

Depositional history of the fluvial Lower Carboniferous Sortebakker Formation, Wandel Sea Basin, eastern North Greenland

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The Lower Carboniferous non-marine Sortebakker Formation is restricted to the south coast of Holm Land. It is estimated to exceed 1000 m in thickness and is subdivided by a low-angle disconformity into a lower mudstone-dominated unit (c. 335 m) and an upper sand-dominated unit (c. 665 m). The lower mudstone-dominated succession consists of stacked 0.5–6 m thick fining-upward cycles of fine- to medium-grained sandstone and mudstone. Cycles in the upper part of the formation are up to 20 m thick. They are dominated by thick tabular sandstones up to 13 m thick overlain by shaly units that resemble those in the lower mudstone dominated cycles. Six facies associations are identified and together describe a fluvial–lacustrine depositional system. Five of the facies associations characterise different parts of a meandering river-dominated flood plain whereas the sixth facies association represents more permanent lakes.

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The Lower Carboniferous non-marine Sortebakker Formation in Holm Land, eastern North Greenland (Fig. 1), was deposited during the initial phase of Late Palaeozoic rifting of the northern North Atlantic and the Arctic Ocean. Time equivalent non-marine deposits are known from central East Greenland, Svalbard, western Barents Sea and Arctic Canada (e.g. Steel & Worsley 1984; Gjelberg 1987; Davies & Nassichuk 1988; Stemmerik *et al.* 1991; Bugge *et al.* 1995). Sedimentation took place in a humid climate and in most areas the sedimentary succession dominantly consists of humid-type fluvial deposits with some coal.

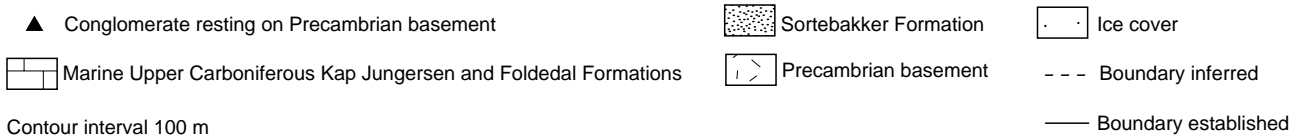
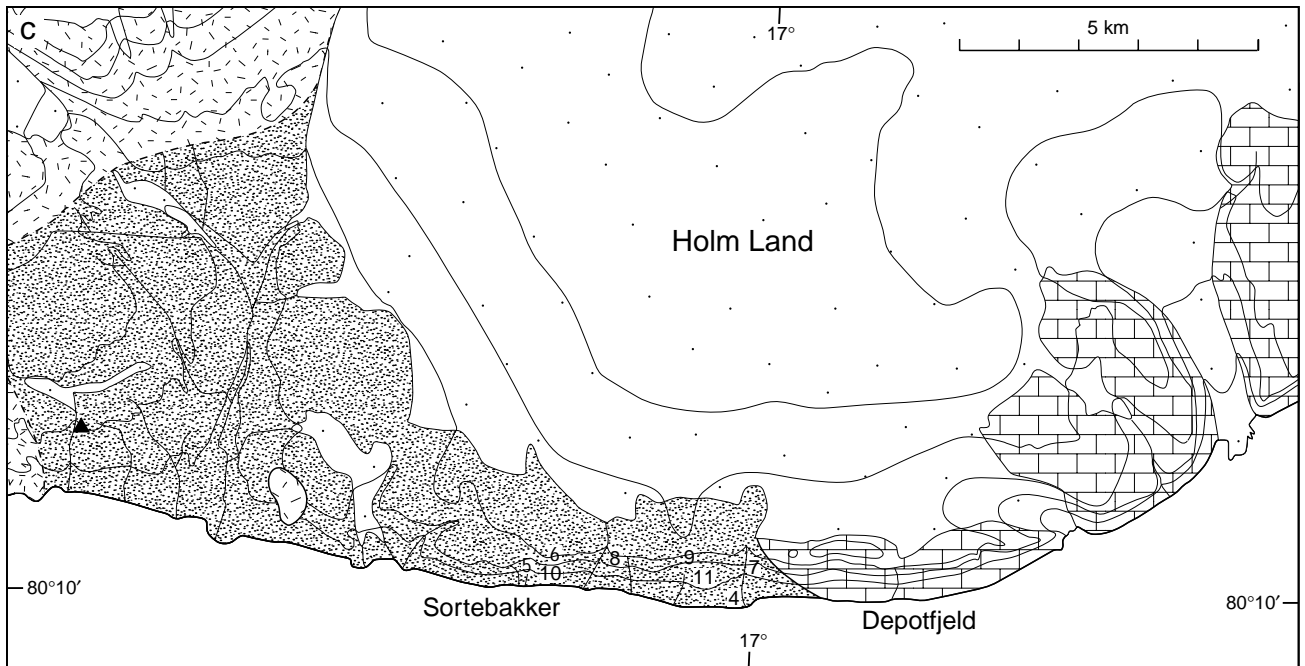
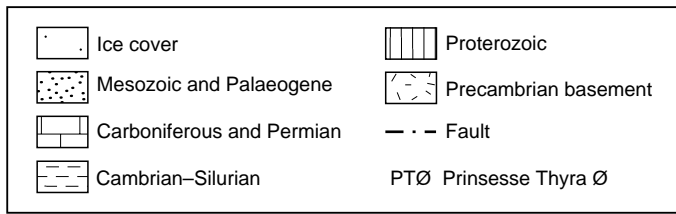
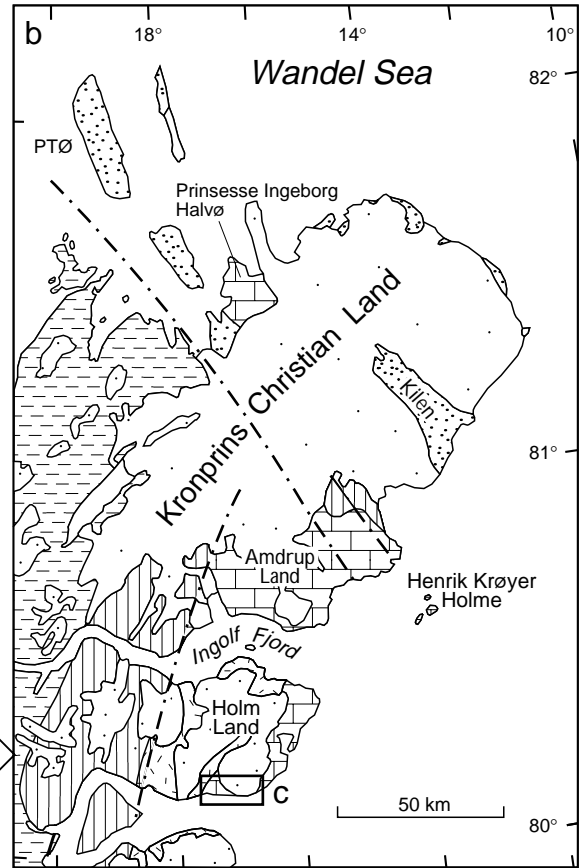
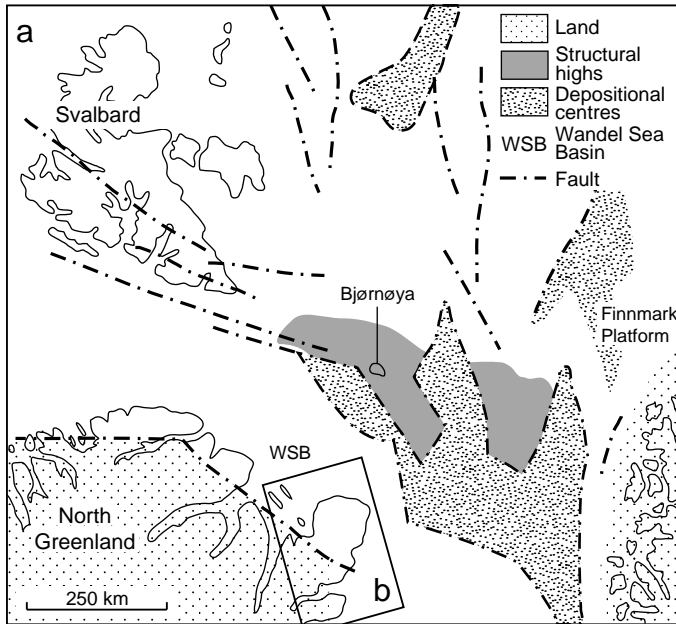
The Sortebakker Formation (Stemmerik & Håkansson 1989) consists of approximately 1000 m of stacked fining-upward cycles of fluvial sandstone and mudstone with minor lacustrine deposits in the upper part. The formation is divided by a low-angle disconformity into a lower mudstone-dominated unit (c. 335 m thick) composed of 0.5–6 m thick fining-upward cycles and an upper sand-dominated unit (c. 665 m thick) composed of up to 10–20 m thick fining-upward cycles. Even finer scale cyclicity is seen within the fine-grain-

