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.

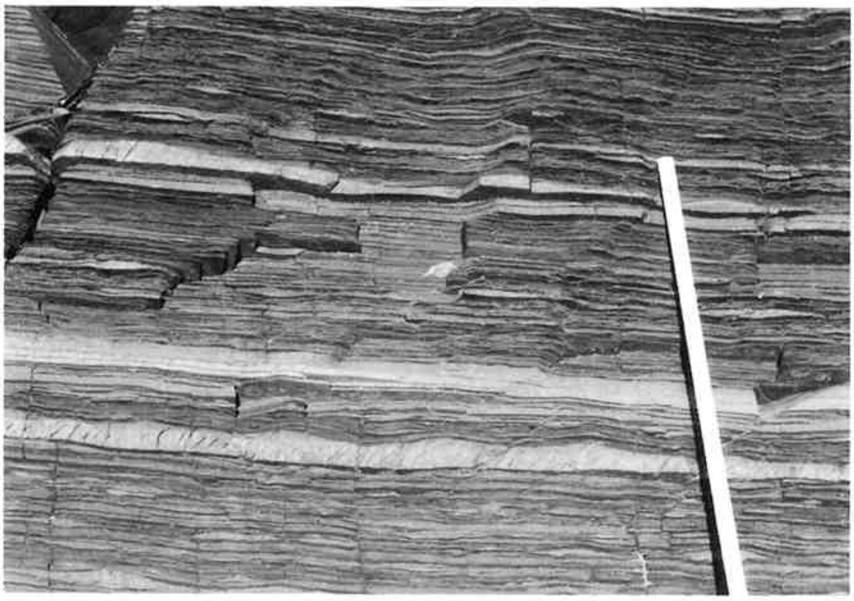

Fig. 32. Laminated outer shelf mudstones interbedded with thin sandstone beds and lenses showing sharp bases and in some cases well-developed ripple form sets. Skjoldungebræ Formation, Jägmästarens Ø.

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

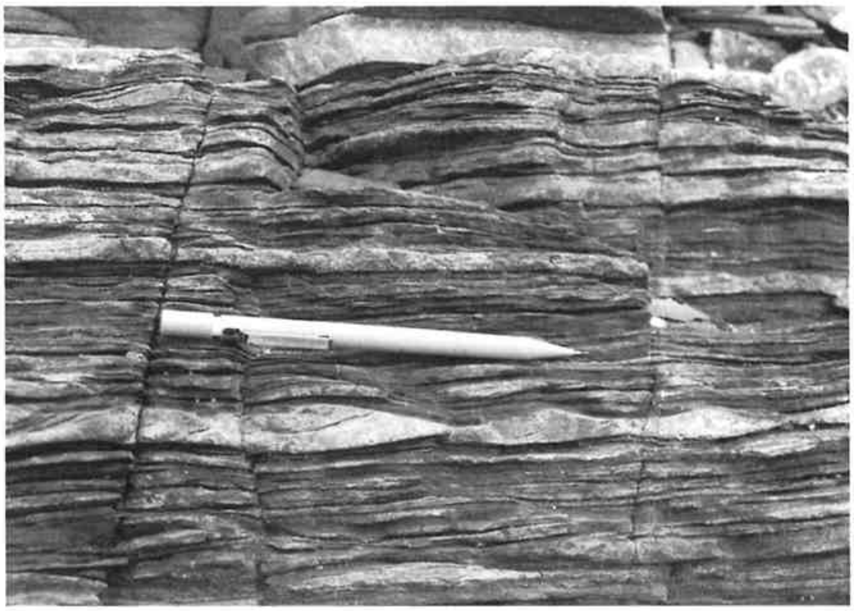

Fig. 34. Upward coarsening succession within heterolithic mudstone deposits of the storm- and wave-dominated inner shelf association. A thin sandstone lens with well-developed ripple form sets is succeeded by a succession showing an increasing occurrence of sandstone lenses. Type locality of Skjoldungebræ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

