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High-energy ephemeral stream deltas; an example from the Upper Silurian Holmestrand Formation of the Oslo Region, Norway

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Abstract

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The late orogenic deposits of the Upper Silurian Holmestrand Formation of the Oslo Region, Norway, comprises sharply alternating ephemeral stream and sandy beach face deposits. The formation is divided into three units reflecting the down-slope change on an extensive ephemeral stream delta system. The lower unit of the formation comprises ephemeral stream sediments as stacked sheet-sandstone bodies, deposited on a broad coastal floodplain. Each sheet is bounded by a lower intraclast strewn scoured surface overlain by massive, horizontally stratified, low-angle and trough cross-bedded sandstones. In the medial and upper units of the formation the ephemeral stream sediments alternate with beach face deposits, forming ephemeral stream deltas. The ephemeral stream deltas are marked by intraclast strewn scoured surfaces, and dominated by trough cross-bedded sandstones. They may contain escapement burrows, marine bioturbation and wave-working of the delta surfaces.

The beach face deposits are composed of alternating irregular, horizontally stratified sandstones with current and wave ripple cross-lamination and tabular cross-bedded sandstones. Deposition took place in a coastal, non- to micro-tidal, shallow-water environment, influenced by longshore currents and low palaeo-wave energy.

Seven ichnotaxa are recognized and support the sedimentary record of a transitional environment between a broad coastal floodplain and a shallow marine environment. The presence of calcretes indicate an arid to semi-arid palaeo-climate.

Introduction

Alluvial multistorey sheet-sandstone bodies, composed mainly of horizontally stratified and low-angle cross-bedded lithofacies, have been interpreted as the product of a series of high-energy ephemeral flooding events (e.g. Miall, 1977, 1978; Stear, 1980, 1985; Tunbridge, 1981, 1984; Sneh, 1983). Since the classical work on flood deposits from Bijou Creek, Colorado, U.S.A., by McKee et al. (1967) most studies have concentrated on stream systems terminating in muddy floodplains, ephemeral lakes and sabkhas (Mukerji, 1976; Hardie et al., 1978; Stear, 1980, 1985; Tunbridge, 1981, 1984; Parkash et al., 1983; Sneh, 1983; Olsen, 1987). Only few works on modern deposits have dealt with ephemeral sandy systems on coastal floodplains forming ephemeral stream deltas in perennial lakes or shallow marine basins (Frostick and Reid, 1986; Hicks and Inman, 1987). Frostick and Reid (1986) focused on the three-di-

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mensional morphology and alluvial architecture of Holocene ephemeral river deltas in lakes in the Turkana basin, northern Kenya. Hicks and Inman (1987) described recent sand dispersion from an ephemeral river delta of the central California coast.

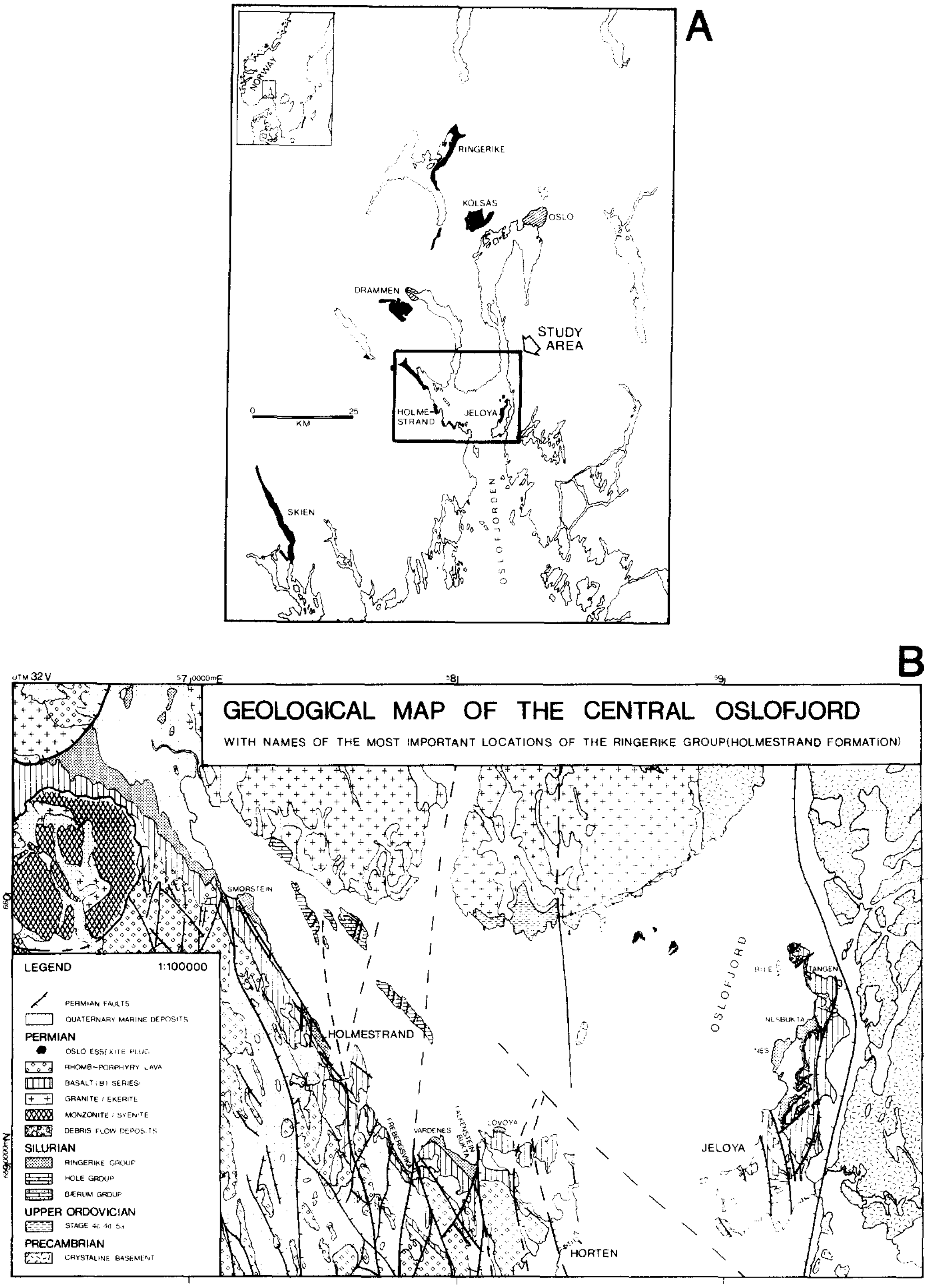

Fig. 1. Map of the Oslo Region showing the districts of the Ringerike Group (A) and the main localities (B) referred to in the text.

This paper documents facies and sequences of an ancient high-energy ephemeral stream delta system. Special attention is paid to the hydrodynamics of the ephemeral streams. The depositional model presented in this paper contrasts in several aspects from the proposed interpretation of the Holmestrand Formation by Turner (1974) and Turner and Whitaker (1976).

Stratigraphic setting

In its regional extent, the Ringerike Group represents an Upper Silurian clastic wedge topping the Caledonian foreland basin in the Oslo Region (Fig. 1). The wedge is attributed to the final advancement of the Caledonian thrust front that commenced at the end of Wenlock and Ludlov time (Bjørlykke, 1983) and led to crustal displacement in the Region (Morley, 1987).

In the type area in Ringerike the succession coarsen upwards from marine to terrestrial deposits and comprises the Sundvollen and Stubdal Formations. Palaeo-current measurements suggest a source area in the Caledonides extending NW-NNW of the area (Turner, 1974; Turner and Whitaker, 1976) (Fig. 2). To the south, in the Holmestrand and Jeløya districts, the Holmestrand Formation constitutes the Ringerike Group (Fig. 1). In these districts the thickness of the group is 425–600 m and makes up an independent petrographic province (Turner, 1974; Turner and Whitaker, 1976). Based on the clast composition, petrography and a limited number of palaeo-current measurements in the Holmestrand Formation, Turner and Whitaker (1976) suggested a source area in the Precambrian basement, which flanks the eastern edge of the Oslo Graben. Previously, several authors have attributed these data to the existence of a landmass to the east, indicating that a connection between the Oslo Region and the Baltic Sea no longer was present in late Silurian times (e.g. Ramberg and Spjeldnæs, 1978; Worsley et al., 1983; Bassett, 1985; Steel et al., 1985). The studies of Andreasen (1980) and Dam (1987) contrast this model and they showed that the source area was in the Caledonides extending NW-NNW of the districts. Moreover, Dam (1987) suggested that the deposits of the Holmestrand Formation could represent the western coastal section of an Upper Silurian shallow water basin that streched across most of Scandinavia. This is in accordance with the presence of marine redbeds of the same age, known from the Pridolian Öved Sandstone Formation in Skåne (Jeppson and

