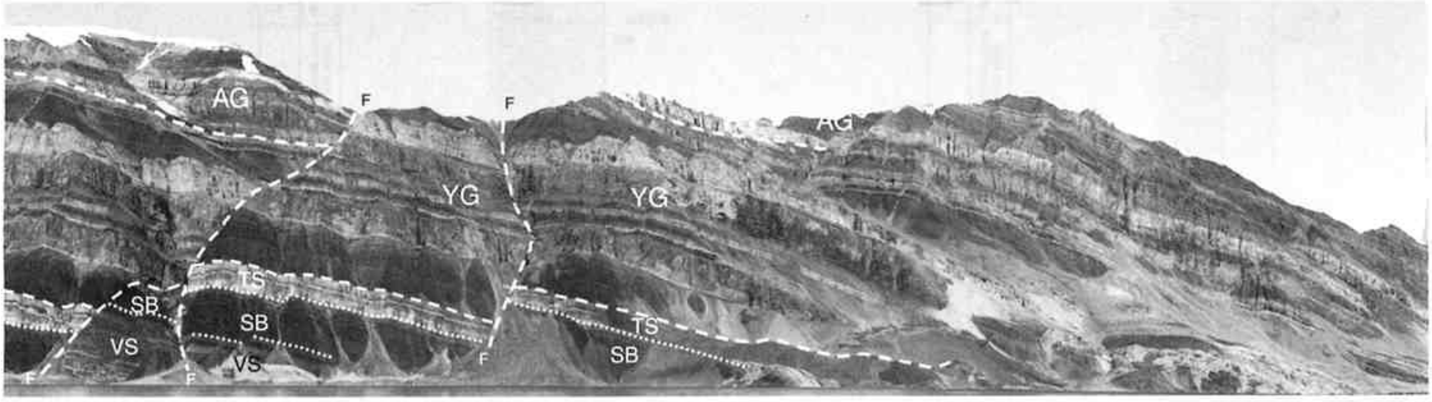
Fig. 7. Photomosaic of Berzelius Bjerg in southern Lyell Land, showing the typical development of the contact between the Lyell Land Group and the overlying Ymer Ø Group (YG), in the central fjord zone. The characteristic development of sandstone and mudstone units constituting the upper four formations of the Lyell Land Group is well exposed. KA: Kap Alfred Formation, VS: Vibeke Sø Formation, SB: Skjoldungebræ Formation, TS: Teufelsschloss Formation, AG: Andrée Land Group, F: fault. Height of Berzelius Bjerg is approximately 1900 m.

to light brown or light purple weathering, fine- to medium-grained sandstones. In the type section (Fig. 9), it can be separated into four units (a–d) based on colour and sedimentary structures. All units have gradational transitions.

The lower unit (a), approximately 85 m thick, consists entirely of structureless white sandstone beds. Bedding is poorly developed but, when visible, is generally a few metres thick. Above follows an approximately 100 m thick white sandstone unit (b) with a low mudstone content and some preserved internal structures, comprising horizontal lamination and large-scale cross-bedding, 10–30 cm high. Locally, herringbone cross-stratification can be observed. Bedding thickness varies from 0.5 m to 2.0 m.

The third unit (c) is approximately 300 m thick and consists of light brown weathering sandstone; individual beds are 0.3–3.0 m thick and display a characteristic sheet-like geometry. The lower contact of each sand sheet is erosive, while the upper surface is covered by a millimetre to centimetre thick mudstone drape often showing desiccation cracks. Beds of wavy and flaser laminated heterolithic sandstone, 0.2–1.0 m thick with numerous desiccation cracks locally separate the sand

Fig. 8. Boundary (dashed) between the light grey sandstones of the Kempe Fjord Formation (KF) and the overlying dark grey mudstones of the Sandertop Formation (ST) at the type locality at Kap Alfred in Lyell Land. Some of the thicker sandstone beds within the Sandertop Formation are exposed. The contact is generally covered in scree, but is exposed at this locality. Above the Sandertop Formation the lower section of the Berzelius Bjerg Formation (BB) is exposed. Width of exposure shown on photograph is approximately 150 m.



sheets. Internally the sand sheets are dominated by horizontal lamination interbedded with sets of large-scale, wedge-shaped cross-bedding and cross-lamination. Individual cross-bedded sets are 10–40 cm thick with tangential or sigmoidal, locally overturned foresets. Reactivation surfaces and herringbone cross-stratification are common. Foreset dip directions show a distinct bi-polar development, with north-north-westerly and south-easterly dip directions at the type locality (Kap Alfred), while dip directions in the southern part of Lyell Land are towards the north-north-east and south.

In the uppermost 100 m of the formation (d), sandstones become more fine-grained and the content of mudstone increases, while the weathering colour becomes more purple. Horizontal lamination is rare, and sets of cross-bedding decrease in size, reaching only 5–20 cm in height, but still showing herringbone cross-stratification. Small-scale cross-lamination becomes more dominant, while desiccation cracks are less common.

Boundaries. The lower boundary is placed where the greenish weathering heterolithic mudstones of the upper part of formation NL3 of the Nathorst Land Group give way to structureless white sandstones of the Kempe Fjord Formation (Fig. 6). The contact is sharp although sandstone beds 10–30 cm in thickness, intercalated with the heterolithic deposits, can be seen to increase in abundance in the uppermost 4–5 m of formation NL3. The upper boundary is placed where the light purple sandstones are succeeded by brownish weathering heterolithic mudstones of the Sandertop Formation (Fig. 8).

Sandertop Formation

History. The formation was named by Sønderholm & Tirsgaard (1993) without formal description. The formation corresponds to the upper dark argillaceous interval of 'bed-group 1' of Teichert (1933), Katz (1952), Eha (1953), Fränkl (1953a, b) and Sommer (1957a, b), and to the upper dark argillaceous interval of Member 1 of the Agardhsbjerg Formation (Fig. 3; Katz, 1961).

Name. Derived from Sandertoppene, a series of mountain peaks in the northern part of Lyell Land, just south-west of Kap Alfred (Fig. 1).

Type locality. The type locality forms a well exposed coastal section on the southern side of Kempe Fjord just west of Kap Alfred in Lyell Land (Figs 4, 10). A reference section is located in southern Lyell Land, on the eastern side of Polhelm Dal on the gently dipping mountainside of Berzelius Bjerg. Other well exposed sections may be found in Andrée Land, around Eremitdal in the innermost part of Geologfjord (Fig. 1; Katz, 1961).

Thickness. At the type locality, the formation measures 405 m in thickness (Fig. 10). A similar thickness is present in Scoresby Land (Fränkl, 1953b), while a thickness of only 200 m was reported from Andrée Land

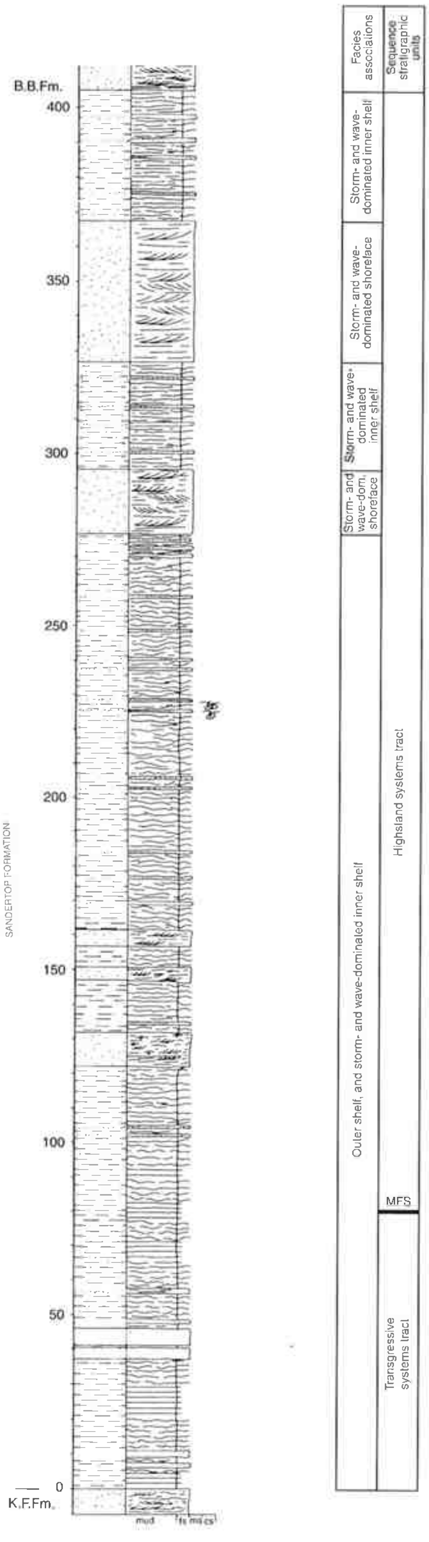


Fig. 9. Type section of the Kempe Fjord Formation (Kap Alfred, northern Lyell Land) showing facies associations and sequence stratigraphic units. The log illustrates the very small variations in grain size throughout the formation. The section has been divided into four units (a–d, see text). N.L.G.: Nathorst Land Group, ST. FM.: Sandertop Formation, SB: sequence boundary. For legend see Fig. 5.

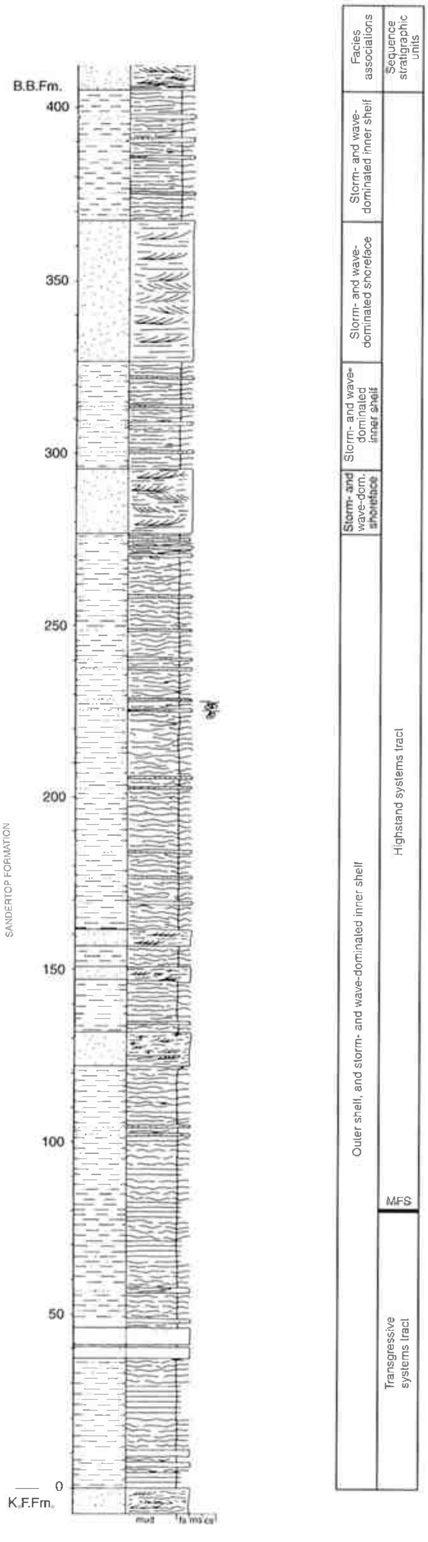
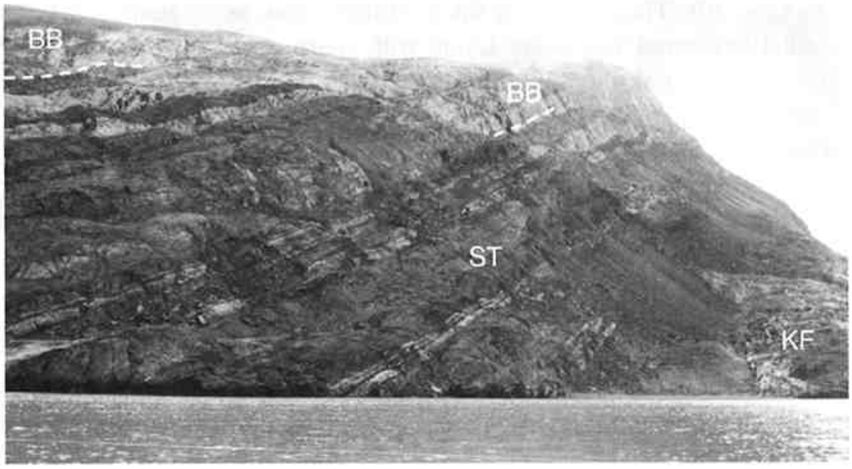


Fig. 10. Type section of the Sandertop Formation (Kap Alfred, northern Lyell Land) showing facies associations and sequence stratigraphic units. The section displays the occasional presence of thin sandstone units within mudstones and heterolithic deposits and the two main sandstone units in the upper part of the formation. K.F. FM.: Kempe Fjord Formation, B.B. FM.: Berzelius Bjerg Formation, MFS: maximum flooding surface. For legend see Fig. 5.

Fig. 11. Characteristic development of the Sandertop Formation (ST) at the type locality (Kap Alfred, northern Lyell Land) showing the strong dominance of dark mudstones and heterolithic deposits, with rare 0.5–2 m thick sandstone units (seen as pale units). The two thick sandstone units in the upper part of the formation are seen immediately below the contact to the overlying Berzelius Bjerg Formation (BB). KF: Kempe Fjord Formation. Width of exposure shown on photograph is approximately 150 m.



and Strindberg Land by Katz (1952) and Fränkl (1953a). In the Bredefjord–Ardencaple Fjord region a thickness of 300 m is reached (Sommer, 1957b).

Distribution. The Sandertop Formation forms a recessive, dark brown unit sandwiched between the white or slightly reddish weathering cliff-forming Kempe Fjord and Berzelius Bjerg Formations (Figs 6, 8, 11). It is present within the Bredefjord–Ardencaple area (Sommer, 1957b) and is widely distributed in the central fjord zone. It may also be present on Kuhn Ø, where a 200 m thick unit dominated by mudstones probably can be correlated with the Sandertop Formation (Sønderholm & Tirsgaard, 1993). In Canning Land, an isolated outcrop at Ålborg Fjord comprising a 400 m thick succession of silty mudstones was tentatively correlated with the upper part of 'bed-group 1' (Sandertop Formation) by Caby (1972). As correlation of the various sandstone and mudstone units of the lower Lyell Land Group is difficult in this area, the unit may be part of the overlying formations in the Lyell Land Group or the underlying Nathorst Land Group.

Lithology. At the type locality the formation is dominated by brownish weathering mudstones and heterolithic mudstones interbedded with 2–10 m thick, white or brownish weathering sandstone units. Two distinct sandstone units, 20 m and 40 m thick, are found in the upper part of the formation (Figs 10, 11).

Mudstones are mainly present in the lower 120 m of the formation where they are dominated by horizontal lamination; individual laminae may locally show micrograding. Lenticular and wavy bedded heterolithic mudstones dominate the upper 280 m of the forma-

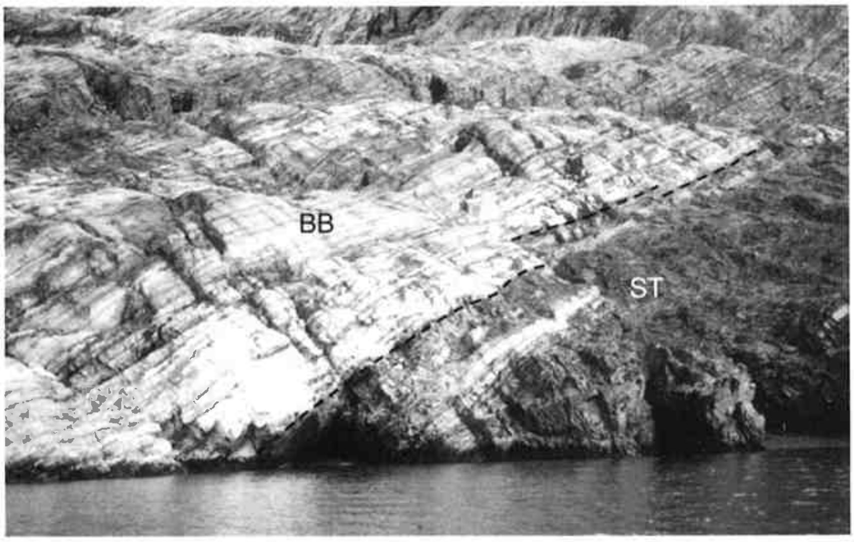


Fig. 12. Well exposed boundary between the Sandertop Formation (ST) and the overlying Berzelius Bjerg Formation (BB) as seen at Kap Alfred, northern Lyell Land. The contact is relatively sharp and marks a transition from inner shelf mudstones to shoreface sandstones. The latter form the basal part of the Berzelius Bjerg Formation and are seen as pale beds which are overlain by tidal channel sand sheets (light grey). Thickness of section shown on photograph is approximately 100 m.

tion (Fig. 10). Thin, 1–15 cm thick, structureless or parallel laminated sandstone layers with sharp contacts are present throughout the formation.

The sandstone units consist of 0.5–1.0 m thick sandstone beds. These are often structureless or show poorly preserved sets with large-scale planar and trough cross-bedding, horizontal lamination and cross-lamination. Contacts with surrounding mudstones may be either sharp or gradational with thin sandstone layers increasing in abundance towards the base of the sandstone units (Fig. 10). The two uppermost thick sandstone units contain better preserved sedimentary structures. They consist of 0.2–1.0 m thick beds separated by thin mudstone interbeds. Internally they reveal large-scale planar cross-beds, often showing herringbone cross-stratification, horizontal lamination and cross-lamination. Numerous clay flakes are scattered throughout the units.

The formation is similarly developed in most other areas within the central fjord zone, except in Strindberg Land and in Andrée Land where sandstone units are more abundant (Katz, 1952; Fränkl, 1953a).

Boundaries. The lower boundary is sharp and is placed at the base of the heterolithic mudstone succession following abruptly upon the white or purple weathering sandstones of the Kempe Fjord Formation (Figs 8, 11). The upper boundary is placed where heterolithic mudstones give way to the overlying sandstone succession of the Berzelius Bjerg Formation (Figs 8, 11, 12).

Berzelius Bjerg Formation

History. The Berzelius Bjerg Formation was named by Sønderholm & Tirsgaard (1993) without formal description. The formation corresponds to 'bed-group 2' of Teichert (1933), Katz (1952), Eha (1953), Fränkl (1953a, b) and Sommer (1957a, b) and to Member 2 of the Agardhsbjerg Formation (Fig. 3; Katz, 1961).

Name. From the mountain Berzelius Bjerg, located on the southern coast of Lyell Land, along the northern side of the Segelsällskapet Fjord (Figs 1, 7).

Type locality. The type locality is a very well exposed section on the south-western side of the mountain Berzelius Bjerg (Figs 13, 14A). A well exposed reference section has been measured in northern Lyell Land, at Kap Alfred (Figs 4, 14B). Other well exposed sections may be found in Andrée Land, around Eremitdal in the innermost parts of Geologfjord (Fig. 1; Katz, 1961).

Thickness. At the type locality, the formation reaches a thickness of 470 m (Fig. 14A) and in northern Lyell Land it attains a thickness of 530 m (Fig. 14B). From other parts of the central fjord zone thicknesses of 250–300 m have been reported (Katz, 1952; Eha, 1953; Fränkl, 1953a, b). Bengaard (1989), in a detailed photogrammetrical analysis, calculated a similar range of thicknesses in the central fjord zone and confirmed that the Berzelius Bjerg Formation, of all the formations in the Lyell Land Group, shows the most significant thickness variations in the central fjord zone. This variation was not recognised by earlier workers as Sommer (1957a) reported a thickness of only 280 m in Lyell Land. In the Bredefjord–Ardencaple Fjord region the formation reaches a thickness of 350 m (Sommer, 1957b).

Distribution. The Berzelius Bjerg Formation is a cliff-forming, white to reddish or light pink weathering sandstone unit, sandwiched between the dark green or dark brown to black, recessive mudstones of the Sandertop Formation beneath and the Kap Alfred Formation above (Fig. 13). It was reported from the Bredefjord–Ardencaple Fjord region by Sommer (1957b) and Sønderholm *et al.* (1989). It is present in the region between Waltershausen Gletscher and Wordie Gletscher (Haller, 1971; Sønderholm *et al.*, 1989) and widely distributed in the central fjord zone (Katz, 1952; Eha, 1953; Fränkl, 1953a, b; Sommer, 1957a; Bengaard, 1989, 1992). A 210 m thick white sandstone unit with a distinct tripartite subdivision due to a middle brownish section, has been observed on Kuhn Ø and may correspond stratigraphically to the Berzelius Bjerg Formation (Sønderholm & Tirsgaard, 1993). In northern Canning Land around Kap Tyrrell, an at least 100 m thick white sandstone unit, bounded below by a fault, has been suggested to correspond to 'bed-group 2' (Berzelius Bjerg Formation) by Caby (1972). This sandstone unit is considered here to form the basal part of the Vibeke Sø Formation. North of Ålborg Fjord in Canning Land, the upper 100 m of an isolated outlier, possibly belonging to the Lyell Land Group, was tentatively proposed by Caby (1972) to correspond to the Berzelius Bjerg Formation. Correlations in this area are, however, problematic and the unit may be part of overlying formations in the Lyell Land Group or the underlying Nathorst Land Group.

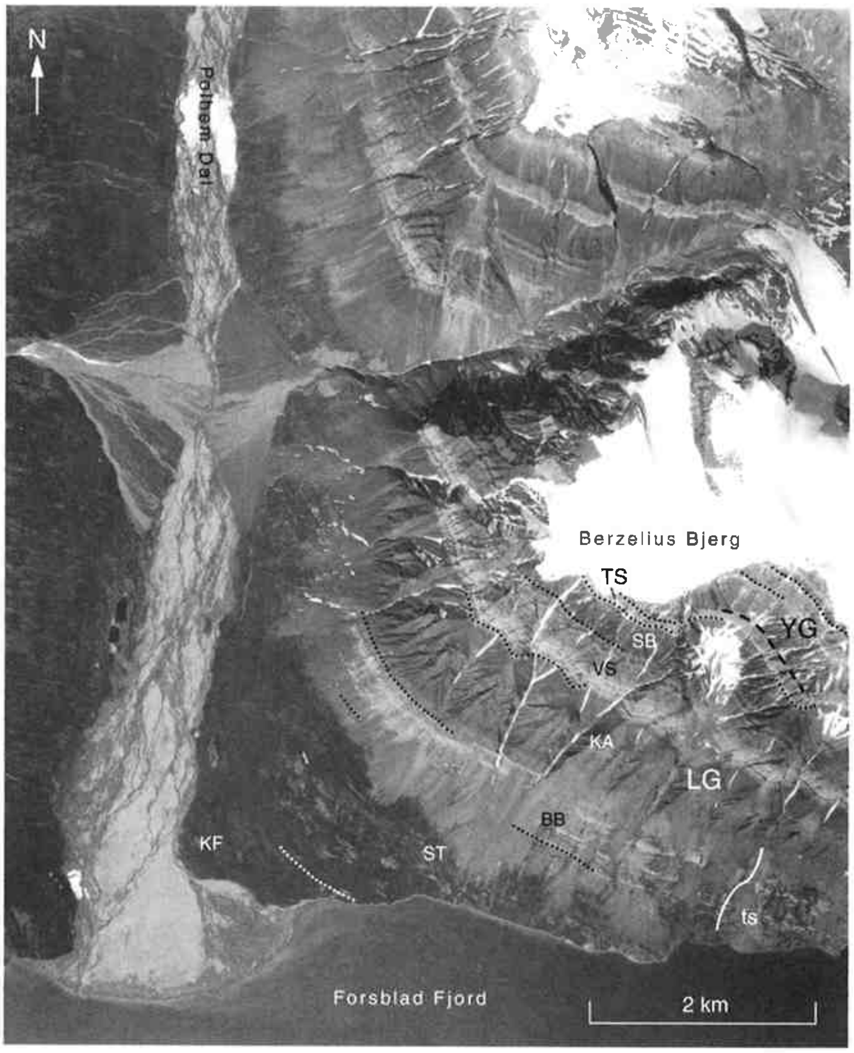


Fig. 13 Aerial photograph of the southern part of Lyell Land showing the type locality of the Berzelius Bjerg Formation (BB; ts: type section). KF: Kempe Fjord Formation, ST: Sandertop Formation, KA: Kap Alfred Formation, VS: Vibeke Sø Formation, SB: Skjoldungebræ Formation, TS: Teufelsschloss Formation, LG: Lyell Land Group, YG: Ymer Ø Group. After Sønderholm & Tirsgaard (1993). Photo: Kort- og Matrikelstyrelsen, Denmark, route 853 H-5568 (1972).

