Depositional environments, diagenetic history and source areas of some Bunter Sandstones in northern Jutland

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Cores from the wells Mors 1 and Gassum 1 representing the Lower Triassic Bunter Sandstone Formation in the Danish Subbasin have been reexamined with regard to their primary sedimentary structures and their petrology. Four sedimentary facies are recognized within the series of fine- and mediumgrained, reddish sandstones in which fossils and trace fossils have not been found. The facies and the facies sequences suggest deposition of the sandstones by braided rivers.

The petrographical study of thin sections demonstrates two separate phases of diagenetic alterations. The first: infiltration of clay and precipitation of iron oxides comprises features wellknown from recent desert sediments. This phase may or may not be accompanied by growth of authigenic quartz and feldspar. The second phase: growth of authigenic clay and dolomite or ankerite represent deeper burial diagenesis.

The mineralogy of the sandstones indicate a metamorphic-plutonic terrain as the main source area, presumably the Fennoscandian Shield. However, zeolitic aggregates of volcanic origin in the Mors 1 samples and absence of these aggregates in the Gassum 1 samples coupled with the occurrence of sillimanite-bearing grains suggest different sub-source area for the two localities.

It is concluded that the regional pattern of sediment transport into the Danish Subbasin has involved transportation from various parts of the Fennoscandian Shield via a fringe of alluvial fans along the Fennoscandian Border Zone. The present study thus adds new evidence in support of the existing interpretations of early Triassic paleogeography and palaeoclimatology.

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The Lower Triassic Bunter Sandstone Formation (~ Lower and Middle Buntsandstein) comprises mainly red-coloured sandstones. In the Danish-North German Basin finegrained sand- and siltstones are found, which have recently been studied at Helgoland (Clemmensen 1979). These sediments grade northwards into more coarsegrained sandstones in the Danish Subbasin and further northwards into the coarsegrained sediments of the Skagerrak Formation (Bertelsen 1980). The geological setting and the spatial relationship of the Bunter Sandstone Formation are discussed extensively by Bertelsen (1980) in his paper on lithostratigraphy and depositional history of the Danish Triassic.

In the Danish Subbasin the Bunter Sandstone Formation has been cored in the wells Mors 1 and Gassum 1 (fig. 1) where it is represented by a 700–900 m thick series of sandstones contemporaneous to both the Bunter Shale Formation and the Bunter Sandstone Formation distinguished in the Danish-North German Basin (Bertelsen 1980). These cores were redescribed in 1979 at the Geological Survey of Denmark in connection with a geothermical project, and the results are presented in this paper.

It has been the aim of the present study of the sedimentary structures and the petrography of the cores to characterize the depositional environment and describe the diagenetic history of these red, unfossiliferous sandstones, in which trace fossils have not been observed, and hereby to contribute to the knowledge of the Early Triassic palaeogeography.

Sedimentary facies

General

In Mors 1 the thickness of the Bunter Sandstone exceeds 900 m (fig. 1), and the upper boundary is identified below 4.3 km depth (Bertelsen 1977). Two relatively closely spaced intervals at depths between 5.0 and 5.1 km were cored (fig. 1,2) and two 12–13 m long cores are available which allow recognition of facies sequences. The cores consist of medium and finegrained, grayish red (5R 4/2), well-sorted, largescale crossbedded sandstones with a varying content of intraformational clasts of dark reddish clay (10R 3/4, 5YR 3/4). All colours are named according to the rock-color chart by Goddard et al. (1975). Wire line log data indicate that sandstones are the dominant lithology in Mors 1, and the two cores may be representative for the formation as a whole.

In Gassum 1 the Bunter Sandstone Formation occupies depths between 2.7 and 3.4 km (Bertelsen 1977) and nine intervals from depths between 2.8 and 3.1 km were cored (figs. 1,3). These 3–5 m long cores and the scarce wire line log data indicate that the formation is lithologically uniform throughout. In Gassum 1 the sandstones are medium- to finegrained, well-sorted, pale reddish brown (10R 5/4) and dominantly largescale crossbedded, and they contain varying amounts of thin intraformational clasts, at times resembling drapes, of moderately brown clay (5YR 3/4).

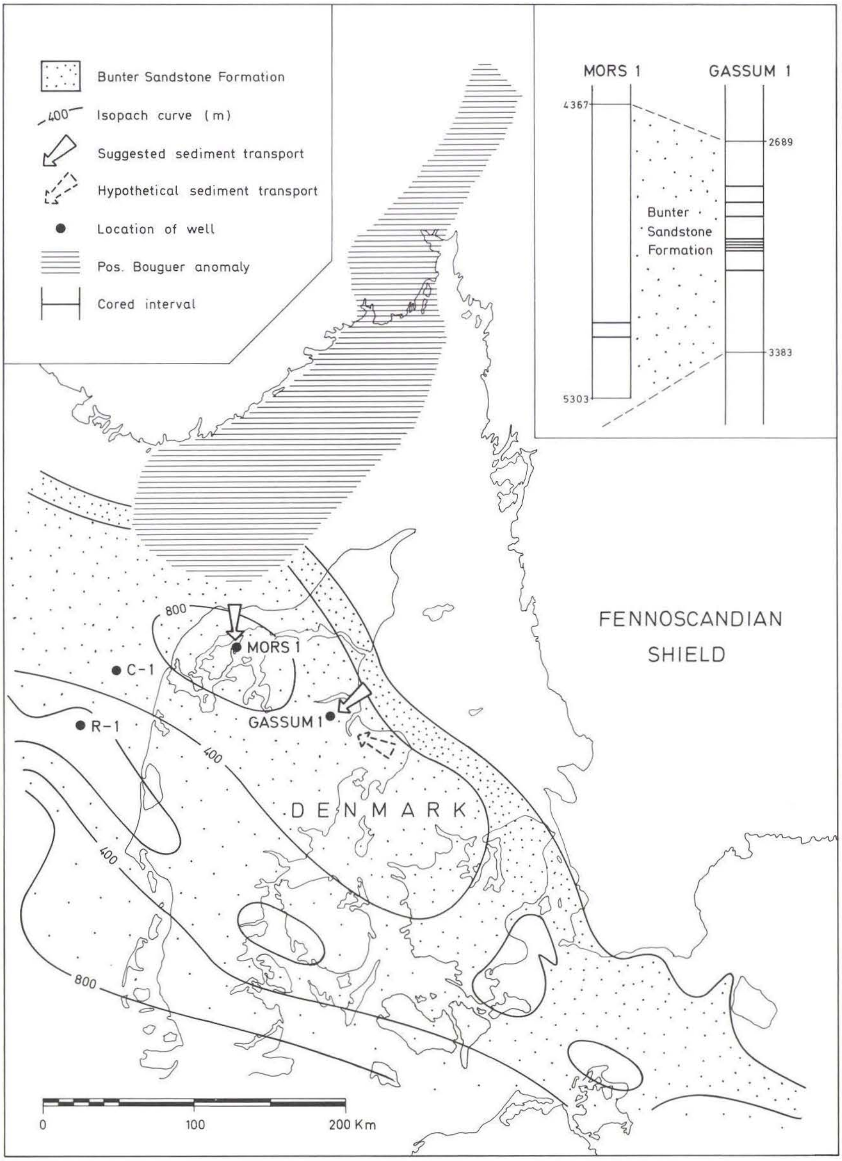


Fig. 1. Location map. The isopach map of Lower and Middle Buntsandstein is drawn from Michelsen & Bertelsen (1979). The spacing between the dots indicate the proportion of sand to finer grain-sizes, with sand/siltstones dominating to the south. The positive Bouguer anomaly, outlining the Oslo palaeorift igneous province, is drawn from Husebye & Ramberg (1978). On the inset figure, showing the relative position of the Mors 1 and Gassum 1 cores within the Lower and Middle Buntsandstein Series, the depths are given in meters below mean sea level. Drawn from Bertelsen (1977). Please note, that the cores are correlated along the upper boundary of the Bunter Sandstone Formation and that this is situated at different depths in the two wells.