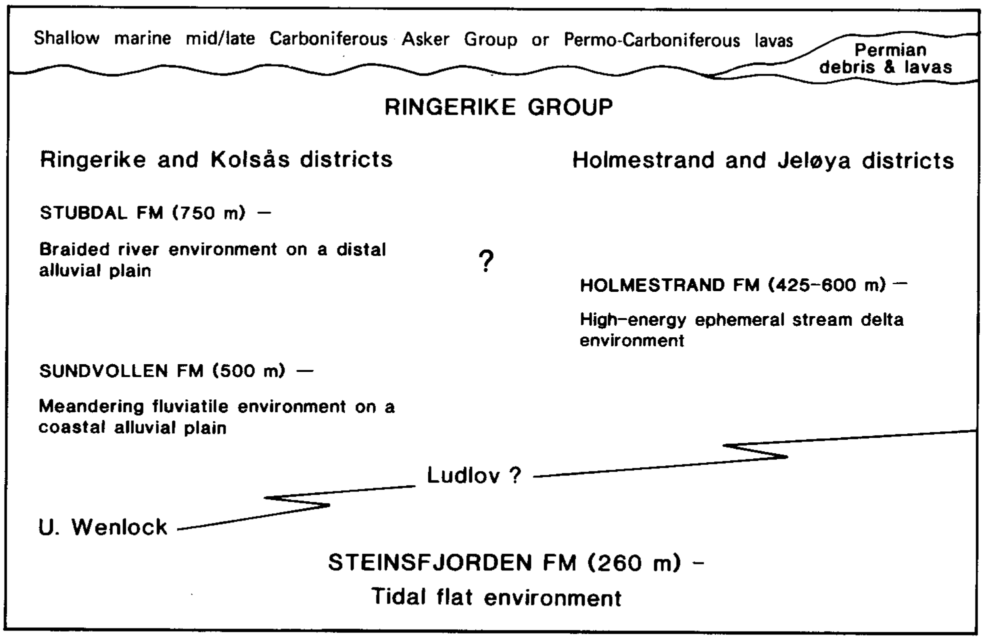

Fig. 2. Stratigraphy of the Ringerike Group.

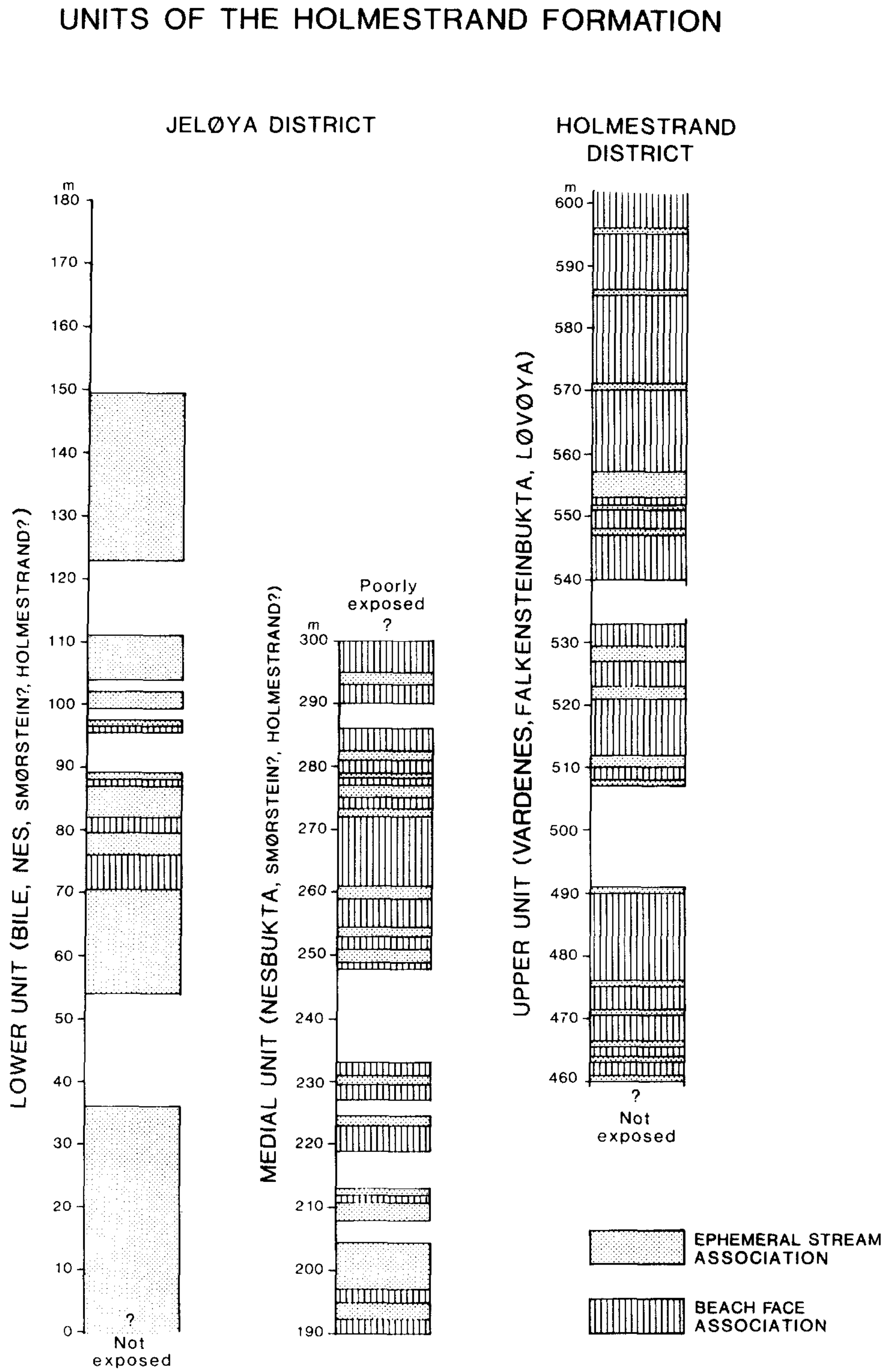

Fig. 3. Stratigraphic succession of the Holmestrand Formation measured between Holmestrand and Horten, on Bile and along the west coast of Jeløya. The lower unit is dominated by ephemeral stream deposits. The medial unit is characterized by having an equal amount of beach face and ephemeral stream deposits and the upper unit is dominated by beach face deposits. The names refer to the most important locations.

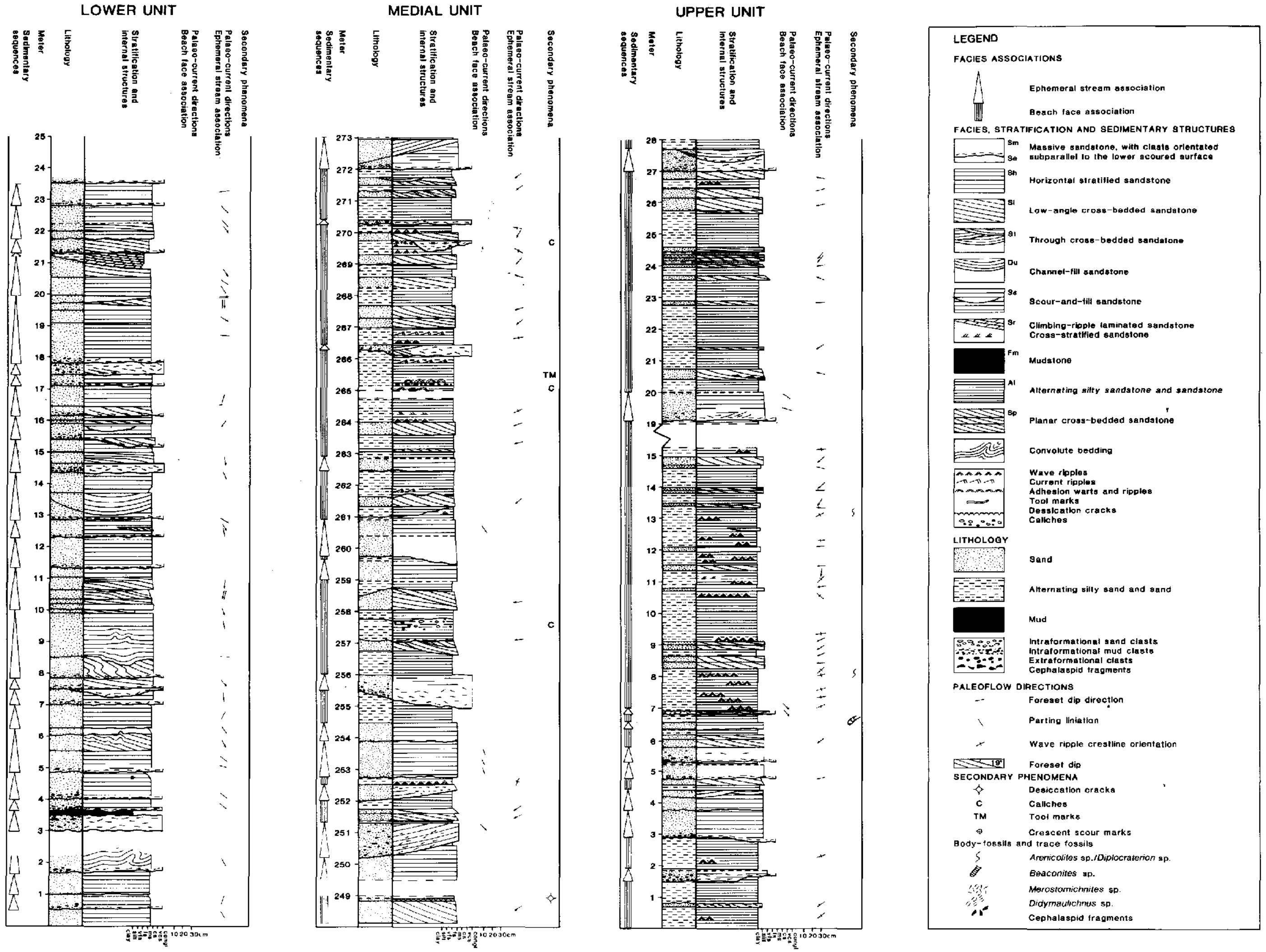

Fig. 4. Three sections from the lower, medial and upper unit of the Holmestrand Formation. Measured on Bile, at Nesbukta and Vardenes, respectively.