Lithology. At the type locality, the Berzelius Bjerg Formation forms a homogeneous unit of white, light purple to pink or light red weathering sandstone with very subordinate amounts of heterolithic sandstone and mudstone (Fig. 14A).

The formation consists of sand sheets, 0.3–3.0 m in thickness, which are amalgamated to form 30–70 m thick units separated by either 0.3–1.0 m thick heterolithic sandstone or mudstone beds, or 2–15 m thick, structureless white sandstone beds. In the uppermost 40–80 m of the formation the sand sheets die out and are followed by structureless, more fine-grained sandstone deposits, which have a very poorly developed bedding (Fig. 14A, B).

The sand sheets have sharp erosive lower contacts and mud-draped upper contacts with desiccation cracks and ripple-marks. Sedimentary structures are dominated by large-scale planar cross-bedding (10–40 cm sets), interbedded with horizontal lamination, scour and fill structures, and small-scale cross-bedding. Cross-bedded sets may show well-developed herringbone cross-stratification. Measurements on foreset dip directions show a dominantly bi-polar trend with dip directions mainly towards the north-north-west and south-south-east. North-easterly foreset dip directions, roughly perpendicular to the main orientation, occur in southern Lyell Land. The sand sheets lack any vertical evolution of sedimentary structures, but may show a weak upward fining.

The thin heterolithic mudstone and sandstone beds are primarily wavy bedded with varying proportions of mudstone and fine-grained sandstone. On bedding planes desiccation cracks and wave ripple marks are commonly found. The interbedded white sandstone beds reveal very few sedimentary structures, but occasionally large-scale sets of cross-bedding, 20–60 cm thick, are visible.

A similar lithological development is seen in other

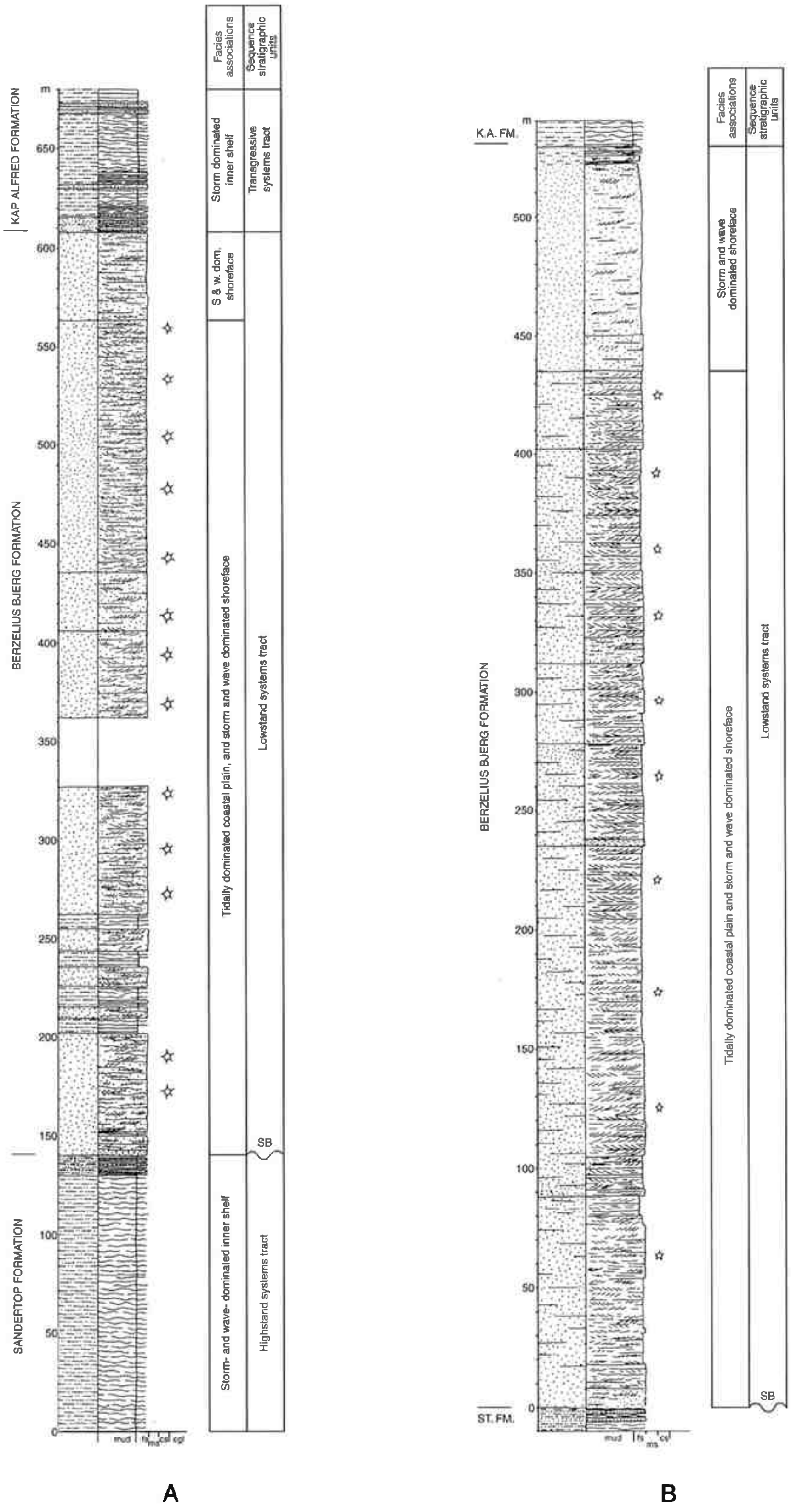


Fig. 14. **A**: Type section of the Berzelius Bjerg Formation (Berzelius Bjerg, southern Lyell Land) showing facies associations and sequence stratigraphic units. At this locality sedimentary structures are extremely well preserved. **B:** Reference section of the Berzelius Bjerg Formation (Kap Alfred, northern Lyell Land) showing facies associations and sequence stratigraphic units. This section is more complete than at Berzelius Bjerg, but sedimentary structures are less well preserved. The log reflects the same depositional environments as in southern Lyell Land, but shoreface deposits in the uppermost part of the formation are better developed in northern Lyell Land. ST. FM.: Sandertop Formation, K.A. FM.: Kap Alfred Formation, SB: sequence boundary. For legend see Fig. 5.

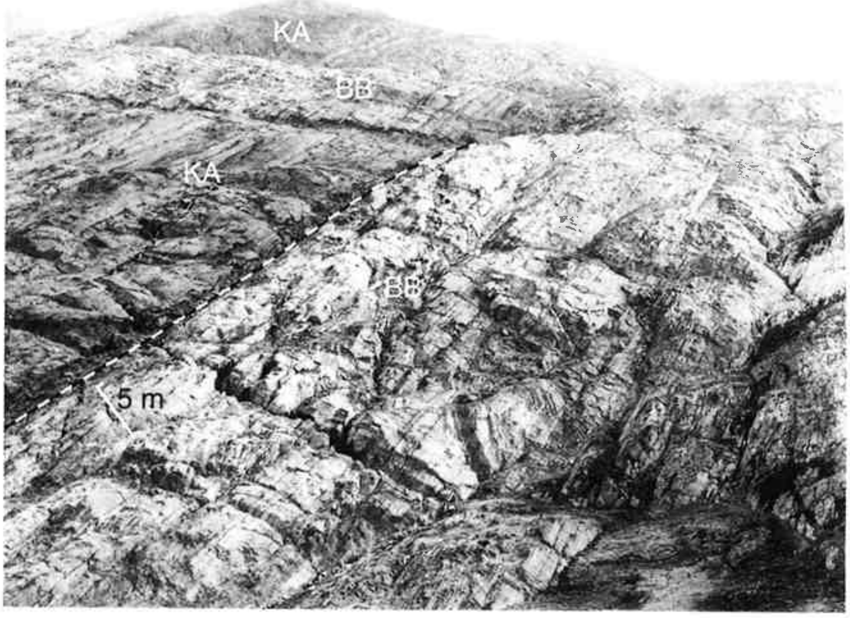


Fig. 15. Boundary (dashed) between shoreface sandstones of the Berzelius Bjerg Formation (BB) and the dark heterolithic inner shelf mudstones of the Kap Alfred Formation (KA) as exposed at Kap Alfred (northern Lyell Land).

parts of Lyell Land. No detailed descriptions currently exist from other parts of the central fjord zone but, based on the descriptions of Katz (1952), Eha (1953), Fränkl (1953a, b) and Sønderholm *et al.* (1989), the Berzelius Bjerg Formation appears to show only minor lateral variations in lithology.

Boundaries. The lower boundary is placed where heterolithic mudstones of the underlying Sandertop Formation are followed by sandstones of the Berzelius Bjerg Formation (Fig. 12). The boundary is sharp, although a weak upward coarsening is seen in the upper 3–5 m of the Sandertop Formation. The upper boundary is placed where white or reddish weathering sandstones are followed by dark green mudstones and heterolithic mudstones of the Kap Alfred Formation (Fig. 15).

Kap Alfred Formation

History. The Kap Alfred Formation was named by Sønderholm & Tirsgaard (1993) without formal description. It corresponds to 'bed-group 3' of Teichert (1933), Katz (1952), Eha (1953), Fränkl (1953a, b), Sommer (1957a, b) and to Member 3 of the Agardhsbjerg Formation (Fig. 3; Katz, 1961). It includes the 'Basiszone', the 'Untere Schieferzone', the 'Bänderzone' and the 'Obere Schieferzone' of Katz (1952), Fränkl (1953a) and Sommer (1957a).

Name. From Kap Alfred, the northernmost point of Lyell Land (Figs 1, 4).

Type locality. The type locality is at Kap Alfred, where the formation is well exposed in an easily accessible coastal section along Kempe Fjord (Fig. 4). Reference sections are located in southern Lyell Land at Berzelius Bjerg (Fig. 7) and in Andrée Land, around Eremitdal in the innermost part of Geologfjord (Fig. 1; Katz, 1961).

Thickness. At the type locality, the formation reaches a thickness of 640 m (Fig. 16). A similar thickness was calculated photogrammetrically by Bengaard (1989), while Sommer (1957a) reported a thickness of only 500 m at Kap Alfred. In the central fjord zone, outside Lyell Land, the Kap Alfred Formation attains a thickness of approximately 500 m (Katz, 1952; Eha, 1953; Fränkl, 1953a, b; Bengaard, 1989; Sønderholm *et al.*, 1989). In the Bredefjord–Ardencaple Fjord region, Sommer (1957b) calculated a thickness of 500–600 m.

Distribution. The Kap Alfred Formation forms a dark, recessive unit between white cliff-forming sandstones of the Berzelius Bjerg Formation below and the lower part of the Vibeke Sø Formation above (Fig. 7). It is widely distributed in the region between Waltershausen Gletscher and Wordie Gletscher (Haller, 1971; Sønderholm *et al.*, 1989) and in the central fjord zone (Katz, 1952; Eha, 1953; Fränkl, 1953a, b; Sommer, 1957a; Bengaard, 1989, 1992). On Kuhn Ø, an at least 250 m

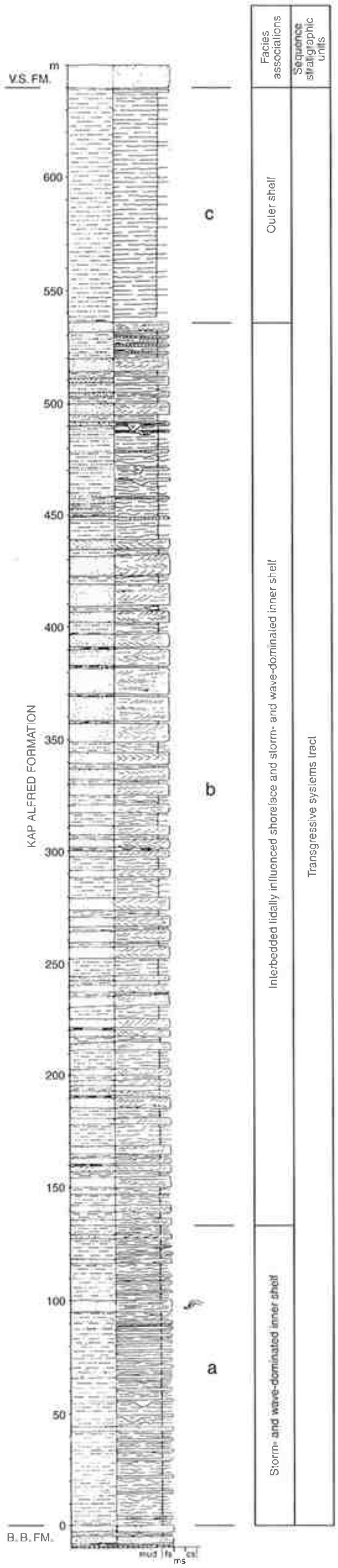


Fig. 16. Type section of the Kap Alfred Formation (Kap Alfred, northern Lyell Land) showing facies associations and sequence stratigraphic units. The log shows the well-developed tripartite division of the formation (a–c, see text). B.B. FM.: Berzelius Bjerg Formation, V.S. FM.: Vibeke Sø Formation. For legend see Fig. 5.

thick succession consisting of sandstones and mudstones may possibly correspond to the Kap Alfred Formation (Sønderholm & Tirsgaard, 1993). The formation is probably not preserved in Canning Land, although Caby (1972) suggested that the entire Lyell Land Group, with the exception of the Kempe Fjord and Sandertop Formations ('bed-group 1'), was included in an approximately 750 m thick succession occurring around Kap Tyrrell in northern Canning Land. Here this mapping unit is considered to comprise only the formations overlying the Kap Alfred Formation.

Lithology. The Kap Alfred Formation consists of dark green to dark grey weathering mudstones and heterolithic mudstones alternating with white, fine- to medium-grained sandstone beds. Variations in the amount of sandstone and mudstone at the type locality has led to a conspicuous tripartite subdivision of the formation (Fig. 16).

The lower part (a) is approximately 130 m thick and is dominated by horizontally laminated mudstones and heterolithic, lenticular and wavy bedded mudstones (Fig. 16). Thin sandstone layers, 5–30 cm thick, with sharp bases are interbedded with the mudstones. These are structureless or show horizontal lamination or cross-lamination. Thicker beds may display hummocky cross-stratification. In southern Lyell Land, and in parts of the central fjord zone, the lower part can be split into a lower 60 m thick section characterised by a high concentration of sandstone layers – 'Basiszone' of Katz (1952), Fränkl (1953a) and Sommer (1957a) – and an upper 60 m thick section consisting predominantly of mudstone – the 'Untere Schieferzone' of Katz (1952), Fränkl (1953a) and Sommer (1957a). In the lower part of the formation, load structures are common in some intervals and diastasis cracks are often observed on bedding planes.

The middle part of the formation (b) is approximately 410 m thick and consists of alternating 1–10 m thick sandstone and heterolithic mudstone units with gradational contacts (Fig. 16). Sandstone units have a sheet-like geometry and generally increase in thickness upwards, thereby creating an upward coarsening succession. The sandstone units are dominated by large-scale planar cross-beds, 5–40 cm thick, interbedded with horizontally and cross-laminated sandstones. Herringbone cross-stratification is common. Foreset dip directions show a strong bimodal trend, indicating dominantly north–south flowing currents. The heterolithic mudstone units are lenticular and wavy bedded. In the Bredefjord–Ardencaple Fjord region this middle

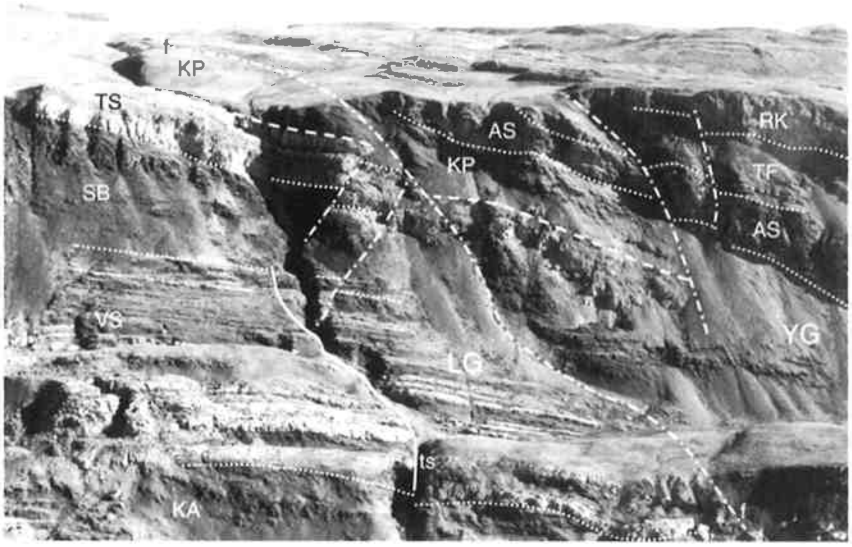


Fig. 17. Type locality of the Vibeke Sø Formation (VS), at the eastern end of Vibeke Sø in Steno Land, showing well exposed contacts to the underlying Kap Alfred Formation (KA) and the overlying Skjoldungebræ Formation (SB). The type section at the eastern end of the Vibeke Sø Formation is shown by the white line (ts). A major fault (f) runs through the central part of the photograph juxtaposing formations of the Lyell Land Group (LG) with the lower formations of the Ymer Ø Group (YG), TS: Teufelsschloss Formation, KP: Kap Peteséns Formation, AS: Antarctic Sund Formation, TF: Tågefjeld Formation, RK: Rytterknægten Formation.

part of the formation contains very little sandstone and the tripartite division, therefore, is much less distinct (Sønderholm *et al.*, 1989).

The upper part (c) is approximately 100 m thick and characterised by dark brown to greenish weathering mudstones with very few sandstone layers, 5–20 cm thick. The mudstones are dominated by horizontal to lenticular lamination (Fig. 16).

Boundaries. At the type locality, the lower boundary of the formation is sharp and is placed at the change from the homogeneous white sandstones of the Berzelius Bjerg Formation to dark, greenish weathering heterolithic mudstones (Figs 7, 15). Where sandstone layers are more common, as in some areas of the central fjord zone (Katz, 1952; Eha, 1953; Fränkl, 1953a; Sommer, 1957a), the contact is more gradational. The upper contact is placed where the dark brown to greenish weathering mudstones are sharply overlain by white sandstone beds forming the base of the Vibeke Sø Formation (Fig. 17).

Vibeke Sø Formation

History. This formation was named by Sønderholm & Tirsgaard (1993) without formal description. The formation corresponds to 'bed-group 4', described from the central fjord zone by Katz (1952), Eha (1953), Fränkl (1953a, b), Sommer (1957a) and Sønderholm *et al.* (1989) and to the lower part of Member 4 of the Agardhsbjerg Formation (Fig. 3; Katz, 1961). In Canning Land around Kap Tyrrell, 'bed-group 4' has not been recognised as a separate unit by Bütler (1948) or Caby (1972) who grouped 'bed-groups 3–6' into a single mapping unit overlying 'bed-group 2'. However, Caby & Bertrand-Sarfati (1988) reinterpreted the stratigraphy of the Kap Tyrrell region and suggested that 'bed-group 2' corresponds to 'bed-group 4' and that 'bed-groups 3–6' correspond to 'bed-group 5' and 'bed-group 6'; this interpretation is followed here.

Name. From the lake Vibeke Sø in Steno Land (Fig. 1).

Type section. The type section is located on the south-facing cliffs at the eastern end of Vibeke Sø in Steno Land (Figs 17, 18A). Reference sections were measured at Kap Alfred in northern Lyell Land, at Kap Peterséns in northern Scoresby Land and at Kap Tyrrell in northern Canning Land (Figs 18, 19).

Thickness. The formation is 325 m thick in the type section (Fig. 18A). Similar thicknesses are found at other localities in the central fjord zone: 300 m at Kap Alfred (Fig. 18B), 315 m at Kap Peterséns (Fig. 18C) and at least 290 m in Canning Land (Fig. 19).

Distribution. The Vibeke Sø Formation forms a characteristic banded unit with a cliff-forming weathering appearance in the basal part. It is readily recognised between the dark, more recessive weathering mudstones of the underlying Kap Alfred Formation and the overlying brick-red mudstones of the Skjoldungebræ Formation (Figs 4, 7, 17). The most northerly outcrops are seen in a restricted area around Ardencaple Fjord, where only the basal, approximately 200 m of the for-

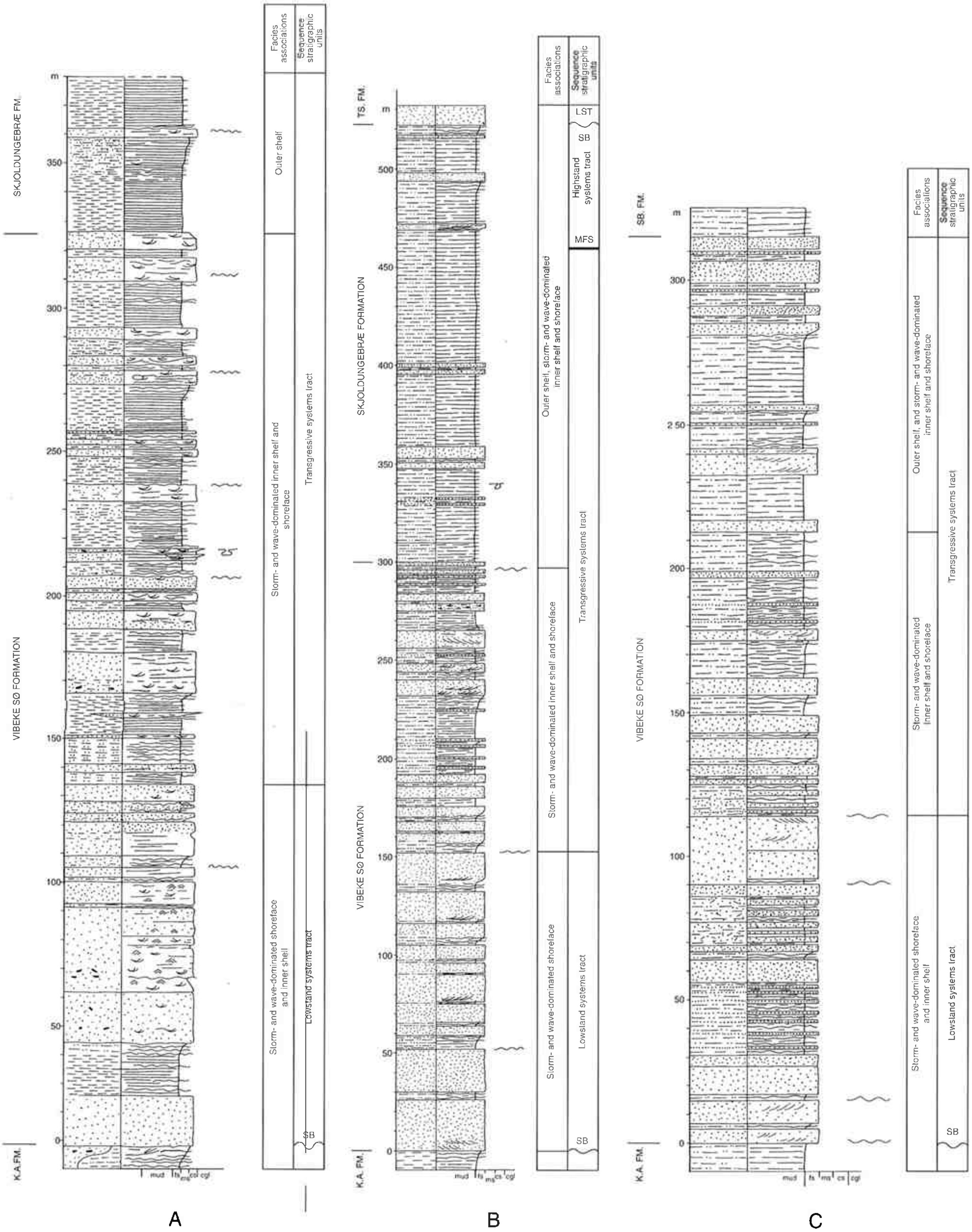


Fig. 18. **A:** Type section of the Vibeke Sø Formation (Vibeke Sø, Steno Land), **B:** reference sections of the Vibeke Sø Formation and Skjoldungebræ Formation (Kap Alfred, northern Lyell Land) and, **C:** reference section of the Vibeke Sø Formation (Kap Peterséns, northern Scoresby Land) showing facies associations and sequence stratigraphic units. The logs all show the characteristic development of overall upward fining in the Vibeke Sø Formation where the thickness of sandstone units decreases upwards, while heterolithic mudstone units increase in thickness. Smaller cycles of upward fining sandstone units are visible within the overall trend. Note that the logs are drawn at different scales. K.A. FM.: Kap Alfred Formation, SB. FM.: Skjoldungebræ Formation, TS. FM.: Teufelsschloss Formation, SB: sequence boundary, LST: lowstand systems tract, MFS: maximum flooding surface. For legend see Fig. 5.

mation are preserved (Sommer, 1957b; Sønderholm *et al.*, 1989). Further south, it occurs throughout the region between Steno Land and Scoresby Land (Fig. 1; cf. Bengaard, 1992). In Canning Land it forms the basal part of the succession found in the Kap Tyrrell area (Fig. 19).

