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A Giant Sand Injection Complex: The Upper Jurassic Hareelv Formation of East Greenland

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Key words: Sediment remobilisation, Intrusion and injection, Sandstone dykes and sills, Upper Jurassic, Hareelv Formation, East Greenland.

Abstract

A major intrusive sandstone complex of Late Jurassic age is spectacularly exposed in Jameson land, East Greenland. It is probably the largest in the World, and covers an area of 55x70 km with a thickness of 200–400 m, and forms the Upper Oxfordian–Volgian Hareelv Formation. The complex consists of black basinal mudstones and highly irregular sandstone bodies, dykes and sills. The sand was derived from collapse of the front of sandy shelf-margin wedges, which triggered hyperconcentrated to concentrated density flows, and deposited massive sands further down the slope, at the base-of-slope and in the basin. The sand of some flows was loaded into the slope muds while elsewhere it flowed in steep-sided gullies formed by retrogressive slumping of the slope muds. All sand bodies were liquefied subsequent to burial and the sand was intruded into the surrounding black compacted muds and mudstones. Intrusion took place repeatedly over a long time interval, in environments ranging from very shallow to relatively deep burial, and the primary sediment structures of the sands were generally lost during these processes. It is rarely possible to determine the degree of post-burial remobilization but it ranges from rather small-scale modifications to wholesale liquefaction and out-of-place intrusion of the sand over many tens of metres. Sandstone dykes and sills occur ubiquitously and were emplaced by all combinations of stoping and dilation. The intrusive sand bodies range in dimensions from centimetres to many hundreds of metres. Deposition took place during the most important Mesozoic rift event in East Greenland and the pervasive remobilization and liquefaction of all sand bodies in the Hareelv Formation is interpreted as having been caused mainly by cyclic earthquake 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 also possibly of biogenic and thermogenic gas. The Hareelv Formation is an excellent field analogue for deeply buried hydrocarbon reservoirs, which have been modified by remobilization and injection of the sands.

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1. INTRODUCTION

Sandstone intrusions have always caught the attention of geologists and are in many cases highly spectacular due to the contrast between light-coloured intrusive sandstones and dark host mudstones. In recent years it has become increasingly clear, that large, irregular bodies of massive sandstone may also be of intrusive origin, but the timing and nature of remobilization of the primary deposit, and of the subsequent injection are less well understood. It is also being recognized that remobilized and injected sands, mainly of relatively deep-water origin, may form important hydrocarbon reservoirs, which are difficult to interpret.

The Upper Jurassic Hareelv Formation of Jameson Land, East Greenland is probably the World's largest intrusive sandstone complex (SURLYK, 1987; SURLYK & NOE-NYGAARD, 2001). It comprises sandy submarine density flow deposits, which have undergone post-depositional remobilisation, liquefaction and subsequent intrusion in the surrounding compacted muds and mudstones. The sediments were sourced from shelf-edge wedges and deltas. Interpretation of the depositional processes is, however, hampered by destruction of the primary sedimentary structures during remobilisation and liquefaction. However, a spectrum of sedimentary density flows involving hyperconcentrated and concentrated density flows (in the sense of MULDER & ALEXANDER, 2001) can be interpreted, depending on the position on the slope, degree of confinement and travel distance (SURLYK & NOE-NYGAARD, 2001; BRUHN & SURLYK, in press). Deposition took place in steep-sided slope gullies or in a non-confined base-of-slope and basinal setting. The aim of this study is to review the main processes acting during sand intrusion, and to interpret the possible causes. The extensive intrusive complex of the Hareelv Formation serves as a key example in order to facilitate the interpretation of similar subsurface examples.

2. LATE JURASSIC GEOLOGICAL SETTING, PALAEOGEOGRAPHY AND FACIES PATTERNS

The Upper Oxfordian–Volgian Hareelv Formation was deposited in the southern end of the Mesozoic rift-basin of East Greenland during the Jurassic rift climax. The