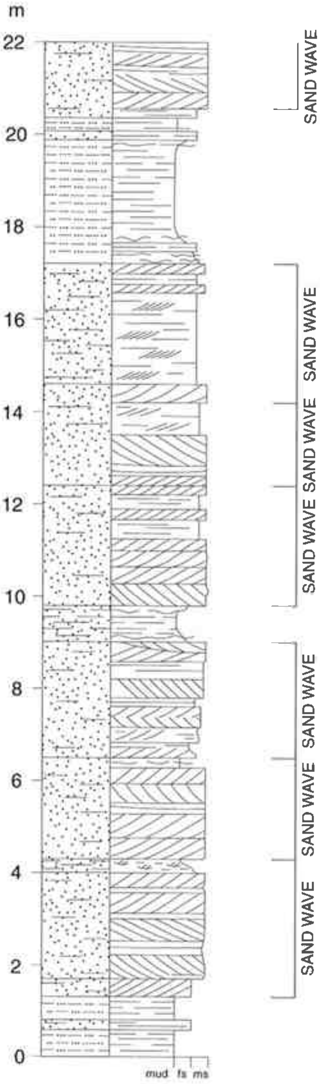

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Fig. 37. Detailed sedimentological log of the tidally influenced shoreface association (Kap Alfred Formation, northern Lyell Land) showing the characteristic vertical stacking pattern of sand waves, which combine to form tidal sand sheets. Intervals 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

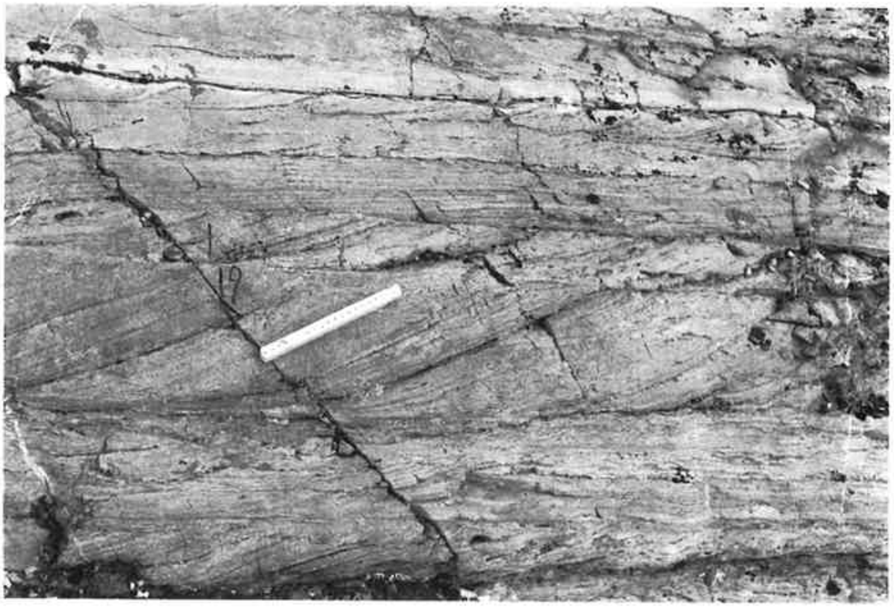


Fig. 38. Characteristic, well preserved internal development of a sandstone body within the tidally influenced shoreface association showing alternating deposition of large-scale cross-bedding and cross-lamination. Cross-beds show numerous reactivation surfaces. Scale bar is 20 cm long. Kap Alfred Formation,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

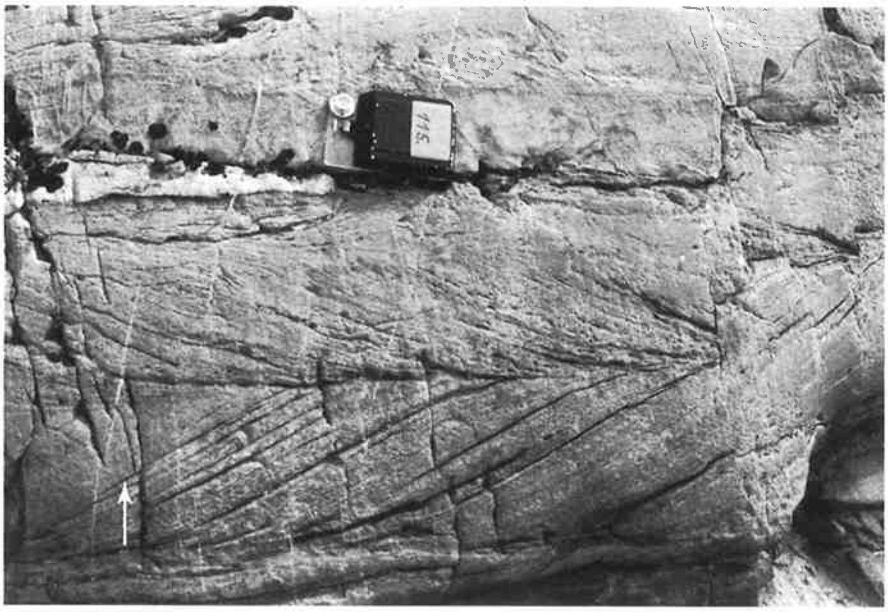


Fig. 39. Herringbone cross-bedding with clay drapes along foresets from the tidally influenced shoreface association. Within the lower cross-bed individual foresets show a gradual thinning towards the left, followed by a sudden thickening (arrow). This rhythmic upbuilding of the set possibly reflects 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

