Sand remobilisation and intrusion in the Upper Jurassic Hareelv Formation of East Greenland

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An extensive Late Jurassic intrusive sandstone complex is exposed in Jameson land, East Greenland. The sandstones and the host mudstones form the Upper Oxfordian – Volgian Hareelv Formation. The formation covers an area of 55×70 km, is 200–400 m thick and consists of black basinal mudstones and highly irregular sandstone bodies, dykes and sills. Failure of shelf-margin sandbodies resulted in downslope sediment gravity flows and deposition of massive sands on the slope, at the base-of-slope and in the basin. The sands flowed in steep-sided gullies formed by retrogressive slumping of slope muds or loaded directly into the muds. Sandbodies deposited within the gullies have steep commonly stepped margins while those deposited at the downslope termination of gullies have a sheet-like geometry. All sandbodies underwent some degree of fluidization and liquefaction subsequent to burial and sand was intruded into the surrounding black mudstones. Remobilisation and intrusion took place over a long time interval ranging from almost syndepositional to relatively deep burial and primary sediment structures were lost in most cases. Sandstone dykes and sills are ubiquitous and were emplaced by all combinations of stoping and dilation. The intrusive sandbodies range in dimensions from centimetres to many hundreds of metres. The degree of post-burial remobilisation ranges from rather small-scale modifications to wholesale fluidization, liquefaction and out-of-place intrusion of the sand over tens to hundreds of metres. The Hareelv Formation was deposited during the most important Mesozoic rift event in East Greenland and the pervasive remobilisation of all sandbodies in the formation is interpreted as caused mainly by cyclic loading by seismic shocks. Additional important factors were slope shear stress, build up of pore pressure due to loading, slumping, upwards movement of pore waters expelled from the compacting muds and possibly also of biogenic and thermogenic gas. The Hareelv Formation is an excellent field analogue for deeply buried hydrocarbon reservoirs, which have been modified by remobilisation and injection of the sands.

Keywords: Sediment remobilisation, intrusion and injection, sandstone dykes and sills, Upper Jurassic, Hareelv Formation, East Greenland.

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Clastic dykes and sills have been described from numerous localities covering a broad array of depositional environments (e.g. Dzulynski & Radomski 1956; Peterson 1966, 1968; Smyers & Peterson 1971; Truswell 1972; Surlyk et al. 1973; Hiscott 1979; Winslow 1983; Archer, 1984; Parize & Beaudoin 1986, 1987; Surlyk 1987; Parize 1988; Parize et al. 1988; Dixon et al. 1995).

Large, irregular bodies of massive sandstone may also be of intrusive origin but this is not always recognised and their mode of formation is not well understood. The reservoirs of a number of major oil fields in the North Sea and elsewhere are now considered to have formed by remobilisation and subsequent injection of sands into a fine-grained host rock, commonly a basinal mudstone (e.g. Jenssen et al. 1993; Dixon et al. 1995); similar interpretations have been offered for other massive, pod-shaped subsurface sandstone bodies (Nichols 1995; Brooke et al. 1995).

The Katedralen Member of the Upper Jurassic Hareelv Formation of Jameson Land, East Greenland is an outstanding example of a major, laterally extensive intrusive sandstone complex (Figs 1–3). The formation is interpreted as comprising sandy submarine mass flow deposits, which had undergone post-depositional liquefaction, fluidization and subsequent intrusion in the surrounding mudstones. The depositional model involves deposition from high-density turbidity currents with linear sand sources represented by shelf-edge deltas (Figs 2, 4, 5) (Surlyk et al. 1973; Surlyk 1973, 1987, 1989).

Interpretation of the depositional processes is hampered by the wholesale destruction of primary sedimentary structures during fluidization and liquefaction but a spectrum of sediment gravity flows involving sandflows, liquefied flows and high-density turbidity currents were operational, depending on position on the slope, degree of confinement and travel distance (Surlyk 1987; Surlyk & Noe-Nygaard, 1998, 2000b, 2001). The sands were deposited in steep-sided slope gullies, or at the end of the gullies in a non-confined setting. The Hareelv Formation thus represents a commonly overlooked class of line-sourced, disorganised sandy mass flow system derived from shelf margin wedges (cf. Heller & Dickinson 1985; Surlyk 1987).

The main emphasis in earlier studies (Surlyk 1987, 1989) was on the interpretation of processes active during transport and deposition of the massive sands. The aim of the present paper is to describe and interpret the extensive intrusive complex of the Hareelv Formation with special focus on the remobilisation and injection of the sands. In addition comparison is made with similar subsurface examples in order to facilitate their interpretation. Post-burial remobilisation of sand in this type of system is an important modifying factor to consider within the range of deep-water facies models (Surlyk & Noe-Nygaard 1998).

Geological setting and stratigraphy

Jurassic rifting in East Greenland started in the Late Bajocian, intensified during late Middle and Late Jurassic times and reached a climax in the Kimmeridgian–Volgian (Surlyk & Noe-Nygaard 2000a; Surlyk in press). The rifting and associated tilting of blocks is reflected by a change from shallow to increasingly deeper marine deposition. The Upper Oxfordian – Volgian Hareelv Formation was deposited in the southern end of the Mesozoic rift-basin of East Greenland during maximum rifting (Fig. 1). The formation is 200–400 m thick, extends over an area of 55×70 km and is well exposed in southeastern Jameson Land (Figs 1, 3).

The Hareelv Formation has in a recent revision been extended upwards to include the Volgian Sjællandselv Member formerly belonging to the overlying Raukelv Formation (Surlyk et al. in press). The mainly poorly exposed sandstones of the Sjællandselv Member are massive and of a similar origin as the sandstone bodies of the Hareelv Formation, while the sandstones of the Raukelv Formation are cross-bedded and shallow marine. The Hareelv Formation of Surlyk et al. (1973) corresponds to the new Upper Oxfordian – Kimmeridgian Katedralen Member, which shows a sandstone/mudstone ratio of about 0.5, whereas the Volgian Sjællandselv Member has a ratio of about 0.9 (Figs 2, 3). The main focus of this paper is on the Katedralen Member (Fig. 2A).

Deposition of the spectacular slope and basin facies of the Hareelv Formation was heralded in Early – Middle Oxfordian time by deposition of the Olympen Formation, which consists of shallow-marine sandy shelf-edge deltas and slope and basinal mudstones with massive sandstone bodies (Larsen & Surlyk in press; Bruhn & Surlyk 2001). The Katedralen Member is represented by slope and basinal deposits, while correlative shallow-marine sediments are not preserved due to recent erosion. Interpretation of depositional environment is accordingly supported by evidence from the Olympen and Raukelv Formations where the shallow marine parts of the shelf–slope–basin system is preserved.

Late Jurassic palaeogeography and facies patterns

The long-term Late Jurassic sea-level rise and associated transgression culminated during the Kimmeridgian. The Late Jurassic highstand represents the combined effect of long-term eustatic rise (e.g. Hallam 1992) and increasing rifting and associated subsidence (Surlyk & Noe-Nygaard 2000a; Surlyk in press). Deep-marine conditions existed throughout Middle Oxfordian – Kimmeridgian time south of the shelf-slope break in central Jameson Land (Figs 1, 4, 5). The Katedralen Member does not show any evidence of sea-level fluctuations due to its chaotic appearance and deep-water nature (Figs 3, 6). The correlative succession to the west in Milne Land closer to the basin margin (Callomon & Birkelund 1980; Birkelund et al. 1984; Piasecki 1996; Larsen et al. in press) was deposited in somewhat shallower water and shows evidence of repeated Late Jurassic relative sea-level changes (Surlyk in press).

Sedimentary facies

The primary sedimentary facies of the Katedralen Member of the Hareelv Formation include dark-grey to black mudstone and massive yellow-weathering