Laufeld, 1986) and two boreholes in Jylland; Nøvling 1 and Rønde 2 (Christensen, 1971, 1973). However, more detailed work on the stratigraphy is clearly necessary, and studies of the Drammen and Skien districts are also needed before more reliable regional palaeo-geographical interpretations can be presented.

The Holmestrand Formation, which is well-exposed in shore sections in Vangenes, Falkensteinbukta, Løvøya, Nes, Nesbukta and Bile (Fig. 1), is in this paper subdivided into three informal lithostratigraphic units; a lower, medial and upper unit. This division is based on the relative abundance of beach face and ephemeral stream deposits (Fig. 3). The lower unit is almost entirely composed of ephemeral stream deposits (Fig. 4) and is well-exposed along the coast of Jeløya at Nes and on Bile (Fig. 1). The medial unit is characterized by having an equal amount of beach face and ephemeral stream deposits (Fig. 4). This unit is exposed along the coast of Nesbukta and Jeløya (Fig. 1). The uppermost part is exposed along the coast of Løvøya, Falkensteinsbukta and Vardenes in the Holmestrand district (Fig. 1) and is dominated by beach face deposits (Fig. 4).

Ephemeral stream association

Facies

The ephemeral stream association is composed of nine lithofacies made up of well-sorted fine to medium-grained sandstones with only very little mudstones (Table 1). The ephemeral stream deposits occur as single or stacked sheet-sandstone bodies, each sheet 0.1–3.0 m thick, bounded by laterally extensive intraclast strewn scoured surfaces (Figs. 5, 6). The sandstone bodies are made up entirely of horizontally stratified sandstones, or arranged in poorly developed fining-upward sequences composed of massive and/or horizontally stratified and/or low-angle cross-bedded and/or trough cross-bedded sandstones. Lunate megaripples, linguoid current ripples, climbing-ripple lamination, mudstones or cross-cutting channel-fill sandstones, infrequently top the sequences. The sheet-sandstones show very little lateral facies changes.

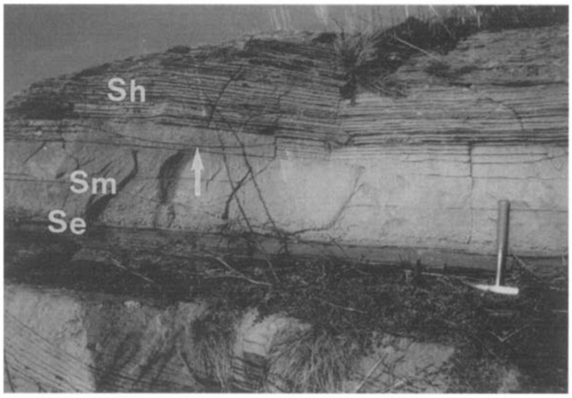

Fig. 5. Ephemeral stream sequence bounded by a lower erosive intraclast strewn surface (*Se*). Scoured surface is succeeded by massive bedded (*Sm*) and horizontally stratified (*Sh*) sandstones with an intersequence scour-and-fill structure (arrow). Hammer for scale (35 cm long).

Two notable facies are massive sandstone and low-angle cross-bedded sandstone. The massive sandstone is only present immediately above the basal scoured surface of each depositional sequence (Fig. 5). It often shows a lateral and vertical transition into horizontal stratified sandstone and often contains mudstone and cemented sandstone intraclasts with a diameter up to 15 cm, "floating" in the matrix.

The low-angle cross-bedded sandstones are internally composed of concave-upward, sigmoidal or convex-upward cross-strata (Fig. 8). Each set often shows a gradual down-stream change from concave-upward to sigmoidal cross-strata with knickpoint to sigmoidal cross-strata without knickpoint. Parting lineation on topsets and foresets and scattered clasts along cross-strata are common features. Upstream, the topsets may grade into horizontal stratification. Downstream the low-angle cross-bedded sandstones generally pass into horizontal stratified sandstones. Based on the external and internal geometry of the low-angle cross-sets (viewed parallel to the palaeo-flow) they have been grouped into four types (Figs. 7, 9).

Palaeo-current data from this association show a very narrow dispersion of orientation of parting lineation and dip azimuths of foresets from NW to NNW, both within individual sheet sandstones and in the two districts as a whole (Fig. 10).

TABLE 1

Facies of the ephemeral stream association

Facies		Characteristics	Interpretation	References	Average facies thickness (m)	% of facies association Units		
						lower	medial	upper
Se	Scoured surfaces overlain by intraclasts	Laterally extensive scoured surfaces overlain by mudstone and calcite cemented sandstone intraclasts. Caliche nodules, scattered disarticulated fragments of the cephalaspid *Hemicyclaspis kiaery* and extraclasts are less common.	Initial scoured surfaces overlain by lag deposits.	McKee et al. (1967) Leeder (1973) Rust (1984) Stear (1985) Reid and Frostick (1986)				
Sm	Massive bedding	Massive sandstones with "floating" clasts. Often show a lateral and vertical transition into horizontal stratified sandstones.	Hyper-concentrated flows formed during upper flow-regime conditions.	Lowe (1982) Olsen (1987)	0.21	11.7	19.4	10.9
Sh	Horizontal stratification with parting lineation	Plane bedded sandstones with parting lineation.	Upper flow-regime plane bed conditions.	Allen (1964)	0.58	54.1	42.5	33.1
Sl	Low-angle cross-bedding	Sets of concave-upward, sigmoidal or convex-upward low-angle cross-bedding. Intimate association with horizontal stratified sandstones. Occasionally parting lineation on topsets and foresets and clasts scattered along foresets.	Dune to upper-stage plane-bed transition.	Williams (1971) Picard and High (1973) Allen (1983) Saunderson and Lockett (1983) Røe (1987)	0.59	13.8	8.3	0.0
St	Through cross-bedding	Cosets of trough cross-bedded sandstones with upward decrease in set hight. Lunate megaripple formsets or lingoid ripple formsets locally present on top of cosets.	Migrating lunate megaripples generated during upper part of lower flow regime.	Allen (1968)	0.72	13.8	18.0	56.0
Sc	Channel-fill sandstones	Channels (1–25 m wide). Stratification types include conform	Channels formed during waning-flood conditions.		0.90	3.2	8.3	0.0

	laminae, low-angle cross-bedding, massive bedded sandstones or climbing-ripple lamination.						
Ss Scour-and-fill sandstones	Spoon-shaped scours with solitary cross-sets present in distinct horizons within horizontal stratified beds.	Erosive pulses accompanying flood peaks or surges during flood episode.	Jopling (1965) Stear (1985)	0.44	1.1	3.4	0.0
Sr Climbing ripple-lamination	Climbing-ripple lamination and current ripple formsets.	Migrating small-scale ripples during lower flow-regime conditions.	Allen (1968)	0.21	2.1	0.0	<1.0
Fm Mudstones	Lateral extensive homogeneous mudstones.	Suspension deposition from slowly moving or ponded water.	Sneh (1983) Rust (1984)	0.13	0.2	0.0	0.0
Penecontemporaneous structures							
Convolute bedding	Dome-shaped soft-sediment folds developed throughout or confined to the upper part of the depositional sequences. Massive core and periphery of unbroken strata. Underlying beds may appear partly massive.	Vertical dewatering possible due to rapid accumulation of sands.	Lowe (1975)				
Calcretes	Lenses and nodules, averaging 2–3 cm in diameter, with a maximum of 10 cm. Horizons are laterally extensive and less than 0.5 m thick.	Stage II development of calcil soil horizons in arid and semi-arid climates.	Gile et al. (1966) Allen (1986)				
Trace fossils:	Ethological classification:	Possible originator:					
Beaconites isp.	Repicnnia/pascichnia	Arthropod	Bradshaw (1981) Allen and Williams (1981)				
Didymaulichnus isp.	Repichnia/pascichnia	Arthropod	Chrisholm (1985) Dam (1987)				
Arenicolites isp.	Domichnia	Annelid-like organism	Fürsich (1975)				
Straight tube-like burrows	Fugichnia	Deposit-feeder					
	Average thickness of ephemeral stream sequences (in m): 1.0, 0.74, 0.45						

Penecontemporaneous features include convolute bedding, calcretes and bioturbation.