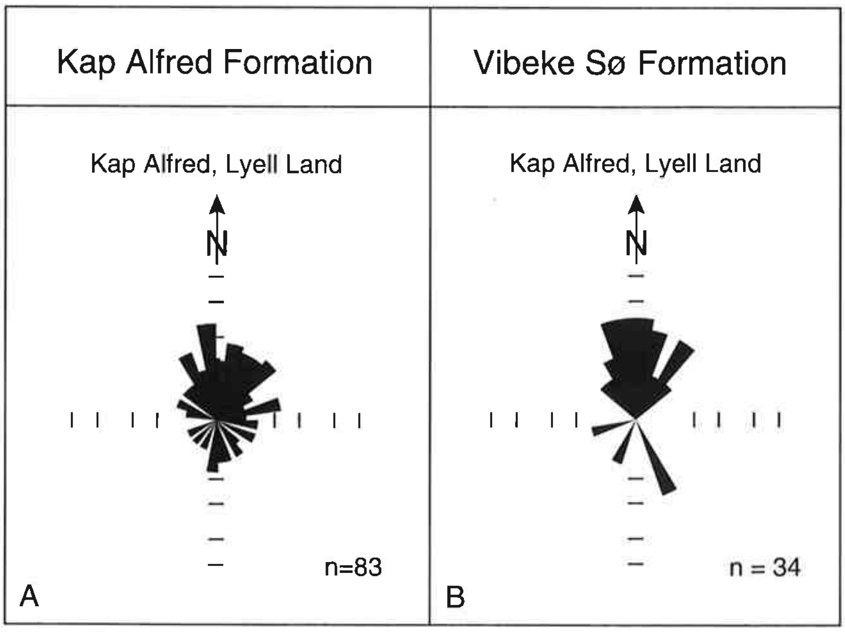


Fig. 40. **A:** Palaeocurrent measurements from the tidally influenced shoreface association (10° intervals). The measurements are made on large-scale planar cross-beds within tidal sand waves from the middle part of the formation. **B:** Palaeocurrent measurements from the storm- and wave-dominated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

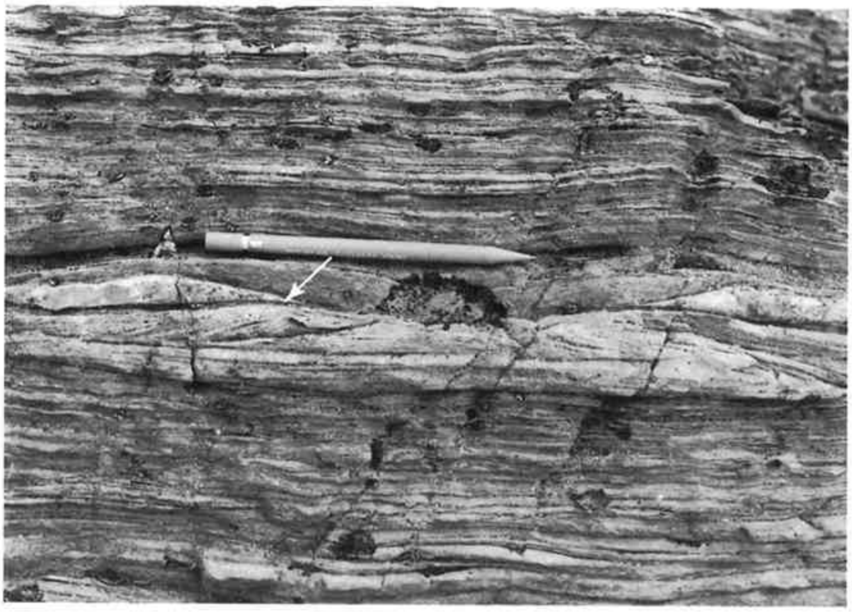


Fig. 41. Heterolithic mudstones from the tidally influenced shoreface association interbedded with thin sandstone lenses. The sandstone lenses contain well-developed ripples with foresets showing bi-directional bundling (arrow). Kap Alfred Formation, northern Lyell Land.