ed parts of each cycle, and three levels of cyclicity are recognised within the succession.

This paper describes the depositional facies of the Sortebakker Formation and discusses the controls on the different levels of cyclicity seen within this fluvial succession.

Geological setting

In eastern North Greenland, Lower Carboniferous sediments are restricted to Sortebakker on the south coast of Holm Land (Fig. 1; Stemmerik & Håkansson 1989). The Sortebakker Formation is approximately 1000 m thick and rests directly on Precambrian basement. It is unconformably overlain by Upper Carboniferous (Moscovian), marine deposits (Håkansson & Stemmerik 1984). The Sortebakker Formation is internally subdivided by a low-angle, possibly tectonically induced disconformity. Prior to deposition of the overlying marine sediments, the formation was faulted and eroded; modelling data indicate that as much as 2000 m of



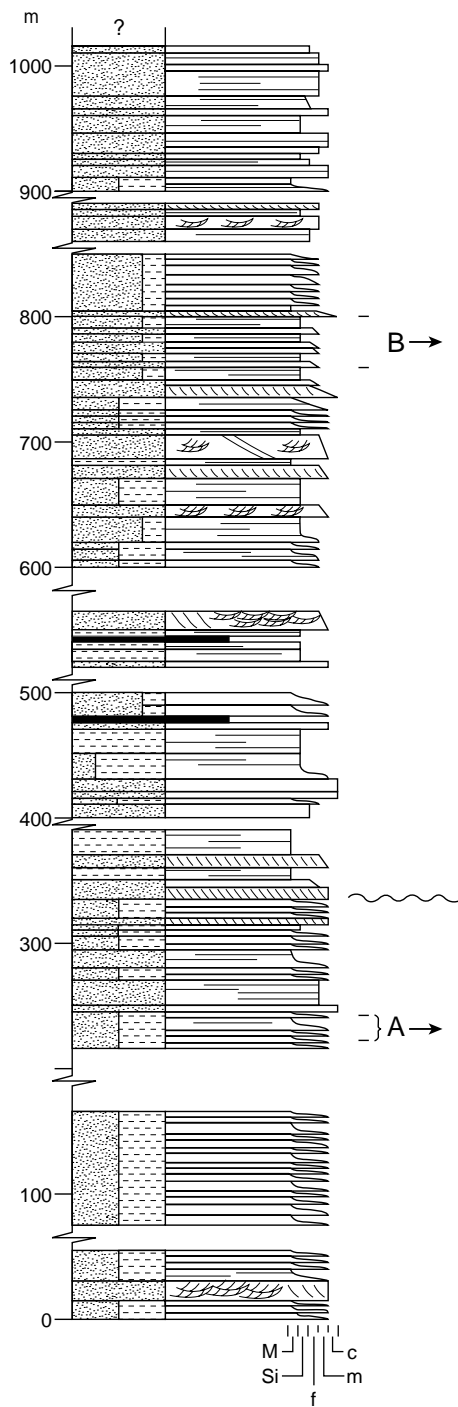


Fig. 1. **a:** Map with major structural outline and palaeogeographic reconstruction of the Wandel Sea and Barents Sea regions. Modified from Stemmerik & Worsley (1995). **b:** Simplified geological map of Kronprins Christian Land and environs showing the distribution of Upper Palaeozoic sediments. Modified from Stemmerik *et al.* (1994). For location, see Fig. 1a. **c:** Geological map of the southern part of Holm Land showing distribution of the Sortebakker Formation. **Numbers 4–11** indicate the locations of Figs 4–11. For location, see Fig. 1b.