Convolute bedding is present as more or less regular folds developed throughout or confined to the upper part of the sheet sandstones. The contact between successive sheet sandstones in which the lower exhibits folds, is typically sharp without indications of sediment mixing across the contact.

Calcretes may cap the ephemeral stream sequences and form up to 0.5 m thick horizons. They can be traced laterally for well over 40 m, only limited by the lateral extent of the exposures.

Trace fossils make a minor contribution in the ephemeral stream association. In sections where ephemeral stream deposits alternate with beach face deposits escape structures may be present. Besides escape structures the trace fossil assemblage include *Beaconites* isp., *Didymaulichnus* isp. and *Arenicolites* isp. (Table 1, Fig. 11). *Arenicolites* isp. occurs in the medial and upper unit of the Holmestrand Formation, on top of the ephemeral stream sequences.

Interpretation

The lateral consistency of each sheet, the dominance of upper plane-bed deposits, and the unimodal low variance palaeo-currents suggest that the sediments were deposited in wide, shallow, flat-bottomed low-sinuosity channels, dominated by high-energy ephemeral flows. This facies assemblage is characteristic of many modern and ancient high-energy ephemeral stream deposits (e.g. McKee et al., 1967; Frostick and Reid, 1977; Stear, 1980, 1985; Tunbridge, 1980, 1984; Sneh, 1983; Reid and Frostick, 1986). The presence of "floating" clasts in the massive sandstones suggest deposition from hyper-concentrated flows in which rapid deposition hindered the development of bedforms. In hyper-concentrated flows pebble- and cobble-sized clasts are supported by the combined effect of fluid turbulence, hindered settling owing to high concentration of grains, matrix buoyant lift and dispersive pressure resulting from grain collision (cf. Lowe, 1982). The close association with horizontal stratification suggests that the massive beds were deposited during upper flow-regime conditions. Similar massive sandstones have been recorded from the base of recent flash floods deposits by McKee et al. (1967). They did, however, not interpret this facies hydrodynamically. All internal features of the low-angle cross-bedded sandstones are characteristic of bedforms formed in the dune to upper-stage plane-bed transition (Allen, 1983; Saunderson and Lockett, 1983; Røe, 1987) (Table 2).

The cross-cutting of the folds by the overlying sequence indicates that the folds formed during or just after one flood period and before the next. Water-escape structures like these are a prevalent structure formed in loose, unconsolidated sediments. They reflect episodic deposition from aqueous currents of declining velocity at high and instantaneous sedimentation rates (Lowe, 1975) and support an ephemeral stream interpretation.

Early calcite cement and calcretes indicate a semi-arid to arid climate with seasonal rain during deposition of the Holmestrand Formation and sufficiently long periods of low sedimentation to develop stage II calcrete horizons (Gile et al., 1966; Allen, 1986). The low palaeo-latitude suggested by Piper (1985), together with the presence of ephemeral stream deposits, are also suggestive of an arid to semi-arid palaeo-climate.

Flow characteristics of ephemeral streams

The abundance of scoured surfaces, marking the lower boundary of each sheet-sandstone body, is evidence for the large energy changes of the system, in which the rising flood discharges continually scoured the pre-flood surface. This process probably continued until peak discharge was reached. The presence of massive sandstones with floating intraclasts, overlying the scoured surfaces, suggests that the flow was characterized by upper flow-regime hyper-concentrated currents and high depositional rates during the early phase of deposition. This phase was generally followed by a period of essentially steady flow conditions. This is indicated by either a general consistency of the foreset shape, dip azimuths and dip angles of facies Sl within the individual cross-sets, or a vertical and lateral consistency of facies Sh. However, the down-current change from concave-upward to sigmoidal cross-strata as well as the pres-

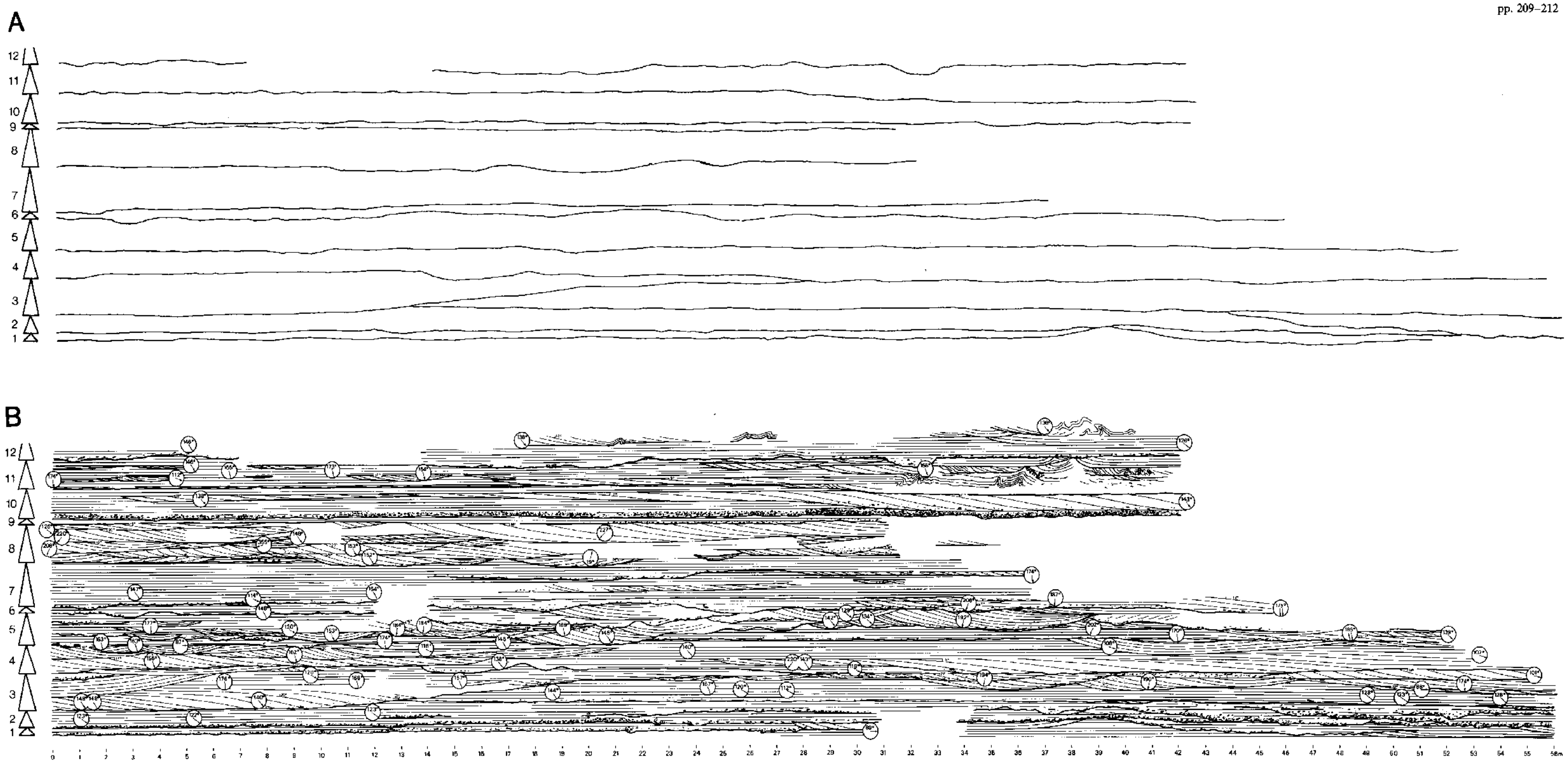

Fig. 6. A. Cross-section from the lower unit showing the characteristic appearance of the ephemeral stream association as stacked sheet sandstone bodies. Each sheet is outlined and numbered. B. Same section showing the lateral and vertical facies development of the ephemeral stream deposits. Note the large occurrence of low-angle cross-stratification. Scour-and-fill structures are present in one horizon in cycle 11, indicating short-term velocity pulsation of the flow during deposition. Horizontal stratification is the main and often the only sedimentary structure present in each sheet.