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

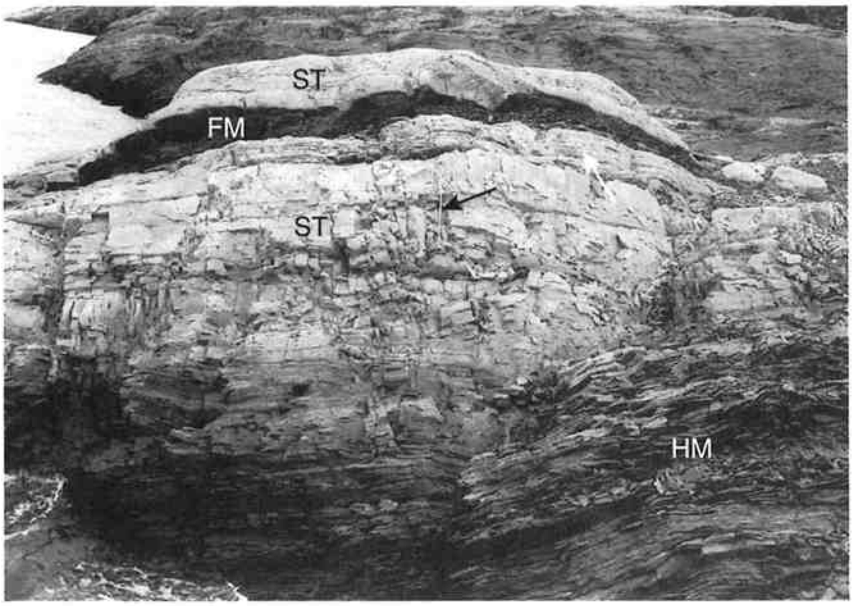
The occurrence of herringbone cross-stratification, undulatory lower set boundaries, thickening and thinning of foresets coupled with the presence of clay draped foresets and abundant reactivation surfaces, suggest a tidal origin for the large-scale cross-bedded sandstone bodies (e.g. Soegaard & Eriksson, 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).

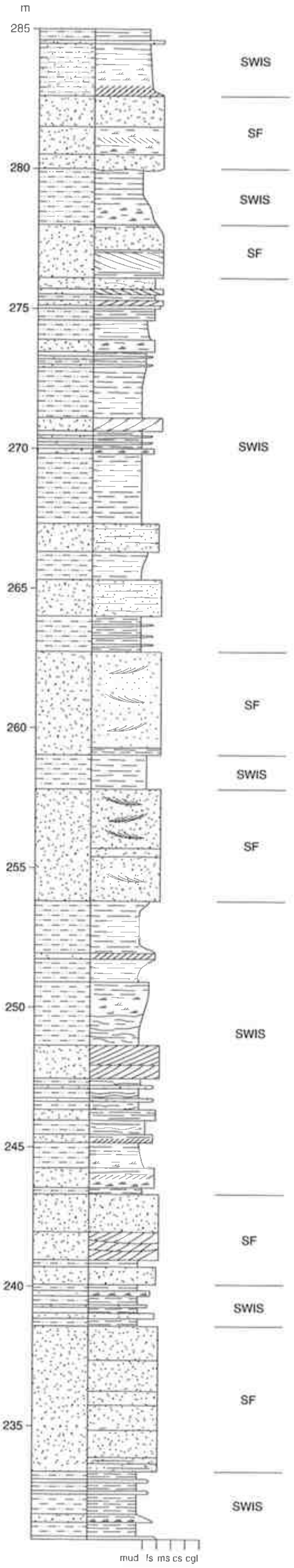


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Fig. 43. Section showing the characteristic vertical development of the storm- and wave-dominated shoreface association (SF) and the storm- and wave-dominated inner shelf association (SWIS) (Vibeke Sø Formation, Kap Alfred, northern Lyell Land). Most 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.