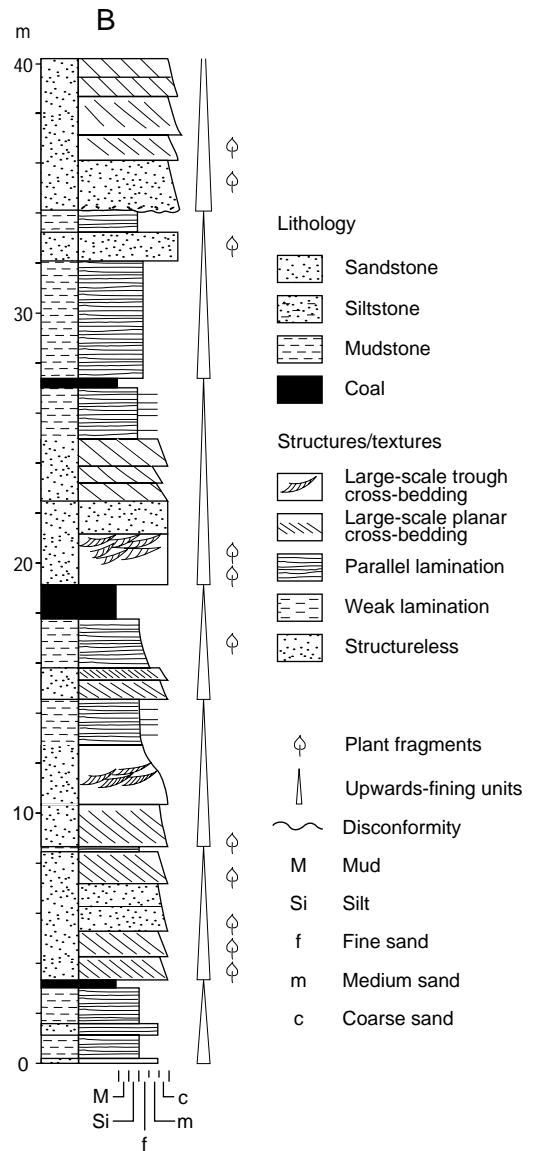
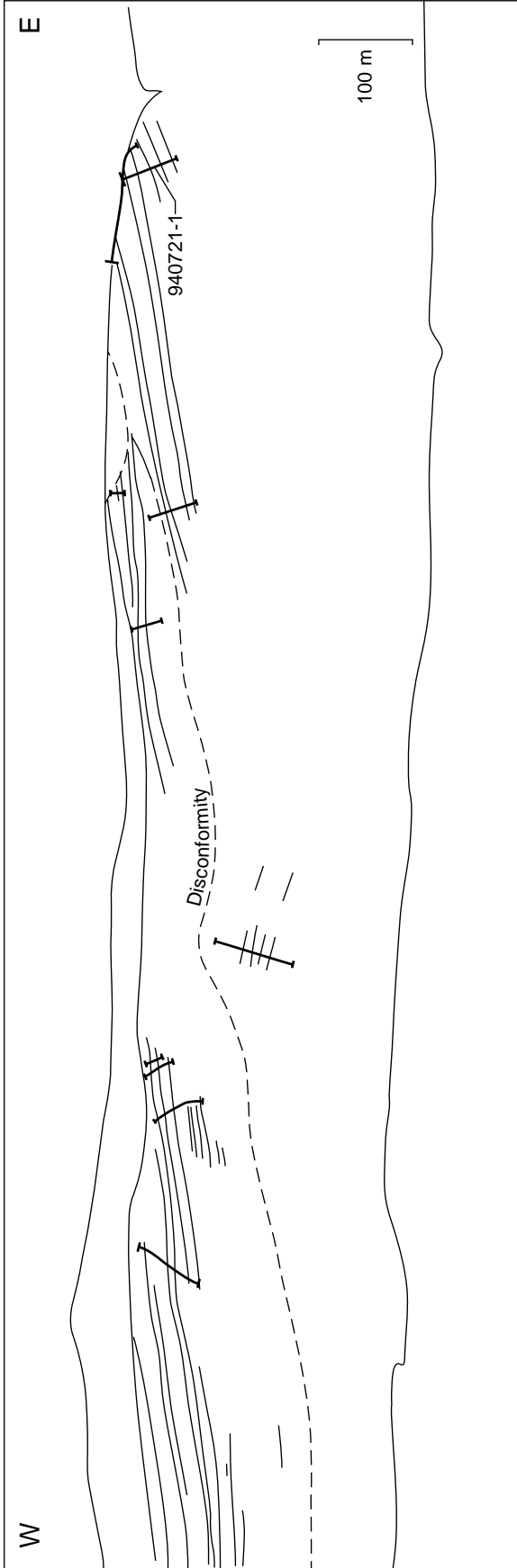


Fig. 2. Composite sedimentological log from the Sortebakker Formation with two representative detailed vertical sections comprising several complete cycles as indicated by the triangles. **A:** from lower part; **B:** from upper part above the disconformity. For location of sections, see Fig. 3. The total thickness is estimated to exceed 1000 m.



sediments were eroded away prior to the Late Carboniferous transgression (Stemmerik *et al.* 1998). The upper part of the formation is dated as Viséan (Dalhoff *et al.* 2000, this volume) which means that deposition was coeval with that of the lower part of the Traill Ø Group in East Greenland (Vigran *et al.* 1999) and the Billefjorden Group on Svalbard and its equivalents in the Barents Sea.