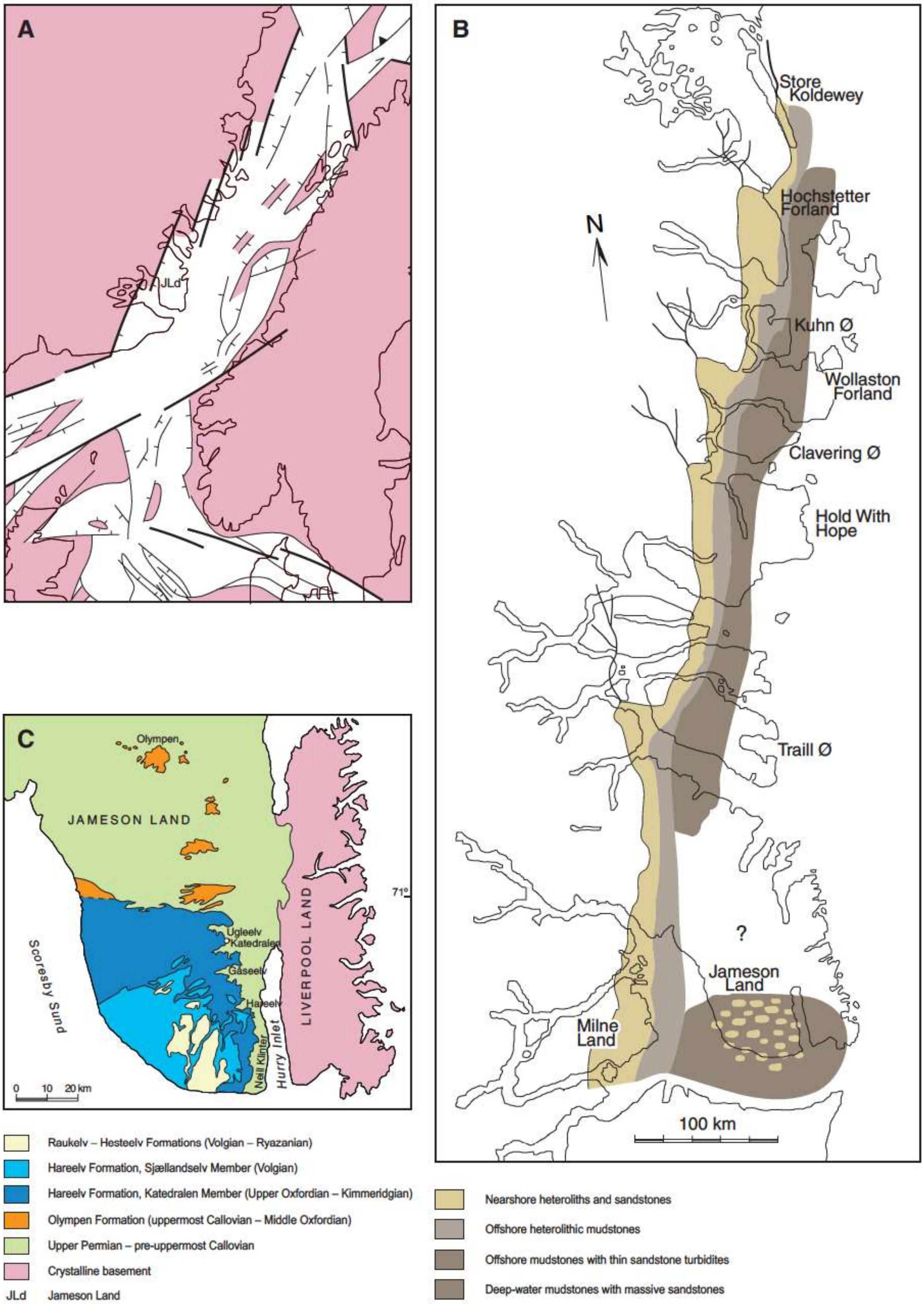
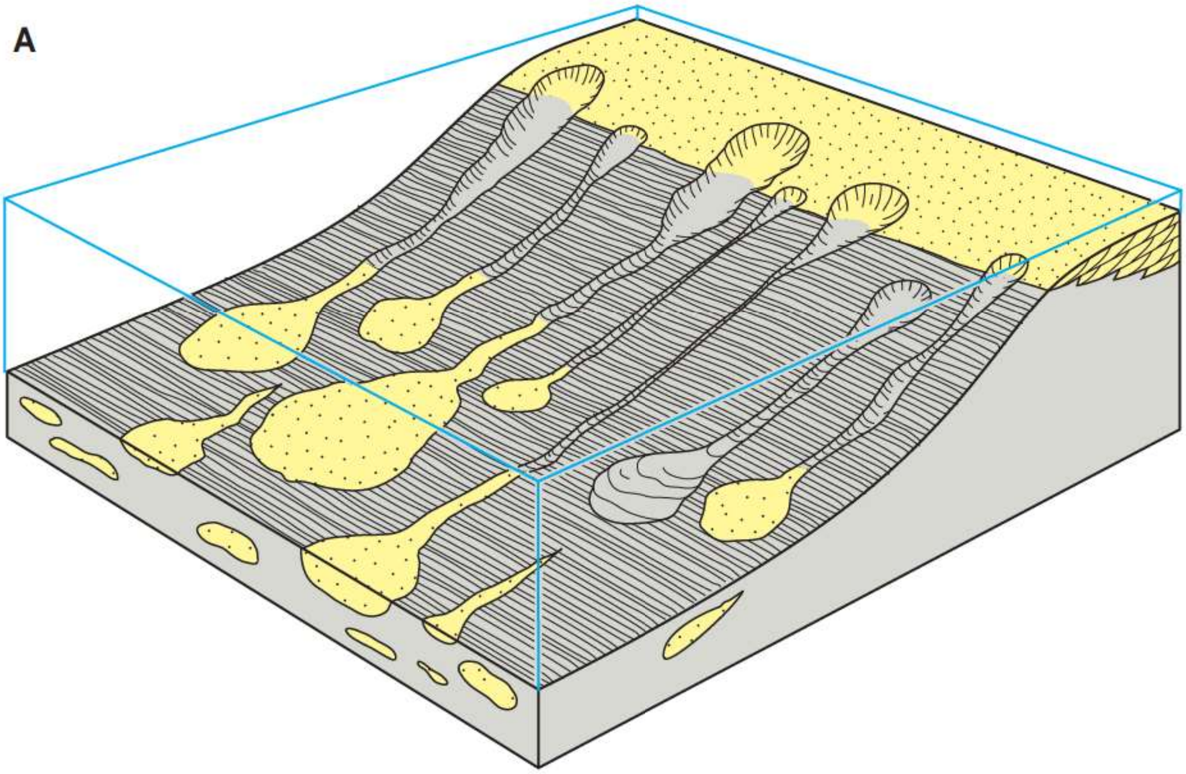


Fig. 1. A. Pre-drift map showing the position of Jameson Land in Late Jurassic time and the main basin-controlling faults. B. Palaeogeographic map of East Greenland in the Late Oxfordian. C. Geological map of southern and central Jameson Land showing the distribution of the Olympen, Hareelv and Raukelv Formations and the location of the main outcrops of the Katedralen Member.

A



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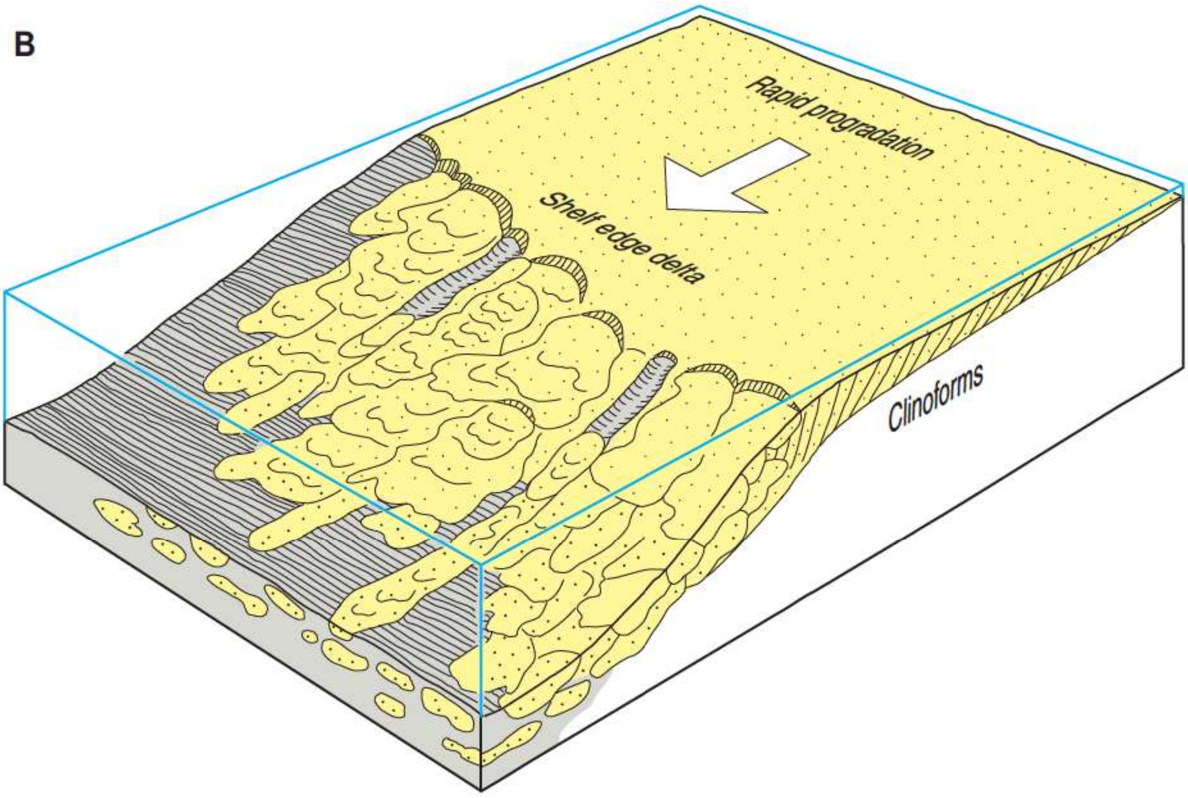

Fig. 2. Depositional model for the Hareelv Formation. A. The Upper Oxfordian – Kimmeridgian Katedralen Member (sandstone/mudstone ratio 0.5). B. The Volgian Sjællandselv Member (sandstone/mudstone ratio about 0.9).