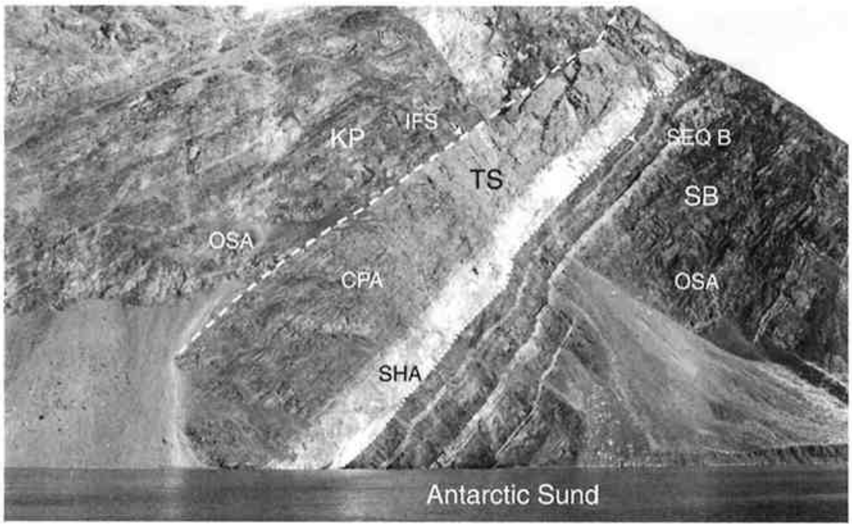

Fig. 44. Succession showing the transition from mudstones of the outer shelf association (OSA), to structureless white sandstones of the shoreface association (SHA), into tidal channel sand sheets of the coastal plain association (CPA) and back to mudstones of the outer shelf association, as developed 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).

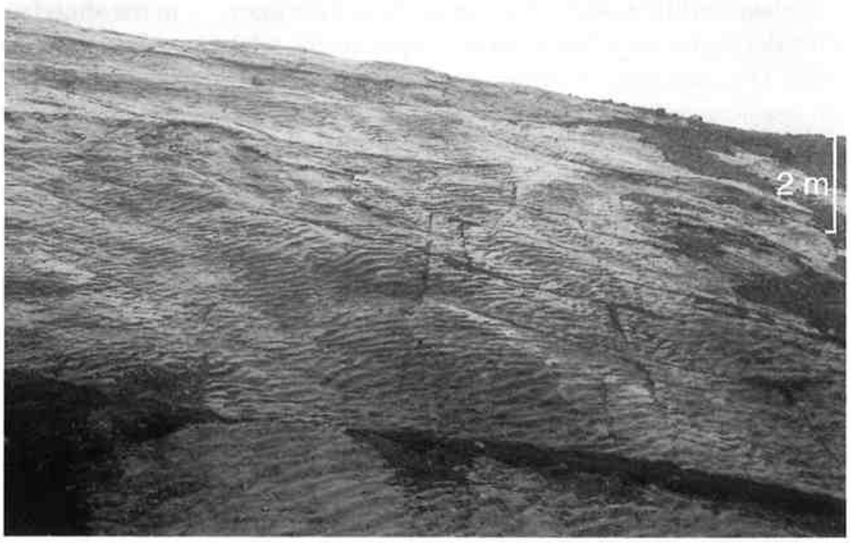

Fig. 45. Upper surface of a sandstone body from the storm- and wave-dominated shoreface association showing remoulded dunes, covered by bifurcating wave ripples. Ripple-crests are orientated approximately perpendicular to the crests of the dunes suggesting that the dunes formed in response to coast-parallel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

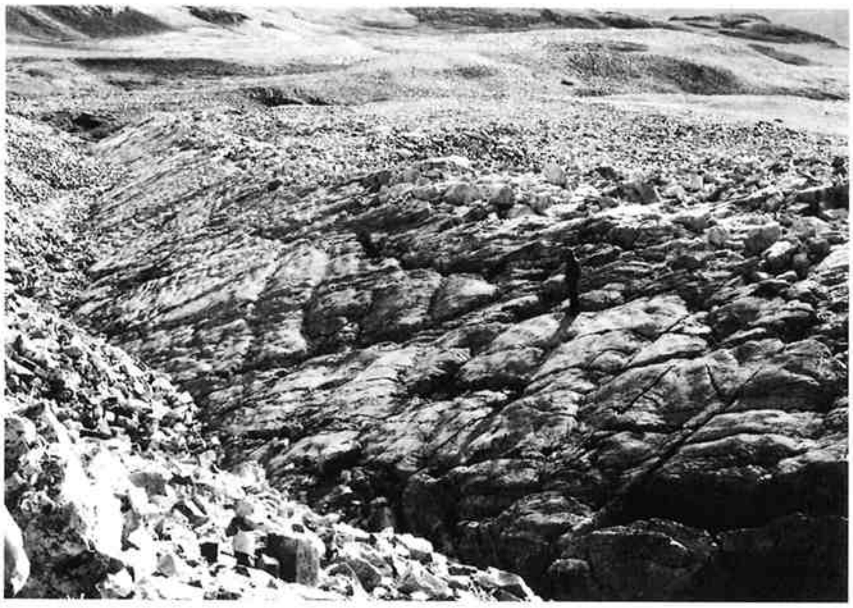

Fig. 46. Upper surface of a shoreface sandstone body from the storm- and wave-dominated shoreface association, with dunes passing laterally into large-scale wave-ripples in the background. Person for scale. Teufelsschloss Formation, Vibeke Sø, Steno Land.