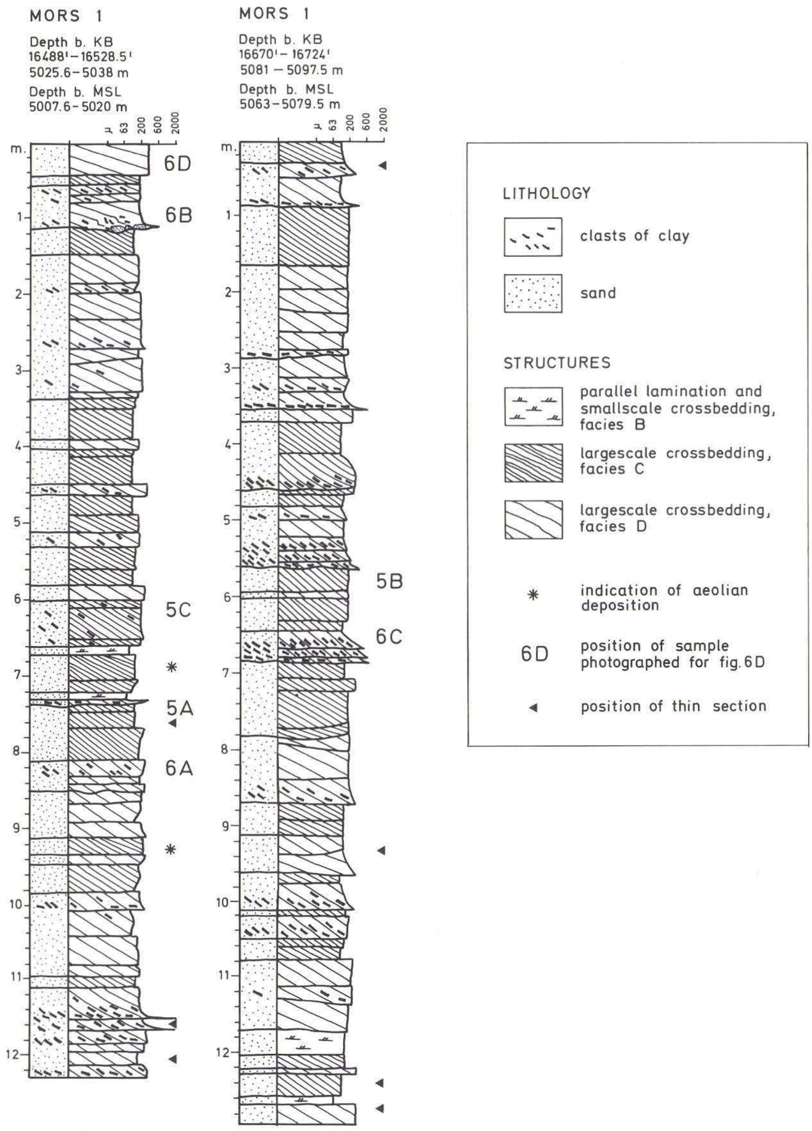


Fig. 2. Sedimentological logs of the Mors 1 cores. The dominance of the facies C and D is seen. The depth in feet below Kelly Bushing to the interval that was cored is the figure used in the captions to figs. 4–7. When the length of the cored interval is compared to the length of the cores it is seen that recovery was high.

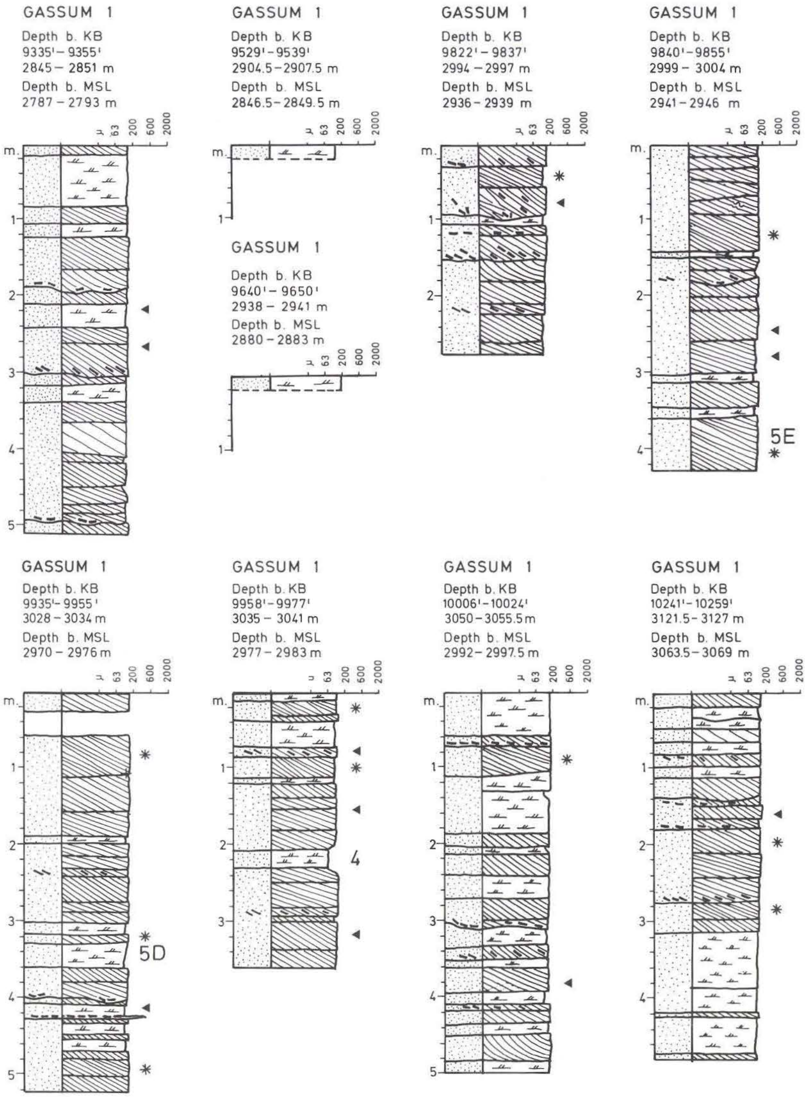


Fig. 3. Sedimentological logs of the Gassum 1 cores. The dominance of the facies B and C is seen. For further explanation see fig. 2.

Recognition of largescale sedimentary structures in cores represent some difficulties which are very well illustrated by Glennie (1970, figs. 120–122.). Still it is thought possible to recognize four sedimentary facies in the Mors 1 and Gassum 1 material, and they will be described in the following.

The cores were not oriented during drilling and therefore the direction of the currents depositing the crossbedded sands cannot be determined.

Facies A: Intraformational clay clasts

Description

Silty, non-calcareous, brown (10R 3/4, 5YR 3/4) clay constitutes intraformational clasts. These are often angular and 3–5 mm thick, but rounded clay pebbles are also seen. The clasts are lying 1) parallel to foreset laminae in largescale crossbedded sand (figs. 6A, C) or 2) they may be concentrated as a lag conglomerate at the bottom of a crosslaminated bed (fig. 6B, see also figs. 2,3).