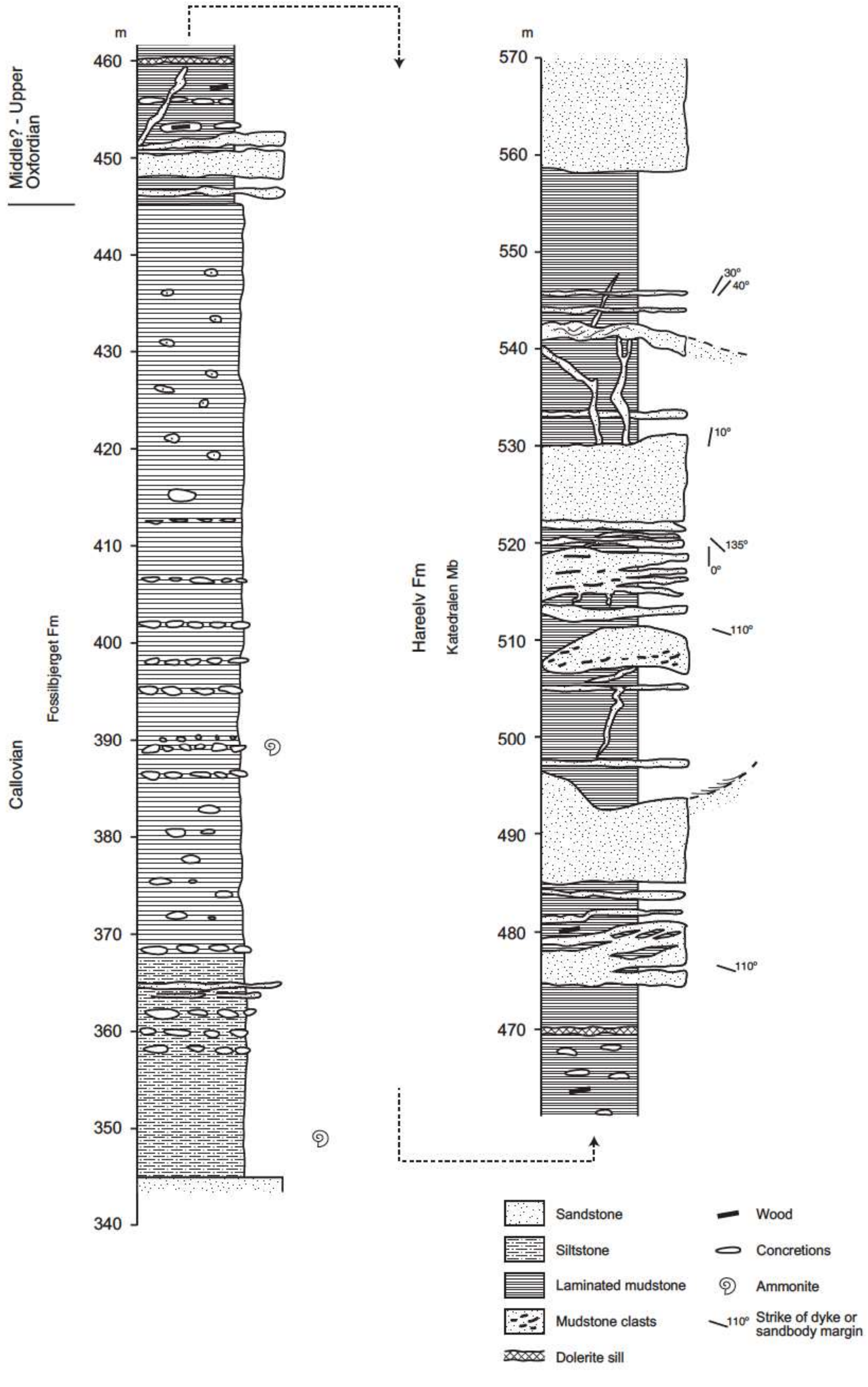

Fig. 3. Log through the upper Fossilbjerget Formation – lower Hareelv Formation (Katedralen Member) at Katedralen (Fig. 1C). Note the regular layering of the Middle Jurassic siltstones and mudstones of the Fossilbjerget Formation and the disorganised nature of the Katedralen Member.

Fig. 4. High-angle clinoform-bedded shelf-margin wedge of the Raukelv Formation. Stippled lines indicate the top of successive wedges which form a southwards progradational stack. The offlap break line marks the position and strike of the shelf–slope boundary. Collapse of the front of the prograding sandy wedge resulted in mass flows down the steep slope and deposition of massive sands on the slope, at the base-of-slope and in the basin. Arrow indicates position of the massive sandstone shown on Fig. 5. Raukelv Formation, southernmost Jameson Land.

sandstone (Figs 3, 6); thin sandy turbidites also occur but are volumetrically insignificant. The sandstone facies are, however, somewhat difficult to categorize and describe due to the extensive post-depositional remobilisation. The most proximal sandstones which occur interbedded with clinoform-bedded shelf-edge sandstones (Fig. 5) have not been remobilised and thus give important clues to the original appearance of the facies. The Sjællandselv Member (Fig. 2B) is almost devoid of mudstones and sandstone injections are accordingly essentially absent. The sandstones of this member are thick, massive, sheet-like and also more or less identical to the original deposit.

Dark mudstone. – The mudstone is organic-rich, in part with excellent hydrocarbon source rock potential. It is laminated, and has a total organic content (TOC) up to 12%, but the amount of marine kerogen is lower, about 4%; the hydrogen index (HI) varies between 150-300 mg HC/g organic material, but is mainly within the 200-300 range (Christiansen et al. 1992; S. Piasecki personal communication 2001). The

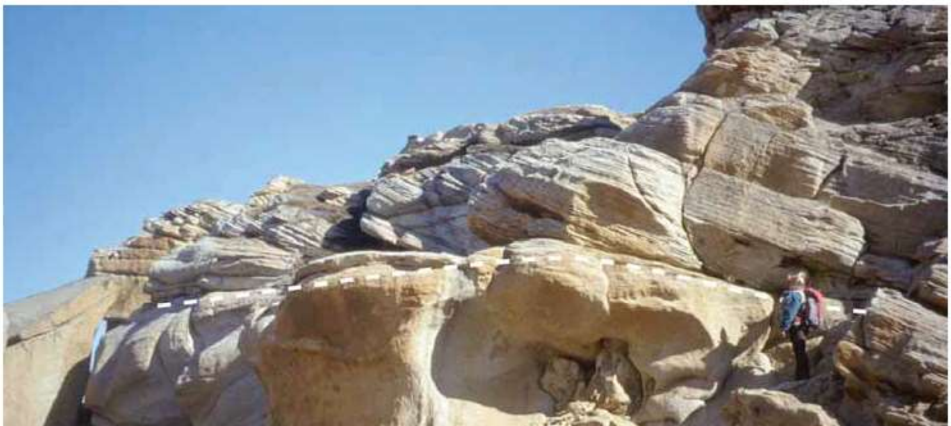

Fig. 5. Detail of the front of the shelf-margin wedge shown on Figure 4 (arrow). Sandflows and liquefied flows were triggered at the shelf-slope break and flowed for a few tens of metres down the slope before they were arrested and overridden by the high-angle clinoform bedded shelf-margin wedge. Raukelv Formation, southernmost Jameson Land.

Fig. 6. Sheets of massive sandstone intercalated with black mudstones. Note highly irregular upper surfaces of the sandstone bodies, which step op and down over several metres. This reflect post-depositional liquefaction, fluidization and remobilisation of the original gravity flow deposit. Katedralen Member, Ugleelv, southernmost Jameson Land (Fig. 1C).

mudstones contain a body fossil fauna of ammonites (mainly *Amoeboceras*), the bivalve *Buchia* and a sparse trace fossil fauna including *Chondrites*. Fossil wood and disseminated plant debris is common. Deposition took place in relatively deep water, well below storm wave base under poorly oxygenated, dysoxic to anoxic environmental conditions and the facies represents the basinal background deposit of the formation.

Thin sandstone turbidites. – This facies, which forms a volumetrically insignificant part of the formation, consists of planar beds of muddy sandstone, a few millimetres to about one centimetre thick. Some beds are structureless, while others show an upwards succession of structureless, parallel laminated and very low-amplitude ripple cross-laminated parts. Grading is common. The beds are interpreted as classical turbidites showing T_a, T_{ab}, T_b, T_{bc} and T_c Bouma divisions deposited from low-density turbidity currents (Bouma 1962; Walker 1965).

Massive sandstones. – The most conspicuous facies consists of thick, massive sandstone varying in geometry from almost sheet-like to extremely irregular bodies (Figs 2, 3, 6–8). The sandstone bodies occur throughout the formation and are interbedded with the basinal mudstones in a highly complex way. They are up to 50 m thick and may be up to many hundreds of metres wide.