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

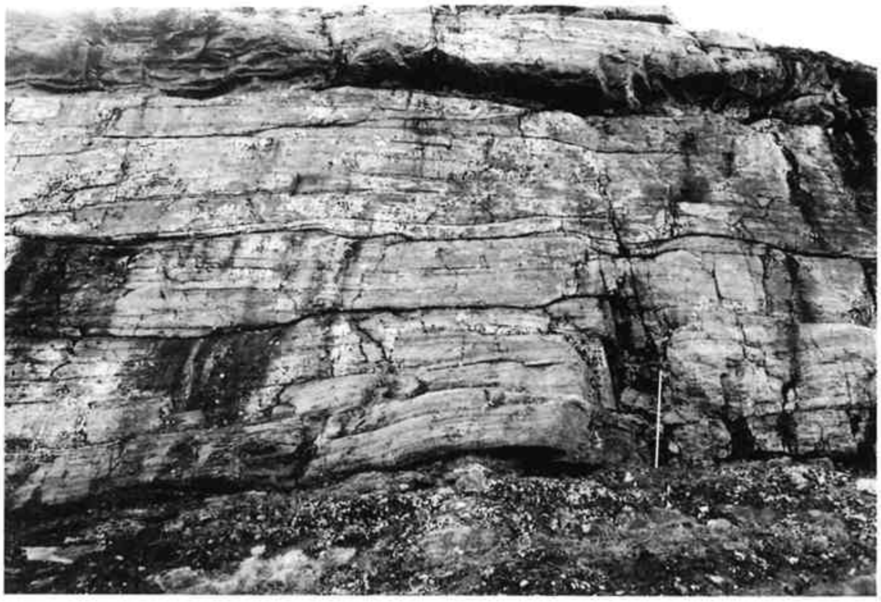

Fig. 47. Stacked tidal channel sand sheets of the tidally dominated coastal plain association, displaying sharp, erosive bases and internally dominated by parallel lamination. Scale bar is 1 m long. Teufelsschloss Formation, from the type locality, Andrée Land.

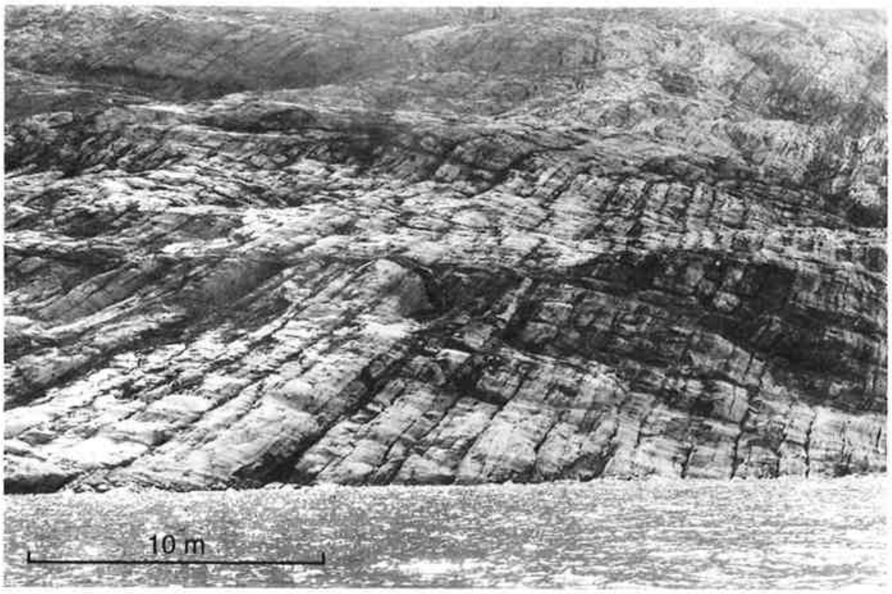

Fig. 48. Characteristic development of the tidally dominated coastal plain association. Sharp based sand sheets form stacked successions several tens of metres thick. Each sand sheet can be traced laterally for at least a few kilometres. Structural dip is 55° to the east. Berzelius Bjerg Formation, Kap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