Interpretation

Smith's (1972) studies of mud clasts indicate that angular clasts generally have undergone very little transport and therefore largely represent erosion and redeposition of layers of clay. Contrary the rounded clay pebbles represent separated phases of erosion and deposition but probably only transport over short distances.

If the thickness of the original clay layers correspond to the thickness of the clasts, the clay layers may have represented single episodes of deposition of suspended matter in quiet waters. Sedimentation of facies A may have taken place in abandoned courses of rivers or in small (temporary) lakes.

The strength of wet clay clasts is considerably larger than flakes of dry clay (Smith 1972) so presumably at least the angular clasts were transported wet and deposited by the same current that eroded them. Therefore the presence of intraformational clasts in the Bunter Sandstone Formantion is interpreted to indicate alternating periods of deposition, subaerial exposure and fluvial redeposition (see also Blatt, Middleton & Murray 1972, p. 286).

Distribution

The total amount of clay clasts is less than 5 %, but the repeated occurrence of intraformational clasts indicate that deposition of clay layers continually took place during sedimentation of the Bunter Sandstone Formation.

Facies B: Finegrained sand with parallel lamination or smallscale crossbedding

Description

This facies is characterized by very finegrained, silty, relatively well-sorted sand with parallel laminae c. 5 mm thick or smallscale, often planar, crossbedding (fig. 4). The foresets are unidirectional. Intraformational clasts are absent.

The sediment may have the red colours characteristic for the cores as a whole, but often light brownish gray (5YR 6/1) or greenish gray (5G 6/1) colours are seen. Facies B appear to be stronger cemented than the more coarsegrained sediments.

Interpretation

As the content of clay and fine silt is negligible, and because small current ripples were formed, it is inferred that the finegrained sediment was deposited in slowly flowing water during lower flow regime conditions. There is an absence of fossils or trace fossils in all facies and facies B may accordingly represent either fluvial or lacustrine deposits.

Distribution

Facies B occurs almost exclusively in the Gassum 1 cores where it constitutes up to c. 40 % of the cores (fig. 3).

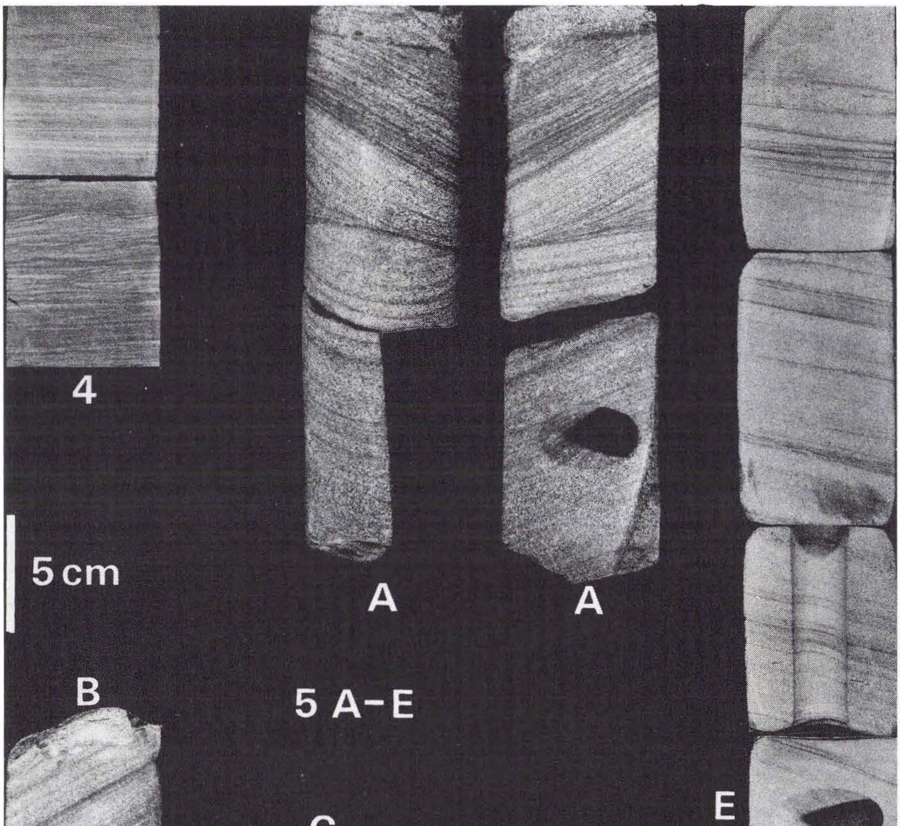
Facies C: Fine- to mediumgrained, largescale crossbedded sand

General

The sand is greyish red (5R 4/2) in the Mors 1 cores and pale reddish brown (10R 5/4) in the Gassum 1 cores. The facies comprises largescale crossbedded, generally well-sorted, sand with clearly defined foreset laminae at times distinguished by clear variations in grain-size.

The facies is divided into two subfacies through the presence or absence of intraformational clay clasts.

Facies C is the dominant facies in the Bunter Sandstone Formation in the Mors 1 and Gassum 1 wells (figs. 2,3) where it constitutes 40–55 % of the cores.


4
5 cm
A
A
B
5 A-E
C
E
D

Subfacies C1: Fine- to mediumgrained, largescale crossbedded sand without clay clasts

To the above general description may be added: The subfacies is developed as up to 60 cm thick, planar crosslaminated sets of well-sorted sand without intraformational clasts. The individual foreset laminae may be wedgeshaped (fig. 5E), or subfacies C1 may display unusual »high angle contacts« to underlying sedimentary units (fig. 5D).

Aeolian sediments are described from the Bunter Sandstone Formation at Helgoland (Clemmensen 1979) and might be expected to occur in the Mors 1 and Gassum 1 cores, too. The clast-free, largescale crossbedded sand with wedgeshaped foreset laminae of subfacies C1 resemble the descriptions of aeolian sediments given by McKee (1966), Glennie (1970, 1972), Clemmensen (1978, 1979). Also the deposition of the angular foresets without bottomsets »uphill« against an inclining surface (fig. 5D) reflects a depositional mechanism presumably only possible in aeolian sediments: Deposition must have taken place from a migrating bedform in which the particles rolled down the foreset without forming bottomsets, and where the surface in front of the migrating bedform was not eroded by the depositing current.

Thus subfacies C1 is interpreted as aeolian deposits. Its distribution is seen in figs. 2 and 3, where it is marked as facies C with an asterix to the right.

Fig. 4. Facies B. Finegrained silty sand with parallel lamination or smallscale crossbedding. A well preserved current ripple is seen approximately in the middle of the picture. Gassum 1, 9,958'–9,977'.

Figs. 5 A-E. Facies C. A-C illustrates subfacies C2, and D-E illustrates subfacies C1. (A) Two crosslaminated sets deposited by currents from two directions c. 90° apart. The core is seen from the outside (left) and cut, parallel to current, (right). Foresets are tangential. Subfacies C2 is erosively overlain by facies D. Mors 1, 16,488'–16,528.5'.

(B) Largescale crossbedded sand with clearly defined foreset laminae, subhorisontal in the bottom. Intraformational clasts are not seen. Mors 1, 16,670'–16,724'.

(C) Subfacies C2 with few intraformational clasts and some examples of wedge-shaped foreset laminae. The pale spots are strongly cemented by dolomite. Mors 1, 16.488'–16,528.5'.

(D) Subfacies C1. »High angle contact« between upper and lower crossbedded units. Gassum 1, 9,935'–9,955'.

(E) Subfacies C1. No intraformational clasts, some wedge-shaped foreset laminae. Well-sorted sand with heavy minerals concentrated as dark streaks along some foresets. Gassum 1, 9,840'–9,855'.