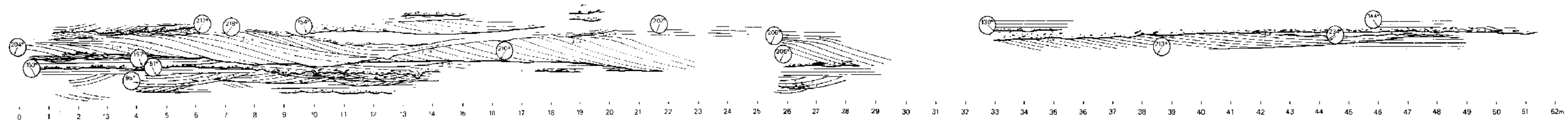

Fig. 7. Lenticular coset, with concave-upward and sigmoidal cross-strata. In the right-hand set the internal cross-strata display the transition from concave-upward to sigmoidal cross-strata. The sigmoidal cross-strata reveal knickpoints in the up-current direction, whereas they down-current pass into cross-strata without. Down-current the set thins and close to the termination of the set, bottomsets become more tangential and grade into low-angle trough cross-bedding with parting lineation. The same trend is seen in left-hand set. The stoss-side of the right-hand set has a convex-upward shape. The sigmoidal cross-strata show a continuous series of transitions down-current from horizontal stratification into low-inclined topsets and steeper foresets that finally down-current pass into bottomsets. The abundance of sigmoidal foresets and the preservation of topsets indicate that the individual sets represent the original dune height. Moreover, the presence of a convex-upward stoss-side and the pass of the cross-strata suggest the presence of a formset of a bedform generated in the dune to upper-stage plane bed transition. Røe (1987) attributed the preservation of such bedforms to rapid vertical aggradation of the dunes and to rapid fall-out of suspended sand in front of the advancing bedform.

Fig. 8. Low-angle cross-bedded sandstone. Hammer for scale.

ence of scour-and-fill structures as intrasets within facies Sh, suggest some short-term velocity pulsation. Likewise, the occasional occurrence of reactivation surfaces is attributed to the erosion caused by minor fluctuations in the flow pattern (Jones, 1977; Røe, 1987).

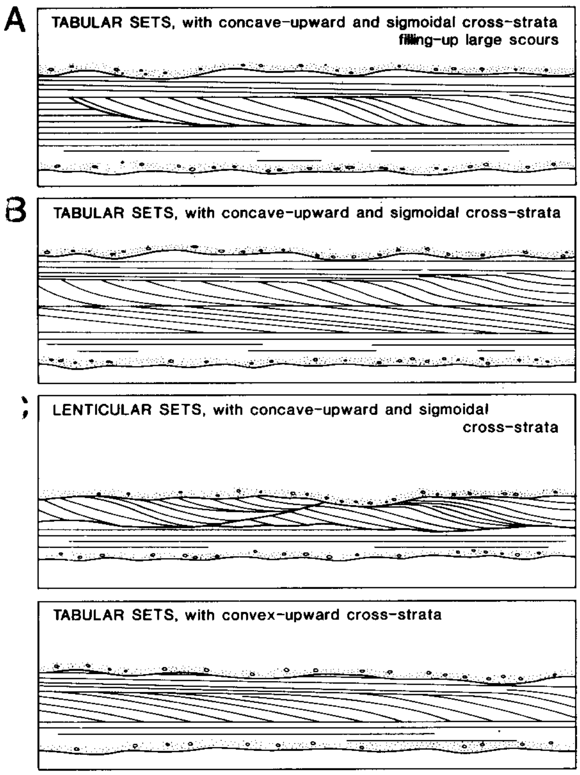

Fig. 9. Types of low-angle cross-bedded sandstones, based on their external and internal geometry (viewed parallel to the palaeo-flow).

Horizontal stratification is often the main, or only, sedimentary structure present in the sequences. In fluvial deposits it suggests rapid waning flow with no low-stage reworking of the flood deposits (Jones, 1977; Tunbridge, 1981). A modern example is the flood deposits of the Bijou Creek, Colorado. Climbing-ripple laminated sands were here only locally developed in relative sheltered areas (McKee et al., 1967). The deposits appear similar to the mainly parallel laminated sandy ephemeral stream deposits of the Middle Devonian Trentieshoe Formation of North Devon, U.K. (Tunbridge, 1981, 1984) and are likewise scarce in cross-lamination, suggesting a rapid decline of discharge by the end of the flood period. The local preservation of lunate megaripples on top of sequences also suggests that flow velocity apparently decreased too rapidly for any modification of the bedforms to occur. Flood sequences reflecting a more slowly waning flow are marked by the few examples of thinning-upward cosets of cross-strata topped by current ripples and channel-fill sandstones formed during waning flood.

The abundance of mudstone intraclasts and calcite cemented silt and sand intraclasts indicate a highly fluctuating discharge. Muds, accumulated during periods of low flow, and sand became cemented by early precipitated calcite during dry periods. Renewed flooding eroded the pre-flood

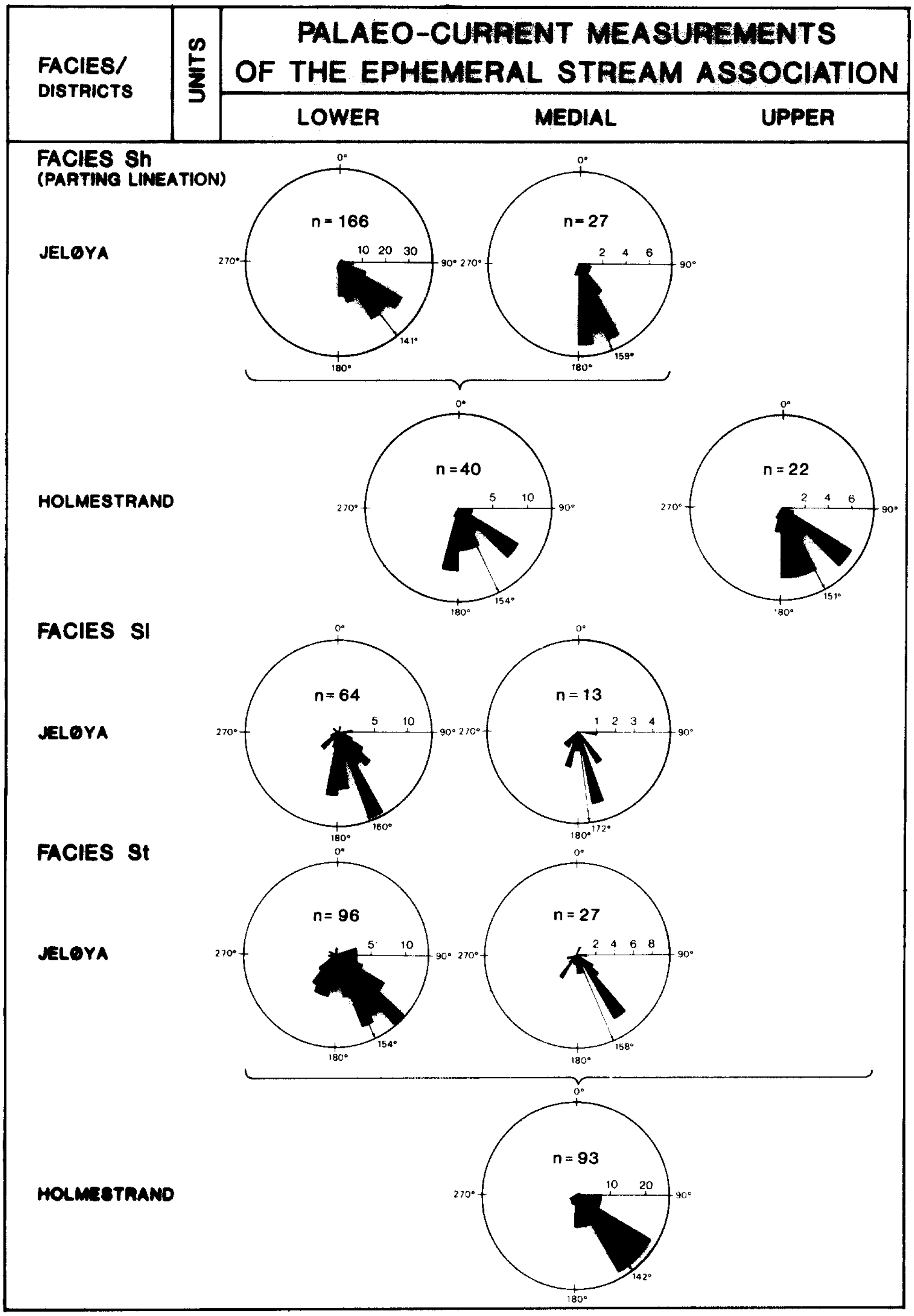

Fig. 10. Palaeo-current measurements of the ephemeral stream association.

surface and mud and sand intraclasts were picked up.

The presence of massive sandstones, upper flow-regime plane-bed deposits and indications of high concentrations of suspended sediment across the bedforms suggest high transport rates. The abundance of massive bedding and convolute bedding indicates high depositional rates and episodic deposition producing loose, unconsolidated sediments. The high depositional rates could be due to initial rapid infiltration of water from the streams to the bed and associated loss of carrying capacity, a well-known feature from semi-arid ephemeral streams (Parkash et al., 1983; Knighton, 1984; Reid and Frostick, 1986). In these areas organic colloids are practically non-existent as a soil binding agent and plant cover is low (Reid and Frostick, 1986). This makes the soil easily erodible by the turbulent flash floods, in which the initial flow often becomes super-critical and may in part change to hyper-concentrated currents (Stear, 1985; Reid and Frostick, 1986).