Sedimentation apparently took place in an isolated basin separated to the west by a major fault zone from the stable Greenland craton and to the north bounded by a basement high (Fig. 1). The western part of the depositional basin is not preserved and the studied outcrops are believed to represent deposition in the axial zone of the basin. The basin forms part of the Late Palaeozoic – Mesozoic rift system which started to form between Greenland and Norway during the Early Carboniferous (Stemmerik *et al.* 1991). The rift system extended westwards between North Greenland and Svalbard to the Sverdrup Basin of Arctic Canada and eastwards through the Nordkapp Basin in the Barents Sea. During Early Carboniferous times, non-marine sedimentation dominated within the rift system and marine deposits were limited to the Finnmark Platform in the easternmost parts of the rift (Bugge *et al.* 1995).

Sedimentary facies

Thirty-two sedimentological sections through various parts of the Sortebakker Formation in the coastal cliffs of Sortebakker form the basis for this study (Fig. 2). Correlation of individual sections is based on tracing beds in the field and on photographs. The outcrops allow firm lateral correlation of individual channel sands for approximately 500 m in the lower part of the succession and for more than 1000 m in the upper part

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Fig. 3. Extensive fining-upward fluvial deposits from the eastern part of the Sortebakker Formation in a coastal cliff section between Sortebakker and Depotfjeld from 17°W and 1.5 km westward in Fig. 1. The line drawing shows correlation of the lower surface of some of the thickest channel sandstones. The dashed line marks the disconformity dividing the formation into a lower mudstone-dominated unit and an upper sand-dominated unit. The thick lines mark the positions of measured sedimentary sections. The detailed vertical section **A** in Fig. 2, forms the lower part of the sedimentary section 940721-1. Section **B** of Fig. 2 is located westward of the outcrops shown on the photograph. The cliff is approximately 350 m high.

(Fig. 3). Six facies associations are defined, five of which characterise different parts of a meandering river system and one facies association represents lacustrine sedimentation.

Facies association 1: channel sandstones

This association includes three different channel sandstones: (1) thin, tabular 0.5–4 m thick multistorey sandstone units, (2) thick, up to 13 m thick, units of tabular multistorey sandstone, and (3) isolated, laterally confined sandstone units.

(1) *Thin tabular sandstone units.* The thin tabular sandstones consist of 0.5–4 m thick, laterally persistent units

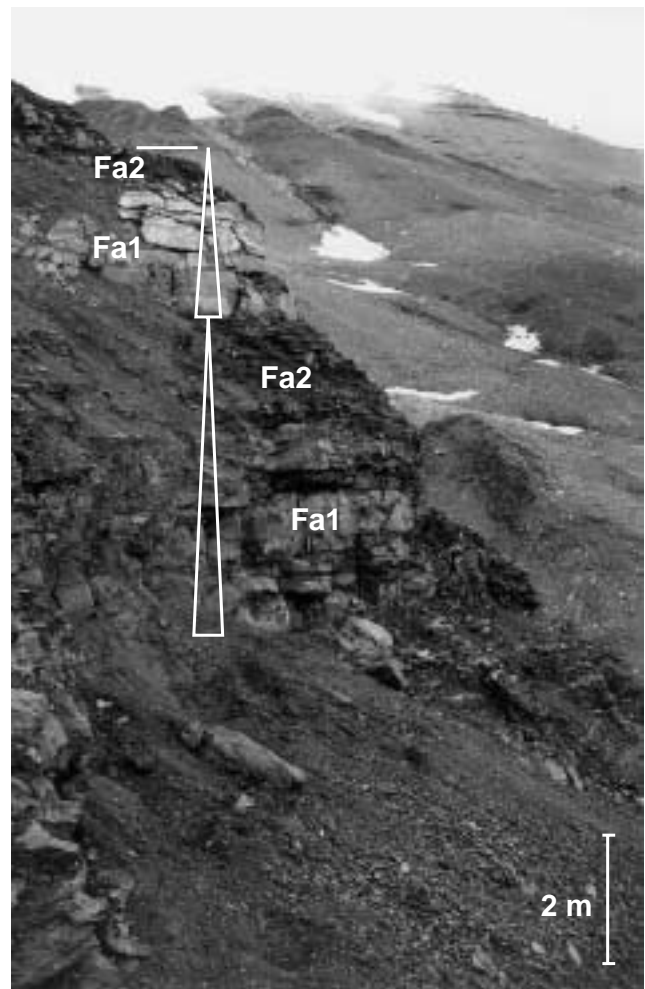


Fig. 4. Thin tabular sandstones of facies association 1 (**Fa1**) overlain by sediments of facies association 2 (**Fa2**), together forming stacked fining-upward fluvial cycles. Individual cycles are indicated by the triangles. Thickness of section shown on photograph is approximately 13 m. For location, see Fig. 1c.