Subfacies C2: Fine- to mediumgrained, largescale crossbedded sand generally with clay clasts

To the general description of facies C may be added: Intraformational clasts occur widely but never abundantly (fig. 5C) or may be absent, and the crossbedding is tabular with angular or tangential foresets. The dip of these may vary from more than 20° to less than 10° (fig. 5B). Some slightly dipping sets show gradual transitions into horisontally bedded sand, assumedly representing the subhorisontal part of tangential foresets. Often several sets (height c. 10 – c. 30 cm) can be seen to have been deposited by unidirectional currents, but changes in current directions are also observed (fig. 5A). The subfacies may be erosive or overlie an eroded surface.

The subfacies is interpreted as fluvial, deposited by migrating megaripples under upper lower flow regime conditions. The well-sorted sediment with distinct crosslamination and at times contrasts in grain-sizes between foreset laminae indicate slipface sedimentation and low rates of suspension transport.

Subfacies C2 includes all beds of facies C that does not posses the characteristica of subfacies C1. The distribution of subfacies C2 is shown in figs. 2 and 3 as facies C.

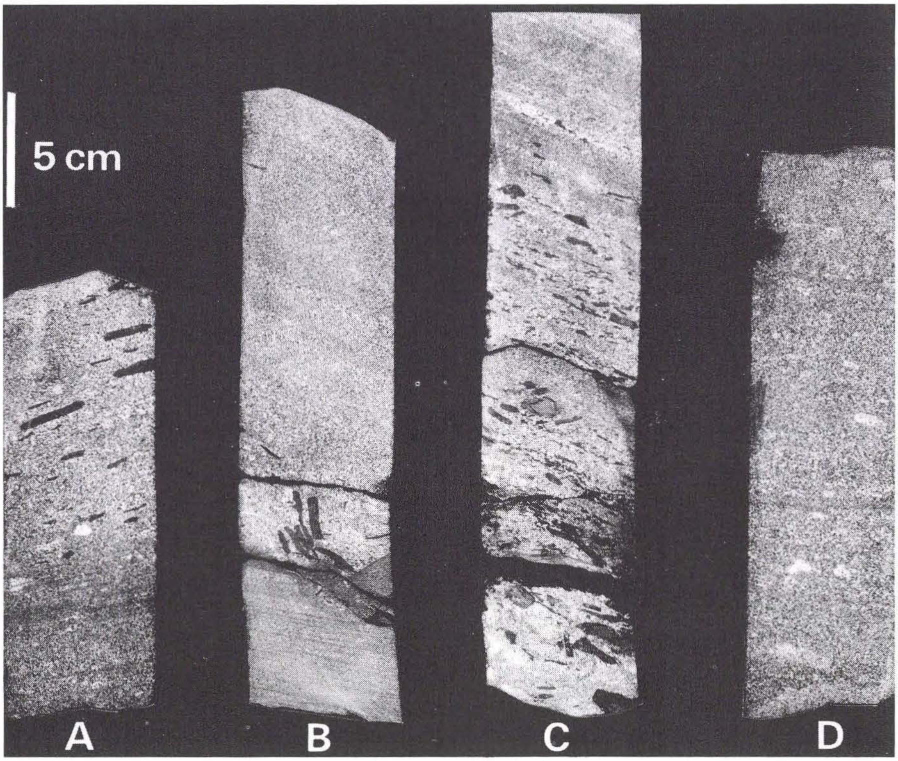
Facies D: Mediumgrained, largescale crossbedded sand

Description

Medium grained, grayish red (5R 4/2), relatively poorly sorted sand locally with a high content of intraformational clasts (fig. 6). Facies D is largescale crossbedded, the height of the sets varies from 2 to 50 cm, the foresets dip between 10° and 30°, and the individual foreset laminae are thick (0.5–3 cm) and are often difficult to distinguish (fig. 6D). Clay clasts in varying numbers are lying parallel to the foreset laminae (fig. 6 A,C). Lag-conglomerates containing imbricated and almost overturned clasts are also observed (fig. 6 B). The facies is seen with concordant as well as clearly erosive boundaries towards other facies.

Interpretation

The facies is, in the present depositional context, interpreted as fluvial due to the large content of intraformational clasts, the erosive boundaries, the largescale crossbedding and the grain-size of the sand. The imbricated clasts (fig. 6 B) and the indistinguishable foreset laminae indicate that deposition occurred rapidly from a current with high velocity and with a large sediment load.



Figs. 6 A-D. Facies D. The content of intraformational clasts is varying and the clasts often occur parallel to foresets, either spread through the bed (A) or concentrated in certain levels (C). In (B) facies D erosively overlies facies C and the lag-conglomerate contains both sandstone clasts and clay clasts. The latter are imbricated and almost overturned. In (D) the sediment is almost structureless and clasts are absent. The pale spots are strongly cemented by dolomite. (A), (B), (D): Mors 1, 16,488'–16,528.5'. (C): Mors 1, 16,670'–16,724'.

Distribution

Facies D is predominantly seen in the Mors 1 cores where it alternates with facies C. Facies D here constitutes c. 60 % of the cores (fig. 2).

Discussion of facies sequences and depositional conditions

The immediate impression from the sedimentological logs (figs. 2,3) is that cyclic facies sequences are not developed. This is confirmed when the facies transitions are tested by Selley's (1970) method, which further illustrates that:

1. The number of transitions from facies X up into facies Y corresponds exactly to the number of transitions from facies Y up into facies X.
2. Transitions between facies B and D are very rare.
3. Facies C alternates with either facies B or facies D.

The last two points agree well with the interpretation that facies D represents the highest fluvial energy conditions, while facies C, though generally fluvial, was deposited at lower energy conditions, and facies B and especially facies A represent low energy environments of quiet waters.

From the lack of pattern in the facies sequences it is inferred that the river changed its course often and randomly so that systematic facies sequences did not develop. It is concluded that the Mors 1 and Gassum 1 cores represent distal and finegrained braided river deposits.

Lower Triassic palaeoclimatic conditions have been interpreted by Clemmensen (1979). Denmark was situated at a palaeolatitude of c. 20° N within a central trade wind region and characterized by desert environments with short rainy seasons.

In such climates braided river deposits characteristically are formed (Glennie 1970, p. 29) and because channels become filled with their own, or aeolian, deposits, the next flood finds its old route partially or completely blocked. It must then seek alternative routes and, in so doing, builds up a braided alluvial plain. A model for the depositional environment of the Bunter Sandstone formation is illustrated in fig. 7.

The primary sedimentary structures and the facies sequences seen in the Bunter Sandstone Formation in Mors 1 and Gassum 1, thus corresponds closely to those described by Glennie (1970) from recent desert environments. Also the early diagenetic textures: clay infiltration and iron oxide precipitation, described in the following and indicating an oxidizing environment, are in agreement with the otherwise interpreted palaeoclimatical conditions for the Bunter Sandstone Formation.

Microscopic petrography

Methods and samples

The petrographical study is based on 18 thin sections whose position are indicated on figs. 2, 3. The number of thin sections is limited, because examination of the cores at low magnification indicated close similarity in compositions of the various facies within the same well but larger differences between the sediments cored at the two localities. For identification of certain minerals X-ray diffraction and universal stage methods has been used.