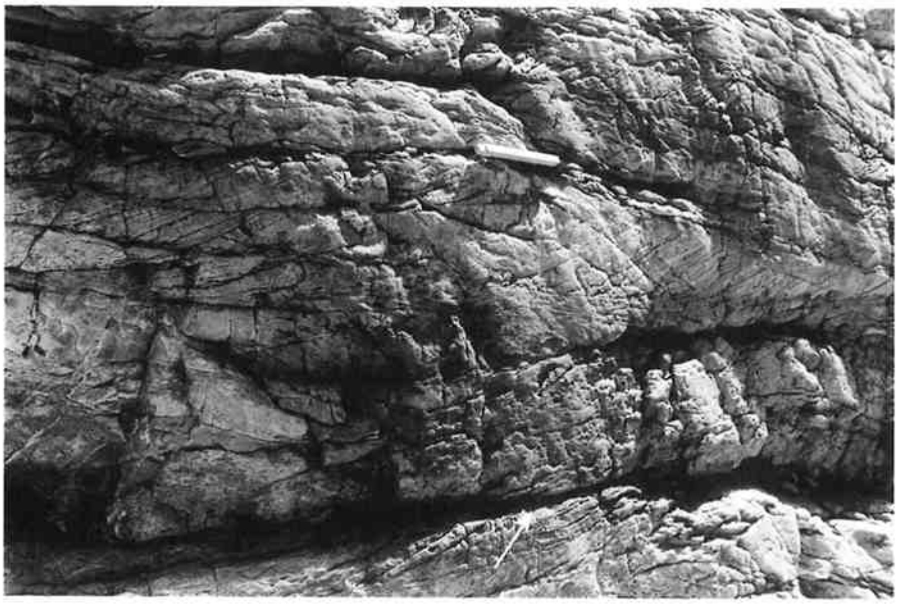

Fig. 49. Example of the development of internal structures of the sand sheets of the tidally dominated coastal plain association characterising the third unit of the Kempe Fjord Formation. The base of the sand sheet is shown by an arrow. The sand sheet is dominated by sets of large-scale cross-bedding,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

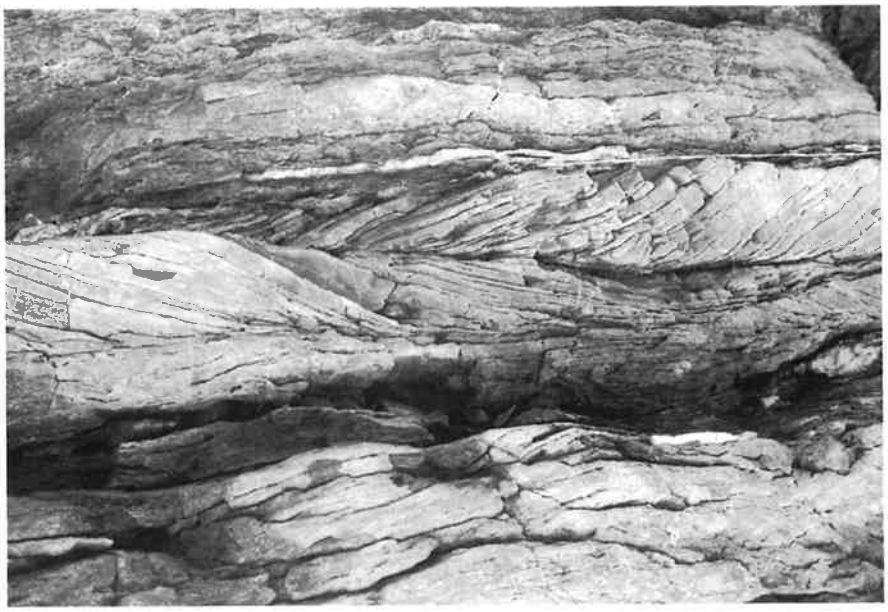

Fig. 50. Herringbone cross-stratification seen within the tidally dominated coastal plain association. Both sets are approximately 25 cm high. Kempe Fjord Formation. Kap Alfred, northern Lyell Land.

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.