The narrow dispersion of orientation of parting lineation and dip azimuths, both within and between individual sheet sandstones, suggests that the sediments were deposited by unidirectional currents (Fig. 8). Together with the high current velocities, indicated by the preponderance of upper flow-regime structures, and the high rates of sedimentation, this is consistent with deposition during a high flow-stage.

Beach face association

Facies

The beach face association is composed of silty fine-grained sandstones to medium-grained sandstones. The association is simple with only two major lithofacies (Table 3). The geometry of the sequences is sheet-like without any apparent lateral variability.

Parting planes of the alternating horizontally stratified silty fine-grained sandstones and medium-grained sandstones (facies Al) show a large variety of wave and current ripples, interference ripples, double-crested wave ripples, wave-generated mini-ripples, tool marks, adhesion warts and ripples, desiccation cracks and biogenic structures (Fig. 12).

Wave ripples are generally form-concordant and have crest spacings of 1.2–6.0 cm with amplitudes of 0.2–0.6 cm. Ripple symmetry index (RSI) range from 1.0 to 1.6. Crestline orientation of the wave ripples is ESE–WNW throughout the Holmestrand Formation (Fig. 13). Occasionally, large symmetrical medium to coarse-grained ripples (CGR) are present (Fig. 14). CGR have crest spacings up to 1.3 m and amplitudes up to 25 cm. CGR occasionally occur just above planar cross-bedded sandstones. Subaerial markings are given by mini-ripples (cf. Singh and Wunderlich, 1978), adhesion warts and ripples and desiccation cracks. Sections indicating subaerial emergence are vertically and horizontally separated from the subaqueous deposits, although they may form small "drying-upward" sequences.

Trace fossils in this facies include five ichnotaxa (Table 3, Fig. 11); *Didymaulichnus* isp., *Polarichnus* isp., *Merostomichnus* isp., *Muensteria* isp., and *Arenicolites* isp.

Planar cross-bedded sandstones (facies Sp) generally occur as solitary sets, closely associated with facies Al. Reactivation surfaces are a common feature and may be marked by either mud-draping or bioturbation along foresets. Locally, mud-draped small-scale straight-crested current ripples and intrasets occur along foresets. Down-current the sets become more low-angled and grade into facies Al. *Arenicolites* isp. is occasionally present on top of sets or along foresets. Palaeo-current directions are unimodal towards WSW, perpendicular to the palaeo-current directions of the ephemeral stream deposits (Fig. 13).

Interpretation

The association of wave ripples, current ripples, mini ripples, double-crested ripples and tool marks, indicative of very shallow water, with adhesion structures and desiccation cracks, indicative of intermittent subaerial exposure, points towards a low-energy environment (e.g. Klein, 1977; Stear, 1978, 1985; Reineck and Singh, 1980, Allen and Collinson,1988).

The crestline orientation of the wave ripples suggests a stable palaeo-coastline orientated WSW–ESE, perpendicular to the palaeo-slope indicated by the ephemeral stream association. In order to estimate the palaeo-depth and the fair-weather palaeo-wave climate during deposition, the method of Diem (1985) based on wave-ripple formsets was used. The calculated maximum palaeo-water depth is less than 4.6 m. Palaeo-wave periods ranges from 0.4 to 2.4 s and maximum palaeo-wave height range between 0.11 and 1.24

TABLE 2

Characteristics and interpretation of the low-angle cross-bedded sandstones

Facies	Characteristics	Interpretation	References
Tabular sets with concave-upward and sigmoidal cross-strata filling up large scours	Sets fill-out erosive depressions and show a down-current gradual transition from concave-upward cross-strata to sigmoidal cross-strata without knickpoints to horizontal stratification. Up-current the sets are truncated by horizontal stratification. Down-current topset may pass continuously into horizontal stratification with parting lineation.	Sets were generated by shallow, high-velocity flows into broad scours formed during erosional pulses accompanying the floods.	Rust (1984)
Tabular sets with concave-upward and sigmoidal cross-strata	Solitary sets or cosets with a lower non-erosive boundary. Sets are generally composed of either concave-upward or sigmoidal cross-strata throughout. May show a lateral transition into horizontal stratification. Topset of the sigmoidal cross-strata pass up-current into horizontal stratification with parting lineation or are truncated erosively by these.	Periodic to quasi-periodic bars or dunes generated by flows in the dune to upper-stage plane-bed transition.	Culbertson and Scott (1970) Brady and Jobson (1973) Picard and High (1973) Røe (1987)
Lenticular sets with concave-upward and sigmoidal cross-strata	Cosets with a convex-upward or planar upper boundary and/or a concave-upward lower erosive boundary. Foresets are either concave-upward, tangential or sigmoidal.	Periodic dunes generated in the dune to upper-stage plane-bed transition	Saunderson and Lockett (1983) Røe (1987)
Tabular sets with convex-upward cross-strata	Solitary sets with convex-upward foresets that down-current grade into horizontal stratification.	Non-periodic dunes or bars generated by flow in the dune to upper-stage plane-bed transition. Foresets formed from bedload that was carried on over the crest by inertia and draped over the lee side. Flow separation absent.	Williams (1971) Shaw (1972) Saunderson and Lockett (1983)

TABLE 3

Facies of the beach face association

Facies	Characteristics	Interpretation	References	Average facies thickness (m)	% of facies association Units		
					lower	medial	upper
Sp Solitary sets closely associated	Low-marine straight-crested with facies Al. Reactivation surfaces are common and may be marked by mud-drapings and bioturbation. Current ripples and intrasets are locally present along foresets.	Bars formed from storm-induced coast parallel NE currents.		0.23	2.7	21.9	22.7
Al Alternating laminated silty fine and medium-grained sandstones with ripples	Parting planes show a large variation of wave and current ripples, interference ripples, mini ripples, tool marks adhesion structures, desiccation cracks and biogene structures.	Beach face.		0.62	97.3	78.1	77.3
Trace fossils:	Ethologically classification:	Probable originator:					
Arenicolites isp.	Domichnia	Annelid-like organism	Fürsich (1975)				
Didymaulichnus isp.	Pascichnia/Repichnia	Xiphosurid	Chrisholm (1985)				
Merostomichnus isp.	Repichnia	Eurypterid	Dam (1987) Hanken and Størmer (1975)				
Muensteria isp.	Pascichnia/Repichnia	Deposit-feeder					
Polarichnus isp.	Domichnia	Arthropod	Narbonne et al. (1979)				