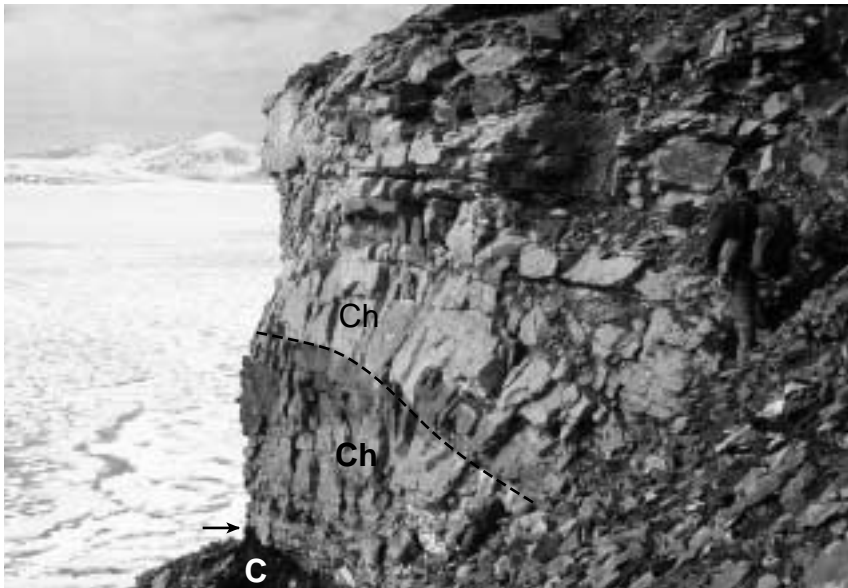


Fig. 5. Thick tabular sandstone unit (**Ch**: facies association 1) composed of two storeys, erosively overlying coals (**C**) from facies association 6. The arrow marks the erosive base of the channel sandstone. Person for scale. For location, see Fig. 1c.

of medium- to fine-grained sandstone. Individual beds may be up to 1 m thick, but are usually 0.3–0.5 m thick. The base of the sandstone bed is usually sharp and erosional, commonly with mudflake clasts. The sandstone is typically structureless; in rare cases, inter-

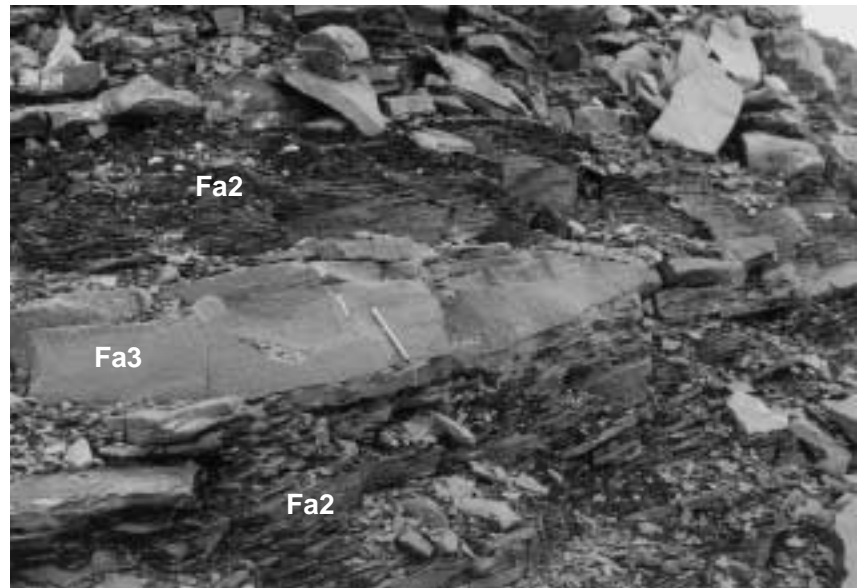
vals of cross-bedded or cross-laminated sandstone occur. This facies is capped by mudstone or siltstone belonging to facies association 2 (Figs 3, 4). This facies is limited to the lower part of the formation, below the disconformity.



Fig. 6. Laterally confined sandstone units of facies association 1, marked by arrows, enclosed by fine-grained lake deposits. Thickness of illustrated section is approximately 65 m. For location, see Fig. 1c.

(2) *Thick tabular sandstone units.* The thick tabular sandstones form up to 13 m thick fining-upward units grading from medium- to fine-grained sandstone to mudstone; the thickest units are laterally persistent and have been traced for more than a kilometre (Figs 3, 5). Pebbly lag deposits occur rarely at the base of the sandstone where they consist of coarse-grained pebbly (< 1 cm) sandstone with large coaly plant fragments. Sedimentary structures are rare and mainly consist of trough cross-bedding. The sandstone passes upwards into fining-upward units of medium- to fine-grained sandstone. They are well sorted, light grey to yellowish in colour and display weak bedding, up to 2 m thick, but usually about 0.5 m thick. The sandstones may be structureless, or show planar or trough cross-bedding. The planar cross-bedding is seen as tabular sets; cosets of weak cross-bedded sandstone occur locally. Intraformational clasts of mudstone and silty mudstone, plant remains and groove marks are observed in the sandstone, and in places tree stumps in growth position are seen to extend vertically up from the underlying beds. The upper part of these sandstones display ripple cross-lamination and, locally, internal deformation structures such as convolute bedding. Mudstones or siltstones belonging to facies association 2 generally cap this facies. Transition from

Fig. 7. Wedge-shaped structureless sandstone bed of crevasse splay origin (**Fa3**: facies association 3) embedded in floodplain deposits of facies association 2 (**Fa2**) composed of laminated to weakly laminated mudstone. Pencil for scale. For location, see Fig. 1c.



facies association 1 to facies association 2 can be either gradational or abrupt. The thick tabular sandstone units are only present above the disconformity and inferred epsilon cross-stratification has only been observed in one, inaccessible locality.

(3) *Isolated, laterally confined sandstone units.* These sandstone bodies have a maximum thickness of 3–15 m and a maximum width of up to 25 m (Fig. 6). They have a concave and undulating erosional base, often showing groove marks, and they commonly consist of a basal coarse-grained to conglomeratic lag which passes upwards into medium-grained sandstone. The medium-grained sandstone consists of massive, planar and trough cross-bedded sets, 0.5–2 m thick, with abundant poorly preserved coaly plant fragments in the lower part. The erosional basal contact is typically incised into sediments belonging to facies association 4, and there is commonly a sharp boundary between the isolated, laterally confined sandstone units (1) and association 4.

Measurement of palaeocurrent directions in the three types of channel sandstone was only possible in a few places. Groove casts trend NE–SW and ripple cross-lamination indicates palaeocurrents towards the north-east.