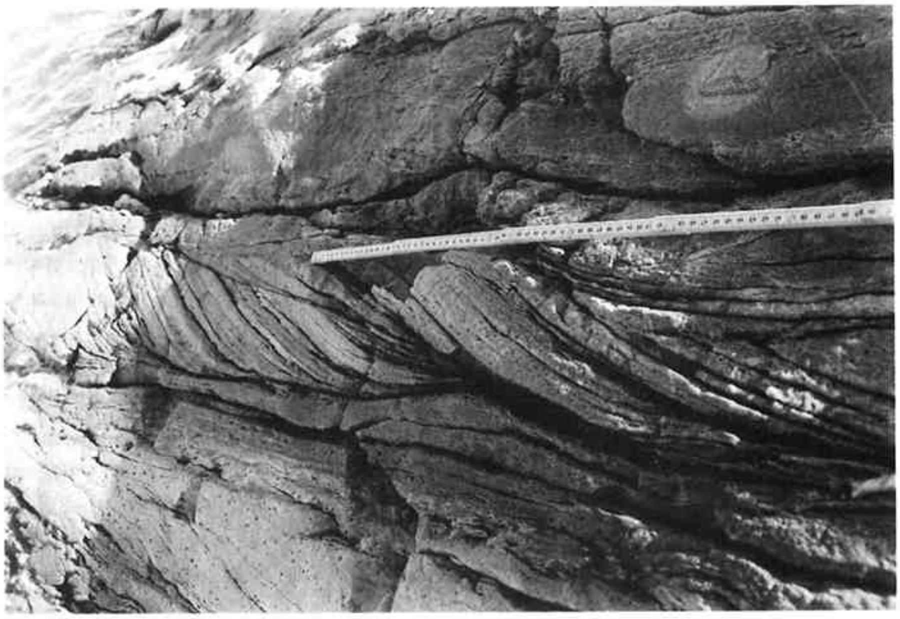

Fig. 51. Well preserved planar cross-bedding of the tidally dominated coastal plain association showing undulating lower set boundaries, mudstone draped foresets, multiple reactivation surfaces and a bundle-wise upbuilding. Length of scale is 80 cm. Kempe Fjord Formation, from the type locality, northern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

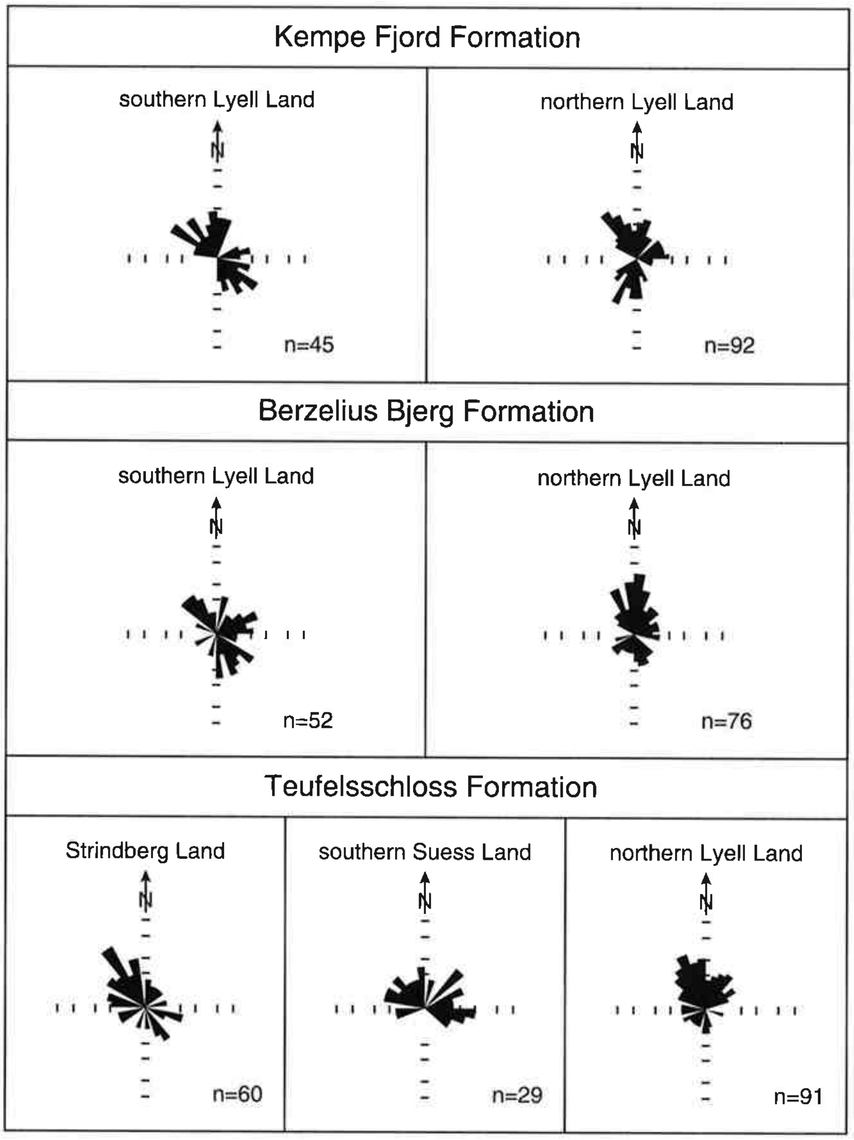

Fig. 52. Palaeocurrent measurements from the tidally dominated coastal plain association (10° intervals). The palaeocurrent measurements from the Kempe Fjord and Berzelius Bjerg Formations were made on large-scale planar cross-beds from tidal channel sand sheet deposits in Lyell Land. Palaeocurrent measurements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