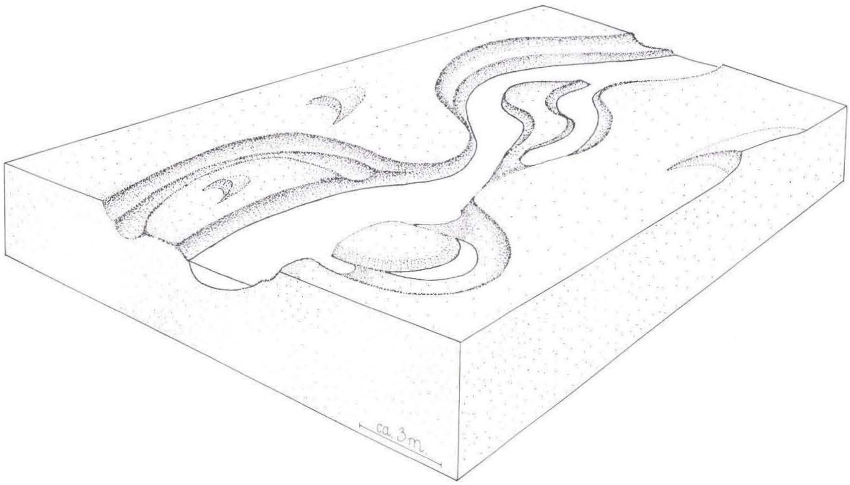


Fig. 7. A model for the depositional environment of the Bunter Sandstone Formation. In the main course of the river facies D was deposited under relatively high energy conditions. The repeated shifting of the course and the accompanying erosion of previously deposited clay layers, facies A, produced the clay clasts so abundantly found in facies D. In little more sheltered parts of the braided river the fluvial sediments of subfacies C2 were deposited, while sedimentation of the fine-grained facies A and B took place in more or less abandoned courses of the river. Aeolian redistribution of the fluvial deposits producing subfacies C1 is illustrated by the scattered barchanes, though other morphological forms are just as likely to have existed.

Detrital constituents

General

Quartz and feldspars, with the predominance of kalifeldspars, constitute the main detrital components. Rockfragments are of less importance apart from a special type, zeolite-haematite aggregates. These comprise 11–26 % of the detrital constituents in Mors 1, but has not been observed in Gassum 1 (fig. 8). Of minor and accessory occurrence are micas (biotite, muscovite, chlorite), opaque minerals (magnetite, haematite, ilmenite), zircon, rutile, tourmaline and apatite.

Omitting the zeolite-haematite aggregates, the detrital mineralogy is dominated by metamorphic-plutonic constituents, monomineralic as well as rockfragments, listed in fig. 8. These assemblages are found to be very similar for the two localities (fig. 8, B1–B2). Of special interest are the sillimanite containing fragments, which occur as fibrolite-quartz and fibrolite-microcline fragments, and which are found in Gassum 1 only. They occur in subordinate amounts and are incorporated with fragments of type 1 and 2 in fig. 8.

	Type of aggregate	A1 Gassum 1	A2 Mors 1	B1 Gassum 1	B2 Mors 1
		%	%	%	%
Metamorphic	1. Quartz aggr.	14	11	67	68
	2. Quartz-feldspar aggr.	2	2	8	10
	3. Quartz-mica aggr., metamorphic	2	1	7	6
Plutonic	4. Mica aggr., metamorphic	< 1	< 1	1	1
	5. Mica aggr., sed. or met.	< 1	< 1	2	1
	6. Chert	2	1	10	8
Sedimentary	7. Sand-/silt-/claystone fragments		1		4
	8. Clay clasts, intraformational	1	< 1	5	2
	9. Zeolite-haematite aggr.		18		
	Sum	21	35		
	Sum – zeolite-haematite aggr.	21	17	100	100

Fig. 8. Content of rockfragments in Bunter Sandstone samples from Gassum 1 and Mors 1. A1–A2: The content of various rocktypes as percent of detrital components (average of 11 and 5 samples respectively). B1–B2: To fasciliate comparison of the non-zeolitic rock fragments (types 1–8) between the two wells the values from A1–A2 is recalculated to a sum of 100 %. (It should be remembered, that the quartz aggregates (type 1) and quartz-feldspar aggregates (type 2) are allotted to the Q- and F-pole respectively, when using the classification method of Folk (1968)).

The sandstones from Gassum 1 cluster inside the subarkose field, while Mors 1 samples with their high content of rockfragments fall within the field of feldspatic litharenite, (fig. 9). The fabric in the sandstones is illustrated in figs. 10 A-B.

Zeolite-haematite aggregates

The zeolite-haematite aggregates occurring in Mors 1 consist of eu-subhedral, acicular or stubby zeolite prisms with 5–10 % of interstitial haematite. Euhedral apatite prisms as well as very rare, ellipsoidal quartz grains may occur in the aggregates, figs. 10 B-C.

An attempt to determine the zeolites by X-ray diffraction on whole-rock samples was impeded by interference from other minerals, wherefore universal stage microscopy was applied. This, however, was limited by the small size of individual grains, which may occasionally reach 250 μm but commonly are less than 50 μm, and by the common occurrence of thin twin lammellae. However, the existence of two different minerals was established: a) one mineral occurring as stubby prisms, sometimes twinned, was undeterminable by the optic method; b) a mineral with often subparallel acicular prisms with the following optical data: colourless, monoclinic, length-fast, optically