Lithology. The Vibeke Sø Formation consists of generally thinning-upwards successions of sheet-like, quartzitic sandstone units (5–20 m thick), interbedded with 2–20 m thick dark mudstone units (Figs 17–21).

In the type section, the basal part of the formation is characterised by two approximately 20 m thick almost structureless sandstone units which have highly erosive bases showing a relief of up to 20 cm. These two basal sandstones are separated by a mudstone unit (Figs 17, 18A) and are followed by a series of 5–10 m thick sandstone units dominated by small-scale structures interbedded with 2–20 m thick mudstone units (Fig. 21). The sandstone units gradually thin upwards and towards the top of the formation attain thicknesses around 5 m, while the mudstone units gradually thicken upwards (Figs 17–19). Internally the sandstone units consist of 1–2 m thick beds which amalgamate laterally. The sandstone units are dominated by large-scale planar cross-bedding, sometimes with discontinuous mud-drapes on foresets, and by wave ripple lamination. Foreset dip directions show a well-developed unimodal orientation, indicating dominantly northerly flowing currents. In Canning Land, hummocky cross-stratification can be seen within several sandstone units. In Scoresby Land, large-scale three-dimensional sand waves with a relief of up to 50 cm and a wavelength of 5–8 m cover the upper surfaces of many sandstone units. The sand waves have been strongly modified by large- and small-scale wave ripples.

The mudstone units consist largely of dark, greenish to bluish heterolithic mudstone. Variegated red and

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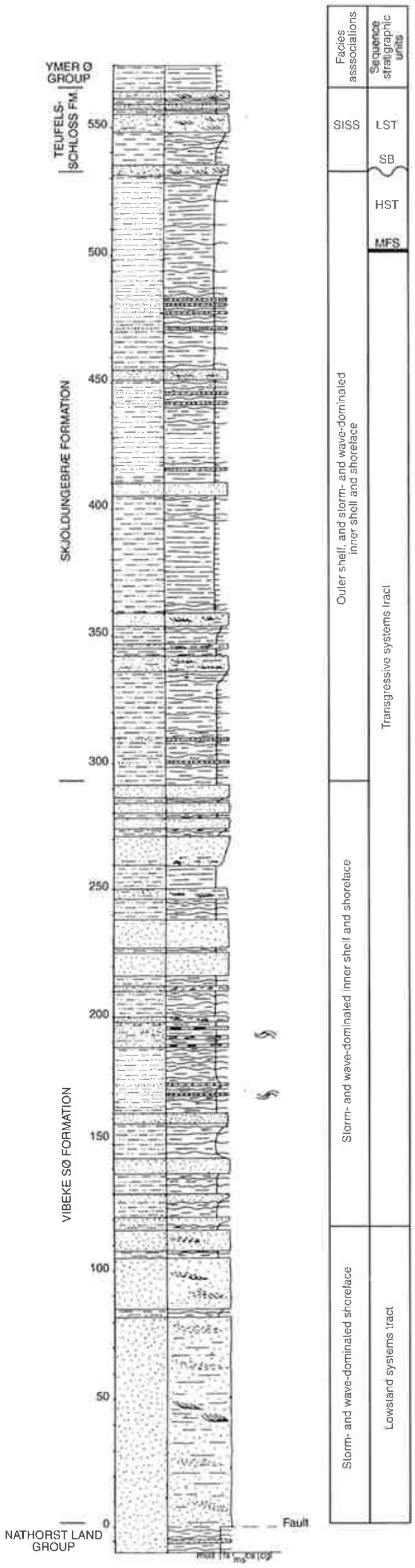


Fig. 19. Sedimentological log of upper part of the Lyell Land Group as exposed around Kap Tyrrell in Canning Land showing facies associations and sequence stratigraphic units. The log includes reference sections of the Vibeke Sø, Skjoldungebræ and Teufelsschloss Formations. The basal part of the Vibeke Sø Formation may have been faulted out, but the thickness of the formation is very similar to that of the central fjord zone and it is possible that the fault is located right at the base of the formation. Smaller cycles of upward fining sandstone units are weakly discernible within the major upward fining trend. SISS: storm-dominated inner shelf and shoreface. SB: sequence boundary, LST: lowstand systems tract, HST: highstand systems tract, MFS: maximum flooding surface. For legend see Fig. 5.

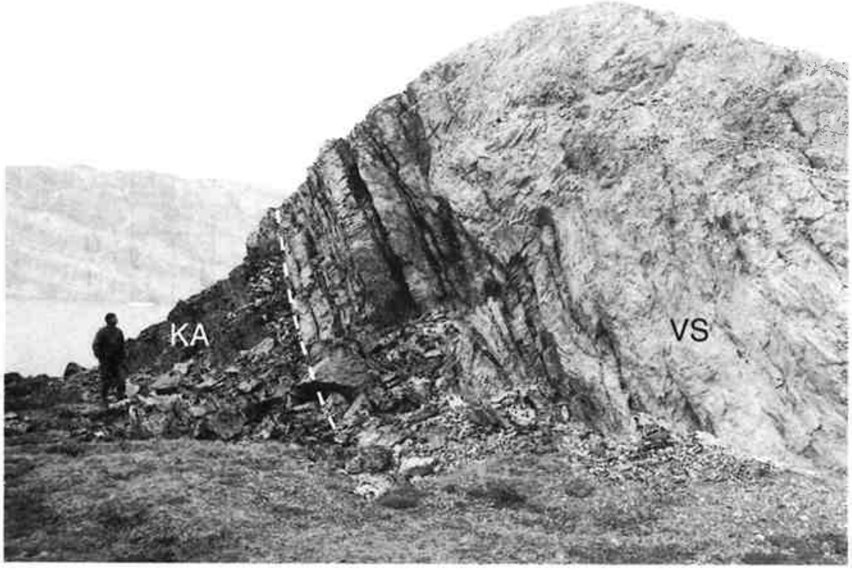


Fig. 20. Well exposed boundary (dashed) between the Kap Alfred Formation (KA) and the Vibeke Sø Formation (VS) at Kap Alfred on Lyell Land. The contact marks a shift from outer shelf mudstones of the Kap Alfred Formation to structureless sandstone, interpreted as shoreface deposits, of the Vibeke Sø Formation. The sandstones show an upward increase in bed thickness over the basal 2 m before they pass into a more than 20 m thick sandstone unit. Person for scale.

green mudstone and dark brownish-red mudstone form minor components. The mudstones are dominated by parallel lamination, sometimes showing a distinct micrograding. Thin, lenticular and wavy bedded sandstones, typically 2–10 cm thick, may locally occur. These sandstone layers are sometimes graded, showing internal parallel lamination or cross-lamination. The heterolithic mudstone units often show a coarsening upward trend caused by a gradual increase in sandstone content (Figs 18, 19).

A similar development is observed at the other localities, although variations do occur. In Lyell Land, the thickness of the two basal sandstone units reaches 26 and 22 m (Fig. 18B), whereas in northern Scoresby Land, three basal sandstone units, 6 m, 10 m and 14 m in thickness, are developed (Fig. 18C); in Canning Land, the two units appear to have amalgamated into a single unit some 80 m thick (Fig. 19).

Boundaries. The lower boundary of the formation is sharp and locally demonstrably erosive, showing scours up to 20 cm deep. The boundary is placed at the base of the first thick, white, structureless sandstone unit above the dark mudstones of the Kap Alfred Forma-

Fig. 21. Characteristic development of the lower part of the Vibeke Sø Formation at Kap Alfred (northern Lyell Land). Structureless sandstone bodies, several metres thick, alternate with 1–2 m thick mudstone units, which in most places are covered by vegetation. The characteristic development of overall upward fining (towards the left) of the formation, where the thickness of sandstone bodies decreases upwards, is well displayed. Structural dip is 55° towards the east (left).

Fig. 22. Boundary (arrow) between the Vibeke Sø Formation (VS) and the Skjoldungebræ Formation (SB) just west of Kap Peterséns, northern Scoresby Land (type locality of the Skjoldungebræ Formation). The boundary is taken at the last more than 3 m thick sandstone bed of the Vibeke Sø Formation and marks the transitional shift from dominantly greenish and grey, inner shelf mudstones and shoreface sandstones to brick-red outer shelf mudstones of the Skjoldungebræ Formation.

tion (Figs 17, 20). In Canning Land, the lower boundary is a fault which is coincident with, or close to the base of the formation.

The upper boundary to the Skjoldungebræ Formation is transitional as mudstones become increasingly dominant towards the top of the Vibeke Sø Formation. It is placed at the top of the last thick (>2 m) laterally persistent sandstone package (Figs 17, 22, 23), which is also associated with a change in colour of the associated mudstones from dominantly greenish and dark grey to dominantly brick-red.

Skjoldungebræ Formation

History. This formation was named by Sønderholm & Tirsgaard (1993) without formal description. It corresponds to 'bed-group 5' of Teichert (1933), Katz (1952), Eha (1953), Fränkl (1953a, b) and Sommer (1957a), and to the upper, dark, flaggy siltstones of Member 4 of the Agardhsbjerg Formation (Fig. 3; Katz, 1961).

Name. From the glacier Skjoldungebræ located in northern Scoresby Land (Figs 1, 24).

Fig. 23. Berzelius Bjerg in southern Lyell Land (west-facing cliffs along Polhelm Dal), showing a complete section of the Vibeke Sø Formation (VS) and Skjoldungebræ Formation (SB). The characteristic overall upward fining exposed by the two formations is readily observed. The abrupt transition from outer shelf mudstones to shoreface sandstones, which marks the contact between the Kap Alfred Formation (KA) and the Vibeke Sø Formation and between the Skjoldungebræ Formation and the Teufelsschloss Formation (TS) is also visible. KP: Kap Peterséns Formation. Thickness of the Skjoldungebræ Formation is 200 m.

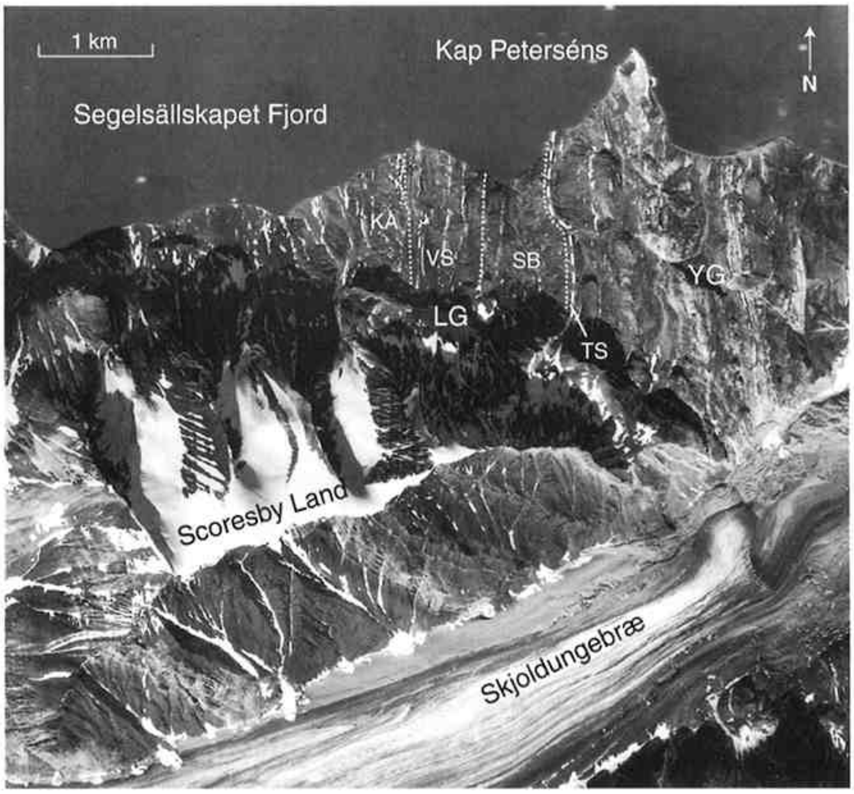


Fig. 24. Aerial photograph of northern Scoresby Land around Kap Peterséns, showing the type locality of the Skjoldungebræ Formation (SB) along the shore of Segelsällskapet Fjord. Good exposures are also present of the Vibeke Sø Formation (VS) and the Teufelsschloss Formation (TS); the latter is very thin in this part of the central fjord zone. Only the top of the Kap Alfred Formation (KA) is well exposed, as the main part of the formation is covered by vegetation and scree. LG: Lyell Land Group, YG: Ymer Ø Group.
Photo: Kort- og Matrikelstyrelsen, Denmark, route 888 L-3785 (1985).

Type locality. The type locality is immediately west of Kap Peterséns in northern Scoresby Land (Figs 24, 25), where it crops out in easily accessible coastal cliff sections. Reference sections are located around Vibeke Sø in Steno Land (Fig. 17), at Kap Alfred in northern Lyell Land (Fig. 18B) on Jägmästarens Ø in Segelsällskapet Fjord (Fig. 26) and in Canning Land (Fig. 19).

Thickness. The thickness of the Skjoldungebræ Formation shows very little variation throughout the region of outcrop. At the type locality, the formation is 206 m thick (Fig. 25), 205 m have been measured at Vibeke Sø in Steno Land (Fig. 17), 220 m at Kap Alfred in northern Lyell Land (Fig. 18B), 205 m on Jägmästarens Ø in Segelsällskapet Fjord (Fig. 26) and 240 m in Canning Land (Fig. 19).

Distribution. The Skjoldungebræ Formation forms a characteristic dark purple, brick-red and dark green, recessive weathering unit, overlying the banded Vibeke Sø Formation and overlain by white, cliff-forming sandstones of the Teufelsschloss Formation (Figs 23, 27, 28). It is widely distributed in the region between Waltershausen Gletscher and Wordie Gletscher and in the central fjord zone (cf. Bengaard, 1992). It is also preserved in the northern part of Canning Land, just south of Kap Tyrrell, where it was grouped into a single mapping unit ('bed-groups 3–6') by Caby (1972) but later recognised as a separate unit (Caby & Bertrand-Sarfati, 1988). The formation is not exposed north of Wordie Gletscher.

Lithology. The Skjoldungebræ Formation consists of a relatively monotonous succession of brick-red, dark purple or dark green mudstones and heterolithic mudstones (Figs 18, 19, 25, 26). Marly mudstones have been described from the Geologfjord area (Katz, 1961). The mudstones and heterolithic mudstones form 20–70 m thick packets, which are separated by 1–3 m thick, locally up to 5 m thick, sandstone beds; this alternation is laterally persistent and exceeds the lateral extent of the exposures.

Mudstones constitute more than 75% of the formation. These are dominated by horizontal lamination, often represented by graded rhythmites, 5–20 mm thick, grading from very fine-grained sandstone or siltstone to mudstone or claystone at the top. The lamination can be compared to the D and E divisions of the Bouma sequence (cf. Bouma, 1962). Heterolithic mudstones locally form 5–10 m thick units. These show lenticular and wavy bedding and are often associated with 5–100 cm thick, fine- to medium-grained sandstone lay-

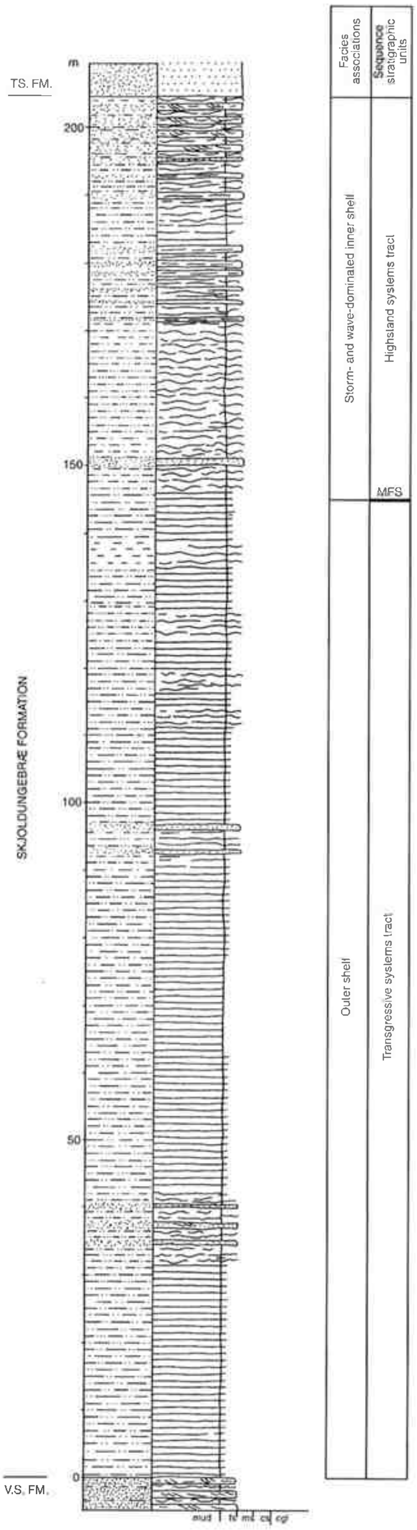


Fig. 25. Type section of the Skjoldungebræ Formation (Kap Peterséns, northern Scoresby Land) showing facies associations and sequence stratigraphic units. The formation is relatively homogeneous, dominated by outer shelf mudstones; thin storm sands are only occasionally present. V.S. FM.: Vibeke Sø Formation, TS. FM.: Teufelsschloss Formation, MFS: maximum flooding surface. For legend see Fig. 5.

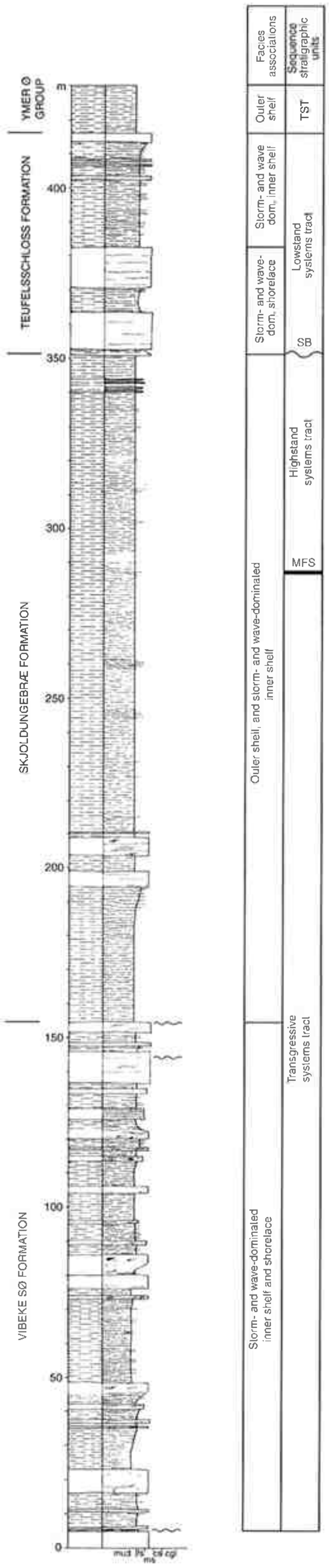


Fig. 26 Sedimentological log of the Lyell Land Group as exposed on Jägmästarens Ø in Segelsällskapet Fjord showing facies associations and sequence stratigraphic units. Only the upper part of the Vibeke Sø Formation is exposed, while complete reference sections of the Skjoldungebræ Formation and Teufelsschloss Formation are well exposed. The Teufelsschloss Formation is relatively thin and consists of interbedded shoreface deposits and heterolithic mudstone deposits of storm dominated inner shelf origin. Coastal plain deposits are absent. SB: sequence boundary, TST: transgressive systems tract, MFS: maximum flooding surface. For legend see Fig. 5.

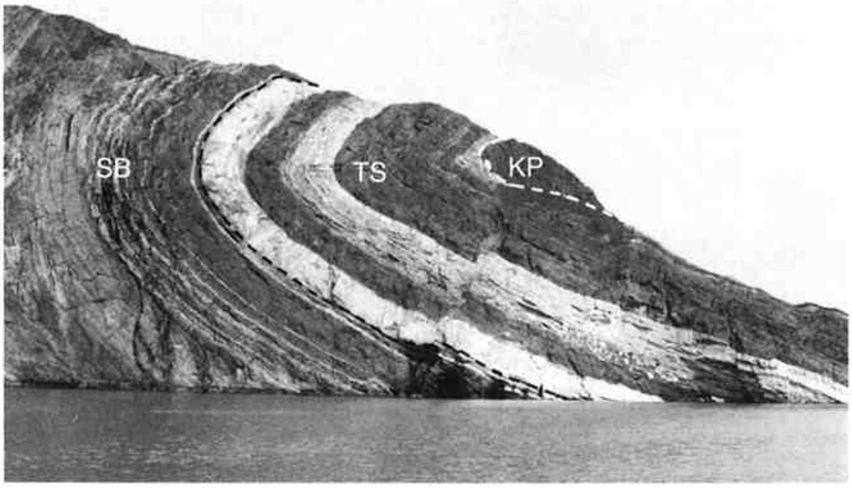


Fig. 27. Boundary between the Skjoldungebræ Formation (SB) and Teufelsschloss Formation (TS) and between the Teufelsschloss Formation and Kap Peterséns Formation (KP) as exposed on Jägmästarens Ø in Segelsällskapet Fjord. The photograph shows the characteristic development of the Teufelsschloss Formation in the southern part of the central fjord zone, where it only comprises storm-dominated inner shelf and shoreface deposits. Tidal channel deposits are absent. The two basal sandstone units, which occur at the base of the formation at the type locality, are also present on Jägmästarens Ø. The lower sandstone unit is approximately 10 m thick.

ers. These have sharp contacts and are dominated by horizontal lamination and cross-lamination. Tool marks and current lineation are locally well developed on bedding planes in some areas, particularly in Canning Land.

The sandstone beds are generally structureless and have very sharp upper and lower contacts (Figs 19, 25–27). Locally, large-scale cross-bedding and horizontal lamination can be observed, commonly in association with mudstone clasts. Large-scale, coarse-grained wave ripples may be observed locally.

Overall vertical trends are absent within the formation, but in the central fjord zone a weak upwards coarsening is seen in the uppermost 40 m of the formation where heterolithic mudstones increase in abundance at the expense of laminated mudstones (Figs 18, 25–27). Significant lateral lithological variations have not been observed within the formation, which appears to be homogeneously developed across the entire area of exposure.