The sandstones are mainly well sorted, fine to medium grained and quartzose with a relatively high content of mica, some glauconite and occasional re-

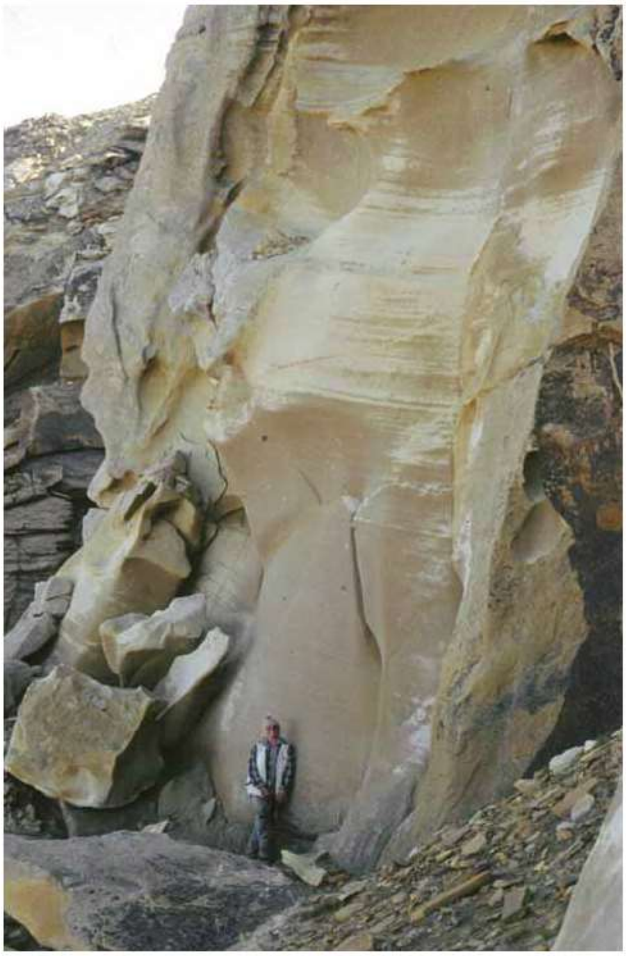

Fig. 7. Thick, massive sandstone body showing consolidation lamination. This facies is typical of the Katedralen Member, Hareelv Formation. Ugleelv, southernmost Jameson Land (Fig. 1C).

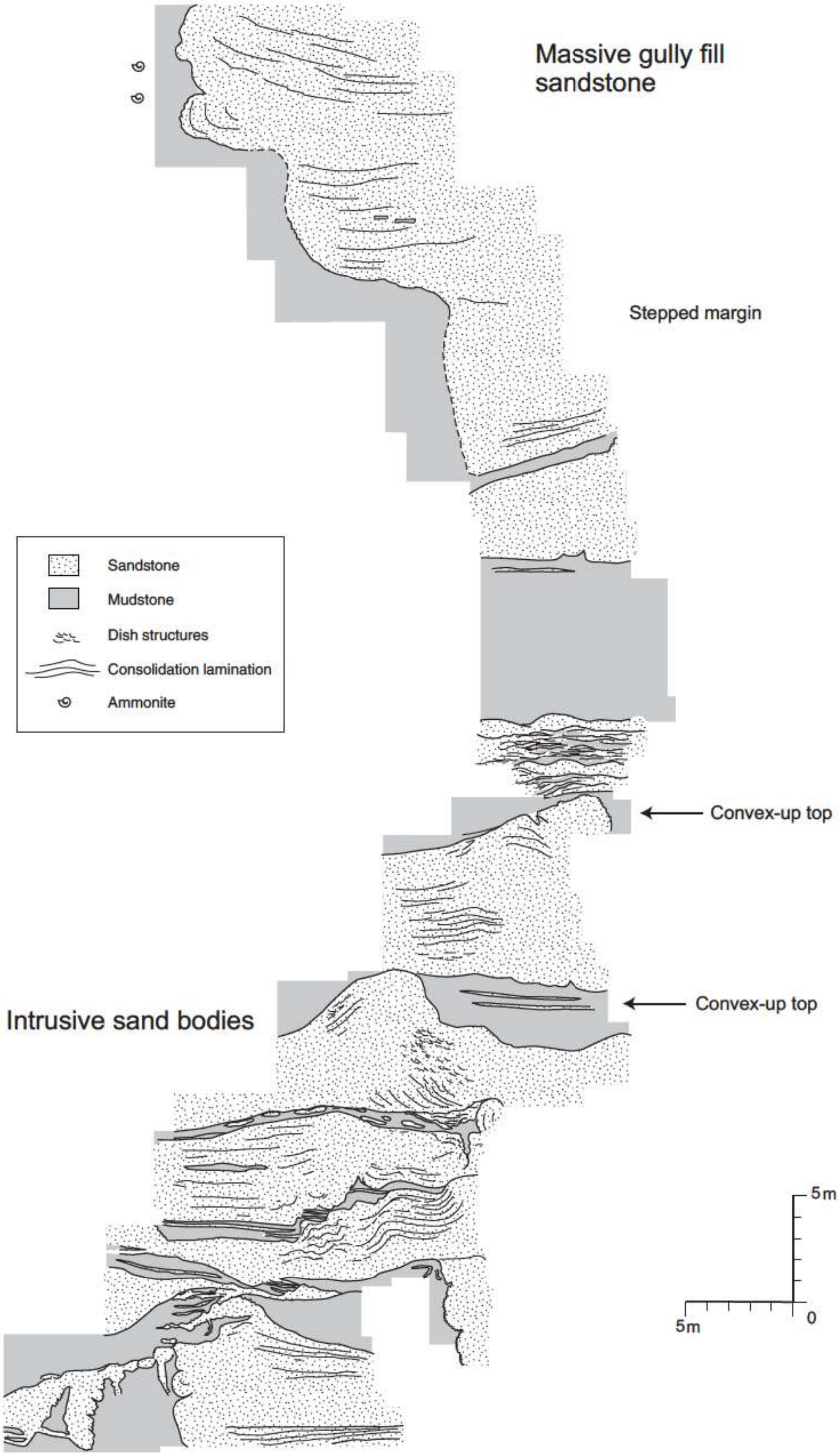

Fig. 8. Section of extremely irregular injection complex. Most of the lower sandstone bodies have mounded tops with an amplitude of 3–5 m and show gently curved consolidation lamination, in some cases followed upwards by dish structures. The upper sandstone body was deposited in a gully with stepped, vertical wall. Katedralen Member, Hareelv Formation, southernmost Jameson Land (Fig. 1).

Fig. 9. Steeply mounded top of massive sandstone body. Person is sitting on scree covering draping black mudstones. Note the flow marks on the margin of the sandstone body showing orientations varying from horizontal to a 45° plunge down to the left. The marks were formed during post-depositional diapirism of the fluidized sand. Katedralen Member, Hareelv Formation, southernmost Jameson Land (Fig. 1).

worked marine fossils. They are virtually devoid of primary sedimentary structures. Mudstone clasts are common and range in size from minute chips over metre-sized flakes to slabs more than ten metres long. The clasts are mainly angular and commonly book-shaped with flat surfaces following the primary lamination as seen by their common content of flattened ammonites oriented parallel to the lamination and flat clast surfaces. Some clasts may have curved shapes caused by plastic deformation but this is less common. Isolated closely spaced mudstone laminae representing a disrupted mudstone booklet are common. The clasts may occur completely isolated in the middle of a sandbody but are commonly most abundant along its margins.

Amalgamation surfaces occur in many sandstone bodies and are loaded, gently curved or flat and commonly outlined by irregular bands of mudstone chips. The only type of structure is diffuse, subhorisontal wavy consolidation lamination in some of the thicker bodies (Fig. 7) (cf. Lowe & LoPiccolo 1974; Lowe 1975). Dish structures and irregular water escape pipes occur but are not common (Fig. 8). A vertical succession from subhorisontal, gently curved to more irregularly curved consolidation lamination and finally to dish structures have been noted in some beds (Fig. 8) as also described by Lowe (1975) and Hurst & Cronin (2001).

The sandstones are clean and show a strong contrast to the black mudstones. Muddy sandstones are extremely rare. Fining/coarsening or thinning/thickening-upward successions are notably absent. Sandstone–mudstone boundaries are knife-sharp but extremely irregular, and all sizes of pods, wedges, tongues and sheets of sandstone are interbedded with the mudstones (Figs 3, 6–12). The base of the sandstone bodies is always sharp, commonly loaded and flat and horizontal at least over several metres. It is rarely, if ever faulted. Some of the thicker sandstone bodies have steep, vertical or even overhanging margins, which have been modified by loading and other types of flow between sand and mud (Fig. 8).

The most proximal sandstones of this facies, which are interbedded with well structured shelf-edge sands (Fig. 5) have not undergone any remobilisation but are equally structureless. This is also the case with the sheet-like sandstones of the Sjællandselv Member. The massive, structureless appearance is thus probably a primary feature.