Interpretation. The multistorey sandstones (1) and (2) are interpreted as fluvial channel deposits. The sandstones represent lateral and vertical accretion and the multistorey character of the sandstone bodies is the result of lateral meander loop migration during net

aggradation (Allen 1963; Bridge 1975; Bridge & Diemer 1983; Diemer & Belt 1991). Each storey is a single point bar deposit which was superimposed on a previous point bar deposit (e.g. Bridge 1975). The scarcity of sedimentary structures and the presence of convolute bedding may reflect rapid fall out from suspension (Collinson & Thompson 1989), or it may be an artifact due to difficulties observing internal structures. However, the presence of *in situ* tree stumps indicates limited erosion and deposition from suspension. The thickness variations of the sandstone units probably reflect variable discharge with time, implying that the thickness of the channel deposits roughly equals the maximum depth of the channel, although the degree of accretion and erosion are also factors controlling bed thickness. A meandering system is the most obvious considering the scarcity of planar tabular cross-bedding which is typically produced by bars in sandy braided systems (Gersib & McCabe 1981); angular and trough-shaped cross-bedding are interpreted as the product of migration of dunes and sandwaves (Collinson & Thompson 1989).

The laterally confined sandstone units (3) are interpreted as channel-fill deposits from a fixed channel. Fixed channels produce laterally restricted sand ribbons commonly isolated in finer grained sediment (Collinson 1986). The infilling of sand enclosed by finer deposits suggests a combined load stream with a high suspended load. Furthermore, it implies a gradual waning of flow in the channel so bedload transport persisted approximately to the time of abandonment (Allen 1964; Collinson 1986).

Facies association 2: overbank fines

Description. This facies association comprises up to 10 m thick units of laminated to weakly laminated mudstone and siltstone interbedded with thin-bedded structureless sandstone and parallel-laminated silty sandstone (Fig. 7). In the lowermost part of the formation rare 0.5–3 cm thick coal streaks occur within this facies. The overbank fines association has a transitional or planar to irregular base and comprises mainly fining-upward units with flaser and lenticular bedding. Locally, coarsening-upward units are observed. The sandstone beds are 0.5–10 cm thick with wavy or planar lower and upper boundaries. Successions of this type usually overlie the channel sandstone of facies association 1. Poorly preserved plant fragments are the only fossils recorded in this association. The facies as-

sociation can be traced laterally for more than a kilometre.

Interpretation. Facies association 2 records deposition of fine material from suspension and is closely comparable to facies 6 of Fielding (1984). Deposition took place in interchannel areas. The fine-grained units represent the result of vertical accretion of floodplain deposits. The thin intercalations of massive and ripple cross-laminated sandstone represent infrequent overbank flooding, where bedload capacity was sufficient to transport sand material into the flood basin areas (Fielding 1984; Farrell 1987; Diemer & Belt 1991). The coarsening-upward units are interpreted to represent infilling of the interchannel areas by fine-grained splay sediments as minor delta lobes. The thin coal streaks are thought to represent detrital organic matter transported into the interchannel areas during flooding (Alexander & Gawthorpe 1993).

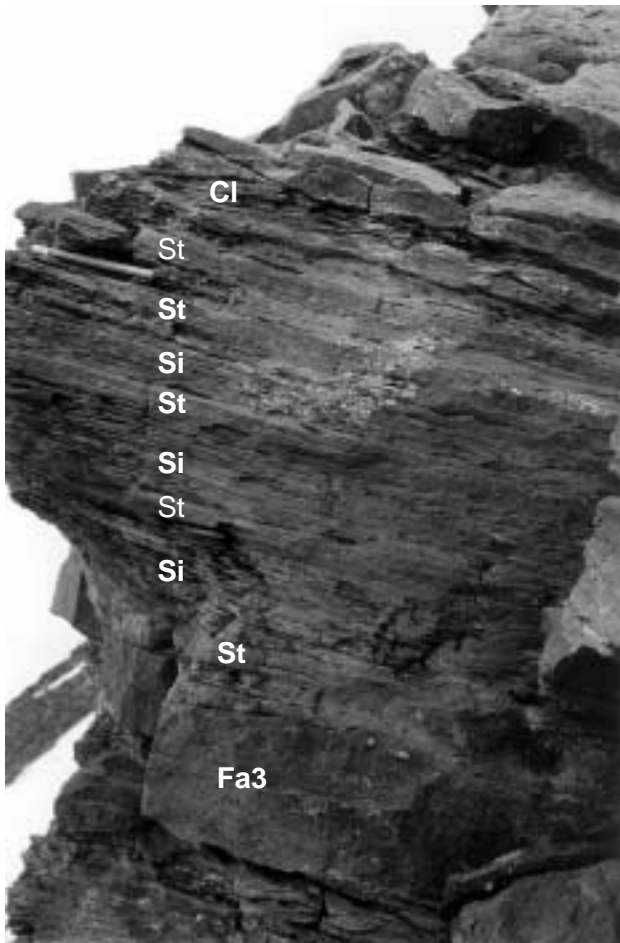


Fig. 8. Interbedded fine-grained sandstone (**St**) and siltstone (**Si**) from facies association 4 overlying a thin-bedded unit of fine-grained sandstone from facies association 3 (**Fa3**). Notice cross-lamination (**Cl**) above the pencil. For location, see Fig. 1c.

Facies association 3: crevasse splay sandstones

Description. Facies association 3 comprises up to 5 m thick units of composite medium- to fine-grained sandstone. Individual beds are up to 1.5 m thick and they locally contain lens-shaped clasts of mudstone up to 10 cm across (Fig. 7). The base is sharp, planar or wavy and erosional. The sandstone is structureless or planar cross-bedded, laminated or ripple cross-laminated. Flattened coaly clasts of plant debris and tree stumps are sometimes preserved, but no other fossils have been found. Individual beds are often wedge-shaped; when stacked into thicker units, they form tabular sheets. The thickest units are laterally persistent for more than 500 m along the cliff exposure and no channel forms are recognised. However, the sandstone may split laterally into 10–40 cm thick beds, alternating with mudstone and siltstone from facies association 2. In a few places, above the disconformity, structureless beds up to 40 cm thick are seen to be recumbently folded whilst bedding above and below are undisturbed.