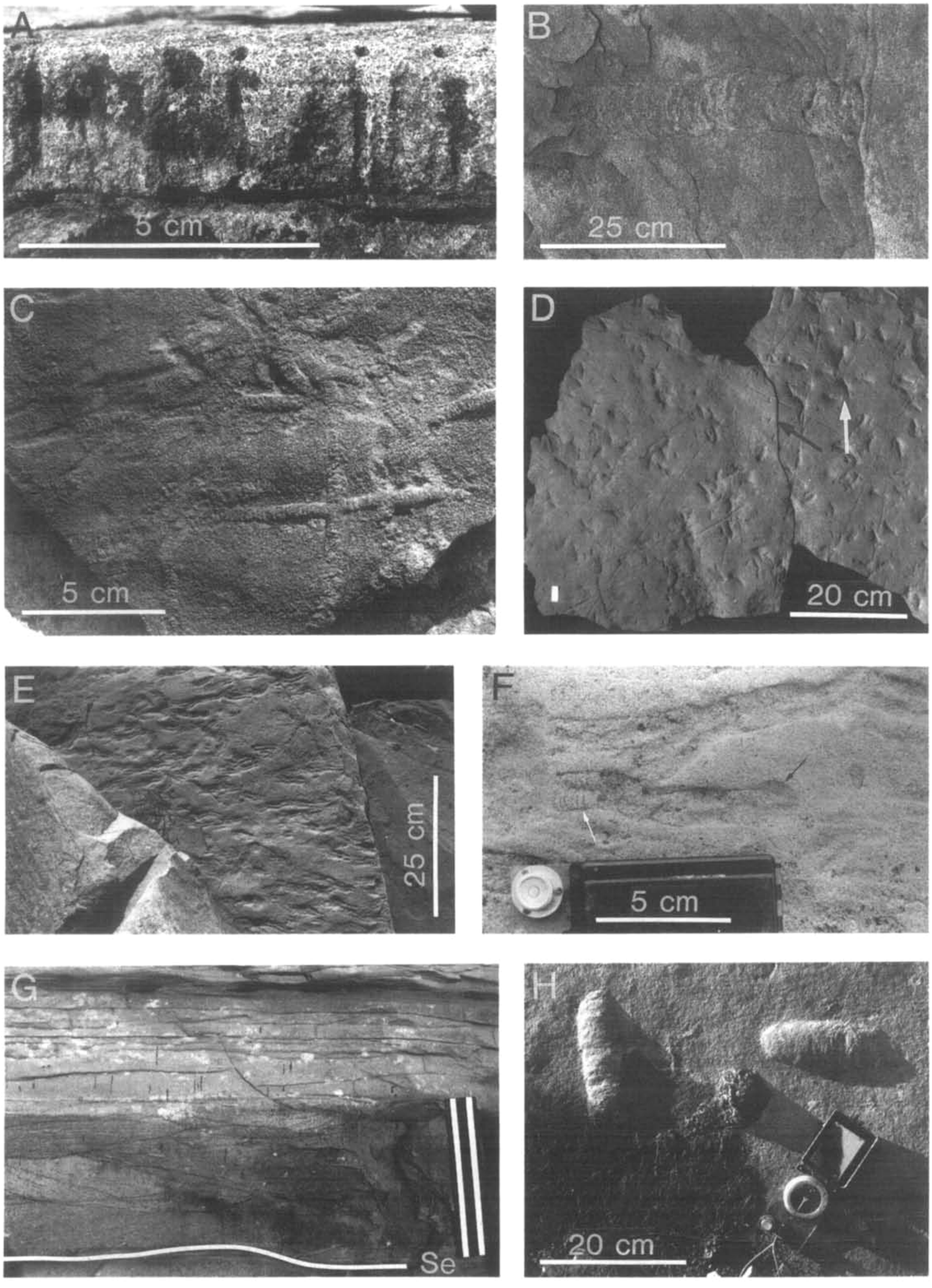

Fig. 11. Trace fossils of the Holmestrand Formation. A. *Arenicolites* isp. B. *Beaconites* isp. C. *Muensteria* isp. D. *Merostomichnus* isp. Series of trackways composed of two kind of tracks and one kind of grooves representing the rapid gait or swimming of several eurypterid individuals in shallow water (Dam, 1987). Crescent-shaped furrows (white arrow) represent tracks of a paddle-like appendage (swimming leg); small crescent-shaped or straight furrows (black arrow) represent tracks of a flat spine (walking leg); straight grooves, formed either by tail spines or appendages protruding from the underside of the organism. D, E. *Didymaulichnus* isp. At the end of one trail the convex outline of the burrowing organism is preserved (black arrow), which compares well with the imprints produced by juveniles of the modern horseshoe crab, *Limulus polyphemus* and suggests a xiphosurid origin of the present species (Dam, 1987). The burrow-infill is composed of sand in oval layers (white arrow). F. Escapement burrows (marked with a pen) in an ephemeral sand sheet. Ruler is 25 cm long. G. *Polarichnus* isp.

Fig. 12. Parting planes with wave, current and interference ripple formsets in the beach face association. Ruler is 25 cm long.

m, indicating low palaeo-wave conditions (Diem, 1985). Periods less than approximately 4 s point to an environment of shallow water and restricted fetch (Allen, 1981). Large symmetrical medium to coarse-grained ripples occur in modern environments mostly on broad, open shelf settings. However, they can also form in lakes and bays, having fetches of only few tens of kilometres. They are generally the result of storms, and formed from oscillatory of combined flow (Leckie, 1988). The presence of large medium to coarse-grained wave-formed ripples are suggestive of water depths of 3–160 m, generally in the order of 10–20 m during storms (e.g. Hunter et al., 1988; Leckie, 1988).

The palaeo-current orientation of the solitary planar cross-bedded sandstones suggests that they were produced by bars migrating parallel to the coastline, towards WSW. This suggests that short-lived longshore bottom currents, dominantly from ENE, at least at times occurred at the shoreface. As the sedimentary records and the estimation of the wave climate indicate a non- to micro-tidal, low wave-energy coastline the effect of longshore currents induced by tides and waves can be ruled out. This makes the effect of storms the most likely explanation, and is also supported by the presence of symmetrical coarse-grained ripples succeeding the sets.

Modern examples of storm-driven longshore currents in an otherwise low-energy beach-ridge complex are described from the southwestern shore of Lake Michigan (Fraser and Hester, 1977). The solitary sets and the laterally transition into facies Al suggest that the longshore component of motion was below the threshold velocity of sediment motion during fair-weather periods, a pattern also shown in modern environments (Greenwood and Sherman, 1984). The unidirectional palaeo-current pattern of the bars in the Holmestrand Formation towards WSW indicate a rather uniform palaeo-wind direction from ENE during storms. Taken into account a trade wind dominated marine circulation system, this is fully consistent with the low palaeo-latitude (20°N latitude) estimated for the Ringerike Group (Piper, 1985). A similar unidirectional sediment dispersal pattern influenced by trade winds in a shallow-marine environment has been described by Dott (1974) and Michelson and Dott (1973) from the Wisconsin Cambrian sandstones, U.S.A.

The trace fossil assemblage suggests that a sandy bottom fauna of worms and arthropods was active during deposition. In spite of the fact that only few trace fossils can be considered diagnostic of specific depositional environments the presence of *Merostomichnus* isp. and *Polarichnus* isp. is conspicuous. *Polarichnus* isp. has previously been recorded from late Silurian to early Devonian marine tidal flat environments of Arctic Canada, exclusively (Narbonne et al., 1979). In the Ringerike Group and in the transition strata to the subjacent Steinsfjorden Formation arthropod faunas have only been recorded from inter- to supratidal deposits and coastal alluvial plain deposits (Hanken and Størmer, 1975; Olaussen, 1985). In the light of these observations the present trace fossil assemblage may indicate marginal marine conditions.

Summarized, the beach face association documents an environment of shallow water and low fair-weather palaeo-wave conditions. Crestline

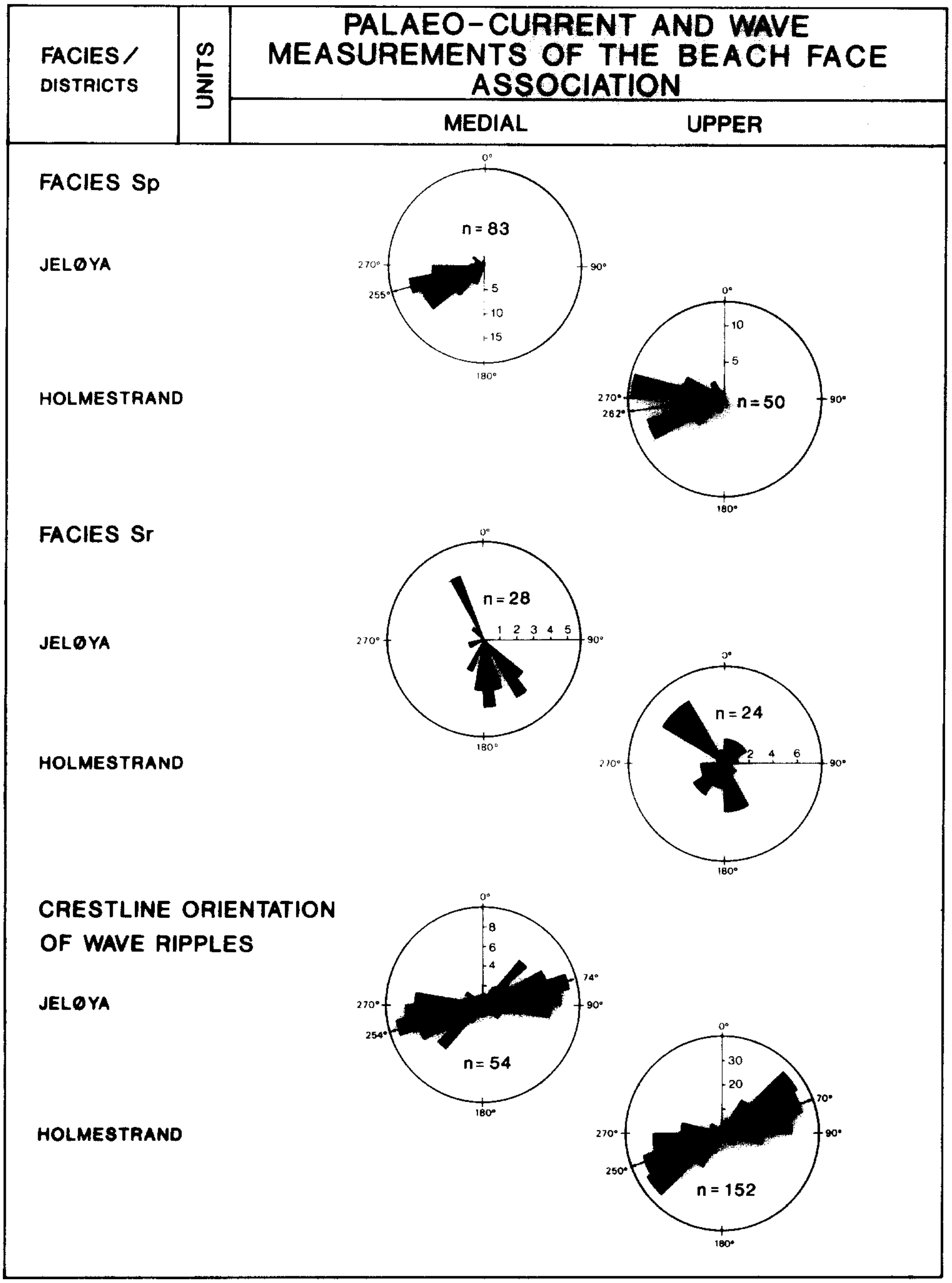

Fig. 13. Palaeo-current and wave measurements of the beach face association.

orientation of the wave ripples indicate a stable WSW–ENE palaeo-coastline. During storms longshore currents were induced on the shoreface giving rise to a coast-parallel sediment transport. No sedimentological, palaeontological or geochemical evidence are offered in the Holmestrand Formation to settle if the setting was a perennial lacustrine or a shallow marine environment. However, the presence of the ichnogenus *Merostomichnus* and *Polarichnus* suggests marginal marine conditions.