The massive sands are interpreted as deposited from sediment gravity flows tapping a well-sorted sand source formed by current and wave winnowing of sand-dominated delta front and shelf sediments (Figs 2, 4, 5). There are no direct indications of the mechanisms of transport and deposition due to the lack of primary structures and the ubiquitous presence of post-depositional structures caused by liquefaction and fluidization. The sandstones of the Hareelv Formation are clean and the presence of fines seems not to have played any role in the development of consolidation lamination in contrast to the suggestion of Lowe & LoPiccolo (1974) and Lowe (1975). We concur with Hurst & Cronin (2001) in their interpretation of the lamination as formed by deformation of primary lamination during gravitational collapse of highly porous sand shortly after deposition. In the

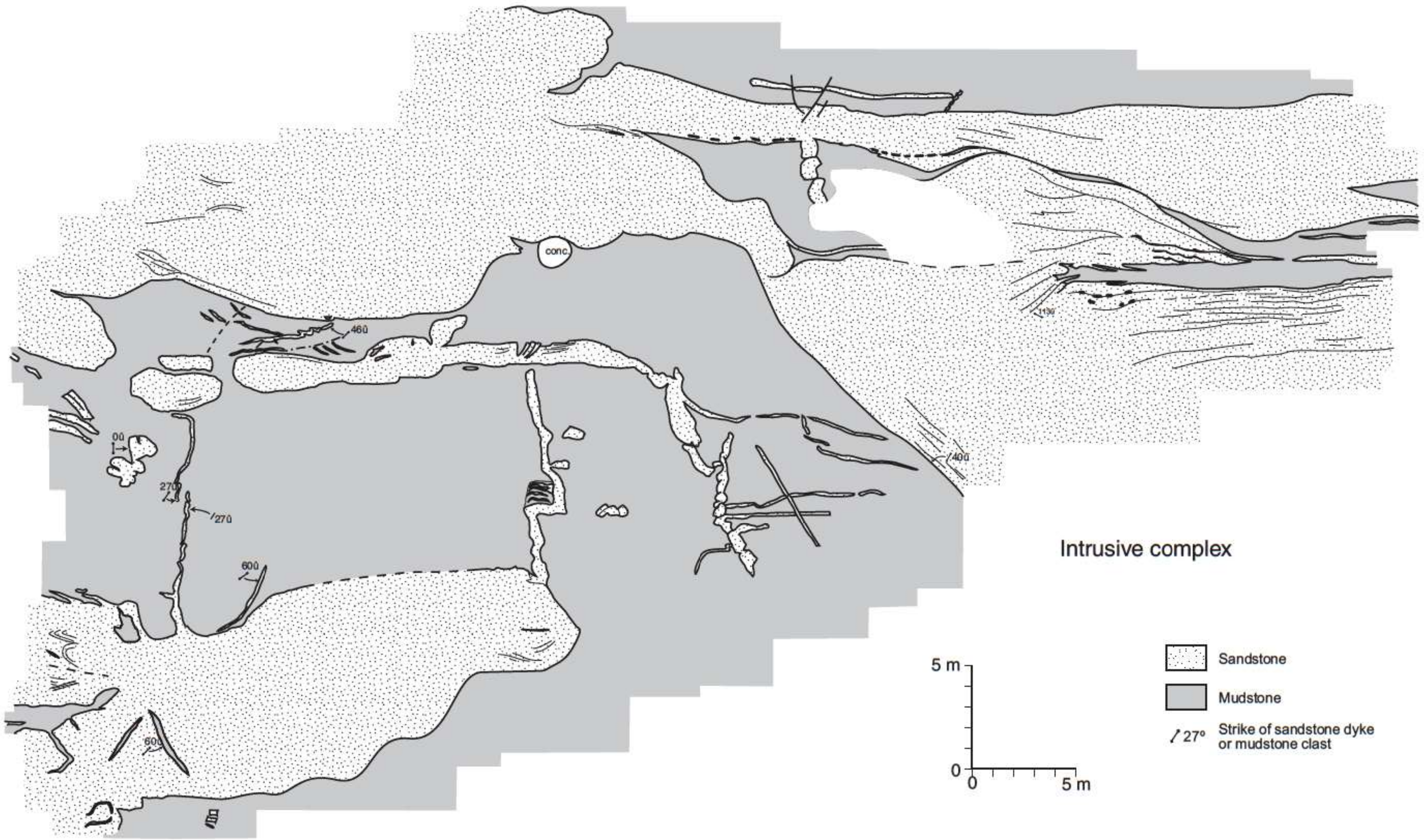

Fig. 10. Section of extremely irregular injection complex. It is impossible to estimate the degree of remobilisation of the larger sandstone bodies. Some of the thin subvertical sandstone dykes have undergone compaction folding reflecting intrusion into poorly compacted mudstone, while the thin dykes in the lower right are straight and were intruded into mudstone which were sufficiently compacted to allow development of joints. Katedralen Member, Hareelv Formation, southernmost Jameson Land (Fig. 1).

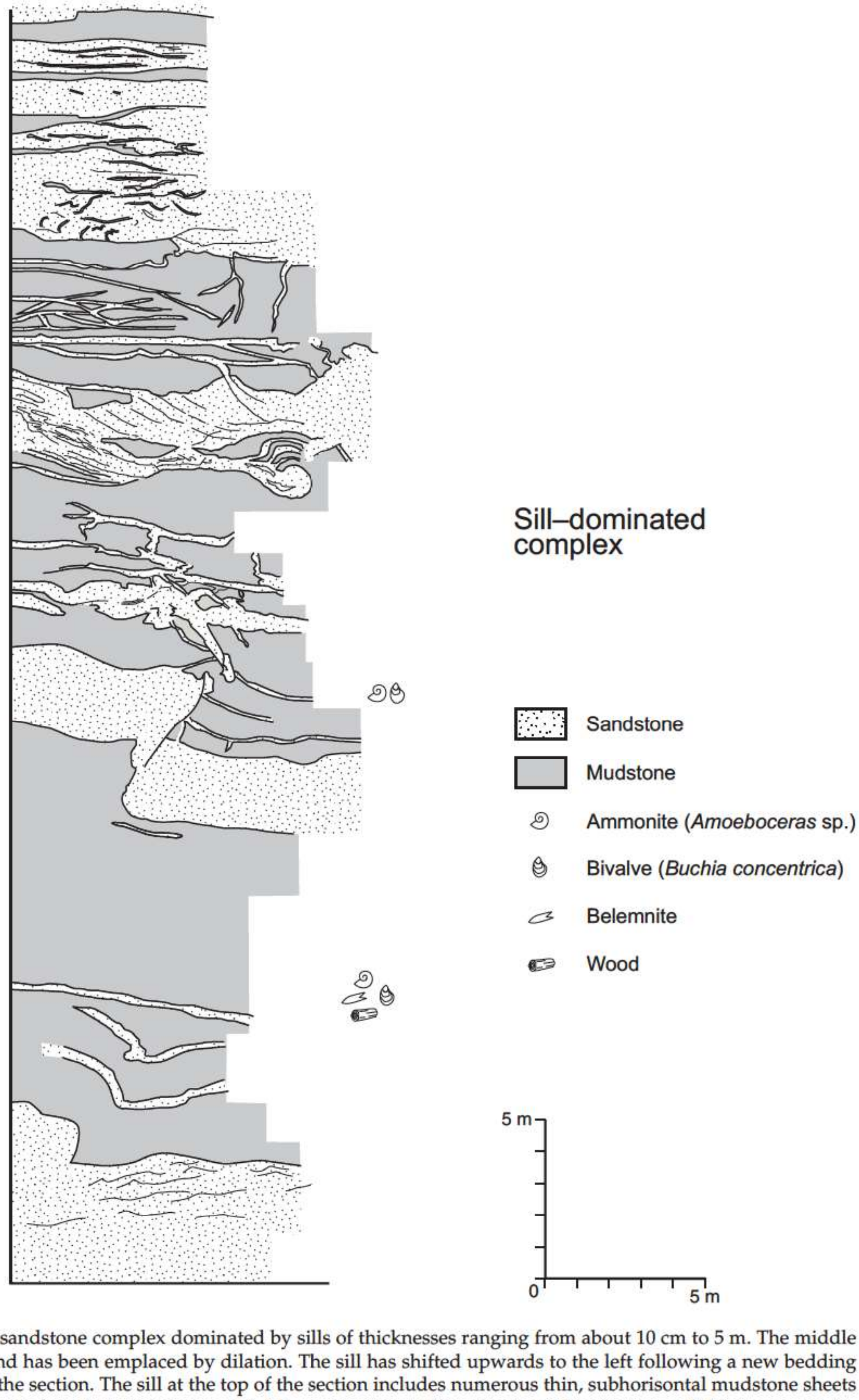

Fig. 11. Section of intrusive sandstone complex dominated by sills of thicknesses ranging from about 10 cm to 5 m. The middle sill consists of clean sand and has been emplaced by dilation. The sill has shifted upwards to the left following a new bedding plane joint, 2.5 m higher in the section. The sill at the top of the section includes numerous thin, subhorisontal mudstone sheets representing split-apart host rock and ripped-down roof. All combinations of emplacement by stoping and dilation occur, reflecting intrusion under different depths of burial and compaction cohesivity of the host mudstones. Katedralen Member, Hareelv Formation, southernmost Jameson Land (Fig. 1).