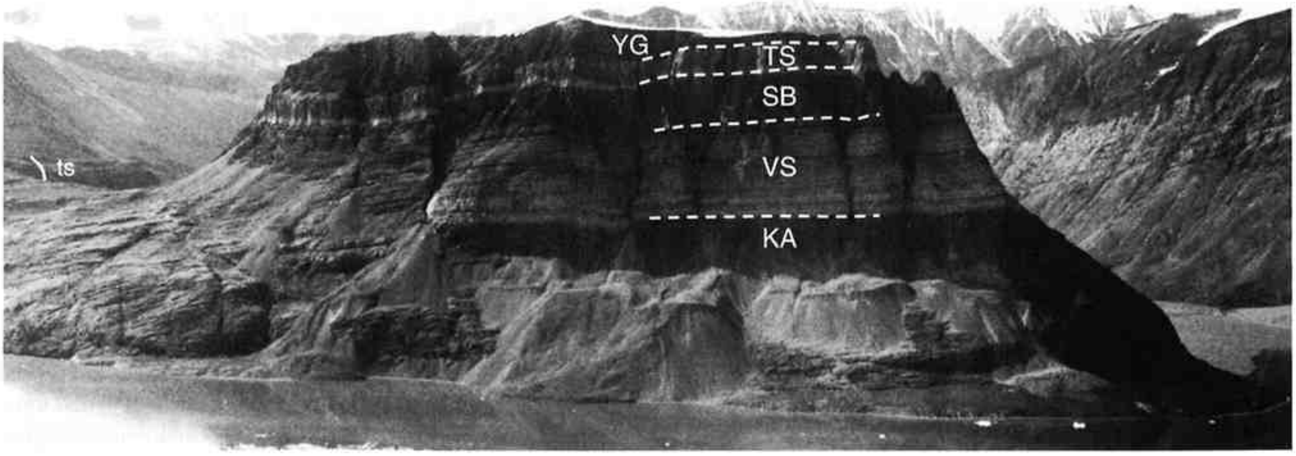
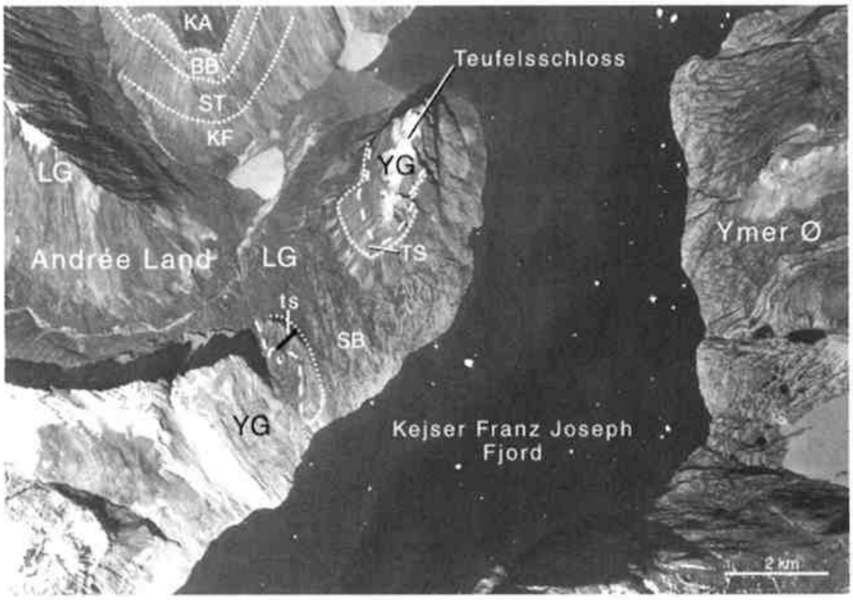


Fig. 28. Type locality of the Teufelsschloss Formation (TS) at the mountain Teufelsschloss, Andrée Land, showing the well exposed contacts to the underlying Skjoldungebræ Formation (SB) and the overlying Ymer Ø Group (YG). The type section (ts) of the Teufelsschloss Formation is located in the valley south of the mountain. Note the conspicuous pale weathering shoreface sandstones forming the base and top of the formation. KA: Kap Alfred Formation. Thickness of Teufelsschloss Formation is 135 m.

Fig. 29. Aerial photograph of eastern Andrée Land, around Teufelsschloss mountain, showing the location of the type section (ts) of the Teufelsschloss Formation (TS). LG: Lyell Land Group, YG: Ymer Ø Group, KF: Kempe Fjord Formation, ST: Sandertop Formation, BB: Berzelius Bjerg Formation, KA: Kap Alfred Formation, SB: Skjoldungebræ Formation.
Photo: Kort- og Matrikelstyrelsen, Denmark, route 888 K-3723 (1985).



Boundaries. The lower boundary to the Vibeke Sø Formation is transitional as mudstones increase in abundance upwards through the Vibeke Sø Formation. However, the boundary is placed at the top of the last sandstone package which is over 2 m thick (Figs 22, 23). This also corresponds with a shift in colour of the mudstones from dominantly dark greenish-grey or brownish to mainly brick-red, dark purple or dark green. The upper boundary is placed at the change from brick-red or dark green mudstones to a more than 5 m thick, structureless white sandstone bed, marking the base of the Teufelsschloss Formation (Figs 23, 27, 28).

Teufelsschloss Formation

History. The formation was named by Sønderholm & Tirsgaard (1993) without formal description. The formation corresponds to 'bed-group 6', described from the central fjord zone by Teichert (1933), Katz (1952), Fränkl (1953a, b), Eha (1953) and Sommer (1957a) and to Member 5 of the Agardhsbjerg Formation (Fig. 3; Katz, 1961).

Name. After the mountain Teufelsschloss on the south-eastern coast of Andrée Land, south of Eleonore Bugt (Figs 1, 28, 29).

Type locality. The type locality is a prominent, north-facing cliff section in the east–west valley south of the mountain Teufelsschloss (Figs 28–30A). Reference sections are found around Vibeke Sø in Steno Land (Fig. 30B), on Jägmästarens Ø (Figs 26, 27) and in Canning Land (Fig. 19).

Thickness. At the type locality, the formation reaches a thickness of 135 m (Fig. 30A). Similar thicknesses of 107 m are attained in Steno Land (Fig. 30B) and as far south in the central fjord zone as northern Lyell Land (130 m). South of this area it thins rapidly towards the south-east, reaching only 65 m at Kap Dufva (Fig. 1) and on Jägmästarens Ø (Fig. 26) and 60 m at Kap Peterséns in northern Scoresby Land. Fränkl (1953b) reported a thickness of only 15 m some 15 km south of Kap Peterséns. In Canning Land, the thickness is 35 m (Fig. 19).

Distribution. The formation is widely distributed in the region between Waltershausen Gletscher and Wordie Gletscher and in the central fjord zone (cf. Bengaard, 1992). It is also present in northern Canning Land where it was grouped into a single mapping unit ('bed-groups 3–6') by Caby (1972) but later recognised as a separate unit by Caby & Bertrand-Sarfati (1988). It is not exposed in the Bredefjord–Ardencaple Fjord region (Sommer, 1957b; Sønderholm *et al.*, 1989).

Lithology. At the type locality, the formation consists of two basal, white, very well sorted, structureless, fine- to medium-grained sandstone units, 20–25 m thick, separated by approximately 5 m of heterolithic mudstone. The upper sandstone unit is erosively overlain by a 75 m thick succession of wine-red, fine- to

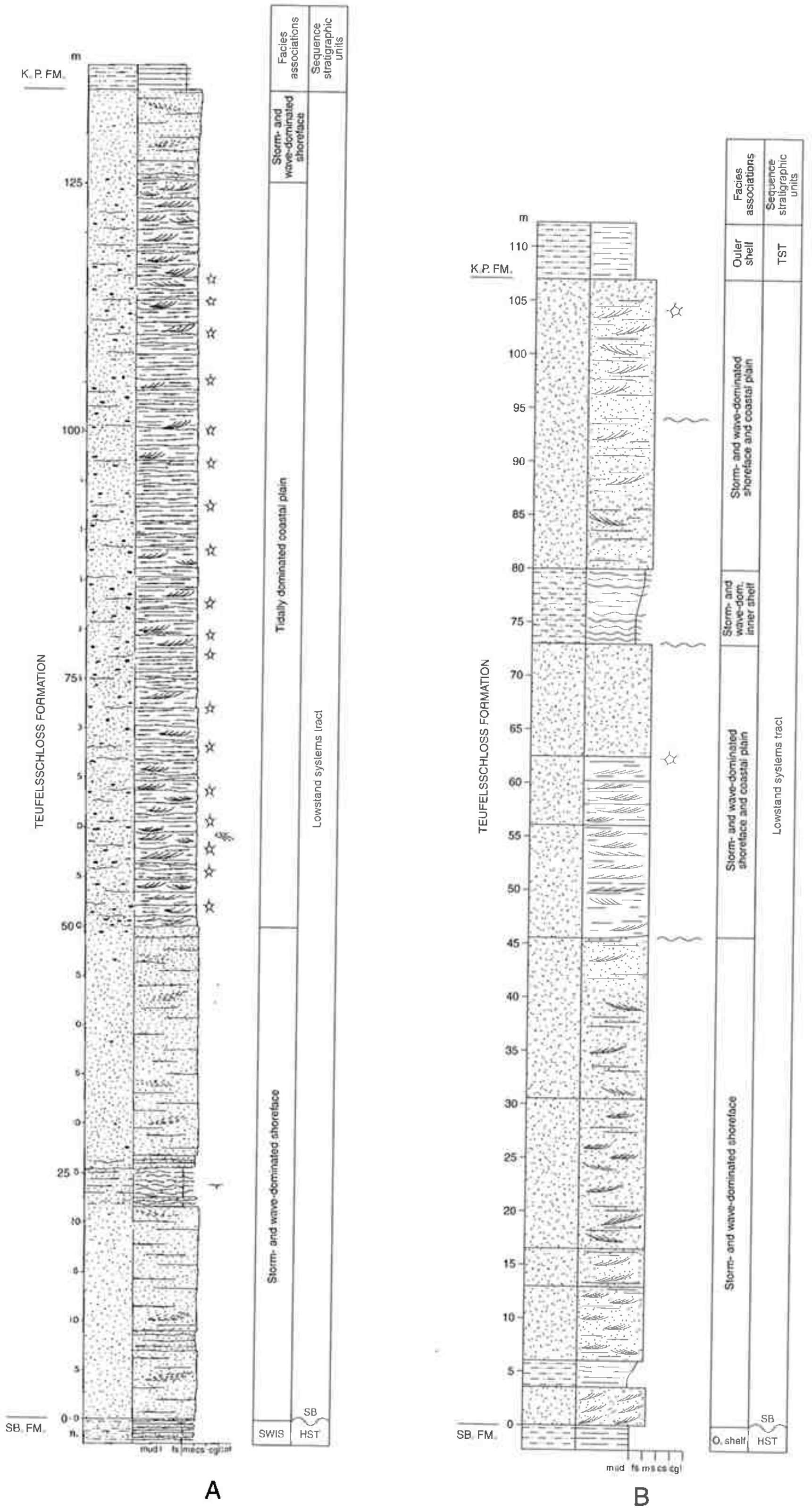


Fig. 30. **A:** Type section of the Teufelsschloss Formation (Teufelsschloss, southeastern Andrée Land) showing facies associations and sequence stratigraphic units. The section shows the characteristic subdivsion of the formation in the northern Lyell Land – Andrée Land region, where the lower 40–50 m consist of nearly structureless shoreface sandstone deposits, the middle 70–80 m comprise well-developed sand sheets with numerous desiccation cracks, representing sub- to intertidal channels and the upper 5–10 m consist of nearly structureless, white sandstone reflecting renewed shoreface deposition.
B: Reference section of the Teufelsschloss Formation (Vibeke Sø, Steno Land). Here the characteristic tripartite division is absent and instead the formation consists of interbedded storm-dominated shoreface deposits and subtidal deposits; desiccation cracks only occur rarely. SB. FM.: Skjoldungebræ Formation, K.P. FM.: Kap Peterséns Formation, SWIS: storm- and wave-dominated inner shelf, SB: sequence boundary, TST: transgressive systems tract, HST: highstand systems tract. For legend see Fig. 5.

medium-grained sandstone. The uppermost 10 m of the formation consists of a white sandstone unit similar to the units at the base (Figs 28, 30A).

The basal and uppermost sandstone units are poorly bedded and contain very few sedimentary structures but 0.1–1.0 m thick sets of large-scale planar cross-bedding, and ripplemarks are sporadically preserved. In Steno Land, large-scale wave ripples and straight to sinuous crested megaripples are locally preserved on bedding planes.

The middle 75 m of the formation comprise wine-red sandstones showing a well defined bedding developed as 0.3–3.0 m thick sand sheets that can be traced the full length of the exposure. Each sand sheet has a highly erosive base with a relief up to 20 cm and, where the top is preserved, it is draped by a thin mudstone veneer with desiccation cracks. The sand sheets contain well preserved sedimentary structures dominated by parallel lamination and large-scale planar cross-bedding, sometimes forming herringbone cross-stratification. Foreset dip directions show a strongly bimodal orientation indicating flow towards the NW and SE. Scour and fill, cross-lamination, and locally climbing ripple lamination form subordinate structures. Vertical trends in sand sheet thickness, or in the internal structures have not been observed. The heterolithic mudstone deposits separating the two basal sandstone units are wavy and lenticular bedded.

In Steno Land and in Strindberg Land, the wine-red sand sheets in the middle part of the formation are absent and this part consists instead of a 30–70 m thick unit of light brown sandstone (Fig. 30B) which lacks indications of a distinct sand sheet geometry. Sedimentary structures include large-scale cross-bedding (sets 10–40 cm thick), with numerous reactivation surfaces, clay drapes and herringbone cross-stratification. Palaeocurrent directions are towards NW and SE. Desiccation cracks are only rarely seen on bedding planes. In southern Lyell Land, in Scoresby Land and in Canning Land the formation consists of two to three white, structureless sandstone units, 8–20 m thick, separated by dark brownish heterolithic sandstone and mudstone units, 0.5–20 m thick (Figs 26, 27). These are dominated by wavy lamination interbedded with 3–10 cm thick, graded, very fine- to fine-grained sandstone beds.

Boundaries. The lower boundary is placed where a thick, laterally continuous white sandstone unit sharply overlies the more recessive dark brown to dark purple or green mudstones and heterolithic mudstones of the Skjoldungebræ Formation (Figs 17, 23, 27, 28). In the southern part of the central fjord zone and in Canning Land, where the Teufelsschloss Formation consists of several sandstone units separated by heterolithic mudstones, the contact is placed at the base of the first sandstone unit which is more than 5 m thick (Fig. 27). The upper boundary of the Teufelsschloss Formation is placed where white sandstones, or dark brown heterolithic mudstones, are sharply overlain by dark red or purple mudstones of the Kap Peterséns Formation of the Ymer Ø Group (Figs 23, 27, 28, 31; Sønderholm & Tirsgaard, 1993). This contact is widely and well exposed from Canning Land in the east and Scoresby Land in the south, throughout the central fjord zone and as far as Wordie Gletscher in the north (Fig. 1; cf. Bengaard, 1992).

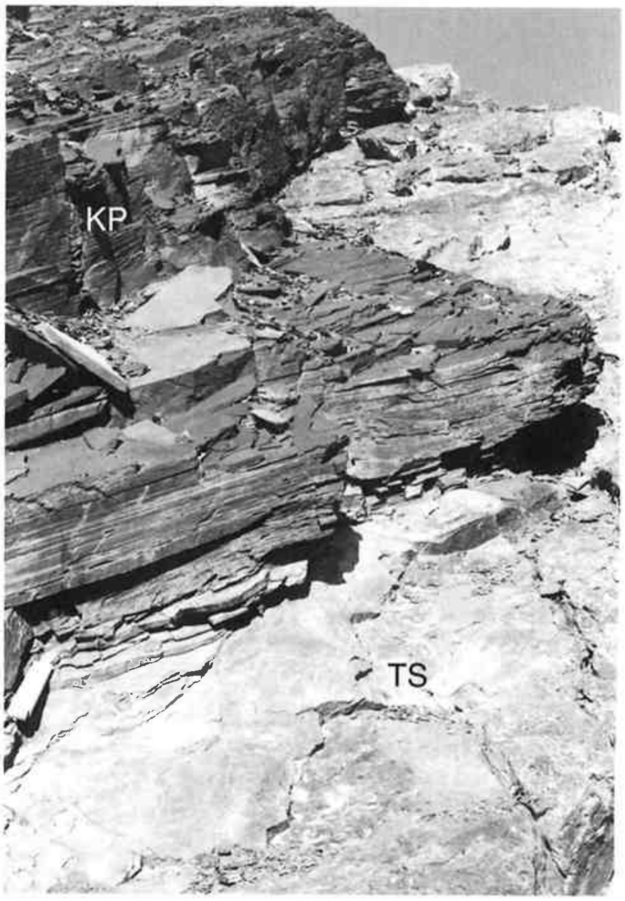


Fig. 31. Close-up of the boundary between the Lyell Land Group (Teufelsschloss Formation, TS) and the Ymer Ø Group (Kap Peterséns Formation, KP) as seen on the southern coast of Ymer Ø. The boundary reflects an abrupt shift from shoreface sandstones to outer shelf mudstones. This marked change in lithology is characteristic of the boundary throughout the central fjord zone. Ruler (20 cm) for scale in lower left corner.

Depositional evolution

Facies associations and depositional environments

The deposits of the Lyell Land Group were laid down on an extensive siliciclastic shelf in environments ranging from coastal plain to outer shelf. Continental deposits have not been observed within the studied outcrops, but may be present in the more western outcrops around Petermann Bjerg (Fig. 1). The preservation of sedimentary structures is often poor due to severe recrystallisation and a very uniform grain size distribution throughout the group. Nevertheless, the Lyell Land Group can be categorised into five broad facies associations representing outer shelf, storm- and wave-dominated inner shelf, tidally influenced shoreface, storm- and wave-dominated shoreface and tidally dominated coastal plain environments.

All five associations can be found within the central fjord zone, where they can be traced from Scoresby Land in the south to Steno Land in the north (Fig. 1). In Canning Land, only outer shelf, storm- and wave-dominated inner shelf, and storm- and wave-dominated shoreface associations have been observed. Around Bredefjord–Ardencaple Fjord severe recrystallisation and deformation has obliterated most sedimentary structures hindering any detailed sedimentological analysis (Sønderholm *et al.*, 1989). However, since it is possible to trace the formations of the Lyell Land Group from the south into this region it is assumed that similar depositional environments are present in this area, but the interpretations of the depositional evolution of the group is based on evidence south of latitude 76°N.

Outer shelf association

General

Deposits of the outer shelf association are found within the lower part of the Sandertop Formation, the lower and upper part of the Kap Alfred Formation and in most of the Skjoldungebræ Formation (Figs 10, 16, 25). The association forms successions 2–40 m thick.

Description

The association consists dominantly of mudstones. They may locally be interbedded with sandstone lenses and beds up to a few centimetres thick (Fig. 32), but these together constitute less than 5% of the deposits. The mudstones have a dark green, brown to dark red, occasionally purplish weathering appearance. They typically form sections many metres to several tens of metres thick, consisting exclusively of 0.5 to 2 cm thick structureless to finely laminated beds (Fig. 33) which show a very fine, but well developed grading from sandstone to claystone. Tool marks can occasionally be seen on bedding planes.

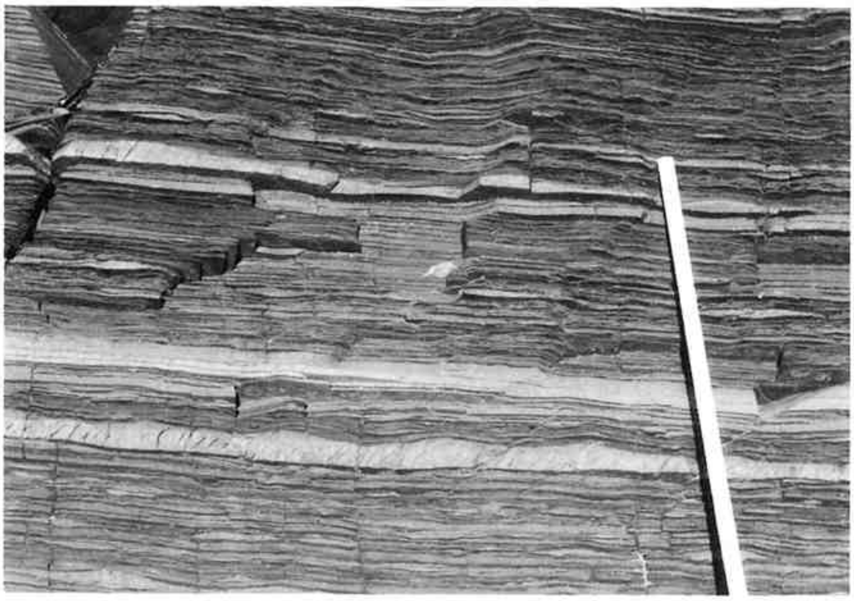


Fig. 32. Laminated outer shelf mudstones interbedded with thin sandstone beds and lenses showing sharp bases and in some cases well-developed ripple form sets. Skjoldungebræ Formation, Jägmästarens Ø.

The sandstone lenses and beds have a yellowish to grey or greenish appearance, and consist of fine- to very fine-grained sand, which in most cases fines upwards into a structureless mudstone cap. Bases are sharp and loading into the underlying mudstones is common. The sandstone layers are either structureless, or show a weak parallel lamination, but in some cases they display extensively developed ripple form sets (Fig. 32), which may show internal ripple cross-lamination. The sandstone layers have lateral extents from less than a metre to several tens of metres, sometimes exceeding the length of exposure (>100 m).

Interpretation

The structureless to finely laminated mudstone beds record slow deposition from suspension settling during fair-weather periods when very little sediment was transported to the outer shelf region. Graded mudstone beds record settling of silt and mud from waning suspension currents. Both the sharp based, laminated, graded sandstone beds and the more fine-grained, graded mudstone beds resemble thin Bouma type D and E beds (Bouma, 1962). Together with structureless sandstone beds, they are considered to reflect deposition from unidirectional currents formed in connection with storm events (e.g. Walker & Plint, 1992). Sediments eroded from coastal areas were transported out onto the muddy shelf by geostrophic flows related to coastal downwelling or storm surge ebb flows (e.g. Hayes, 1967; Nelson, 1982; Aigner, 1985; Snedden & Nummedal, 1991). The rare occurrence of wave-induced structures implies that wave oscillatory movements only rarely affected the sea bed and that deposition occurred in deeper water below both fair-weather and storm wave base.

Storm- and wave-dominated inner shelf association

General

This association is found within the Sandertop, Kap Alfred, Vibeke Sø, and Skjoldungebræ Formations (Figs 10, 16, 18, 25). It is also found within the Teufelsschloss Formation in the southern part of the central fjord zone (Fig. 26) and in Canning Land (Fig. 19). It forms units which vary in thickness from 1 m to more than 100 m and over- and underlies both shoreface and outer shelf deposits.

Fig. 33. Thin bedded outer shelf mudstone which locally shows a fine internal lamination, often associated with a weak grading. The grading is best observed approximately 10 cm below the scale bar. Scale bar is 20 cm long. Skjoldungebræ Formation, Jägmästarens Ø.

Description

This facies association is characterised by very fine- to fine-grained sandstone beds interbedded with heterolithic mudstone (Fig. 34). Black to greyish and greenish, sometimes dark brown weathering, heterolithic mudstones alternate with 1–30 cm, occasionally 100 cm thick beds of very fine- to fine-grained, pale yellow or white sandstone. The heterolithic mudstones display lenticular and wavy bedding. The sandstone beds have scoured, undulatory bases; upper surfaces are planar or undulatory but generally sharp. Internally they show horizontal lamination or ripple structures, mainly developed as form sets, and less commonly showing distinct ripple cross-lamination (Fig. 34). Foreset bundling and bi-directional foreset dip directions can occasionally be observed within the ripple structures. Ripple form sets may either be symmetrical or asymmetrical

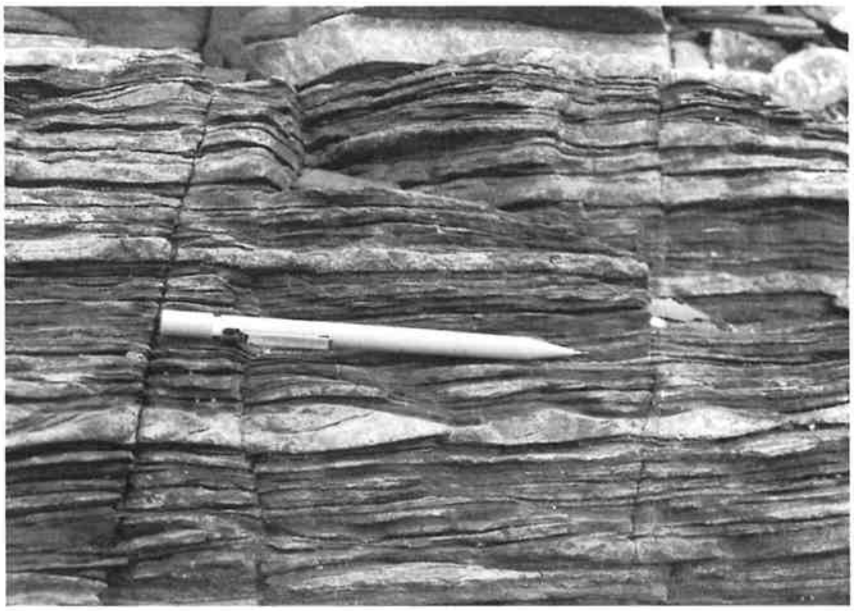


Fig. 34. Upward coarsening succession within heterolithic mudstone deposits of the storm- and wave-dominated inner shelf association. A thin sandstone lens with well-developed ripple form sets is succeeded by a succession showing an increasing occurrence of sandstone lenses. Type locality of Skjoldungebræ Formation, northern Scoresby Land.

in outline. Large-scale ripples, 10-20 cm in height, occur locally (Fig. 35). Within the horizontally laminated sandstone beds a faint grading is commonly developed and ripple structures are almost invariably developed at the top. Hummocky cross-stratification occurs locally.