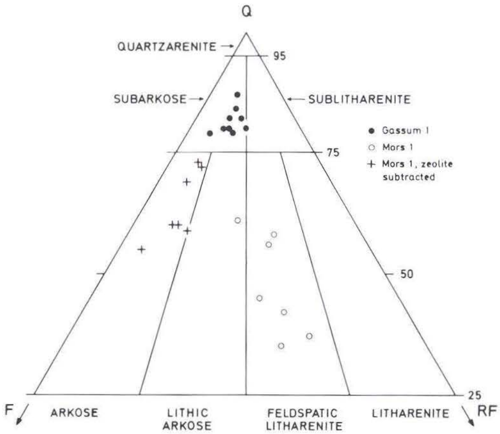


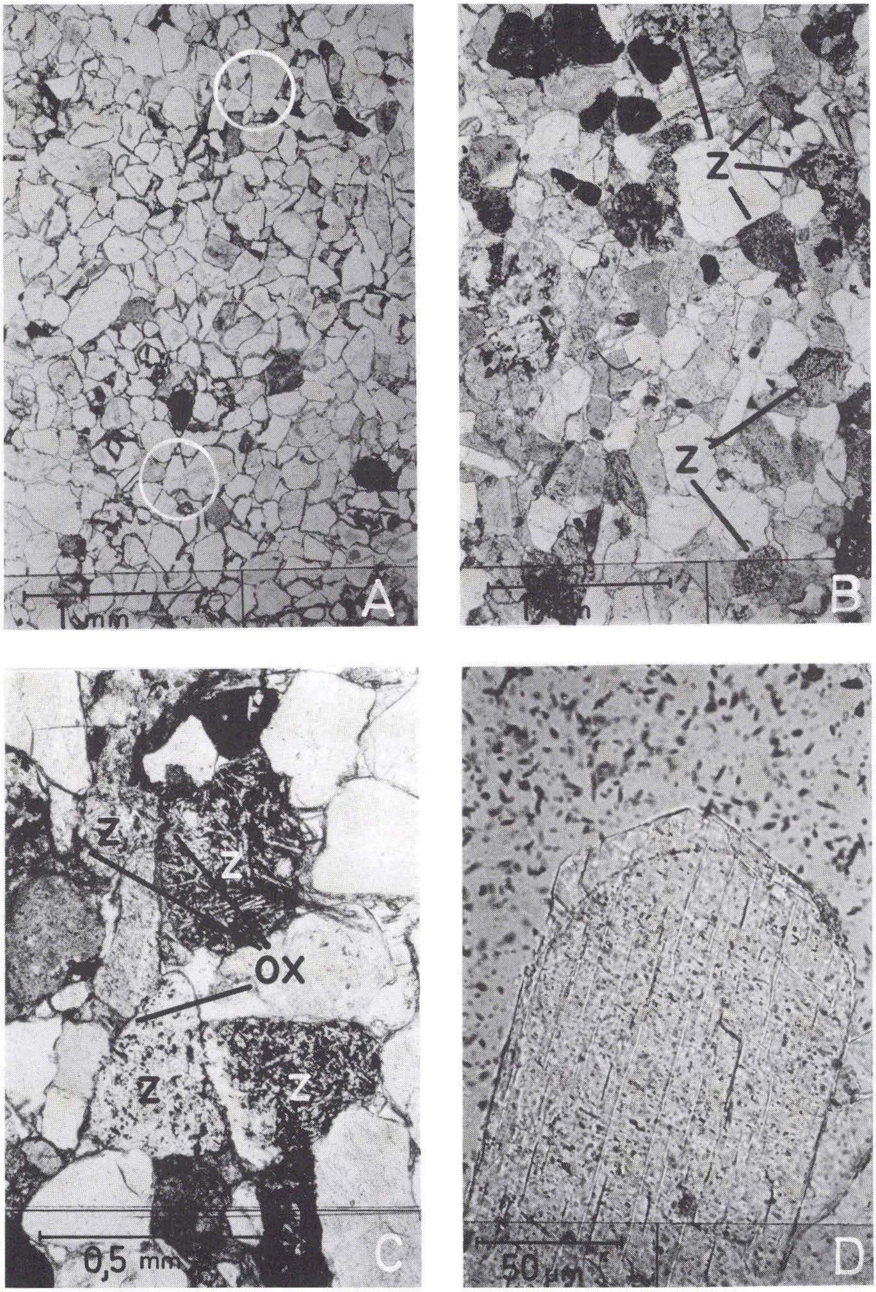
Fig. 9. Triangular classification plot of sandstones from the Bunter Sandstone Formation from the wells Gassum 1 and Mors 1. After Folk (1968). To fasciliate comparison of compositional maturity between the wells Mors sandstones is plottet in two versions: with original composition (o) and secondly with a composition resulting after subtraction of zeolite-haematite aggregates (+). The latter displays that the Mors 1 sandstones are the least mature in terms of feldspar content.

negative, $2V_X$: 50–68° X∧c: 28–35°. These data are reasonably consistent with data for scolecite given by Tröger (1959), though a discrepancy is found for the angle X∧c, which by Tröger is given as 15–18°. However, the data are scarce and separation of the zeolites followed by X-ray analysis will be needed for acurate determination.

Discussion

Zeolites and haematite are known to occur within a wide range of geological environments. Formation of zeolites is though nearly always linked to ignous activity. The occurrence of zeolites in cavities and crevices in lavas is well known. Hay (1966) summarized the occurrence in sedimentary rocks. His work demonstrates that authigenic and metamorphic formation of zeolites are largely dependent upon the presence of volcanic material. Zeolite-forming saline, alkaline lagunal or lake environments may or may not attribute their extreme chemical conditions to nearby igneous activity.

Zeolites easily react with aqueous solutions and are also mecanically very unstable; their occurrence as detrital constituents therefore require a nearby situated source. For the zeolites occurring in the Bunter sandstones in Mors 1 possible sedimentary sources are penecontemporaneous deposits from saline, alkaline lakes or Zechstein lagunal deposits. However, calcium-rich zeolites as scolecite are not likely to occur in deposits of alkaline lakes, and metamorphic scolecite has only been reported in sedi-


A
1mm
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Z
Z
0,5 mm
C
50 µm
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mentary rocks upon burial to about 12000 feet (Hay 1966, table 5). Such conditions are unlikely to have been found in Zechstein deposits in early Triassic times. Scolecite however, occurs at surface conditions in weathered volcanic rocks (Deer, Howie & Zussman 1963). Volcanic activity was intense in the Oslo palaeorift during the Permian. Gravity measurements (Huseby & Ramberg 1978) indicate that the palaeorift, corresponding to a positive Bouguer anomaly, continued at the least as far southwards as the northernmost Skagerrak (fig. 1). Lower Permian volcanics encountered in the wells C-1, D-1, R-1, and L-1 in the Danish North Sea sector (Rasmussen 1974, Michelsen 1976) suggest that the volcanic region have extended even further as indicated by Ziegler (1978).

We suggest that the zeolitebearing sediments in the Mors 1 cores originated from this area. The occurrence of apatite in the aggregates is consistent with such an origin. The ellipsoidal quartz grains may represent relict quartz-phenocrysts from weathered quartz-porphyric rocks, such as are known to occur in the Oslo rift.

In Gassum 1 the lack of zeolite-haematite rockfragments combined with the presence of sillimanitic fragments suggest that the sandstones reflect a source area within purely metamorphic-plutonic basement terrains. Such may be found anywhere within the Fennoscandian Shield outside the Oslo Palaeorift Region.

Diagenesis

Early diagenesis

The sandstones are ferruginous, owing their reddish colour to limonite and haematite coatings. Biotites in these red-coloured zones are found to be strongly oxidized. In the greenish-grey parts, which occur only to a minor

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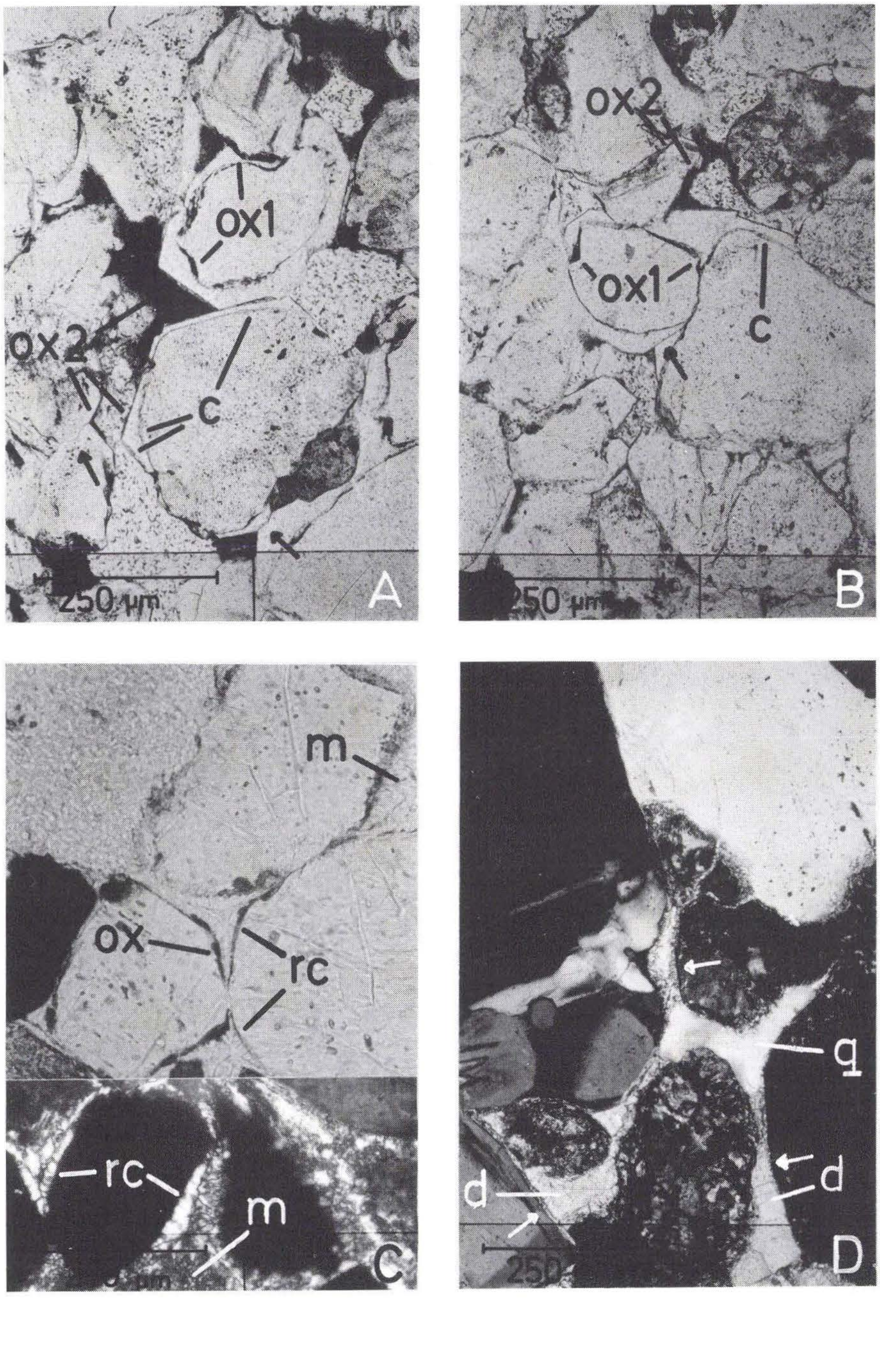
Figs. 10 A-B. Characteristic fabric of Gassum 1 and Mors 1 Bunter Sandstones. Scales are identical; plane light.