Fig. 12. Steeply inclined margin of the mounded top of massive sandstone body to the right. Five sills extend laterally into the adjacent mudstones. Their concave-up dip to the left was caused by differential compaction. Note the flow-lined surface of the sandstone mound formed during post-depositional diapirism. Katedralen Member, Hareelv Formation, southernmost Jameson Land (Fig. 1).

underlying Olympen and overlying Raukelv Formations massive sandstones occur intimately interbedded with cross-bedded delta top and upper delta front sandstones and commonly rest directly on concave-up slump scars (Fig. 5) (Larsen & Surlyk in press; Surlyk in press; Bruhn & Surlyk 2001). These massive sands have only travelled as liquefied sandflows for a maximum of perhaps a few tens of metres and the travel distance was too short to allow development of fluid turbulence. (The term liquefied sandslide is proposed for massive sands resting on a slide scar surface, whereas sandflow is suggested for sand-grade cohesionless debris flows by analogy with mudflow; W. Nemec written communication 2001). Similar massive sandstones occur, however, throughout the Hareelv Formation commonly tens of kilometres away from any shallow marine source (Fig. 6) and in these cases deposition was probably from high-concentration turbidity currents. A downslope transition from massive gully fill sandstones deposited from confined flows to sheet-like but still massive sandstones deposited at the base-of-slope from unconfined flows occurs in the Olympen Formation (Bruhn & Surlyk 2001) and has also been suggested for the Hareelv Formation (Surlyk 1987). Transport and deposition of sand thus appear to have taken place from sediment gravity flows undergoing a downslope, proximal to distal transformation from sandflows and liquefied flows to high-density turbidity currents.

The subvertical, stepped margins of many sandstone bodies reflect deposition in steep-walled chutes and gullies eroded into the slope muds (Fig. 8). However, a superficially similar geometry is in some cases formed by loading of sand directly into the slope muds. The two modes of emplacement can be distinguished by the attitude of the adjacent mudstones. If these are flat-lying and truncated the sand was deposited in a gully, while downwards bending of the mudstones on the other hand may have been caused by both large-scale syn-depositional loading of sand into the muds and by differential compaction of both gully-fill and loaded sands.

The rarity of muddy sandstones shows that the gullies were not cut by the gravity flows because in this case eroded mud would have been incorporated into the flows resulting in downslope deposition of muddy sandstones. The gullies were thus formed independently of the flows, probably by retrogressive slumping, which cut backwards into the front of the shelf-edge delta. They formed traps for those flows, which happened to be triggered upslope of the gully head and acted as funnels and downslope conduits for a few flows as indicated by the presence of amalgamation surfaces in the sandstone bodies. It is important to stress that levee deposits are notably absent. This also serves to testify that the flows and the gullies or chutes are independent phenomena and that the latter did not serve as long-term open transport conduits for the flows. Similar gullies have been described from many modern slopes (e.g. Field et al. 1999; Spinelli & Field 2001).

Post-depositional modifications of sandbody geometry

The upper boundary of the more sheet-like sandstone bodies, the sandstone lobes of Surlyk (1987), steps up and down on millimetre, centimetre, decimetre and metre scales (Fig. 6). Some of the decimetre-scale steps are formed by small, commonly conjugate normal faults, which extend upwards into the overlying mudstones for at maximum a few metres but most of the steps appear unrelated to faulting. The faults may be related to the polygonal faults formed during early burial and particularly well known from the Palaeogene of the North Sea (Lonergan & Cartwright 1999). The faults of the Katedralen Member are obviously also of early burial origin, but have much smaller throws and were not intruded by fluidized sand.

Fig. 13. Sandstone dykes and sill complex. The intrusions in the middle of the picture show an orthogonal relationship indicating that the mudstones were sufficiently compacted to develop joints at the time of intrusion. The lower dykes and sills in contrast show irregular, curved geometries reflecting intrusion during more shallow burial. Katedralen Member, Hareelv Formation. Gåseelv (Fig. 1C).

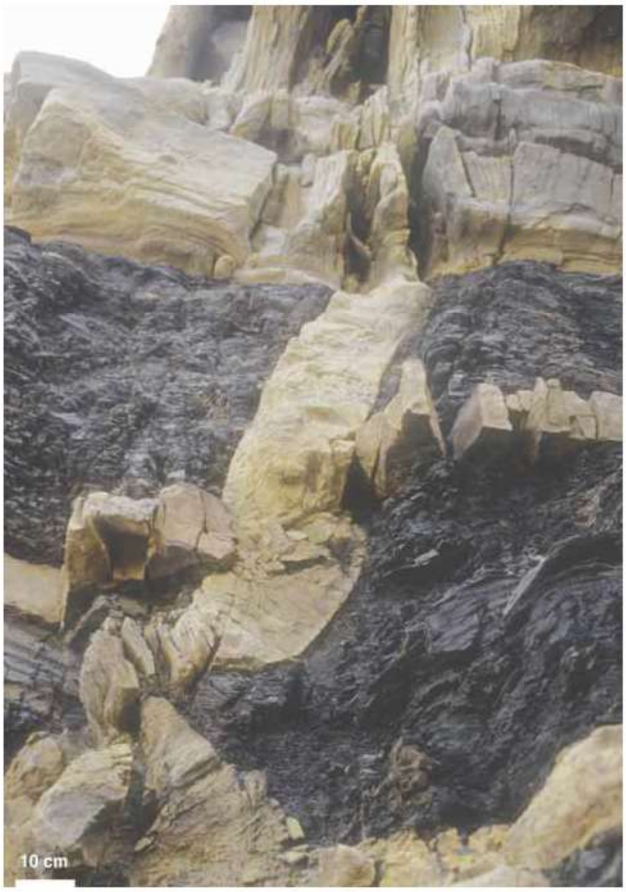

Fig. 14. Cross-cutting sandstone dykes and sills. Note ptygmatic compaction folding of the subvertical dyke. The upper sandstone is also a sill although it shows strong similarity to a massive sandstone turbidite. Katedralen Member, Hareelv Formation, Katedralen (Fig. 1C).

Many of the larger sandstone bodies have a mounded top, quite commonly with a conical onion shape showing flank dips up to 60° (Figs 8, 9, 12). The bedding in the surrounding mudstones is dominantly horizontal except for layers immediately adjacent to the larger sandstone bodies and slump folding is extremely rare. Faults have not been observed along the steeply dipping sandstone-mudstone interfaces and the mudstones did not slide off the mounds along any type of detachment plane. The original depositional upper surface of the sands was undoubtedly flat and horisontal, reflecting their gravity flow origin. The mounded shape of many sandstone bodies was thus formed by intrusive diapirism.

The sandstone–mudstone interfaces, especially of the onion-shaped mounds and the margins of dykes and sills show marks resembling turbidite sole marks such as flute, rill, frondescent and groove marks (Figs

9, 12). They do not show any persistent orientation but may be orientated around the full compass circle on a single onion-shaped sandstone surface. Plunge varies from horizontal to vertical, but low angles between horizontal and about 30° are most common (Figs 9, 12). In spite of the spurious resemblance with sole marks they are formed by flow moulding during post-burial remobilisation and injection. Similar marks were termed rheoplasts and interpreted as resulting from liquefaction, injection and flow moulding by Poll and Patel (1981).

Sandstone dykes and sills occur throughout the formation commonly in great density and showing a high degree of complexity including boudinage, offshoots, branching, ptygmatic folding, and they commonly contain slabs of the host rock (Figs 3, 8, 10–13). The sills may be transgressive on all scales and they vary in thickness from millimetres to many metres. Thicker sills are transitional to remobilised sandstone bodies and there is no clear distinction between the two groups (Figs 3, 8, 10–13). Distinction between sills and turbidites is not difficult due to the transgressive, truncating nature of the sills even on a millimetre to centimetre scale. The sills in addition consist of clean, massive sandstone, while the uncommon thin turbidites consists of muddy sandstone showing various combinations of T_a, T_b and T_c divisions. Dykes and sills may occur in such a high density that they occupy the bulk sediment volume so that the host mudstone is only represented by displaced and irregular, commonly folded, laminae and lamina sets. Curved, concave-up sills commonly extend downwards away from the onion-shaped sandstone mounds (Fig.12). The sills were probably originally horizontal and were intruded laterally into the mudstones from the sand body during diapirism. The present orientation and geometry is interpreted as caused by differential compaction.

Sandstone dykes are commonly folded in a ptygmatic style caused by post-intrusive compaction of the surrounding mudstones (Figs 10, 14). The total length of a folded dyke compared to its vertical extent gives a measure of the degree of compaction, commonly around 40–50% (cf. Hiscott 1979). Some dykes and sills show roughly orthogonal relations where the sills follow bedding planes in the mudstones, while the dykes are subvertical (Fig. 13). The mudstones were in such cases sufficiently compacted at the time of intrusion to allow development of joints. The occurrence of brittle fracture indicates that the injections imposed large strain. Other intrusions are completely irregular, winding and curved, reflecting intrusion in a poorly consolidated mudstone under shallow burial (Figs 10, 11, 13).

The extremely variable geometries of the intruded sandstones commonly occur at the same stratigraphic level in a section reflecting repeated intrusive events under increasing depths of burial. This is also shown by cross-cutting relations and different degrees of compaction folding (Fig. 14). Systematic geometrical relationships between dykes and sills and the larger sandstone bodies have not been identified. Dense networks of dykes and sills seem to occur completely randomly with respect to the sandstone bodies.

Examples of injection complexes above large mounded sandstone bodies as have been interpreted from the Palaeogene of the North Sea (Dixon et al. 1995) have not been observed. The onion-shaped mounded bodies in the Hareelv Formation on the contrary seem to be overlain by relatively thick mudstone successions with relatively few dykes and sills.