The thin sandstone beds extend laterally for several tens of metres, while thicker beds exceed the length of exposures (>100 m). Upward coarsening successions are commonly developed. These show an evolution from mudstone or heterolithic mudstone into gradually thickening sandstone beds separated by thin mudstone partings, with ripple structures and hummocky cross-stratification becoming increasingly dominant. Such coarsening upward successions typically are a few metres thick, but may form stacked successions several tens of metres thick. These successions grade upward into either thick, mature sandstone deposits (shoreface deposits), or they are abruptly overlain by, or grade into, mudstones of the outer shelf.

Fig. 35. Large-scale wave ripples with well preserved foresets within the storm- and wave-dominated inner shelf association; height of the main ripple in the central part of the photograph is 20 cm. Vibeke Sø Formation, Canning Land.

Interpretation

The heterolithic mudstones record deposition in a storm- and wave-dominated setting. The sandstone beds with their sharp scoured bases show the characteristics of storm deposits (e.g. Hobday & Morton, 1984; Driese *et al.*, 1991; Walker & Plint, 1992) and formed in response to dominantly unidirectional currents created by wind-forced geostrophic currents (Swift *et al.*, 1987; Snedden & Nummedal, 1991; Brenchley *et al.*, 1993). The internal structure of the ripples, dominated by bi-directional foreset dip directions and a bundle-like upbuilding, strongly suggests a wave-generated origin (Raaf *et al.*, 1977). Their common occurrence at the top of sandstone beds shows that oscillatory movements periodically affected the sea bed during high energy events remoulding the top of the sandstone beds. Large-scale wave ripples together with hummocky cross-stratification are generally regarded as forming under oscillatory and combined flow conditions during storm events (e.g. Leckie, 1988; Duke, 1990). Deposition within this association was thus strongly influenced by storm events, yet more continuous reworking of the sediment did not occur. This implies that deposition occurred below fair-weather wave base.

The upward-coarsening successions represent a gradual shallowing, reflected in the change from predominantly unidirectional to oscillatory currents or to combined flow (e.g. Duke, 1990; Brenchley *et al.*, 1993). In some cases this upward shallowing continued above the fair-weather wave base leading to deposition of sandstone beds of the shoreface facies association. In other cases the upward shallowing was followed by either a gradual or an abrupt deepening.

Tidally influenced shoreface association

General

This association constitutes the middle 300 m of the Kap Alfred Formation in the type section (Fig. 16), forming a conspicuous unit of interbedded sandstones and heterolithic mudstones, creating upward coarsening successions 3–15 m thick. The association is sandwiched between approximately 100 m thick units of dark grey and brown mudstone and heterolithic mudstone of the outer and inner shelf associations. The tidally influenced shoreface association has not been recognised in the Bredefjord–Ardencaple Fjord region (Sønderholm *et al.*, 1989), but according to Katz (1952), Eha (1953), Fränkl (1953a) and Sommer (1957a) a similar lithological unit is present within the same stratigraphic interval of the Kap Alfred Formation in other areas of the central fjord zone, ranging in thickness from 220 to 270 m.

Description

The association consists of stacked, fine- to medium-grained sandstone bodies separated by heterolithic mudstone beds. The sandstone bodies range from 1 to 6 m in thickness and laterally exceed the length of exposures (>100 m) without showing any indications

Fig. 36. Tidally influenced shoreface association; characteristic internal structures of a tidal sand wave developed within the middle part of the Kap Alfred Formation (Kap Alfred, northern Lyell Land). The tidal sand waves consist of stacked sets of large-scale cross-bedding with reactivation surfaces and mud draped foresets. Some beds show well-developed herringbone cross-stratification. Compass is 10 cm long.

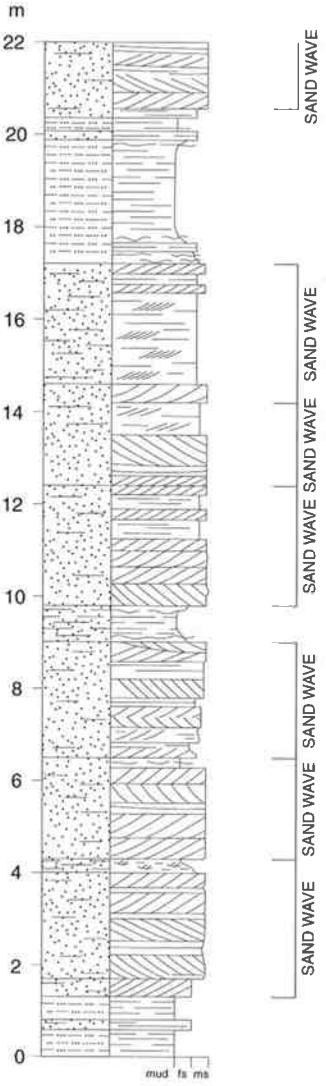


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Fig. 37. Detailed sedimentological log of the tidally influenced shoreface association (Kap Alfred Formation, northern Lyell Land) showing the characteristic vertical stacking pattern of sand waves, which combine to form tidal sand sheets. Intervals dominated by mudstone separate tidal sand sheets. Each sand wave generally lacks distinct vertical structural and textural trends, but the upper part is often characterised by slightly finer-grained beds dominated by wave-ripples, possibly representing periods of reworking of the sand waves.
For legend see Fig. 5.

of marked changes in thickness. In larger inaccessible cliff exposures, the sandstone bodies appear to have a sheet-like geometry, with a lateral extent of at least a few kilometres both normal to, and parallel with, the inferred coastline (see later).

The sandstone bodies consist of stacked, compound cosets dominated by large-scale planar to tangential tabular cross-bedding (Figs 36, 37) alternating with cross-lamination and occasionally horizontal lamination. Sets of cross-bedding are typically 5–40 cm thick often with undulatory lower set boundaries. Foresets may show a characteristic thickening and thinning separated by reactivation surfaces (Figs 38, 39). Discontinuous clay drapes are often seen along the lower part of the foresets and mudclasts may be scattered along the foresets (Fig. 39). Thicker sets can be traced 20–40 m parallel with foreset dip directions, while thinner sets rarely extend beyond 10 m.

Sets of large-scale cross-bedding combine to form

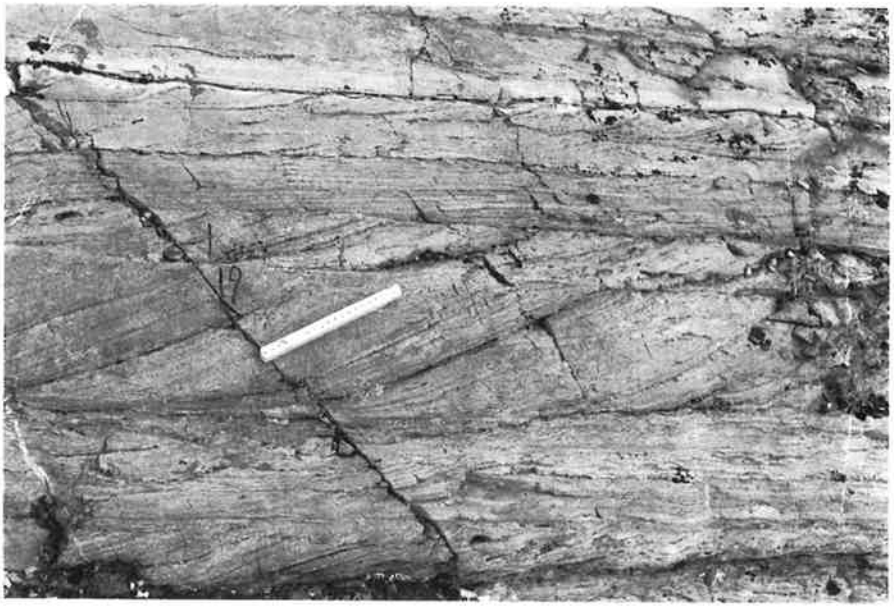
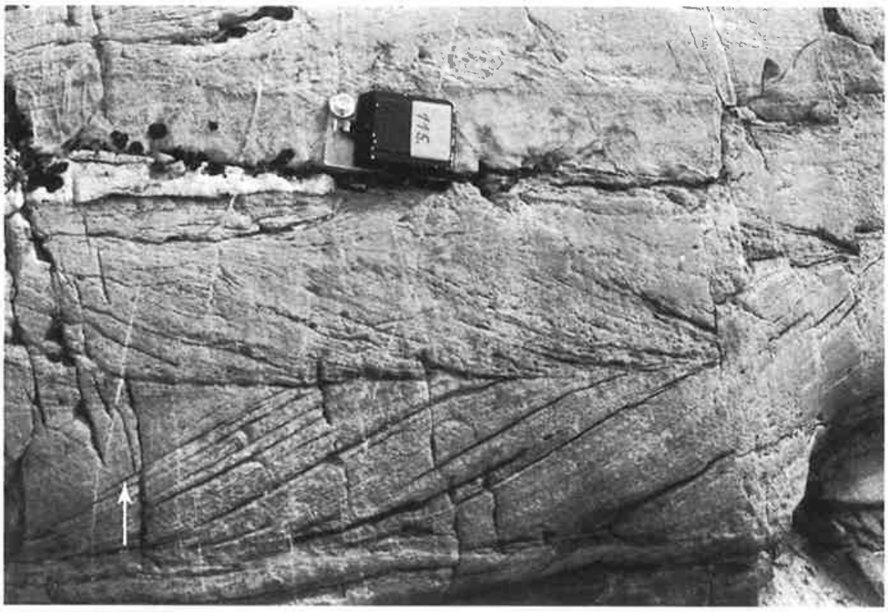


Fig. 38. Characteristic, well preserved internal development of a sandstone body within the tidally influenced shoreface association showing alternating deposition of large-scale cross-bedding and cross-lamination. Cross-beds show numerous reactivation surfaces. Scale bar is 20 cm long. Kap Alfred Formation, northern Lyell Land.

Fig. 39. Herringbone cross-bedding with clay drapes along foresets from the tidally influenced shoreface association. Within the lower cross-bed individual foresets show a gradual thinning towards the left, followed by a sudden thickening (arrow). This rhythmic upbuilding of the set possibly reflects neap-spring tidal cycles. The upper cross-bed shows a similar, although less distinct, thinning of foresets towards the right. Compass is 10 cm long. Kap Alfred Formation, northern Lyell Land.



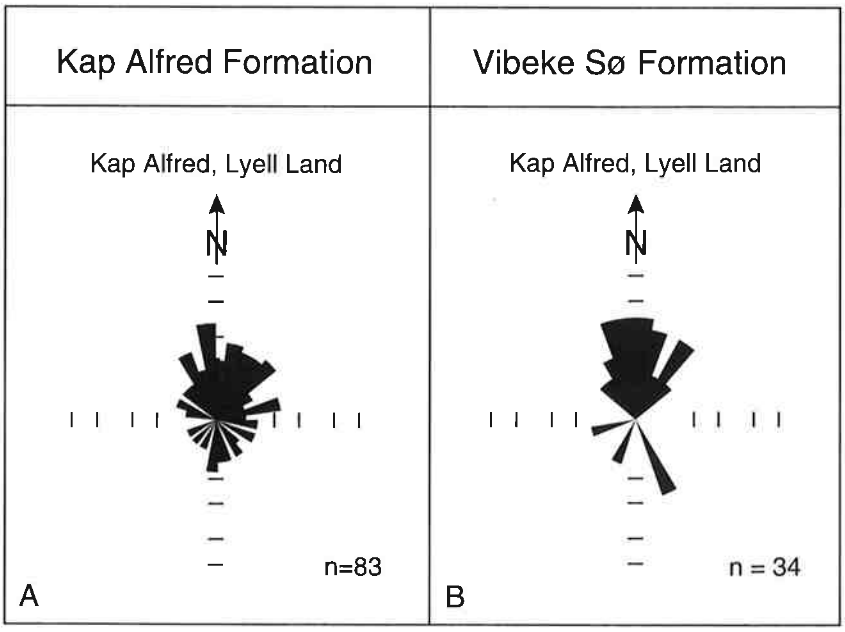
cosets, typically 60–100 cm thick and exceeding the length of exposure. Both the upper and lower coset boundaries are generally sharp and flat. The large-scale cross-beds show dip directions mainly towards the north and north-north-east, with a few indicating flow directions towards the south (Fig. 40A). Herringbone cross-bedding is locally common (Fig. 39).

The sandstone bodies are characterised by a gradational base to underlying heterolithic mudstones. The transition is manifested by several 10–20 cm thick sandstone layers interbedded with the heterolithic mudstones. These sandstone layers show either horizontal lamination or sets of planar cross-bedding.

The sandstone bodies lack any characteristic vertical textural and structural trends, although the uppermost 10–50 cm, often consist entirely of ripple lamination (Fig. 37). The contact with the overlying heterolithic mudstones is sharp.

The heterolithic mudstone beds vary in thickness between 1 and 10 m. They consist of laminated mudstone interbedded with sandstone lenses and more continuous beds (Fig. 41). Sandstone lenses, 1–2 cm

Fig. 40. **A:** Palaeocurrent measurements from the tidally influenced shoreface association (10° intervals). The measurements are made on large-scale planar cross-beds within tidal sand waves from the middle part of the formation.
B: Palaeocurrent measurements from the storm- and wave-dominated shoreface association. The measurements are made on large-scale planar cross-beds in thick sandstone units from the lower and middle part of the Vibeke Sø Formation.



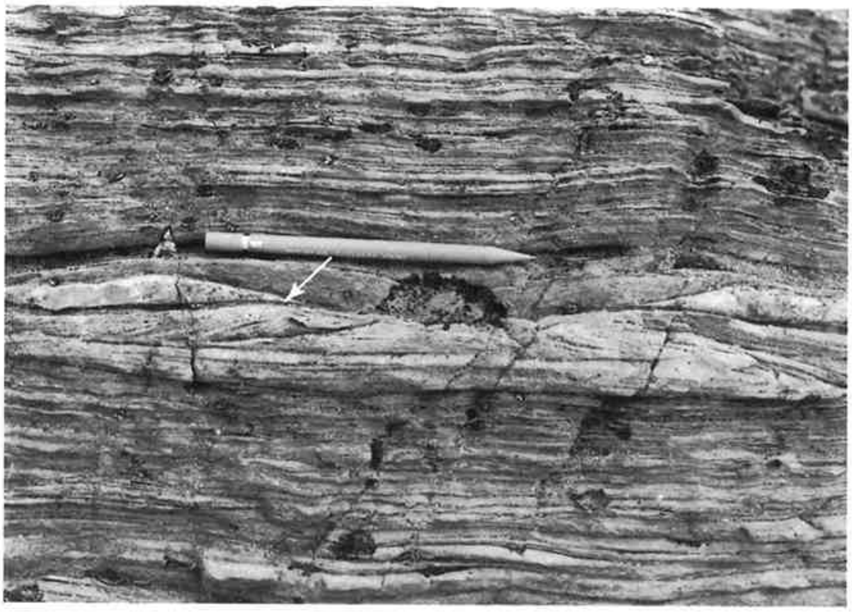


Fig. 41. Heterolithic mudstones from the tidally influenced shoreface association interbedded with thin sandstone lenses. The sandstone lenses contain well-developed ripples with foresets showing bi-directional bundling (arrow). Kap Alfred Formation, northern Lyell Land.

thick consist of sets of ripple lamination, developed either as isolated sandstone lenses or as distinct ripple trains (Fig. 41). Bundled upbuilding and offshoots can be observed within the ripple trains. Discrete fine-grained sandstone beds are 5–15 cm thick sharp based and are either structureless or show faint parallel lamination, which occasionally may grade into hummocky cross-stratification. Load structures are associated with many of the sandstone layers.

Interpretation

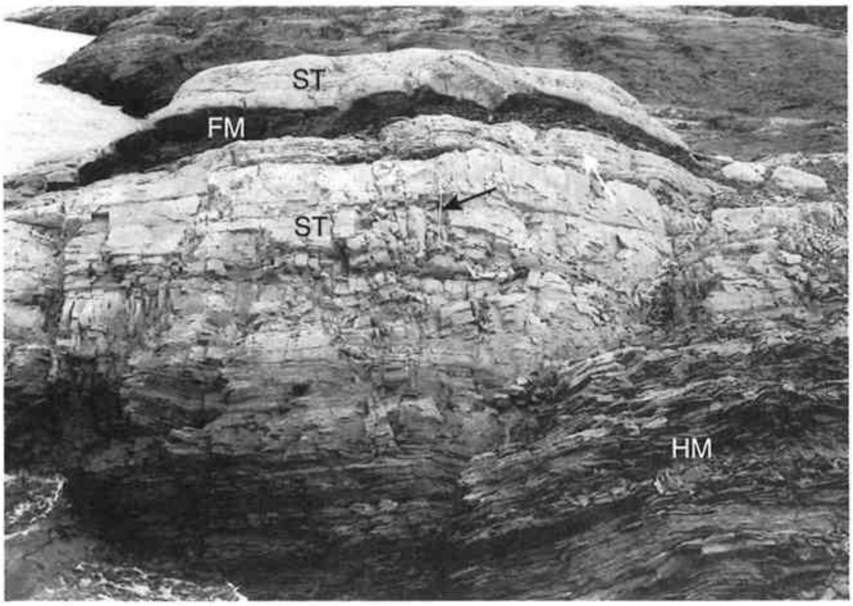
The occurrence of herringbone cross-stratification, undulatory lower set boundaries, thickening and thinning of foresets coupled with the presence of clay draped foresets and abundant reactivation surfaces, suggest a tidal origin for the large-scale cross-bedded sandstone bodies (e.g. Soegaard & Eriksson, 1985; Terwindt, 1988; Simpson & Eriksson, 1991; Tirsgaard, 1993). There is no indication of subaerial exposure and deposition is considered to have occurred in a subtidal environment. Palaeocurrent measurements on foresets indicate only a weak bi-directional trend (Fig. 40A). However, the preservation of only weakly bimodal directional patterns are common in ancient tidal shelf deposits and reflect a time-velocity asymmetry of the tidal currents (Anderton, 1976; Levell, 1980; Bridges, 1982; Chakraborty & Bose, 1990; Harris & Eriksson, 1990; Simpson & Eriksson, 1991).

The presence of compound cross-beds reflects the migration of a hierarchy of bed forms. Individual sets of tabular cross-beds resulted from two-dimensional dunes and each coset is considered to represent a sand wave (Fig. 37).

The internal structure of sand waves is a function of the time velocity asymmetry of the tidal flow. Strong velocity asymmetry results in the development of flow separation on the lee side of sand waves and steep avalanche foresets. Under conditions closer to time-velocity symmetry, flow separation behind the sand wave lee face no longer occurs and transport is confined to the migration of smaller scale two- and three-dimensional dunes (Allen, 1980). The internal architecture of the sand waves here indicates only a moderate time-velocity asymmetry during migration of the bed forms which, nevertheless, was sufficiently pronounced to result in the dominance of northerly migrating dunes.

The presence of ripple laminated sandstones and mud layers separating the individual sand waves suggest that periods of sand wave formation and migration were separated by periods of reworking of the sand waves by wave ripples, followed by slow deposition of mud from suspension fall-out. The sandstone bodies thus formed in a setting in which unidirectional currents alternated with oscillatory flow and where high energy conditions alternated with low energy conditions. The sand waves formed and migrated during high energy events, possibly in response to the combination of spring tides and storms (e.g. Anderton, 1976; Chakraborty & Bose, 1990). In the waning stages of the storm oscillatory movements became dominant and

Fig. 42. Two massive sandstone bodies (ST) of the storm- and wave dominated shoreface association. The lower sandstone body has a gradational base to underlying inner shelf heterolithic mudstone (HM). In the uppermost part of the sandstone body bedding becomes thin (white arrow) and is dominated by ripple lamination, which formed in response to reworking of the top of the sandstone body. The upper contact is sharp and the overlying deposits consist of mudstone (FM) of the outer shelf association. These in turn are sharply overlain by a succeeding sandstone body (ST). Scale is 2 m long (shown by black arrow). Vibeke Sø Formation, Kap Alfred, northern Lyell Land.



wave ripples formed and reworked the upper part of the sand waves. During the subsequent fair-weather period, settling of mud from suspension dominated.

The heterolithic mudstone deposits formed above the storm wave base, but generally below the fair-weather wave base. They represent fair-weather suspension deposition alternating with storm deposition and formed in a similar manner to the heterolithic deposits described under the storm- and wave-dominated inner shelf association.

The upward coarsening succession passing from heterolithic mudstones to tidal sand waves (Fig. 37) reflects a gradual upward shallowing from inner shelf to tidally influenced shoreface environments, where the larger sand waves formed in response to strong tidal currents, periodically enhanced by storms. Tidal currents did not influence the inner shelf deposits or, alternatively, their effect was completely overprinted by reworking of the sediment during storms (e.g. Ghosh, 1991).

Storm- and wave-dominated shoreface association

General

Deposits of this association are present in several intervals within the Kempe Fjord, Sandertop, Berzelius Bjerg, Vibeke Sø, Skjoldungebræ and Teufelsschloss Formations (Figs 9, 10, 14, 18, 25, 30). They are found throughout the entire central fjord zone and in Canning Land (Fig. 19) and probably also extend to the Bredefjord–Ardencaple Fjord region.

Description

This facies association consists of well sorted, highly mature, white to yellowish, fine- to medium-grained sandstone bodies with very little clay or silt (Fig. 42). Thickness of the sandstone bodies ranges from 2 to 25 m, but most commonly they are 3–8 m thick (Fig. 43). They appear to have a sheet-like geometry with a lateral extent exceeding the length of exposure (Fig. 21). A few sandstone bodies can probably be traced along the entire central fjord zone, a distance of more than 150 km.

The lower contact of the sandstone bodies either shows a gradual transition to underlying inner or outer shelf deposits, or it is sharp and erosive (Figs 42–44) occasionally with basal scours more than 20 cm deep associated with sandstone clasts and mudstone chips. In many cases, the sharp-based sandstone bodies directly overlie outer shelf deposits (Fig. 44). The sandstone bodies are sharply overlain by outer or inner shelf mudstones (Fig. 42), or by tidal channel sandstones developed in a coastal plain environment (Fig. 44). Internally, the sandstone bodies show no visible upward trends in grain size or sedimentary structures; they appear to consist of a series of stacked beds with thicknesses from 0.3 to 2.0 m (Figs 42, 44) and with lateral extents often exceeding 20 m. Beds often appear massive, but when structures are visible they are dominated by cosets of laterally amalgamating large-scale planar or trough cross-bedded sets, ranging in thickness from 0.2 to 1.0 m (Fig. 43). Foreset dip directions are generally oriented towards the north and less commonly towards the south or west (Fig. 40B). Sets of wave ripple cross-lamination, 5–10 cm thick, separate either individual cross-beds or cosets. Horizontal lamination is rare, but may be developed between cosets of large-scale cross-bedding. Desiccation cracks occur sporadically both in the central fjord zone and in Canning Land. On the uppermost surface of sandstone bodies, and more rarely on well exposed internal bedding planes, fields of large-scale, sinuous to lunate crested dunes cover extensive areas (Figs 45, 46). They range from 30–70 cm in height, and have wavelengths of more than 25 m. In most cases, the dunes are superimposed by both small and large-scale symmetrical and bifurcating ripples (Fig. 45) which occasionally develop interference patterns. Dunes in some instances pass laterally into fields of large-scale ripples (Fig. 46). The large-scale ripples are 5–10 cm in height and have wavelengths between 25 and 40 cm. Crestlines are dominantly oriented NNW–SSE.