Interpretation. The sediments were deposited by unconfined erosional flows. The stacked sandstones were deposited in a fluctuating discharge regime during several flood pulses. Comparable sediments have been described by McKee *et al.* (1967), Tunbridge (1981) and Fielding (1984). Tunbridge (1981) inter-

Fig. 9. Fine-grained sandstone with desiccation cracks (facies association 5). The hammer is 32 cm long. For location, see Fig. 1c.



preted laterally persistent sandy sediments with bed thickness of 0.4–2.5 m arranged in stacked sequences and with no indication of channelling having formed during high-stage flood deposition of sand followed by rapid waning of flow, with little or no low-stage reworking. The sediments represent vertical accretion at some distance from a feeder channel and are interpreted as crevasse splay deposits. The recumbently folded beds are interpreted as the result of syndepositional slump movements on the basis of the undisturbed nature of the bedding below and above.

Facies association 4: levee heteroliths

Description. Facies association 4 comprises thinly bedded heterolithic units, up to 0.9 m thick, consisting of weakly laminated or non-laminated mudstone to siltstone alternating with fine-grained sandstone. Such units commonly succeed sediments of facies association 1 (Fig. 8). The sandstone sets are generally 1–2 cm thick, massive or weakly cross-laminated, followed by 2–12 cm thick lamina sets of rippled siltstone to fine-grained sandstone. Only rare plant fragments have been observed. Locally this facies association forms coarsening-upward sequences in which sandstones become dominant towards the top. In one section the heterolithic units are arranged in multistorey sequences up to 10 m thick separated by up to 0.5 m thick erosional beds of sandstone. These sandstone beds are structureless or horizontally planar or ripple cross-laminated with an erosional base.

This facies association is difficult to trace laterally; it either interfingers with sediments of facies association 2 or is cut by sediments of facies association 1.

Interpretation. These units are interpreted as levee sediments where each sedimentary rhythm represents a flood event. Fielding (1984), Diemer & Belt (1991), and Platt & Keller (1992), among others, have described similar sediments where the heterolithic deposition is interpreted to represent variation in discharge. The coarsening-upward trend is considered to reflect infilling of interchannel areas by growth or encroachment of the levee. The erosionally based sandstone beds represent sediment-laden floods from the crevasse splay association and the scarcity of rootlets suggests subaqueous deposition (Fielding 1984).

Facies association 5: lake

Description. Facies association 5 consists of dark brown to reddish brown laminated to non-laminated mudstone and silty mudstone sequences up to 28 m thick. Poorly preserved plant fragments are common. Horizons enriched with iron and iron-rich concretions are locally present. Thin, sharp-based beds (5–10 cm) of structureless, laminated and ripple cross-laminated, fine-grained silty sandstone beds are common in these mudstones. They occasionally show desiccation cracks (Fig. 9).

This association is laterally persistent over several hundreds of metres. The lateral transition is not clearly



Fig. 10. A thick coal bed with thin intercalated fine-grained sandy beds overlain by thick tabular sandstone units (2) of facies association 1. Person for scale. For location, see Fig. 1c.

observed but the sediments seem to wedge out laterally. Facies association 5 is cut by laterally restricted, sharp-based channel deposits of facies association 1 (Fig. 6).

Interpretation. The uniform fine grain size and the scarcity of current generated structures suggest that facies association 5 was deposited from suspension in protected basins and accordingly this facies association is interpreted to represent shallow lake deposits. The thin sandstone beds represent distal flood deposits or events of lowered lake level and the basins were periodically subaerially exposed as indicated by the occurrence of desiccation cracks.

Facies association 6: swamp

Description. This facies association is composed of thin, generally less than 1 m thick, coal and shaly coal beds. Thin beds (< 0.1 m) of mudstone or silty mudstone and ripple-laminated or horizontal planar-laminated fine-grained sandstones are occasionally present within the coal (Fig. 10). The coal is black to brownish black with sparse rootlet horizons. Locally, vertical tree stumps in growth position are seen to penetrate upwards into the overlying sediments. Facies association 6 can only be traced laterally for about 200 m.

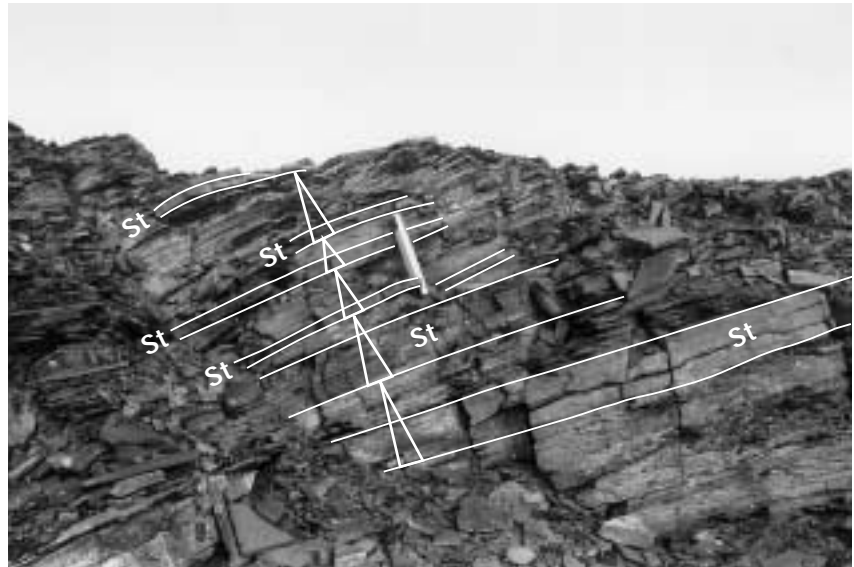
Interpretation. This association probably represents the organic deposits of peat swamps (Fielding 1984). The swamp evolved through the prolific growth of vegetation on the shallow submerged and abandoned surfaces of lake infills and channels. Whether these coals are entirely autochthonous is impossible to determine because of the scarcity of rootlet horizons below and within facies association 6 as a whole. The thickness and distribution of the coals may indicate an autocyclic origin whereas relatively thin and discontinuous coal seams can be interpreted to reflect local sedimentary control by the channels (Belt *et al.* 1992). The thin intercalated clastic beds are the result of overbank sedimentation in the swamp area (McCabe 1984).