Depositional model—discussion

The preserved sequence of the high-energy ephemeral stream delta systems from the

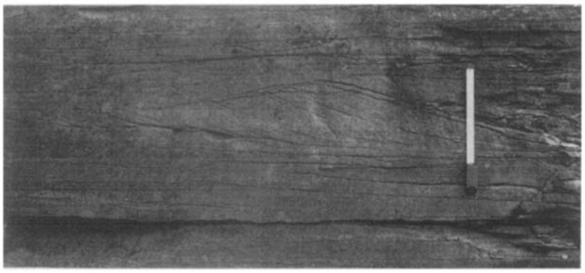

Fig. 14. Large symmetrical medium to coarse-grained ripples of the beach face association. Scale is 20 cm long.

Holmestrand Formation show many features which are comparatively poorly described from elsewhere in the geological record. Within this setting the lower, medial and upper unit of the Holmestrand Formation represent progressive down-slope sedimentation from a proximal coastal floodplain to a shoreface environment (Fig. 15). Proximal coastal floodplain deposits are composed of stacked sheet sandstone bodies, bounded by laterally extensive intraclast strewn surfaces (Fig. 6). Internally, the dominance of upper-stage plane-bed horizontally stratification associated with massive sandstones, deposited from hyperconcentrated flows during upper flow-regime conditions, and low-angle cross-bedded sandstones characteristic of bedforms formed in the dune to upper-stage plane-bed, are diagnostic of high-energy ephemeral stream deposits. Previous workers have generally not fully appreciated the importance of the latter two facies in ephemeral stream sequences.

Due to evaporation and infiltration the discharge of the streams decreased down-slope causing a decrease in channel depth and a decrease in flow-regime conditions. This produced a lateral thinning of sand-sheets, an increase in the ratio of trough cross-bedding (facies St) to horizontal stratification (Sh) and a decrease in size of individual sets and cosets (Table 1). Moreover, some

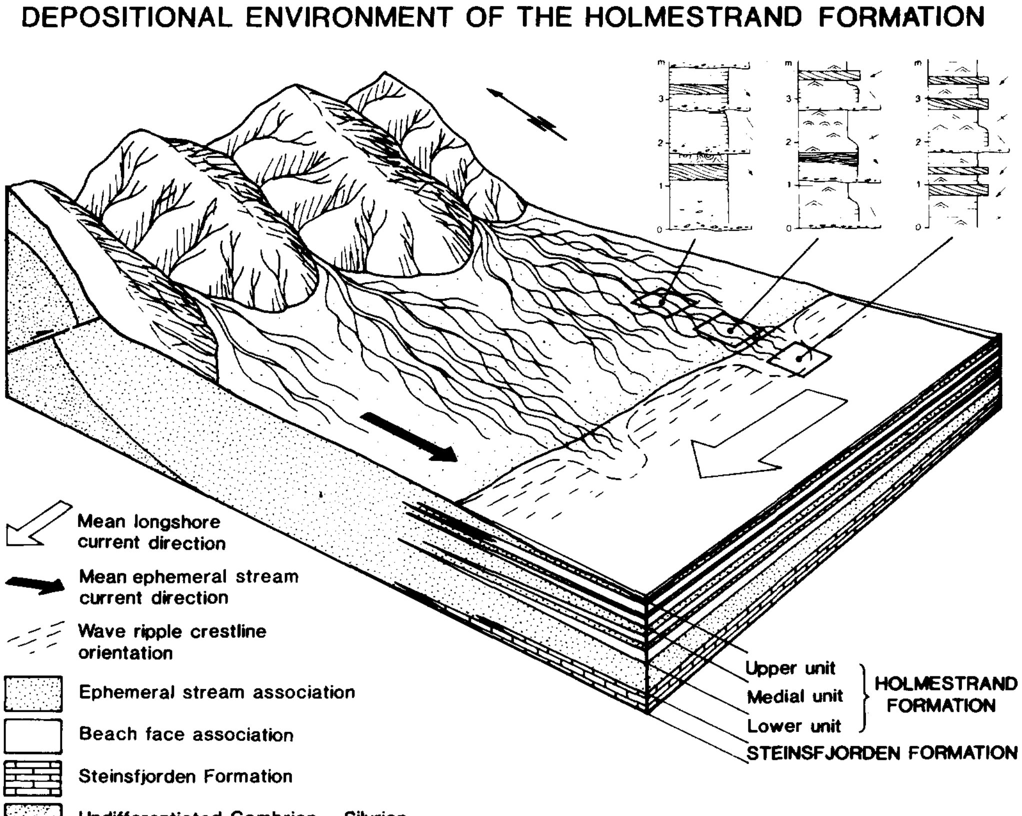

Fig. 15. Regional depositional model for the Holmestrand Formation, showing the basinwards change from high-energy ephemeral stream sediments to ephemeral delta and beach face deposits. Model is diagrammatical only and not drawn to scale.

of the streams became more channelized downstream, resulting in ribbon-shaped channel-fill sandstones in the coastal floodplain sequences.

Ephemeral stream deposits have previously been documented in association with muddy floodplain, ephemeral lake, sabkha and aeolian dune sediments (e.g. Mukerji, 1976; Hardie et al., 1978; Stear, 1980, 1985; Tunbridge, 1981, 1984; Parkash et al., 1983; Sneh, 1983; Olsen, 1987). The only described present-day ephemeral stream delta is the one in front of the San Lorenzo River at the California coast (Hicks and Inman, 1987). When reaching the sea the floodflow from the San Lorenze River dominated the concurrent waves; apparently behaving like a plane jet. It scoured the river mouth and deposited seaward a subaqueous delta elongated several hundreds of metres offshore. Through the following spring and summer, when littoral processes took over, slices of the delta surface were wave-reworked or scraped off and moved alongshore as a low-amplitude accretionary sandwave which migrated and gradually dispersed in the direction of the dominant transport (cf. Hicks and Inman, 1987).

The Holmestrand Formation ephemeral stream deltas show many similarities with the San Lorenzo delta. The internal arrangement of facies with a sharp, erosive base succeeded by massive, horizontal stratified and cross-bedded sandstones, with a bioturbated and wave-worked top, suggests that the deltas of the Holmestrand Formation also were subaqueous, produced by single sedimentation events, which can be compared with the classical turbidite model. These subaqueous deltas produced thin sand bodies, probably several hundred meters long and generally less than 1 m thick. The lower scoured surface and the wave-produced ripple lamination suggest that the floodflows were erosive at the river mouth and that slices of the delta surface were wave-reworked by littoral processes following the floodflow, as in the present-day example from the California coast. Internally, they are very similar to the sand sheets deposited on the coastal flood plain and they do reveal the same palaeo-current directions. The lithological similarities between the ephemeral stream and the beach face sandstones of the Holmestrand Formation indicates that the ephemeral streams supplied the sand for the beach face sandstones.

To our state of knowledge no workers have described similar ancient ephemeral stream systems on coastal floodplains forming ephemeral stream deltas in perennial lakes or shallow marine basins. The main reason for this is probably that the river sands are delivered at irregular intervals from large floods which may last only for a couple of days every few years. In constrast, the littoral processes, that move sand alongshore from the river mouth, may operate with much greater regularity and frequency. The ephemeral river deltas are thus exposed to a large degree of reworking by the basinal processes making it difficult to recognize this type of deltas in ancient deposits. The preservation of the ephemeral stream sequences within the Holmestrand Formation is probably owing to the low palaeo-wave energy of the basin, precluding the ability of the littoral processes to make a complete reworking of the ephemeral stream delta deposits.

Conclusions

(1) The depositional environment of the sediments of the Holmestrand Formation is believed to be a high-energy ephemeral stream delta system. The system drained the Caledonides to the NW-NNW and was deposited in a foreland basin, situated in the Oslo Region between the Baltoscandian craton and the main Caledonian orogen. The formation is divided into three units reflecting the down-slope progradation of the system.

(2) The proximal ephemeral streams were characterized by upper flow-regime conditions and a very fluctuating discharge. Sediment transport and depositional rates were high. Deposition took place during high flow-stage. The discharge declined very rapidly during the end of the flood periods. The discharge of the streams decreased down-slope and resulted in a down-stream change to lower flow-regime conditions of the individual floods. When reaching the beach face the streams behaved like plane jets and sediments were deposited seaward as subaqueous ephemeral stream deltas.

(3) The beach face was characterized by low fair-weather palaeo-wave conditions. The longshore component of motion was only above threshold velocity during storms.

(4) Deposition took place in an arid to semi-arid climate.

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