A. Gassum 1. Note frequent iron oxide rims (black rims). Light grey rims are mechanically infiltrated clay coatings. Both are absent at grain contacts (for example upper right part, lower part; encircled).

B. Mors 1. Of the »dusty« grains most are feldspars. Note high frequency of zeolite-haematite aggregates (z).

Fig. 10 C. Mors 1. Zeolite-haematite aggregates (z). Upper part shows aggregate with typical acicular zeolites. Note that the aggregates are rounded and overgrown by incomplete iron oxide rims (ox), thus proving the detrital origin; plane light.

Fig. 10 D. Gassum 1. Rounded, detrital microcline with authigenic, euhedral feldspar outgrowth. In this case only a dust line marks the detrital surface; plane light.


ox1
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extent and only in Gassum 1, iron oxide overgrowths are insignificant and biotites are less altered.

Clay occur commonly as coatings on detrital grains. The coatings are reddish brown and may reach a thickness of 5μm, but are commonly thinner, and are built up by clay platelets aligned subparallel to the grain surfaces. This is seen from the entire width of the clay rim being extinct, when the edge of the coated grain is orientated parallel to the polarizors. The same type of clay occasionally fill porespaces partly or wholly (figs. 10A and 11 A,B).

A common feature in the Gassum 1 cores is two events of clay infiltration and iron oxide precipitation separated by a period of quartz growth. On detrital quartz grains the oldest clay and oxide rims are overgrown by syntaxial and euhedral secondary quartz. These overgrowths may again be covered by clay coatings, which in turn are impregnated by iron oxides (fig. 11 A-B). Euhedral outgrowths of feldspar on detrital feldspars have occurred more or less simultaneously with authigenic quartz growth (fig. 10 D).

Alignment of clays parallel to grain surface are by Crone (1975), Walker (1976) and Walker, Waugh & Crone (1978) found to be typical of mechanically infiltrated clays deposited by water with clay particles in suspension sinking into dry and very permeable sediments.

The formation of iron oxide rims necessitates water as a medium to dissolve intrastratal iron-bearing minerals and to transport the iron to the sites of precipitation.

Thus clay infiltration is a process occurring above the watertable, while iron oxide precipitation primarily occurs below. Clay coatings are thus expected to be impregnated and overgrown by oxides with time and burial, and this is observed to have occurred in both the Mors 1 and the Gassum 1

Figs. 11 A-B. Gassum 1. Euhedral, authigenic quartz overgrow clay coatings impregnated with iron oxide (Ox1). The authigenic quartz is in turn covered by second generation of impregnated clay (Ox2). Unimpregnated clay is light grey (c). Note that authigenic quartz joining across porespace do not contain clay coatings on crystal faces (arrows) and thus predates second event of clay infiltration; plane light.

Fig. 11 C. Mors 1. Incomplete iron oxide rims (ox) overgrown by colourless clays, which are aligned radially to detrital grain surfaces (rc). Medial sutures have been formed by the juncture of clays growing inwards from opposite sides of the pores. Upper right and lower middle show the colourless clays grown as interlocking crystals to produce a meshwork texture (m). Note that iron oxide rims are missing at grain contacts; upper part: plane light; lower part: crossed polarizors.

Fig. 11 D. Mors 1. Quartz (q) and dolomite (d) filling voids left after growth of porelining, colourless clay (arrows). Quartz and dolomite occupy separate voids; crossed polarizors.

samples. The repeated events of infiltration and iron oxide precipitation found in Gassum 1 are most readily explained as caused by an oscillating watertable, returning drowned zones to dry conditions and thus allowing a rejuvenation of the process.

Late diagenesis

In Mors 1 the clay-oxide rims are overgrown by colourless clay. It forms radiating porelinings up to 12 μm wide, or fill pores producing a meshwork texture, fig. 11C. Replacement of detrital feldspars by colourless clay may be contemporaneous with this episode. A determination of the clays has not been attempted, though the radial growth suggests chlorite or smectite (Wilson & Pittman 1977). This phase of authigenic growth of clay has not been observed in Gassum 1.

The last diagenetic events in Mors 1 is growth of quartz and dolomite. These minerals fill porespace left after growth of colourless clay. Commonly the two minerals occupy separate voids, fig. 11 D; when they occur together dolomite is found to display euhedrality against quartz. This phenomenon, however, does not determine the sequence of growth, as carbonates are known to replace quartz during formation of euhedral crystals.

In Gassum 1 growth of ankerite and white mica follows the early diagenesis. Ankerite acts as porefilling material and occupies domains varying in size from single porespaces to 1 mm large aggregates. Intraformational clay clasts and infiltrated clay can be replaced to varying degrees. Ankerite overgrows all early diagenetic phases and corrosion of both detrital and authigenic quartz and feldspars occur. The dolomite in Mors 1 also display corrosion textures. In Gassum 1 crystallization of white mica from detrital clay has been observed in the samples from the greenish-grey zones. The microscopic texture does not allow determination of growth sequence of ankerite and white mica. X-ray diffraction studies on intraformational clay clasts from Mors 1 shows the presence of 10 Å clays, thus suggesting that growth of white mica took place at Mors as well. X-ray diffraction was also used in the determination of the carbonate cements.

Source areas and transport directions of the sediments

Several authors have, on various grounds, suggested that the clastic material constituting the Bunter Sandstone Formation was derived from the Fennoscandian Shield:

1. Michelsen & Bertelsen (1979) estimated the variations in the ratio of sand versus silt+clay through the Danish and North German Basins and

suggest the Fennoscandian Shield as the source area for the Bunter Sandstone Formation.