Interpretation

The sandstone bodies invariably succeed deposits of the inner and outer shelf and they are overlain either by inner shelf deposits or by coastal plain deposits. This stratigraphic position suggests that the sandstone bodies were laid down in a shoreface environment. This contention is further supported by the absence of mudstone and the highly mature character of the sandstone bodies. Sedimentary structures observed within the sandstone bodies suggest a combination of oscillatory flow, unidirectional traction currents and efficient sorting processes – elements which all characterise a marine shoreface environment (e.g. Swift *et al.*, 1987; Leckie, 1988).

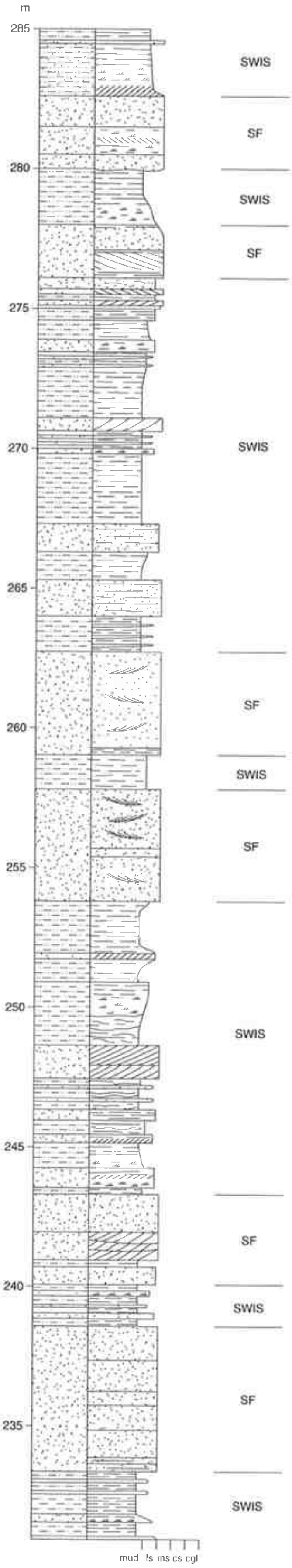


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Fig. 43. Section showing the characteristic vertical development of the storm- and wave-dominated shoreface association (SF) and the storm- and wave-dominated inner shelf association (SWIS) (Vibeke Sø Formation, Kap Alfred, northern Lyell Land). Most of the shoreface deposits have a sharp lower boundary, but gradational bases are also seen. The section shows an overall upward decrease in the thickness of the shoreface deposits, but thinner upward fining cycles within this overall trend can also be recognised (232–253 m and 253–285 m). Section heights refer to section shown in Fig. 18B. For legend see Fig. 5.

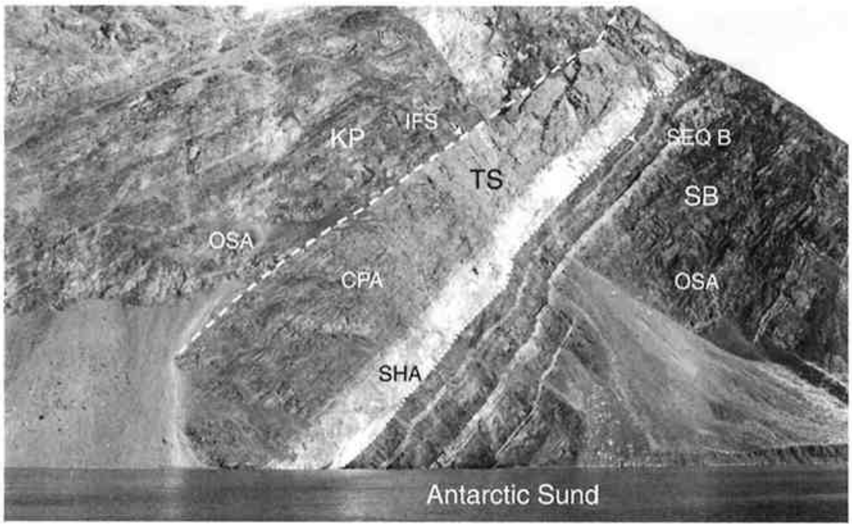

Fig. 44. Succession showing the transition from mudstones of the outer shelf association (OSA), to structureless white sandstones of the shoreface association (SHA), into tidal channel sand sheets of the coastal plain association (CPA) and back to mudstones of the outer shelf association, as developed at Antarctic Sund on the southern coast of Ymer Ø. SB: Skjoldungebræ Formation, TS: Teufelsschloss Formation, KP: Kap Peterséns Formation (Ymer Ø Group), SEQB: sequence boundary, IFS: initial flooding surface. The section shows the upper part of sequence 3 and the lower part of sequence 4. Thickness of the Teufelsschloss Formation is 125 m. After Sønderholm & Tirsgaard (1993).

The co-existence of large-scale wave ripples and two- and three-dimensional dunes, implies that unidirectional currents frequently alternated with oscillatory flow (Leckie, 1988). Two- and three-dimensional dunes are common in modern shoreface environments where they form in response to both storm and fair-weather conditions. However, in storm-dominated settings fair-weather bed forms are commonly overprinted by bed forms forming and migrating during high energy events. During storm peaks and in the early waning stages three-dimensional dunes typically form, while the large-scale wave ripples form and rework the lunate and sinuous crested megaripples in response to waning energy (Leckie, 1988). Most of the bed forms preserved on bedding planes were probably generated during peak energy events with fair-weather bed forms mainly preserved as small-scale wave ripples on the larger bed forms (Figs 45, 46).

During storms, flow in the near-shore areas tend to be offshore, parallel to the horizontal pressure gradient. As flow propagates away from the shore it is deflected alongshore as a result of the Coriolis effect (Swift, 1985; Carr & Scott, 1990). Bed forms generated within the zone dominated by geostrophic flow migrate parallel with the coast (Snedden & Nummedal, 1991; Swift & Thorne, 1991; Walker & Plint, 1992). In the sandstone bodies, most sets of large-scale cross-bedding show northerly migration directions parallel with the inferred coastline (see section on palaeocoastline orientation).

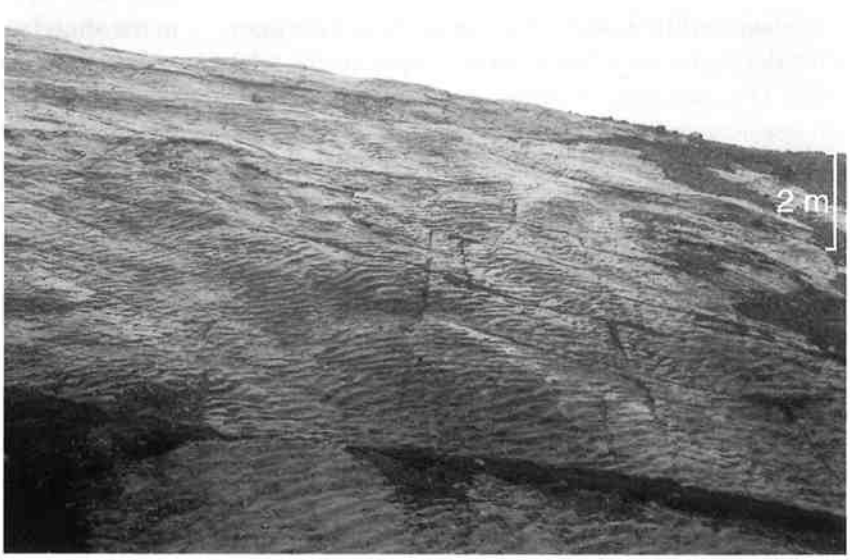

Fig. 45. Upper surface of a sandstone body from the storm- and wave-dominated shoreface association showing remoulded dunes, covered by bifurcating wave ripples. Ripple-crests are orientated approximately perpendicular to the crests of the dunes suggesting that the dunes formed in response to coast-parallel currents, while the ripples formed in response to shore-directed wave movements. Vibeke Sø Formation, Kap Peterséns, northern Scoresby Land.

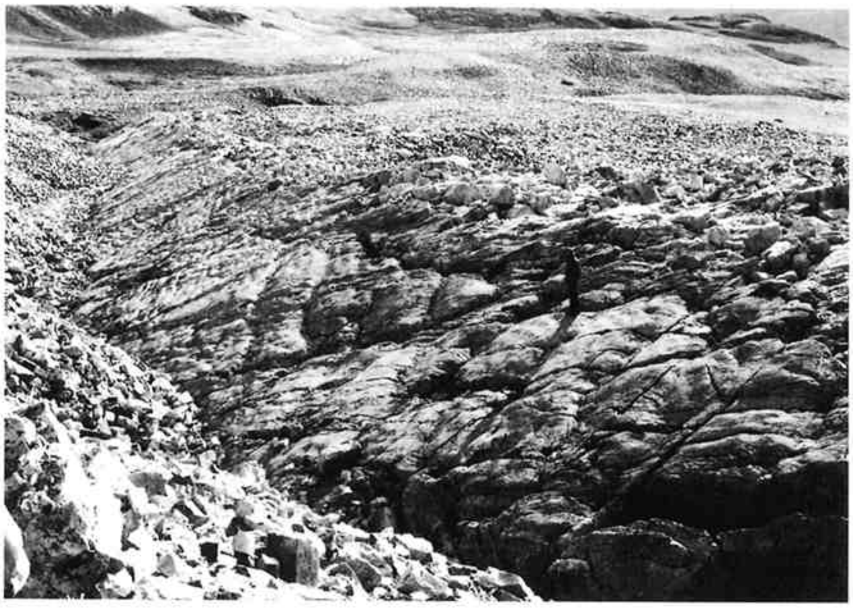

Fig. 46. Upper surface of a shoreface sandstone body from the storm- and wave-dominated shoreface association, with dunes passing laterally into large-scale wave-ripples in the background. Person for scale. Teufelsschloss Formation, Vibeke Sø, Steno Land.

Indications of beach lamination have not been observed, but desiccation cracks show that the sandstone bodies, at least occasionally, were subaerially exposed. In most cases, however, the sandstone bodies were subject to considerable reworking and degradation as they were subsequently flooded. This is indicated by the presence of numerous degraded dunes, covered by both small- and large-scale wave ripples, found on the surfaces of a large number of sandstone bodies (Figs 45, 46). Any beach or aeolian deposits, originally formed in the uppermost part of the shoreface complex in a fore- or backshore environment, would have been extensively reworked and eroded and thus have an extremely low chance of preservation.

A characteristic feature of many modern shorelines is the development of barrier islands separated by tidal inlets. The formation of barrier islands is favoured by low gradient continental shelves adjacent to low relief coastal plains and with moderate to low tidal ranges (Glaeser, 1978). These are features which appear to have characterised the depositional basin in which the shoreface deposits of the Lyell Land Group were formed, but evidence of tidal inlets, or ebb or tidal deltas has not been found, even though formation and preservation of tidal inlets is favoured by longshore currents and a mesotidal regime (Reinson, 1992), both of which, at least periodically, existed in the basin. However, tidal inlet and tidal delta deposits may be difficult to observe in well sorted quartz arenitic deposits. In such sediments a change from coast parallel palaeocurrents within the shoreface or foreshore to bipolar current directions normal to the coast may be the only indications of tidal inlets or tidal deltas. It is characteristic that most accounts of Precambrian coastal deposits provide little detailed description of the shoreface and foreshore environments, probably because of the limited environmental resolution these often highly mature quartz deposits contain (e.g. Ghosh, 1991; Dirks & Norman, 1992; Lindsey & Gaylord, 1992) and well documented accounts of Precambrian tidal inlets or tidal deltas have not been published. The apparent lack of tidal inlet or tidal delta deposits may therefore simply be a result of the low environmental resolution of the arenitic shoreface sediments of the Lyell Land Group, rather than reflect their true absence in the shoreface deposits.

The shoreface deposits formed in response to prograding shorelines, and in some cases developed a characteristic gradual upward coarsening succession reflecting the evolution from inner shelf to the shoreface environments (Fig. 42). In a number of cases this gradual transition is not present and the shoreface deposits sharply overlie outer shelf mudstones or inner shelf fine-grained deposits (Figs 27, 43, 44) suggesting that they formed during forced regressions (e.g. Plint, 1988; Dam & Surlyk, 1992; Hunt & Tucker, 1992; Posamentier *et al.*, 1992; Walker & Plint, 1992; Allen & Posamentier, 1993; Posamentier & Chamberlain, 1993).

During periods of relative sea-level fall on a gently dipping shelf, the shoreline is rapidly translated many tens of kilometres seawards (Posamentier & Allen, 1993a). Due to the concomitant base level fall during this translation, the shoreface erodes into the underlying substrate, eventually forming shelf perched sand wedges surrounded by offshore mudstones (e.g. Posamentier *et al.*, 1992; Tesson *et al.*, 1993). In contrast, shoreface deposits with gradational bases formed as a result of coastal progradation during periods of more stable sea-level (Plint, 1988; Posamentier *et al.*, 1992). Landward of the shelf perched shoreface deposits, subaerial exposure will occur, typically resulting in the development of a sedimentary bypass zone (Posamentier *et al.*, 1992; Posamentier & Allen, 1993a, b).

Direct evidence of bypass zones has not been observed in connection with the shoreface deposits. Some of the sandstone bodies observed in Canning Land and in the central fjord zone show evidence of subaerial exposure, but correlative continental or coastal plain sediments have not been observed within the window of exposure of the Lyell Land Group but could be present further west in the Petermann Bjerg region.

Before the concepts and significance of forced regressions were recognised, marine sandstone bodies encased in mudstones had often been interpreted as offshore bars or shelf sand ridges (e.g. Boyles & Scott, 1982; Swift & Rice, 1984; Tillman & Martinsen, 1984, 1987; Phillips *et al.*, 1985; Tillman, 1985; Gaynor & Swift, 1988; Pozzobon & Walker, 1990; Krause & Nelson, 1991). The weakness in all these interpretations has been the inability to document the existence of transport mechanisms that were able to transport large amounts of sand, sometimes more than 100 km seaward of a correlative coastline and concentrate them into long narrow sandstone bodies. No modern examples are known where sand is supplied from a shoreline and transported across a muddy shelf and concentrated into narrow offshore bars or shelf ridges. A satisfactory explanation has therefore never been achieved for such offshore sandstone bodies (Walker & Plint, 1992). However, following the developments in sequence stratigraphic concepts, a number of the classical sand ridges in the literature have more recently been reinterpreted as shelf perched shoreface deposits (e.g. Pattison & Walker, 1992; Walker & Plint, 1992; Walker & Bergman, 1993). Lowstand shoreface deposits have also been described from Precambrian shelf sandstones of the overlying Ymer Ø Group (Tirsgaard, 1996) and with the current understanding of shelf dispersal systems a similar interpretation appears to be the most attractive for the sharp based shoreface deposits in the Lyell Land Group.

Tidally dominated coastal plain association

General

Deposits of this association have been found in the Kempe Fjord Formation, the Berzelius Bjerg Formation and the Teufelsschloss Formation (Figs 9, 14, 30). Since the Kempe Fjord and Berzelius Bjerg Formations have only been investigated in Lyell Land the regional

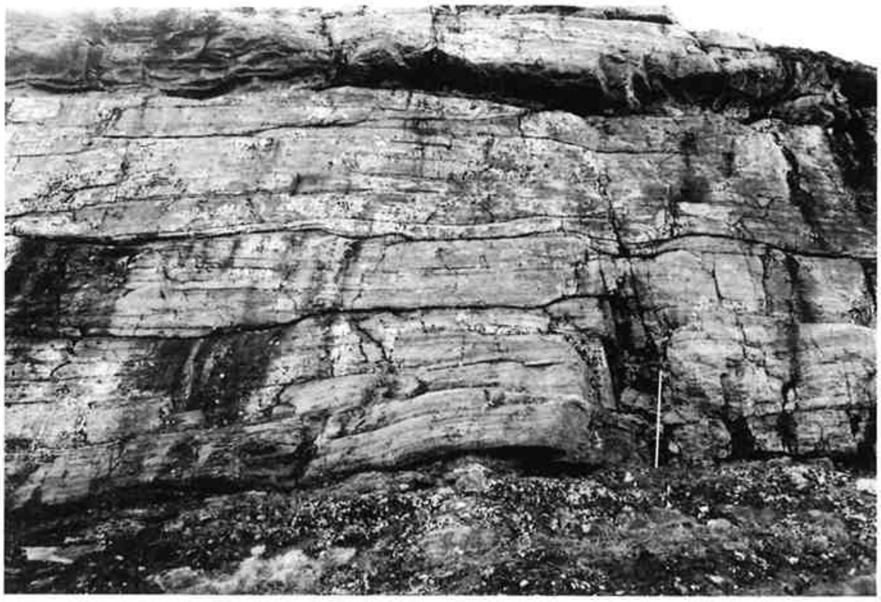

Fig. 47. Stacked tidal channel sand sheets of the tidally dominated coastal plain association, displaying sharp, erosive bases and internally dominated by parallel lamination. Scale bar is 1 m long. Teufelsschloss Formation, from the type locality, Andrée Land.

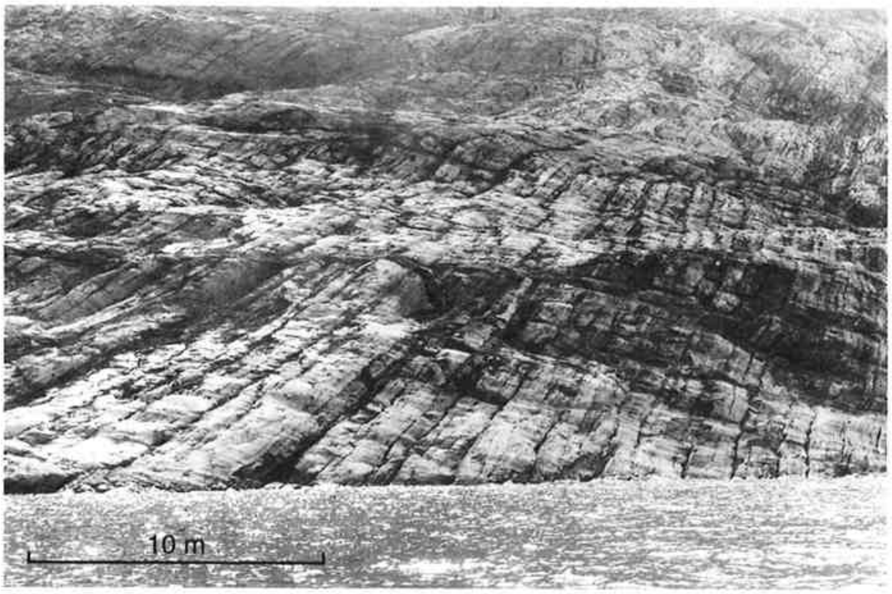

Fig. 48. Characteristic development of the tidally dominated coastal plain association. Sharp based sand sheets form stacked successions several tens of metres thick. Each sand sheet can be traced laterally for at least a few kilometres. Structural dip is 55° to the east. Berzelius Bjerg Formation, Kap Alfred, northern Lyell Land.

distribution of the association in these two formations is unknown, but the association must be expected to have a much wider distribution. Within the Teufelsschloss Formation the association is present from Steno Land to northern Lyell Land, while it is absent in southern Lyell Land, in Scoresby Land and in Canning Land (Fig. 1).

Description

In the area south of Geologfjord (Fig. 1), this association has been described in detail by Tirsgaard (1993). It consists of 0.2–3 m thick, fine- to medium-grained sandstone sheets, stacked to form 5–50 m thick multi-storey units (Fig. 47), each with a lateral extent of at least several hundred metres (Fig. 48), exceeding the width of exposure (Fig. 44). The multi-storey sand sheets are separated by 0.1–1.0 m thick beds of heterolithic mudstone and sandstone that also extend beyond the length of exposures. The individual sand sheets mainly consist of large-scale cross-beds with 10–40 cm thick sets with tangential to sigmoidal foresets, and parallel lamination (Figs 47, 49). Subordinate structures are climbing ripple lamination and cross-lamination. Well-developed herringbone cross-stratification abounds (Fig. 50). Mud drapes are commonly preserved along

Fig. 49. Example of the development of internal structures of the sand sheets of the tidally dominated coastal plain association characterising the third unit of the Kempe Fjord Formation. The base of the sand sheet is shown by an arrow. The sand sheet is dominated by sets of large-scale cross-bedding, up to 60 cm high. Ruler is 20 cm long. Kap Alfred, northern Lyell Land.

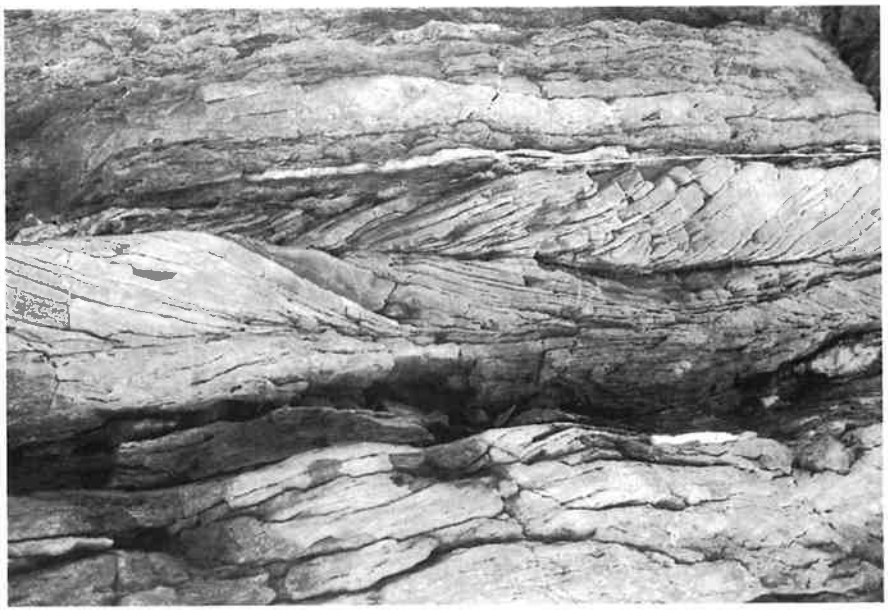

Fig. 50. Herringbone cross-stratification seen within the tidally dominated coastal plain association. Both sets are approximately 25 cm high. Kempe Fjord Formation. Kap Alfred, northern Lyell Land.

the lower parts of foresets and reactivation surfaces are common. Lower set boundaries are slightly erosive, irregular and sometimes show a distinct undulatory pattern which is associated with bundles of successive foresets (Fig. 51). Foreset dip directions indicate a bi-polar to polymodal distribution, with dominant palaeocurrent directions towards the NW and subordinate directions towards the SE and S (Fig. 52). Cross-lamination is frequently superimposed on the larger cross-bedded sets, often with foresets dipping in an opposing direction. Parallel lamination is commonly associated with the cross-bedded sets and may form more than 50% of a sand sheet (Fig. 47). Climbing ripple lamination is locally associated with parallel lamination. Each sand sheet typically has an erosive base, followed by a poorly defined fining upward succession and terminating in a millimetre to centimetre thick mudstone veneer which drapes a surface covered by straight crested bifurcating ripple marks. Commonly this mudstone veneer contains desiccation cracks, sometimes several centimetres wide.

The heterolithic beds are dominated by wavy bedding and desiccation cracks are very abundant on bedding planes. Lower boundaries are non-erosive, while they invariably have a sharp and erosive upper contact to the overlying sand sheet.