Depositional environment

The lack of evidence of marine proximity or evidence of tidal current processes, the abundance of plant remains including *in situ* stems and coal beds and the stacking pattern of the six facies associations suggest deposition in a fluvial sedimentary environment. The individual fining-upward successions and their characteristic sedimentary structures cannot be taken as proof of a meandering fluvial environment (Miall 1992). However, the overall stacking patterns and the distribution of facies associations 1–4 and 6 are in accordance with other inferred ancient meandering river deposits (e.g. Allen 1965; Leeder 1973; Puigdefabregas & Van Vliet 1978; Bridge & Diemer 1983; Diemer & Belt 1991; Alexander & Gawthorpe 1993), and the sediments are thought to represent a complete fossil meander belt where the sandstones represent the individual active channels.

Amalgamation of the channel sandstones reflects downstream progradation of the meanders in association with aggradation. The channel and floodplain

Fig. 11. Fine-grained sandstones (**St**) and silty mudstones from facies association 2 arranged in a cyclic pattern. Notice the overall fining-upward trend. The ruler as scale is 20 cm long. For location, see Fig. 1c.



deposits are interpreted to represent sedimentation in channels of moderate to high sinuosity on the adjacent floodplain. The channel sandstones are thought to have been deposited in moderately high sinuosity streams based on the few channel bodies observed. The finer sediments in facies associations 2 to 6 are laterally and vertically associated with facies association 1 and accumulated as flood basin, crevasse splay, levee, shallow lake and swamp deposits. The thick flood basin sequences probably reflect a more stable flood basin area, distant from the main meander belts, where stream channels had only minor influence on sedimentation. The final shift towards mixed lacustrine and fluvial deposition reflects a change in base level possibly due to increased rates of subsidence, changes in sediment supply or increased precipitation and thereby raised ground water level.

If the thickness of the sandstones corresponds to original channel depth (Collinson 1986), the maximum channel depths were in the order of 3 to 13 m for the upper part of the formation. The lower half of the formation is dominated by facies association 2 suggesting deposition from rivers with an even larger amount of suspended load leading to more extensive flood basin deposits. The channels were shallower than in the upper part with a maximum depth of *c.* 4 m.

Cyclicality

Two orders of cyclicality can be seen in the Lower Carboniferous succession. The thickest cycles consist of

interbedded channel sandstones and overbank fines. Each cycle starts with lateral accretion or avulsion, and scouring of the underlying beds, followed by infilling of the channel or part of it by vertical accretion of sandstone. The cycle is terminated by overbank fines that are erosively overlain by sandstones of the following cycle.

Cycle thickness is 0.5–6 m below the disconformity with an average thickness around 2 m. Cycles from the upper part of the succession range from 3 to 20 m with an average around 11 m. They are dominated by thick tabular channel sandstones up to 13 m thick. This change in cycle thickness is abrupt and apparently reflects a shift from a broad distant floodplain, where the meandering stream channels had limited influence on sedimentation, to a more proximal or laterally confined floodplain where channels were more frequent. The change in cycle thickness and the associated shift from mudstone-dominated cycles below the disconformity to sand-dominated cycles above suggest an analogy with the 1st order cycles in alluvial sediments of Schumm (1977), McLean & Jerzykiewicz (1978) and Wescott (1993) and may be related to tectonic disturbance. Syntectonic disturbance is also indicated by the recumbent slump folds in facies association 3. This disturbance may have led to changes in base level followed by changes in discharge, sediment supply and the river transport capacity.

Cyclicality on an even finer scale is represented in the overbank fines. Each cycle consists of a basal thin-bedded, fine-grained sandstone followed by massive to planar or ripple cross-laminated, fine-grained silt

and silty mudstone (Fig. 11). Cycle thickness ranges from a few tens of centimetres to about 1 m. These cycles represent vertical accretion deposits and are interpreted to be of autocyclic origin (McLean & Jerzykiewicz 1978; Farrell 1987). This type of cyclicity is comparable to the 3rd order cyclicity of McLean & Jerzykiewicz (1978) and the 3rd and 4th order cycles of Schumm (1977) and Wescott (1993).

Conclusions

The Sortebakker Formation consists of a variety of facies that together characterise deposition on a floodplain. The sediments stack in a cyclic fashion with a shift through time from thin mudstone-dominated cycles to thick sand-dominated cycles; the uppermost part of the succession consists of mixed fluvial and lacustrine deposits. The 1st order cyclicity that led to the development of an angular unconformity, is interpreted to have been allogenic in origin. It was related to major changes in accommodation space and is thought to have been created by tectonic movement. The cyclicity below and above the unconformity is interpreted to have been controlled by autocyclic processes. The fining-upward fluvial cycles are interpreted to record unhindered meandering of a river across a floodplain under conditions of steady subsidence and sediment supply (e.g. Friend 1961; Allen 1964). This kind of cyclicity is referred to as 2nd order cyclicity by McLean & Jerzykiewicz (1978) and as 3rd order cyclicity by Schumm (1977) and Wescott (1993). Allocyclic mechanisms such as climatic fluctuations and base level changes are reported to produce cyclicity equivalent to that observed in the Sortebakker Formation, and these mechanisms may alternatively explain the observed patterns.

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