The massive nature of all the sandstones, their extremely irregular geometries, the dramatic changes in thickness over short distances, the loaded bases and margins of the sandstone bodies, the ubiquitous occurrence of sandstone dykes and sills, and the common presence of consolidation lamination and more rarely of dish and pillar structures indicate that the sands of the Hareelv Formation were liquefied, fluidized and remobilised subsequent to deposition. Liquefaction comprises at least three processes: 1) fluidization resulting from pore fluid movement; 2) liquefaction caused by cyclic shear stress; and 3) shear liquefaction resulting from application of a shear stress across a sandbody (Nichols 1995). Each of the processes results in a different set of deformations of the liquefied sandbody. The three processes tend to interact in the natural environment and sands become more susceptible to liquefaction by interaction of the processes (Nichols 1995). The rheology of the surrounding sediment and the nature of the stress field controls the geometry of remobilised and injected sand.

The importance of large-scale loading during deformation of the Hareelv sand bodies suggests that liquefaction and fluidization was caused by shock or vibration as shown by experiments (Anketell et al. 1970; Nichols 1995). Other types of water escape structures are much less common, although some sandstone bodies show abundant convolutions, dish structures and fluidization pipes. Liquefaction by fluidization thus played an additional, albeit minor, role in additions to shocks (cf. Nichols 1995). One of the examined sandstone bodies shows upward transitions from a gently loaded base to more strongly loaded lateral margins, and internal transitions from subhorisontal, slightly wavy consolidation lamination to densely spaced dish structures in the upper part have been observed (Fig. 8). This indicates that more water passed through the higher parts of the sandbody so that both liquefaction by shock and fluidization occurred. The extreme irregularity of the sandstone bodies of the intrusive complex does not allow identification of linear ridges or convolute lamination with preferred orientations indicative of liquefaction by slope shear stress (cf. Anketell et al. 1970).

Measured sections show that it may be extremely difficult or impossible to distinguish true, completely remobilised and far-traveled intrusive sands from sands, which have undergone only minor remobilisation and injection (Figs 8, 10). Even thick subhorisontal, massive beds looking like normal primary beds known from many turbidite successions commonly show intrusive features at their lateral terminations.

The sharp upper surfaces of mounded sandstone bodies show that outflow of liquefied sand on the seafloor did not take place. Liquefaction, fluidization, remobilisation and injection of sand into the surrounding mudstones thus took place after burial ranging from several metres to many tens of metres. It cannot be excluded, however, that some of the smaller dykes and sills were intruded in connection with deposition of large sandbodies. The dominantly regular shape of many mudstone clasts shows, however, that the surrounding mudstones normally had undergone substantial compaction at the time of remobilisation and intrusion. The ubiquitous presence of load structures, compaction folded dykes, flow marks on sandstone–mudstone interfaces and the occurrence in some sandstone bodies of plastically deformed and sheared clasts indicate on other hand that liquefaction, fluidization and injection also took place at shallower depths. Remobilisation and intrusion thus took place more or less continuously during deposition of the formation, i.e. over a time interval of about 10 million years, from the Late Oxfordian through the Volgian.

Causes of fluidization and liquefaction

Factors controlling remobilisation were either allochthonous and operational over a very long time interval or autochthonous and related to the processes active during deposition of the formation. The data from the Hareelv Formation show that fluidization, liquefaction, remobilisation and injection was caused by shocks and vibration, while it is not possible to directly prove the influence of gravitational shear stress. The importance of the latter process can be inferred indirectly, however, because most sands were deposited on a slope and at the base-of-slope. There is thus little doubt that shear-liquefaction also played a role in addition to the two other processes. Important features which have to be considered in the interpretation of the remobilised sandbodies include their isolated occurrence within a sealing mudstone and the timing and duration of causal factors.

The triggering processes were active more or less continuously over at least 10 million years in the Late Jurassic corresponding to the culmination of the main Mesozoic rift event in the North Sea – North Atlantic region. In northern East Greenland rifting intensified through the Late Oxfordian – Kimmeridgian to reach a climax in the Volgian with formation of deep halfgraben basins and deposition of thick successions of deep-water conglomerates (Surlyk 1978, 1984, 1989). In the Jameson Land area further south the rift climax seems to have occurred somewhat earlier, in Late Oxfordian – Kimmeridgian time (Surlyk & Noe-Nygaard 2000a; Surlyk in press).

The pervasive fluidization and liquefaction of all sandbodies in the Hareelv Formation are thus interpreted as caused by earthquake shocks during an extended period of intensive rifting in the region. Additional factors include build up of pore pressure by loading and slumping, slope shear stress, upwards movement of pore waters expelled from the compacting muds, and the presence of mudstone seals (Fig. 15). The repeated rapid loading of the muds by large volumes of sand is considered an important factor. Other possible agents include migration and trapping of shallow gas and dissociation of gas hydrates. Carboniferous lacustrine mudstones exposed on the south coast of Traill Ø are excellent potential source rocks (Christiansen et al. 1992) and the correlative strata in Jameson Land were in the oil window in Late Jurassic time. There is, however, no evidence for migration of hydrocarbons generated in Carboniferous rocks in Jameson Land. Shallow mounded sands from the Quaternary of the North Sea have been attributed to migration of gas to shallow levels along fault conduits (Brooke et al. 1995). The lack of faults cutting the Mesozoic rocks in southern and central Jameson Land and the relatively great thickness of the Hareelv Formation makes this interpretation less likely. It is also significant that signs of remobilisation are unknown from other formations of mixed sand–mud lithology in Jameson Land. Parts of the Hareelv Formation and its correlatives in Milne Land are good source rocks for oil; the sandstone bodies contain light gasses which seem to have formed in the surrounding mudstones (Requejo et al. 1989) and it is possible that shallow gas has been generated in the mudstones during early states of burial. The fact that liquefaction and fluidization took place throughout an extended pe-

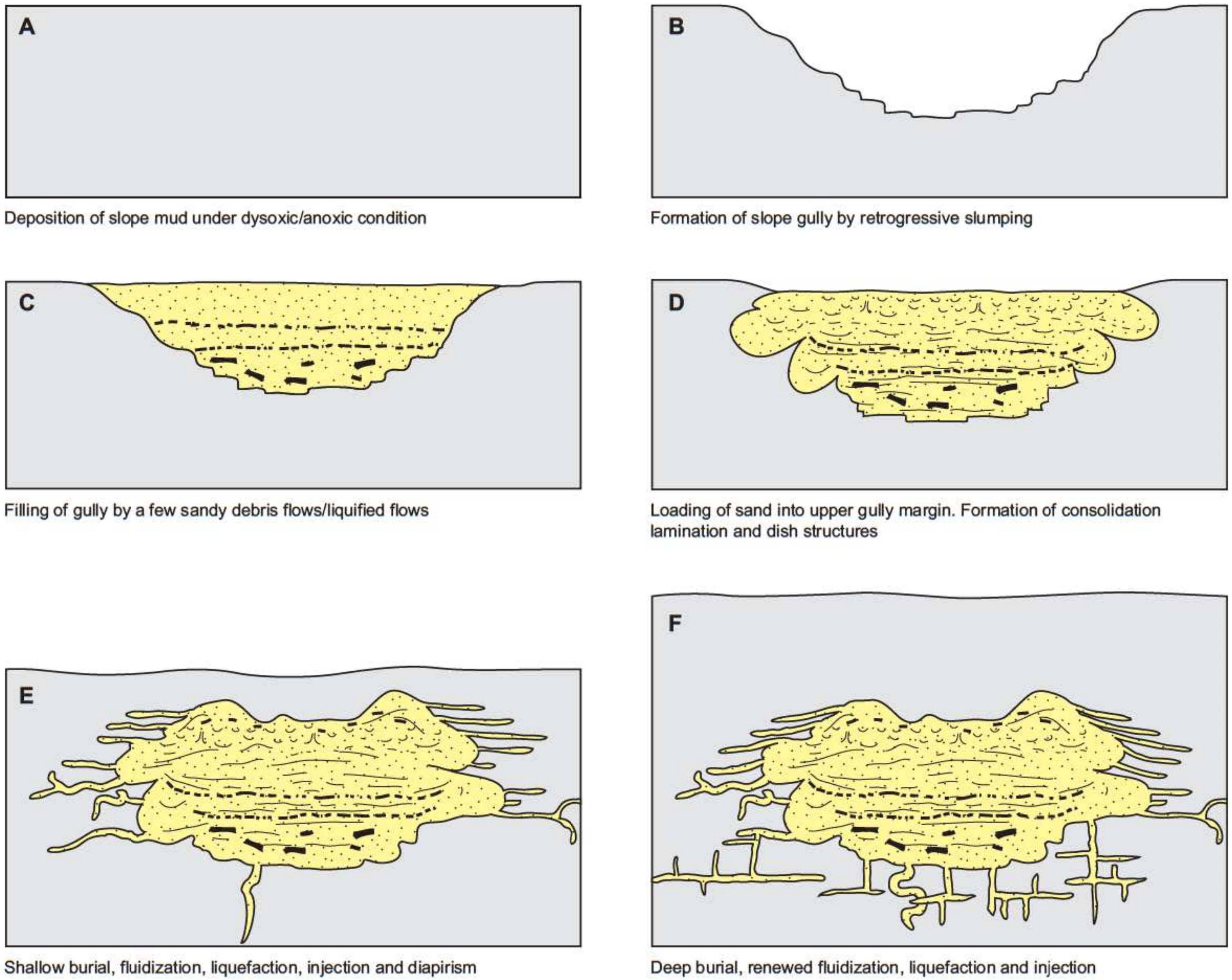

Fig. 15. Model for the fluidization, liquefaction, remobilisation, intrusion and diapirism of sandstones in the Hareelv Formation, Jameson Land, East Greenland. A and B show deposition of black mud under dysoxic to anoxic conditions and formation of slope gully by retrogressive slumping. The gully walls are commonly stepped with subvertical segments. In C the gully is filled by a few sandflows as indicated by amalgamation surfaces outlined by stringers of mudstone chips and small clasts. In D the massive gully-fill sand is loaded into the still unconsolidated upper gully walls. E shows mounding of sandbody and injection of sand dykes and sills after shallow burial. Large mudstone clasts are ripped down from the overlying mudstone during remobilisation and intrusion. F shows a second remobilisation event under deeper burial. The lateral wing-like sills of the mounded top are deformed by differential compaction, early dykes are ptygmatically compaction folded and cross-cut by later intrusions and the consolidated lower part of the mudstone succession has developed regular orthogonal vertical and horisontal joints which are intruded by sand. The indicated depth of burial is schematic and probably amounted to several tens of metres.