2. Larsen & Friis (1975) on basis of heavy minerals in samples of probably Late Triassic age (Bertelsen 1980) from the Skagerrak Formation (Bertelsen 1980) in northern Jutland demonstrated that these sediments were provided from the Fennoscandian Shield. This is supported by Bertelsen (1980) who delineates the Skagerrak Formation as a marginal facies along the Fennoscandian Shield, and notes that the general lithology and the wire line log motifs indicate deposition by braided streams on a continental plain (Bertelsen 1980).
3. Larsen & Friis (1975 p. 40) suggest, that the garnet content of the Bunter Sandstone Formation in the North German Basin indicate sediment transport from the Fennoscandian Shield. However, in Gassum 1 and Mors 1 samples garnets have not been observed. Unless this is due to strong diagenetic alterations, as proposed by Larsen (1970) to occur in the Danish Subbasin below a 2 km level, it suggests that the direction of transport of garnet bearing sediments to the North German Basin was not across the Danish-Norwegian Basin. This is supported by the palaeogeographical evidence presented by Michelsen & Bertelsen (1979) (see also fig. 1), namely that parts of the Ringkøbing-Fyn High formed a land barrier between the Danish and the North German Basins.

The above mentioned papers suggest that the source areas of the detrital, clastic material of the Bunter Sandstone Formation in the Danish Subbasin lay north and northeast of the basin. Transport directions from east have presumably been of lesser importance as the Danish Subbasin probably was separated from the Polish Trough by the Stevns Block in eastern Denmark and the Skurup Platform in southern Sweden (Bertelsen 1980).

The present study of the detrital grains in the Bunter Sandstone Formation adds the following details to this picture:

For the sediments in the Mors area a source area within the Permian Oslo volcanic region is suggested on basis of the content of zeolite-haematite rockfragments. The high content of metamorphic-plutonic rockfragments also found (fig. 8), may also easily reflect a northern sediment transport direction. We therefore suggest that the source area for the Mors 1 samples lay to the north and that sediment transport was towards south (fig. 1).

For the sediments in the Gassum area a source area within the Fennoscandian Shield but east of the Permian Oslo volcanic region is suggested on basis of the presence of silliminite-bearing rockfragments and the absence of zeolite-haematite grains. This implies sediment transport from the source area towards south or southwest to the Gassum area (fig. 1).

If only sediment composition (fig. 9) and grain size distributions were considered the Gassum area sediments might represent more mature equivalents to the Mors area sediments, and the zeolites, being unstable, might have disappeared during transport. This possibility is rejected because it would involve sediment transport towards southeast, parallel to the basin axis but towards the basin margin (fig. 1).

The almost identical assemblages (fig. 8) of rockfragments in the two wells, apart from the zeolitic aggregates, are believed to reflect the presence of vast heterogeneous drainage areas of predominantly metamorthic-plutonic composition and provides no clues to the exact position of the source areas.

The isopach map (fig. 1, after Michelsen & Bertelsen 1979) show that the Mors 1 well was drilled in the depocentre of the Bunter Sandstone Formation in the Danish Subbasin. The thickness of the formation increases more than 250 m over the relatively short distance between the Gassum 1 and the Mors 1 wells, which might suggest that the sediments were to some extent reworked and transported along the basin axis towards the depocentre. Such a northwesterly directed sediment redistribution cannot, however, be traced petrographically.

Conclusions

The well-sorted, mainly large-scale crossbedded sandstones with their varying content of intraformational clasts of clay are interpreted as dominantly fluvial deposits, probably to some extent reworked and redeposited as aeolian sediments. Four water-laid sedimentary facies are recognized representing deposition at increasing energy levels from quiet waters to upper part of lower flow regime.

The random interbedding of the facies indicate rapidly changing depositional conditions, and in connection with the lack of fossils or trace fossils, sedimentation is interpreted to have taken place in an environment dominated by braided rivers.

Two diagenetic stages are recognized, the earliest being formation of rims of infiltrated clay followed by iron oxide impregnation, accompanied in Gassum 1 by a penecontemporaneous growth of authigenic quartz and feldspar. The later stage includes in Mors 1 growth of authigenic clay later followed by growth of quartz and dolomite. In Gassum 1 crystallization of white mica and precipitation of ankerite occurred.

The presence of a mixed assemblage of zeolitic aggregates and metamorphic-plutonic grains in the Mors 1 samples indicate a source area of the sediments within the region influenced by the volcanic activity of the Oslo palaeorift. Drainage patterns apparently roughly followed a north-southerly direction.

The lack of zeolite-aggregate grains and the presence of sillimanite bearing fragments in the Gassum 1 samples indicate sediment transport from metamorphic terrains, presumably the more easterly parts of the Fennoscandian Shield.

Sediment transport was probably perpendicular to the Fennoscandian Border Zone directed into the basin from northeast via a fringe of alluvial fans, but some sediment transport parallel to the axis of the Danish Subbasin and thus from more easterly directions may have taken place.

The red colour of the sandstones indicating highly oxidizing conditions, the early stages in diagenesis, and the deposition of the sediments by braided rivers with occasional aeolian reworking corresponds very well to the desert environments characterizing northern Europe as a whole during early Triassic times. The present paper thus supports the existing picture of the early Triassic palaeogeography with the Fennoscandian Shield as a source area for detrital material and the Bunter Sandstone Formation in northern Jutland as dominantly fluvial, continental plain deposits along the northern margin of the Danish Subbasin.

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Dansk sammendrag

Den foreliggende undersøgelse rummer en nybeskrivelse af de primære, sedimentære strukturer og petrologien i borekerner, som repræsenterer den nedre triassiske Bunter Sandstone Formation, fra dybdeboringerne Mors 1 og Gassum 1 i Det danske Subbassin. Formationen består af en serie rødlige, fin- og mellemkornede sandsten, i hvilke fossiler eller sporfossiler ikke forekommer. Der opstilles fire sedimentære facies, som, sammen med faciessekvenserne, sandsynliggør, at sandstenene er aflejret i et system af braiderende floder.

En petrologisk undersøgelse af tyndslib viser, at to adskilte faser kan skelnes i diageneseforløbet. Den første: nedskylning af lerpartikler og udfældning af jernoxider, omfatter fænomener, som er velkendte fra moderne ørkenaflejringer. Denne fase kan være ledsaget af afsætning af authigent udskilt kvarts og feldspat. Den anden fase: afsætning af authigent ler og dolomit eller ankerit, er processer, som er knyttet til indsynkningen af sedimenterne til større dybder.

Sandstenene indeholder vekslende mængder af bjergartsfragmenter som fjerntransporterede sandskorn. Hovedparten af disse, samt de iøvrigt dominerende sandskorn kun bestående af et enkelt mineral, er ikke karakteristiske for et bestemt, afgrænset kildeområde, men kan kun henføres til et metamorft-plutonisk grundfjeldsområde, formodentlig Det fennoskandiske Skjold. Imidlertid optræder der i prøverne fra Mors 1 zeolitholdige aggregater som detritale korn. Disse er af vulkansk oprindelse og stammer sandsynligvis fra de områder, som prægedes af den permiske vulkanisme i Oslograven. Dette indicerer, at sedimenterne omkring Mors er tilført fra nord. I prøverne fra Gassum 1 mangler zeolitaggregaterne, mens sillimanitholdige korn til gengæld optræder. Heraf sluttes, at sedimenterne i Gassumområdet stammer fra østligere dele af Det fennoskandiske Skjold, og at deres transportretning har været fra nordøst eller nord.

Den foreliggende undersøgelse af de røde, fossilfrie sandsten sandsynliggør, at disse er aflejret af braiderende floder. Dette, såvel som deres tidligt diagenetiske udvikling, indicerer, at Bunter Sandstone Formationen repræsenterer ørkenaflejringer. Sedimenterne stammer fra forskellige dele af Det fennoskandiske Skjold, og de antages at være blevet transporteret til Det danske Subbassin gennem en række alluvialkegler langs Den fennoskandiske Randzone. Undersøgelsen har tilvejebragt nye data, som understøtter de eksisterende tolkninger af de palæogeografiske og palæoklimatiske forhold i tidlig trias tid.

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