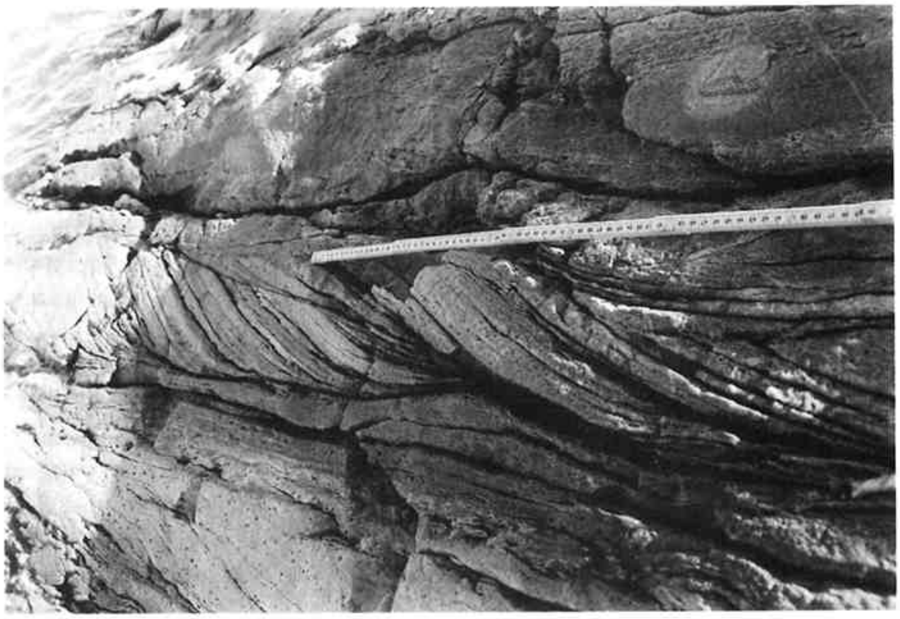

Fig. 51. Well preserved planar cross-bedding of the tidally dominated coastal plain association showing undulating lower set boundaries, mudstone draped foresets, multiple reactivation surfaces and a bundle-wise upbuilding. Length of scale is 80 cm. Kempe Fjord Formation, from the type locality, northern Lyell Land.

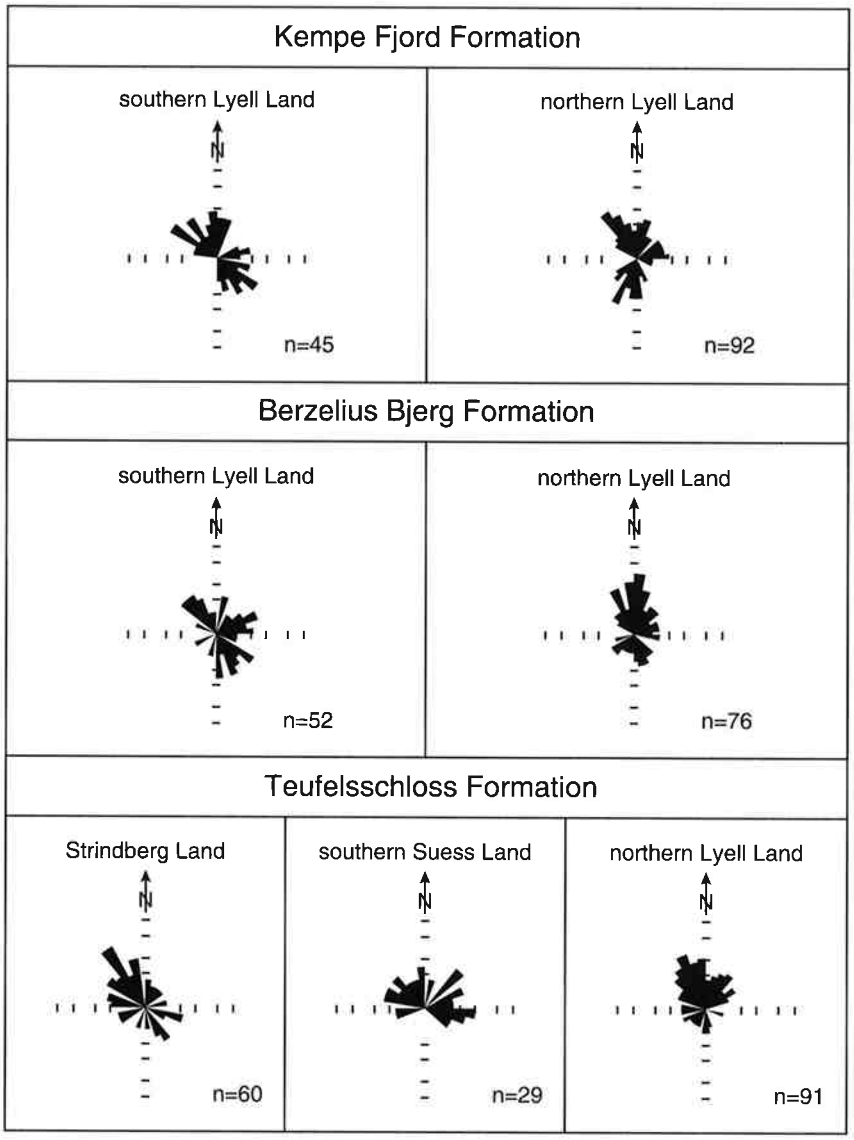

Fig. 52. Palaeocurrent measurements from the tidally dominated coastal plain association (10° intervals). The palaeocurrent measurements from the Kempe Fjord and Berzelius Bjerg Formations were made on large-scale planar cross-beds from tidal channel sand sheet deposits in Lyell Land. Palaeocurrent measurements from the Teufelsschloss Formation were measured on large-scale planar cross-beds from subtidal deposits in Strindberg Land and from tidal channel sand sheet deposits in Suess Land and Lyell Land. Modified from Tirsgaard (1993).

In Strindberg Land and Steno Land, the association shows a different development (Sønderholm *et al.*, 1989) within the Teufelsschloss Formation. Sand sheets are absent and instead stacked beds, 0.5–1.0 m thick, dominated by sets of large-scale planar cross-bedding form successions without any obvious vertical trends (Fig. 30B). Parallel lamination is much less abundant. Interbedded heterolithic deposits are rare, but may locally occur in 10–70 cm thick beds. Sets of large-scale cross-bedding observed within the sandstone beds are 10–40 cm thick. Cross-bedding is dominantly tangential, rarely concave and reactivation surfaces are common. Clay drapes are often observed along the lower part of foresets and in bottom sets. Herringbone cross-stratification is observed locally. Foreset dip directions show a strong dominance towards the NW, with a subordinate orientation towards the SE (Fig. 52). Cross-lamination, sometimes developed as climbing ripple lamination, is commonly developed in beds a few centimetres thick and bifurcating ripple marks are often seen on bedding planes, occasionally with ladder ripples developed in the troughs. Desiccation cracks are present only rarely.

Interpretation

The sedimentary structures associated with the large-scale cross-bedding both north and south of Geologfjord are typical, although not individually diagnostic, of tidal action. The characteristic features include reactivation surfaces, discontinuous mud drapes along foresets, herringbone cross-stratification, ebb and flood caps and undulatory lower set boundaries (Visser, 1980; Boersma & Terwindt, 1981; Terwindt, 1988). Bipolar foreset dip directions are common throughout most of the central fjord zone and combined with the features noted above the deposits are considered to be of tidal origin (Sønderholm *et al.*, 1989; Tirsgaard, 1993). The sand sheet deposits observed south of Geologfjord represent shallow, poorly defined, high energy tidal channels laid down in a dominantly intertidal environment. The multi-storey sandstone sheets represent larger tidal channel complexes, with the interbedded, heterolithic deposits rich in desiccation cracks recording deposition on inter- to supratidal flats, which developed during periods of abandonment of the tidal channel complexes when depositional activity was shifted to other parts of the coastline (Tirsgaard, 1993).

North of Geologfjord, the tidal deposits most likely represent a dominantly subtidal environment, with sets of cross-bedding having formed in response to landward migrating, medium-scale dunes which may have formed in a back-barrier setting, possibly as part of tidal-delta or shoal complexes (e.g. Boersma & Terwindt, 1981; Sha & de Boer, 1991).

Depositional model

Correlation strategies in Precambrian rocks

The development of depositional models of Precambrian successions is invariably hampered by the absence of proper dating. Biostratigraphic resolution is at best low and consequently correlations rely to a very large extent on lithostratigraphic principles. Since sequence stratigraphic concepts began to be addressed more directly towards outcrop studies (e.g. Posamentier & Vail, 1988; Posamentier *et al.*, 1988; Galloway, 1989; Van Wagoner *et al.*, 1990), it has become apparent that extensive lithostratigraphic correlations are hazardous and in many cases lead to false conclusions (Van Wagoner *et al.*, 1990). However, since the identification and correlation of chronostratigraphic surfaces, or units, provide the fundamental building blocks in sequence stratigraphic models (Allen & Posamentier, 1994), and constraining biostratigraphic data nearly always are absent, limitations are placed on the applicability of sequence stratigraphy in Precambrian successions. Surfaces and units with chronostratigraphic significance will have to be inferred on the basis of an interpretation of the surrounding successions. In most cases, correlation and the subsequent generation of depositional models will therefore have to rely on a combination of lithostratigraphic and sequence stratigraphic principles and methodologies. Application of sequence stratigraphic methods may necessitate making such assumptions as constant sediment influx, uniform distribution of sediment along the shelf, or constant and uniform regional subsidence (Tirsgaard, 1996).

Recognition of regional unconformities (i.e. sequence boundaries) is often problematic in Precambrian successions (e.g. Harris & Eriksson, 1990), which are therefore often regarded as thick, conformable stratigraphic successions and sequence stratigraphic principles can only be applied to these successions with difficulty (Christie-Blick *et al.*, 1988). The problem is reduced where substantial fluvial incision has occurred and is marked by visible lithological variations (e.g. Christie-Blick *et al.*, 1988), or where regional, transgressive conglomerates are developed. Where grain size variations are small and indications of fluvial incision absent, sequence boundaries may be difficult to locate. However, the formation of sequence boundaries, particularly on gently dipping shelves and ramps, is very often characterised by an associated, significant basinward translation of facies (van Wagoner *et al.*, 1988; Posamentier & James, 1993) resulting in major palaeogeographic reorganisations of the shelf.

In some successions, flooding surfaces are more readily defined and, where these can be confidently correlated and placed in a sequence stratigraphic framework, they may provide a better basis for the subdivision of a succession and the subsequent definition of genetic stratigraphic packages (e.g. Galloway, 1989).

In the establishment of the depositional evolution of the Lyell Land Group biostratigraphic data are not available. Neither continental deposits nor levels of fluvial incision have been observed and unequivocal evidence of regional unconformities is absent. However, it is apparent that major palaeogeographic reorganisations took place several times on the shelf during the deposition of the group. It therefore seems improbable that the approximately 3 km of sediment comprising the Lyell Land Group should form an entirely conformable succession.

Characteristic of the Lyell Land Group is a large-scale cyclic pattern of the five facies associations described above. In order to divide this large-scale cyclic development into genetically related packages to create an understanding of the shelf architecture and evolution through time, sequence boundaries have been placed where the main regional unconformities are considered to be present. Since direct evidence of major hiati is not available, sequence boundaries have to be inferred from the succession of facies. On this basis, sequence boundaries are considered to be located where the main regional basinward translation of facies have occurred. In all cases this also appears to be associated with laterally extensive erosion of the underlying deposits.

Flooding surfaces have also been defined within the Lyell Land Group to help define the sequences and provide a basis for the subdivision of the sequences into systems tracts. The precise location of maximum flooding surfaces is difficult to determine, but within each of the interpreted sequences the maximum flooding surface has been placed in the middle of the most fine-grained interval, which is commonly 20–50 m thick.

The widespread nature of the major lithostratigraphic units (formations) and their component facies within the window of exposure suggest that depositional conditions, including sediment influx and subsidence rates were uniform and parallel to basin strike for most of the time during deposition of the Lyell Land Group. It is therefore assumed that units showing consistent stacking patterns within each sequence, which are correlatable throughout the entire central fjord zone, have chronostratigraphic significance and formed in response to regional changes in relative sea-level.

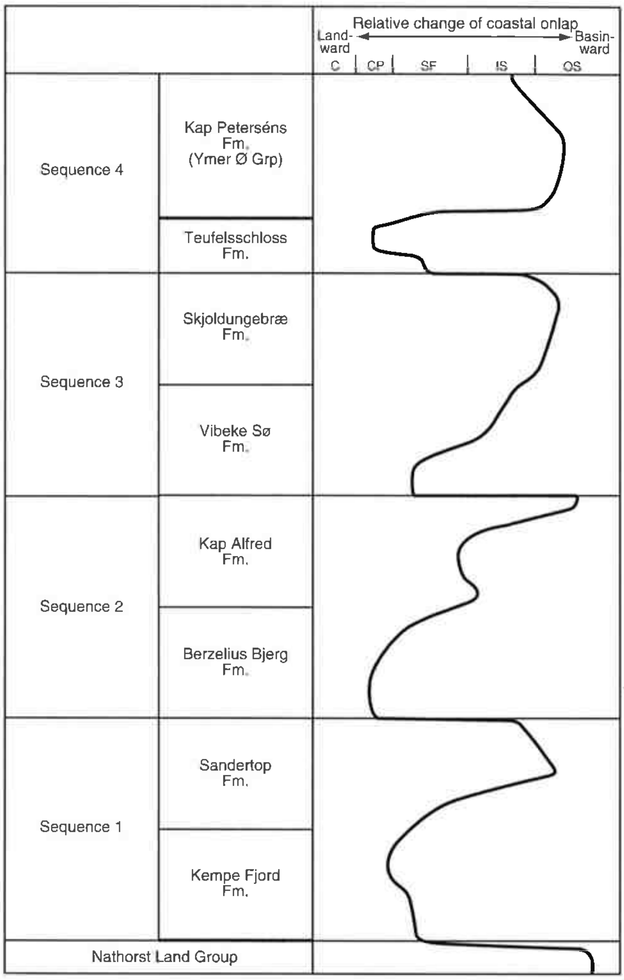

Fig. 53. Relative coastal onlap curve for the four sequences constituting the Lyell Land Group and lowermost part of Ymer Ø Group. The curve is drawn such that each sequence represents the same time span and assumes that no major hiati are present. These assumptions are naturally speculative. The figure should therefore be used with caution, but helps to illustrate that variations in coastal onlap show similar trends in all four sequences. C: continental deposits (not recognised in outcrops), CP: tidally dominated coastal plain association, SF: shoreface associations, IS: storm- and wave-dominated inner shelf association, OS: outer shelf association.

Sequence stratigraphic framework

The deposits of the Lyell Land Group can be subdivided into four, large-scale sequences which overall show the same general sedimentary evolution through time (Fig. 53). The sequences vary in thickness from 400 to 1100 m and are readily traceable for 300 km parallel to the inferred palaeocoastline in the central fjord zone and 100 km basinward to Canning Land.

The sequence boundaries (the bases of all four sequences) are placed where a sharp change occurs from deposits of the outer shelf association, or of the storm-dominated inner shelf association, to deposits of the shoreface or coastal plain association (Figs 9, 14, 18, 26, 30). The vertical development of facies associations indicates that a major regional translation of facies is associated with the abrupt transition from shelf mudstones to shoreface or coastal plain sandstones (Figs 12, 20, 44). This translation is also interpreted to be associated with regional erosion and appears to have formed in relation to a large-scale forced regression. The location of the sequence boundary thus lies at the base of the forced regressive wedge (Posamentier *et al.*, 1992; Kolla *et al.*, 1995).

The lowest 80–500 m of the four sequences consist of progradational to aggradational depositional patterns, which reflect a low rate of relative sea-level rise. In the middle part of the sequences a retrogradational depositional trend reflects a deepening of the shelf related to a rapid relative rise in sea-level. In the upper part of the sequences aggradation dominates, but is sometimes succeeded by very weak progradation indicating a reduced rate of relative sea-level rise (Fig. 53). The maximum flooding surface within each sequence is placed within mudstone intervals where the retrogradational depositional patterns are succeeded by aggradational or progradational patterns (Figs 10, 18, 19, 25, 26).

Evidence of highstand deposition is only present in two of the four sequences, in which progradation patterns become visible in the upper part (Sandertop and Skjoldungebræ Formations), while deposition during the transgressive phase constitutes the middle part of the sequences (Figs 10, 16, 18, 25, 26).

In addition to the regionally developed sequence boundaries, which can be traced throughout the entire central fjord zone and to Canning Land, higher order sequence boundaries can be inferred at the base of a number of sandstone bodies of the shoreface association as these are considered to have formed in response to forced regressions. However, it was not possible with confidence to trace these across the region because of inadequate exposure. More detailed studies and correlations are required if a meaningful sequence stratigraphic model is to be established for higher order sequences.

Sedimentary sequences

Each of the four sequences formed in response to large-scale, cyclic changes in relative sea-level (Fig. 53). Although the overall trends within each sequence are similar, variations occur which show that the palaeogeography varied with time. Each sequence is inferred to represent a package of genetically-related strata.

Galloway (1989) suggested that major palaeogeographic reorganisation occurs during the maximum flooding of the basin, implying that the palaeogeography of a basin may be significantly different during a lowstand and the ensuing highstand. Lowstand shorelines may be characterised by different depositional processes and environments than highstand shorelines. Since the exposures of the Lyell Land Group are nearly all located parallel to basin strike, there is very little control on the variations of the facies associations during sea-level changes (e.g. highstand shorelines are not preserved within the window of exposure).

Sequence 1

This sequence is represented by the Kempe Fjord and Sandertop Formations (Fig. 5) and ranges in thickness between 800 and 1000 m in the central fjord zone. The sequence boundary is marked by a change from outer shelf mudstones to sandstones of the shoreface and coastal plain associations (Fig. 10). The shift corresponds to the contact between the Nathorst Land Group and the Lyell Land Group (Fig. 6).

This initial, abrupt shallowing is followed by a more gradual shallowing, reflected in the lower 200 m of the Kempe Fjord Formation (Figs 9, 53), where deposits of the storm- and wave-dominated shoreface association are overlain by subtidal sandstone deposits of the tidally dominated coastal plain association. Towards the top these grade into a 300 m thick succession of predominantly intertidal deposits. The intertidal channel deposits are succeeded by approximately 100 m of sandstone of mainly subtidal origin. This change implies a subtle rise in relative sea-level.

This weak deepening trend observed in the upper part of the Kempe Fjord Formation becomes more pronounced in the Sandertop Formation (Figs 10, 53). The deepening of the shelf is reflected in a change in the lower 80 m of the Sandertop Formation where deposits of the storm-dominated inner shelf association gradually give way to deposits of the outer shelf association. The latter represent the maximum flooding of the basin and form a roughly 40 m thick succession (Fig. 10). Above this unit, deposits of the storm- and wave-dominated inner shelf association gradually become more important, signifying renewed progradation.

A poorly developed, overall shallowing is signified by the overlying 320 m of sediment, which constitutes the rest of the Sandertop Formation (Figs 10, 53). Sharp-based shoreface deposits occur within the storm-dominated inner shelf deposits and reflect minor progradational events, possibly caused by forced regressions.

Sequence 2

This sequence is represented by deposits of the Berzelius Bjerg and Kap Alfred Formations; it varies in thickness between 750 and 1200 m in the central fjord zone (Fig. 5). The sequence boundary is located at the contact between the Sandertop Formation and the Berzelius Bjerg Formation (Figs 12, 14), defined by an abrupt shift from heterolithic mudstone deposits of the storm- and wave-dominated inner shelf association to sandstones of the tidally dominated coastal plain association. In contrast to sequence 1, shoreface deposits are only a few metres thick and coastal plain deposits are present almost directly above the sequence boundary (Fig. 12). Within the lower 400 m of the sequence, a development similar to the lower part of sequence 1 is seen reflecting the low rate of relative sea-level rise, following the abrupt fall inferred at the base (Fig. 53).

An increased rate of relative sea-level rise is indicated by the deepening trend at the top of the Berzelius Bjerg Formation, where the coastal plain association passes up into 80 m of fine-grained sandstone of the shoreface association (Fig. 14). This trend continues into the Kap Alfred Formation, where the shoreface association passes into the storm- and wave-dominated inner shelf association, which forms a relatively uniform 130 m thick succession (Figs 15, 16). Above follows a 400 m thick succession consisting of interbedded deposits of the tidally influenced shoreface and the storm- and wave-dominated inner shelf association which marks a shift towards a more tidally dominated shelf. The uppermost 100 m of the sequence consists entirely of mudstone of the outer shelf association and represents the culmination of the overall deepening (Figs 16, 53).

The presence of tidally dominated coastal plain deposits in both sequences 1 and 2 suggests that tidal activity was a permanent, rather than a periodic feature on the shelf. The shift from a storm- to a tide-dominated shelf as a result of a change in the basin palaeogeography (which may have led to increased tidal ranges and stronger tidal currents) is therefore unlikely. It is more likely that the change resulted from a period of subdued storm activity on the shelf. This allowed better preservation of tidally induced features within the shoreface deposits where previously storm-induced wave activity and currents resulted in complete reworking of the tidal features.

Sequence 3

Sequence 3 comprises the sediments of the Vibeke Sø and the Skjoldungebræ Formations (Fig. 5); it reaches a thickness of almost 550 m in the central fjord zone and in Canning Land. Sequence 3 is initiated by an abrupt shift from mudstone of the outer shelf association to mature, structureless sandstone of the storm- and wave-dominated shoreface association (Figs 18, 30). Following the initial pronounced sea-level fall, the sequence records shoreface aggradation during a slow relative rise in sea-level followed by a gradual deepening related to an increased rate in relative sea-level rise (Fig. 53). The lower 150 m of the sequence consists primarily of deposits of the shoreface association. However, in the central fjord zone, 10–20 m of heterolithic deposits of the storm- and wave-dominated inner shelf association occurs 20–25 m above the base, reflecting minor, high-frequency variations in relative sea-level (Fig. 18). In Canning Land, shoreface deposits appear to comprise the entire basal 80 m (Fig. 19), but the exact correlation of the shoreface sandstone units is uncertain. It is possible that the 80 m of shoreface deposits in Canning Land should be correlated with only the basal 25 m of the sequence in the fjord zone; the variation in thickness reflecting the distribution of accommodation space on the shelf during the sea-level lowstand.

Above the shoreface deposits follows approximately 150 m of sediment showing a recurrent interbedding of 1–5 m thick shoreface packets and 5–40 m thick units of storm-dominated inner shelf deposits (Fig. 18), reflecting repeated episodes of regression followed by transgression. An overall deepening is manifested by the gradual upward thinning of the sandstone beds and a gradual thickening of the heterolithic deposits (Figs 18, 19, 23). In the uppermost 200 m of the sequence, storm-dominated inner shelf deposits give way to mudstones of the outer shelf association and here, thin sharp-based shoreface sandstone beds directly overlie outer shelf deposits. A weak upward coarsening trend is present in the uppermost 50 m, where there is a return to interbedded deposits of the inner shelf and shoreface (Figs 18, 25, 26).`

The repeated episodes of forced regression seen throughout most of this sequence reflects the superimposition of high-frequency relative sea-level variations upon the overall relative sea-level rise. The high frequency sea-level oscillations give rise to 20-50 m thick regressive-transgressive cycles, similar to those observed in the sequences below. The cycles cannot, with confidence be correlated between outcrops and their lateral extent is unknown. Cyclic regressive-transgressive events on a scale of 70–120 m are also visible within the sequence and appear to be correlatable throughout the fjord zone and eastwards to Canning Land. The cyclic pattern is produced by stacked successions of upward thickening sandstone units (Figs 18, 19, 26).

Sequence 4

Sequence 4 is initiated by the Teufelsschloss Formation and continues into the overlying Kap Peterséns Formation of the Ymer Ø Group (Figs 23, 30, 53). The sequence attains a thickness between 250 and 350 m in the central fjord zone, showing a gradual thinning towards the south. From Steno Land to northern Lyell Land (Fig. 1), the sequence boundary is marked by a shift from heterolithic mudstone deposits of the storm-dominated inner shelf association to sandstones of the storm- and wave-dominated shoreface association (Figs 27, 30, 44). The shoreface deposits form 30–50 m thick successions which contain a 2–5 m thick heterolithic unit in the middle part.

From Strindberg Land to Lyell Land, the shoreface deposits are erosively overlain by sandy tidal channel deposits of the coastal plain association, similar to those observed in sequences 1 and 2, reflecting continuous but modest progradation of the coastline (Figs 30, 44, 53). The coastal plain association forms a 60–70 m thick succession. A slight deepening of the shelf is implied by the regional presence of 1–6 m thick shoreface deposits above the tidal channel sand sheets (Figs 28, 30A). This also constitutes the top of the Teufelsschloss Formation and thus the Lyell Land Group. A dramatic flooding event occurs immediately above the Teufelsschloss Formation (Figs 30, 31, 44, 53), where mudstones of the outer shelf association abruptly overlie shoreface deposits. These outer shelf deposits, which are part of the Kap Peterséns Formation, form a very uniform succession 120–180 m thick which near the top gradually passes up into a 50–100 m thick succession of storm-dominated inner shelf deposits (Fig. 53).