riod of time characterized by high sea-level stand (Surlyk 1990; Hallam 1992) speaks against degradation of gas hydrates as a cause. It is, however, interesting to note that sudden release of methane from buried gas hydrate seems to have taken place during the Early Toarcian, a period of high sea-level stand and widespread oceanic anoxia (Hesselbo et al. 2000) in many ways similar to the depositional conditions of the Upper Jurassic Hareelv Formation. A similar interpretation has been offered for a short-lived Middle Oxfordian negative carbon isotope excursion (Padden et al. 2001).

Field analogue for hydrocarbon reservoirs

The Hareelv Formation is an excellent field analogue for some deeply buried hydrocarbon reservoirs of unusual shapes. The reservoir sandstones of the Gryphon, Alba, North/Harding and other fields in the North Sea have steep-sided, commonly mounded and convex-up geometries and cores show abundant intrusive sands (e.g. Jenssen et al. 1993; Dixon et al. 1995). These reservoir sands have been variously interpreted as turbidite fills of elongate erosional gullies (e.g. Den Hartog Jager et al. 1993), as convex-upward debrites (Shanmugam et al. 1995, 1996) or as remobilised and injected sands (Dixon et al. 1995). The latter explanation is receiving increasing support by better seismic resolution, retrieval of additional cores and not least by increasing attention to the relatively few field analogues such as the Hareelv Formation. The Forth Fields area shows a great resemblance to the Hareelv Formation which appears to have served as a depositional model (compare Fig. 7 in Dixon et al. (1995) with Fig. 3 in Surlyk (1989)). The interpretation of the Gryphon/Harding Field involved intrusion of sand along listric detachment faults (Newman et al. 1993; Dixon et al. 1995). Such faults have not been observed in the Hareelv Formation and the margins of mounded sandstone bodies are non-faulted except for the much smaller conjugate faults commonly intersecting the top of sheet-like sandstones. The mounded sandstone bodies of the Hareelv Formation was deposited during a major rift event, whereas the Palaeogene was a time of tectonic quiescence in the North Sea. Remobilisation of the Hareelv sandbodies took place repeatedly over a long time interval while it appears to have been a short episode in the North Sea.

Remobilised sand bodies such as those of the Hareelv Formation are commonly sufficiently large to form economic hydrocarbon reservoirs. This is especially the case if several sand bodies are amalgamated. They may be difficult to locate and interpret correctly because of their extremely irregular shape especially if they occur in the deeper part of the basin. Sandy intrusions may in addition play an important role in draining potential source rocks such as the Hareelv Formation. Their presence in basinal mudstones improves reservoir connectivity, and they may form pathways for hydrocarbon migration into shallower, regular and more predictable sandbodies such as shelf-margin wedges. Sandstone dykes and sills are commonly observed in cores and if correctly identified suggest the presence of larger sandstone bodies in adjacent strata.

Conclusions

The Upper Oxfordian – Kimmeridgian Katedralen Member of the Hareelv Formation (Jameson Land, East Greenland) represents a common but somewhat overlooked class of line-sourced, disorganized sandy mass-flow system derived from the failure of shelf-margin wedges. The formation is 200–400 m thick and covers an area of 55×70 km. The Katedralen Member consists of black mudstone and interbedded massive sandstone bodies associated with numerous sandstone dykes and sills. The sandstone bodies are large and massive, tens of metres thick, hundreds of metres wide and in some cases of kilometre length. They are randomly distributed throughout the member and consists of well-sorted fine-to-medium grained sand. The sand was deposited on the slope commonly in steep-sided erosional gullies, and as more sheet-like bodies at the base-of-slope and in the basin. Transport and deposition was from liquefied flows which underwent down-slope transformation into high-density turbidity currents. The travel distance of the flows ranged from a few tens of metres to several tens of kilometres.

Post-depositional fluidization, liquefaction, remobilisation and subsequent injection of sand into surrounding mudstones strongly modified the mass-flow system and resulted in the formation of a complex of highly irregular, interconnected sandstone bodies, dykes and sills on all scales. Remobilisation took place over long time intervals ranging from almost syn-depositional to rather deep burial and on scales ranging from a few centimetres to hundreds of metres. Intrusion of sand took place by stoping and dilation depending on the depth of burial and consolidation of the host mudstones. These modifying factors are important to consider in the construction and application of deep-water facies models.

The formation was deposited during the main Mesozoic rift phase in East Greenland and liquefaction is interpreted as caused by cyclic loading of seismic shocks combined with the effects of overpressure induced by loading, rapid burial, slope shear stress and possibly hydrocarbon migration.

The Katedralen Member provides an excellent field analogue for some complex subsurface Jurassic and Palaeogene hydrocarbon reservoirs in the North Sea, the Cretaceous of the Norwegian shelf and many other areas. The excellent exposures allow study of sandbody size, geometry and interconnectedness. Some of the amalgamated sandstone bodies are sufficiently large to be potential hydrocarbon reservoirs in their own right. The network of sandstone dykes and sills provides a highly effect drainage system for the hydrocarbons generated in the host source rock. In addition they may form a migration pathway to shallow, well organized shelf-margin sandstone wedges, which form more obvious exploration targets.

Dansk sammendrag

Hareelv Formationen (Øvre Oxfordien – Volgien) i Jameson Land, Østgrønland er 200–400 m tyk, dækker et areal på 55×70 km og består af sorte muddersten og uregelmæssige massive sandstenslegemer. I Katedralen Leddet (Øvre Oxfordien – Kimmeridgien), der er hovedemnet for denne artikel er sandstens/mudderstensforholdet omkring 0.5. Det repræsenterer en relativt almindeligt men ofte overset type uorganiseret sandet massestrømssystem aflejret på og ved foden af undersøiske skråninger. De sandede strømme opstod ved kollaps af sokkelrandsdeltaer. Sandstenene optræder som massive legemer op til tital af meter tykke, hundreder af meter brede og i nogle tilfælde op til flere kilometer lange. Sandstenslegemerne er tilfældigt fordelt gennem hele leddet og består af velsorteret fin- til mellemkornet sand. Sandet blev aflejret i erosive skråningskløfter med stejle ofte terrasserede sider eller som mere planare legemer ved mundingen af kløfterne. Transport og aflejring skete fra sandede debrisstrømme og likvifierede strømme som undervejs ned af skråningen transformeredes til højdensitetsturbiditstrømme. Transportlængden varierede fra nogle få tital af meter til tital af kilometer.

Efter aflejringen og påbegyndt begravelse blev sandet likvifieret, remobiliseret og intruderet i de omgivende sorte muddersten. Den omfattende modifikation af aflejringsstystemet resulterede i dannelsen af et kompleks af uregelmæssige, forbundne sandstenslegemer, gange og 'sills'. Remobiliseringen fandt sted over et meget langt tidsrum på omkring 10 millioner år fra næsten samtidig med aflejring til relativ dyb begravelse. Formationen aflejredes under den betydeligste tektoniske strækningsfase i Østgrønlands Mesozoikum og likvifieringen tolkes som resultat of jordskælv kombineret med virkningerne af overtryk, udpresning af mudderstenenes porevand, skråningsskærspænding, og mulig kulbrinte migration og udstrømning.

Hareelv Formationen og især Katedralen Leddet udgør en nyttig analogmodel for komplekse, dybtbegravede Jura og Palæogen kulbrintereservoirer i Nordøen, i Kridt reservoirer på den norske sokkel og mange andre steder. De gode blotninger muliggør studiet af sandstenslegemernes størrelse, geometri og rumlige sammenhæng. Nogle af de amalgamerede sandstenslegemer er store nok til at være mulige kulbrintereservoirer i sig selv. Netværket af gange og 'sills' kan fungere som dræneringssystem for kulbrinter dannede i de omgivende muddersten og som migrationsveje til højere liggende, velorganiserede sokkelrandsdeltaer som udgør et bedre efterforskningsmål.

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