In the northernmost part of the central fjord zone, and in southern Lyell Land, Scoresby Land and Canning Land, the coastal plain association is absent, and instead the lower part of the sequence consists of interbedded deposits of the storm- and wave-dominated shoreface and inner shelf associations (Figs 26, 27). In the southern part of the central fjord zone and in Canning Land, where the coastal plain association is absent, the lower more coarse-grained part of the sequence thins dramatically and is only 30 m thick in Canning Land and in Scoresby Land (Fig. 19). It is still recognisable as stacked 8–10 m thick shoreface sandstone successions interbedded with storm-dominated inner shelf deposits (Figs 26, 27). In the southern and eastern part of the shelf, the abrupt deepening of the shelf, marked by the contact to the Kap Peterséns Formation is defined by an abrupt shift from storm-dominated inner shelf deposits to mudstones of the outer shelf association (Figs 26, 27).

Palaeocoastline orientation

Because of the lateral homogeneity of the various formations, unequivocal data regarding the orientation of the coastline during the formation of the Lyell Land Group is not available. However, lithological variation and sedimentary structures in combination can be used to give an indication of the palaeocoastline orientation.

Typically, all formations preserved in the Bredefjord – Ardencaple Fjord region can be readily traced more than 300 km south to Scoresby Land without showing any major variations in lithology and thickness. In contrast, the formations show more variations, albeit still small, in an eastward direction across a distance of only 100 km to Canning Land. These variations are seen as a tendency for formations to become more sand-rich towards the west and more fine-grained towards the east. Such regional lithological variations suggest a roughly north–south running palaeocoastline, with the basin deepening in an eastward direction.

Palaeocurrent directions potentially provide good evidence of coastline orientation, but their value is entirely a function of the validity of the inferred depositional model. Within the storm- and wave-dominated inner shelf and shoreface associations of all four sequences, foreset dip directions indicate a strong dominance of northerly flowing currents. These are here interpreted to have formed in response to shore-parallel geostrophic currents. This interpretation is supported by studies of Recent shelf currents and shelf dispersal systems (e.g. Duke, 1990; Snedden & Nummedal, 1991; Swift & Thorne, 1991), but there are gaps in the understanding of Precambrian shelf circulation systems, particularly on very wide and shallow shelves (cf. Cant & Hein, 1986) and palaeocurrent evidence must therefore always be treated with caution.

Foreset dip directions from intertidal channels suggest general NW–SE palaeocurrent directions, which implies that the palaeocoastline was probably oriented NE–SW (Tirsgaard, 1993). The most reliable indication of coastline orientation is perhaps provided by the large-scale wave ripples, observed in the shoreface association. Large-scale wave ripples are generally accepted as indicators of coastline orientation as they form in response to steady, high energy, oscillatory wave movements with crestlines orientated parallel with the coastline (Leckie, 1988). In nearly all cases, ripple-crests are orientated N–S or NNW–SSE, suggesting an orientation of the coastline similar to that suggested by the palaeocurrents.

The evidence from palaeocurrent data combined with regional lithological variations thus consistently suggests a general N–S, possibly NNE–SSW, orientation of the coastline, with the basin deepening in an eastward direction. Deflection of the geostrophic currents in a northerly, i.e. anticlockwise direction suggests a palaeolatitude in the southern hemisphere. This configuration appears to have existed during deposition of the entire Lyell Land Group.

Sequence stratigraphic model

As a result of the sequence stratigraphic interpretation of the sediments in the central fjord zone and the inferred north–south palaeocoastline orientation a sequence stratigraphic model is suggested for the shelf during the formation of the Lyell Land Group. The model has tentatively been extended 100 km to the west to include the Petermann Bjerg region (Fig. 1). A sequence stratigraphic cross-section showing the characteristic stacking patterns of the systems tracts of all four sequences is shown in Figure 54.

The model depicts a broad and gently dipping ramp where the central fjord zone was located in a relatively distal position dominated by lowstand and transgressive deposits. Further landward, highstand deposition dominated while lowstand periods were characterised by erosion and bypass.

Sequences 1 and 2 (Fig. 54A) were characterised by relatively high sediment input during lowstand periods. Combined with the creation of considerable accommodation space this led to the development of thick, regionally uniform, sandy shallow marine lowstand wedges. Sediments most likely were conveyed to the lowstand wedges via braided stream systems located west of the central fjord zone, possibly in the Petermann Bjerg region. During the ensuing transgression drowning of the ramp resulted in the sharp transition from shallow marine to outer shelf deposits. The highstands were characterised by aggradation and subsequent progradation of the coastline, manifested in the central fjord zone as a gradual transition from an outer to an inner shelf environment.

Sequence 3 contains a relatively larger proportion of outer shelf and mudstone-rich inner shelf deposits than the previous two sequences. It is initiated by a significant seaward translation of facies and the formation of a lowstand wedge in the central fjord zone (Fig. 54B) which shows a less uniform lithological development than the previous lowstand wedges, possibly because less coarse material was available. The transgression and highstand periods show a similar development to the two underlying sequences, but contain a larger proportion of mudstone.

Sequence 4 shows an even more limited coarse clastic input than sequence 3, although this sequence is also initiated by a significant basinward translation of facies and the formation of a lowstand wedge (Fig. 54C). The lowstand wedge is thinner than in the previous sequences and shows considerable variations in lithology. During the subsequent transgression, the coastline was rapidly translated to the west and only fine-grained outer shelf sediments were deposited. In the central fjord zone, the ensuing highstand is manifested only as a shift to mudstone-rich inner shelf deposits.

Because of the limited evidence available to constrain the sequence stratigraphic model in an east–west direction, it can serve only as a first approximation which must await further substantiation from sedimentological studies of the Petermann Bjerg Group as sedimentological evidence from this group is not available at present. However, based on the sequence stratigraphic model of the central fjord zone and the limited lithological and stratigraphical information available from the Petermann Bjerg Group tentative sequence stratigraphic correlation schemes are shown in Figure 55 compared with the lithostratigraphical correlation originally suggested by Wenk & Haller (1953).

Basin physiography and cyclic sea-level changes

It is characteristic of the Lyell Land Group deposits that the individual facies associations form successions which may be many tens, sometimes hundreds of metres thick within each sequence, without showing any major variations in facies, grain size or bed thickness. The facies associations are also readily traceable throughout the central fjord zone for more than 300 km showing only minor thickness variations. The depositional patterns can likewise be correlated 100 km eastwards into the basin to Canning Land.

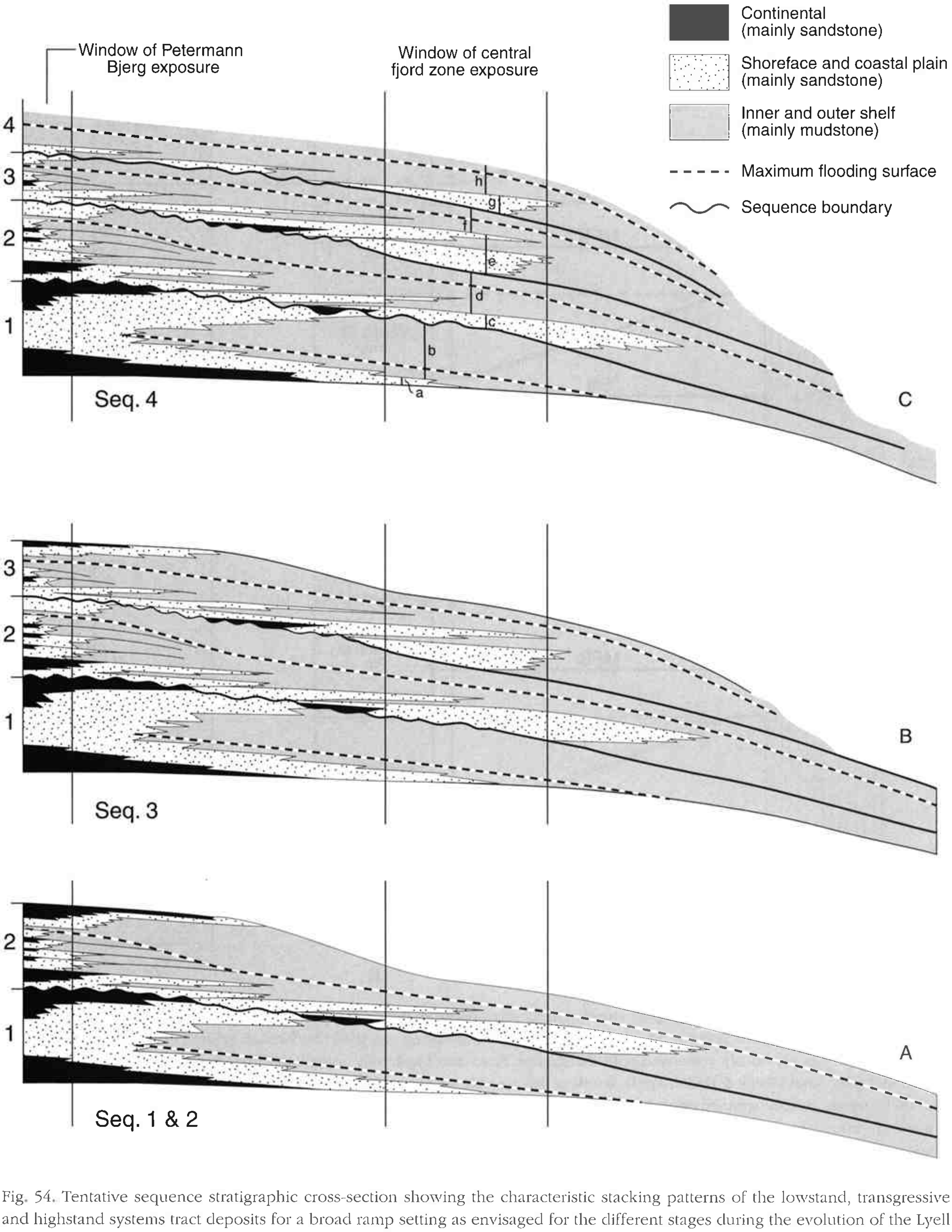

Fig. 54. Tentative sequence stratigraphic cross-section showing the characteristic stacking patterns of the lowstand, transgressive and highstand systems tract deposits for a broad ramp setting as envisaged for the different stages during the evolution of the Lyell Land Group. Window of central fjord zone and Petermann Bjerg exposures is indicated. Top of Kempe Fjord Formation (a), Sandertop Formation (b), Berzelius Bjerg Formation (c), Kap Alfred Formation (d), Vibeke Sø Formation (e), Skjoldungebræ Formation (f), Teufelsschloss Formation (g), Kap Peterséns Formation (h). See text for further explanation.

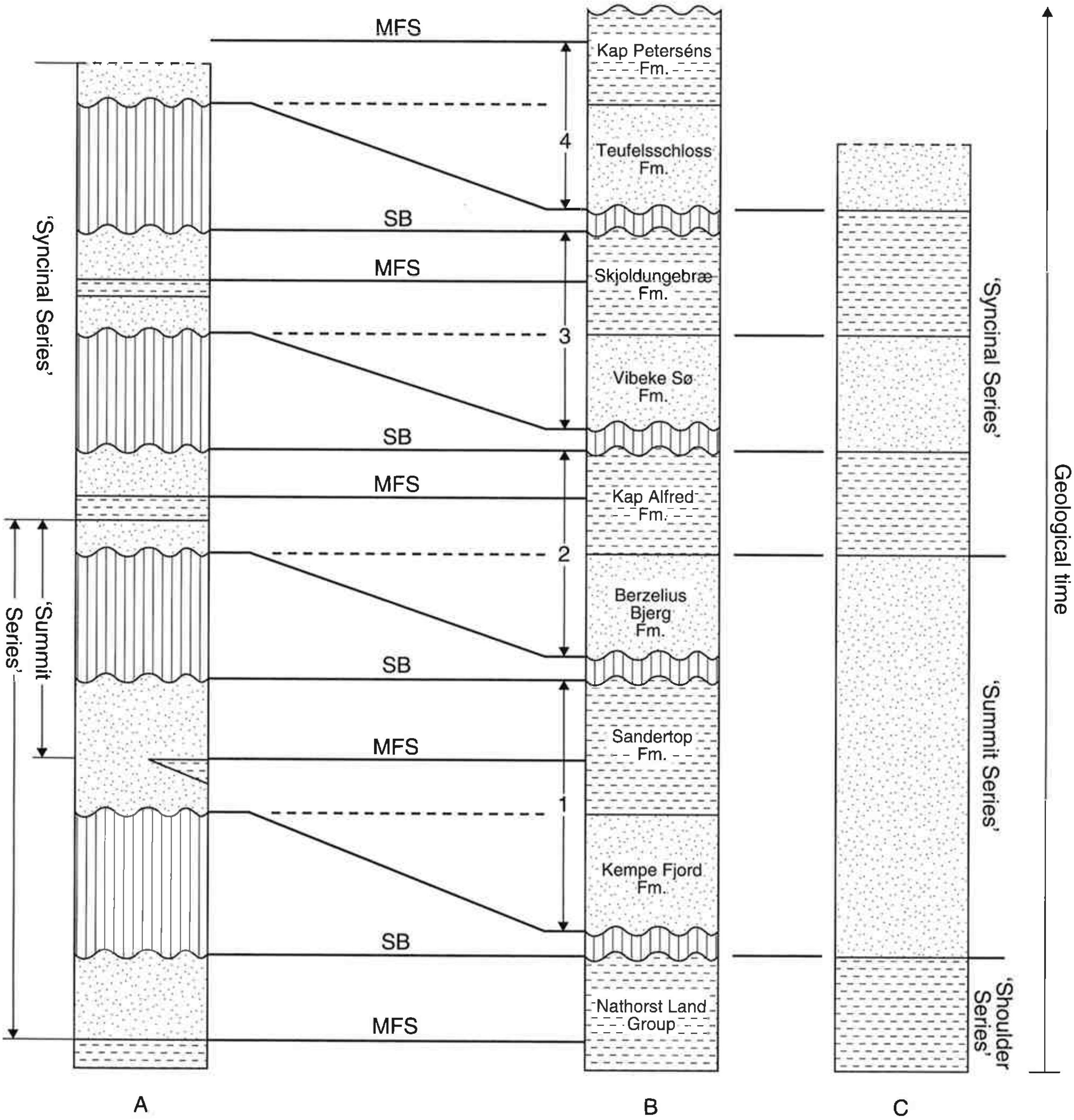

Fig. 55. Two possible sequence stratigraphic correlation schemes between the successions in the Petermann Bjerg region (**A**) and in the central fjord zone (**B**); see also Fig. 53. The lithostratigraphic correlation suggested by Wenk & Haller (1953) is shown in **C**. The 'Summit Series' was previously correlated with the Kempe Fjord and Sandertop Formations ('bed-groups 1 and 2') on a strictly lithostratigraphic basis (Wenk & Haller, 1953). In one of the possible sequence stratigraphic correlations the 'Summit Series' is coeval with both coarse- and fine-grained deposits of 5 units (uppermost part of the Nathorst Land Group, the Kempe Fjord Formation, the Sandertop Formation, the Berzelius Bjerg Formation and the lower part of the Kap Alfred Formation) and includes two major sequence boundaries. The 'Summit Series' may also be coeval with only the upper part of the Sandertop Formation, the Berzelius Bjerg Formation and the lower part of the Kap Alfred Formation and only include one major sequence boundary.

Similar sedimentation patterns appear to be common in many Precambrian and Cambrian successions (e.g. Anderton, 1976; Levell, 1980; Føyn, 1985; Dott *et al.*, 1986; Hein, 1987; Nystuen & Siedlecka, 1988; Eriksson *et al.*, 1993) where thick, laterally very extensive and extremely homogeneous shelf sandstone or mudstone units can reach thicknesses of more than 2 km without showing indications of marked cyclic development or significant changes in depositional environment. Part of this may be explained by the diminished environmental resolution resulting from the low preservation of fine-grained material caused by the absence of land vegetation (e.g. Dalrymple *et al.*, 1985; Dott *et al.*, 1986; Pettijohn *et al.*, 1987; Tirsgaard, 1993). However, the general picture of substantial deposition of homogeneous facies in Precambrian and Cambrian successions depicted by Cant & Hein (1986) can be considered valid; these authors suggested that increased tidal amplitudes or reduced chemical weathering due to the absence of land plants were possible causes. None of these explanations are, however, appropriate for the deposits of the Lyell Land Group. Although environmental resolution in the coastal depositional environments of the Lyell Land Group is reduced there are compelling indications of only a modest tidal amplitude (Tirsgaard, 1993). It seems therefore more plausible that the stable nature of the individual facies belts is a result of a particular combination of basin physiography, subsidence rates, eustasy, sediment influx and shelf circulation systems.

The consistent vertical and lateral development of facies associations seen in the four sequences of the Lyell Land Group imply that subsidence rates parallel to basin strike must have been highly uniform and that sedimentation rates over long periods must have balanced relative sea-level change. No evidence of significant tectonic activity has been observed within the Lyell Land Group suggesting that the major sea-level falls and consequent shelf reorganisations were a result of eustasy.

There are no indications of point sourcing of sediment to the shelf and sourcing of sediment appears to have been evenly distributed along the coast. This in combination with effective dispersal systems driven by consistent coast parallel geostrophic currents which were periodically supplemented by tidal current systems probably helped to create the wide lateral distribution of the facies associations.

The thick development of the individual facies associations also suggests that facies belts were extensive, both parallel to and perpendicular to the basin strike and that they migrated only slowly and over relatively short distances. During deposition of each of the four sequences, periods existed when outer shelf or coastal plain deposits were laid down across large areas within the window of exposure, forming facies belts at least 50–100 km wide. Such a distribution of facies suggests an extremely flat basin physiography. The thickness of the facies associations is dependent upon the combined effect of subsidence, eustasy and sediment input. To preserve thick successions of a single facies association requires prolonged periods with relatively uniform rates of creation of accommodation space on the shelf. Major eustatic changes in sea-level would lead to variations in accommodation space and consequently result in significant lateral translation of facies. This would be particularly conspicuous on a gently dipping shelf, where even small variations in sea-level lead to submergence or exposure of large areas of the shelf. Since major translations of facies are mainly associated with the formation of the four sequence boundaries, and thus lower order cyclic sea-level changes, it implies that high order sea-level cycles during most of the time must have been of small amplitude. The only exception to this occurred during deposition of sequence 3 when recurrent episodes of forced regression led to major shifts in facies belts and to the formation of near coastal shoreface deposits directly above outer shelf deposits.

Palaeogeographic reconstruction

On the basis of the facies development within the four sequences, a general palaeogeographic model of the shelf can be made. The model assumes that no major palaeogeographic reorganisation of the basin occurred in association with the shifts in relative sea-level within each sequence. This is likely to be an over-simplification, but with the minor amount of east–west data on the shelf and the poorly developed highstand deposits, a more detailed model is not achievable. Once integration of data from the Petermann Bjerg area becomes possible, a more refined model may be established.

A reconstruction of the shelf during formation of all four sequences depicts a shelf orientated north–south and deepening towards the east (Fig. 56). Coastal plain deposits formed in the most proximal parts. These were dominated by wide, shallow sandy tidal channels and, to a lesser extent, by tidal flats formed within a micro- to mesotidal regime (Tirsgaard, 1993). Seaward, the coastal plain deposits passed into shoreface deposits

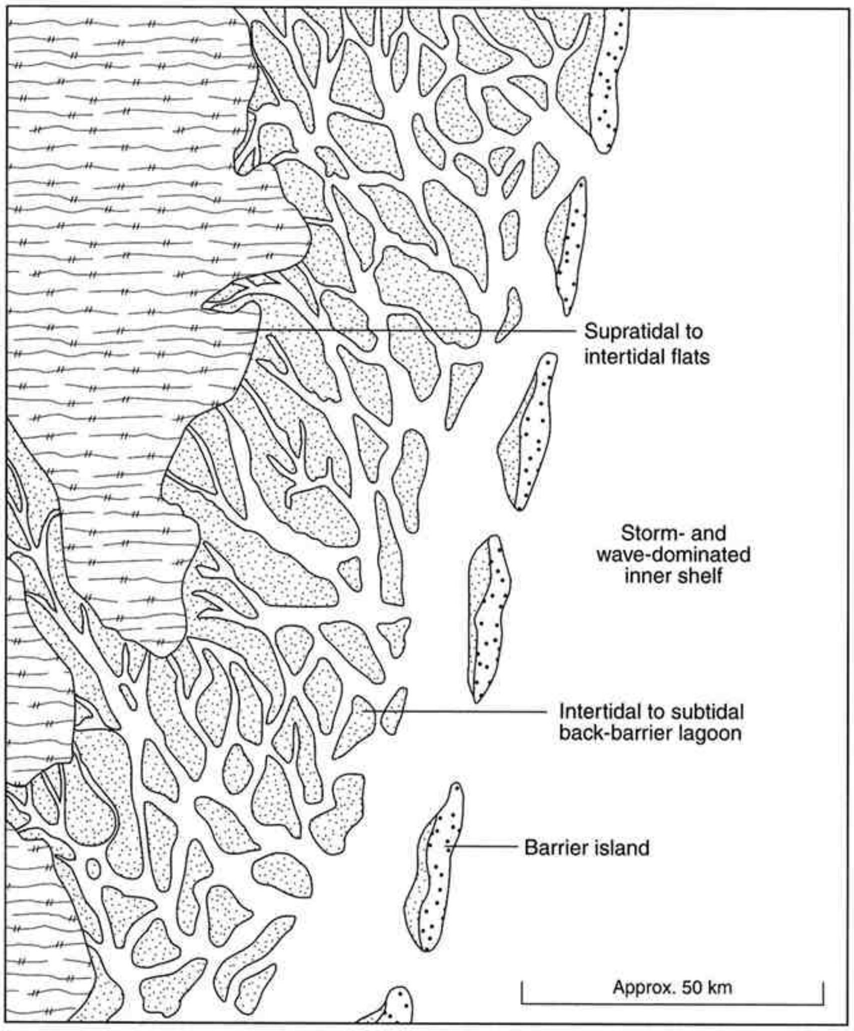

Fig. 56. Simplified, tentative reconstruction of the shelf during formation of the four sequences. Coastal plain tidal channels and supra- to intertidal flats formed at the landward side (these are not developed in the window of exposure of sequence 3, but are suggested to exist west of the central fjord zone). Towards the east, these pass into a series of barrier islands, which seawards pass into storm-dominated inner shelf and eventually outer shelf environments. The coastline was orientated roughly north–south, with the main transport direction on the shelf being towards the north.

which, during most of the time, were strongly influenced by storm and wave activity. Northerly flowing, shore-parallel geostrophic currents were the dominant transport agent. During formation of sequence 2, however, tidal activity became more prominent, probably because of reduced storm- and wave activity in the shoreface environment or, alternatively, because tidal currents periodically became stronger. Similar hydrodynamic changes on shelves have been recorded from late Precambrian deposits by Lindsey & Gaylord (1992). A climatic change towards a more calm environment or palaeogeographic reorganisation on the shelf leading to enhanced tidal amplitudes are both mechanisms likely to have caused such changes (see also discussion of this under the description of sequence 2).

Considering the recurrent evidence of tidal activity both within the coastal plain deposits, and periodically within the shoreface deposits, it is likely that barrier islands formed on the shelf (Fig. 56; Reinson, 1992). However, as previously discussed, direct evidence of their occurrence such as tidal inlet or tidal delta deposits has not be observed. Basinward, the shoreface deposits passed into storm-dominated inner shelf deposits which, further seaward, graded into an outer muddy shelf.

In sequence 3 coastal plain deposits do not occur and evidence of tidal activity is missing throughout the sequence. This does not necessarily imply that tidal channels did not form on the coastal plain, which may have existed further west. Since storm- and wave-dominated shoreface deposits form the most proximal deposits it is likely that the fall in relative sea-level which initiated all four sequences was smaller in sequence 3 than in the other three sequences.

During the final stages of deposition of the Lyell Land Group, indications from sequence 4 suggest that a more diverse depositional pattern developed on the shelf, where sediment influx and coastal progradation were more localised. The tidally dominated coastal plain deposits became localised to the middle part of the central fjord zone, while deeper water developed on the shelf in the southern part of the central fjord zone and in Canning Land. This may reflect a diminishing siliciclastic sediment supply which eventually was reduced to the point at which a carbonate ramp (represented by the deposits of the overlying Ymer Ø Group) began to develop across the entire shelf.

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