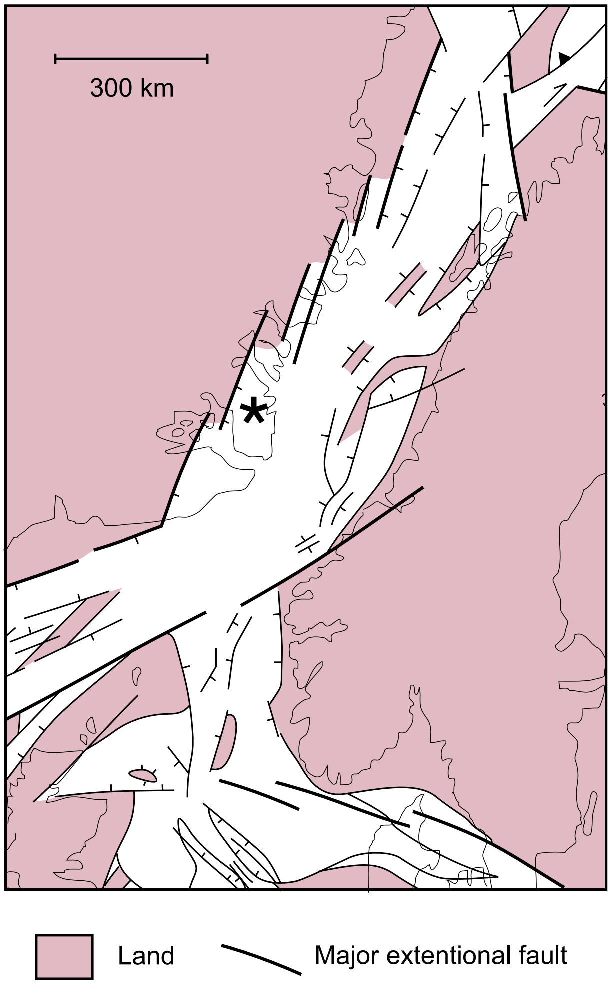

Fig. 1 Pre-drift map showing the position of Jameson Land (asterisk) in Late Jurassic time and the main basin-controlling faults.

formation is 200–400 m thick, extends over an area of 55x70 km and is well exposed (Figs. 1 and 2). The Upper Oxfordian–Kimmeridgian part of the formation belonging to the Katedralen Member is only represented by slope and basinal deposits, and correlative shallow-marine sediments are not preserved, whereas the Volgian part includes a complete shelf-slope-basin transition.

In Late Jurassic time a northern sand-dominated coastal and shallow shelf area was separated from the southern mud-dominated basin by a roughly east–west trending shelf-slope break in central Jameson Land (Fig. 2). Deltaic and shallow-marine sands reached the shelf edge during successive progradational episodes, and shelf edge failure triggered flows of sand, which were deposited as massive sand bodies on the slope, at the base-of-slope and on the basin floor (Figs. 3 and 4). The maximum Late Jurassic transgression took place in the Kimmeridgian, and deep-marine conditions existed south of the shelf-slope break in Jameson Land throughout the Late Oxfordian–Kimmeridgian during deposition of the Hareelv Formation.

The Hareelv Formation consists of clean sandstone and dark-grey to black mudstone (Fig. 5). The mudstone is organic-rich, in part with excellent hydrocarbon source rock potential. It is laminated, and has a TOC content up to 12%, but the amount of marine kerogen is lower, at about 4% (CHRISTIANSEN et al., 1992). The mudstones contain ammonites, 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 dysaerobic conditions, and the mudstones represent the basinal background deposits of the formation.

Thin planar sandstone turbidites occur interbedded with the mudstones, but form a volumetrically insignificant part of the formation. They consist of beds of muddy sandstone, a few millimetres to about one centimetre thick, showing classical Ta, Tab, Tb, Tbc and Tc divisions. They were deposited from low-density turbidity currents.

The most conspicuous facies in the formation consists of massive sandstone forming extremely irregular sandstone bodies. They occur throughout the formation and are interbedded with the basinal mudstones in a highly complex way. They are up to 50 m thick and up to many hundreds of metres wide, but thicker amalgamated sandstone bodies also occur (Figs. 6 and 7). The sandstone/mudstone ratio is approximately 1:1 in the Upper Oxfordian–Kimmeridgian part of the formation. The sandstones are massive, mainly well sorted, fine to medium-grained and quartzose with a relatively high content of mica, some glauconite and occasional reworked fossils. 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. Some clasts may have curved shapes caused by plastic deformation but this is less common.

Amalgamation surfaces occur in many sandstone bodies and may be loaded, gently curved or flat and are commonly outlined by irregular bands of mudstone chips. The only type of structure is a diffuse, sub-horizontal wavy consolidation lamination in some of the thicker bodies (Fig. 8). Dish structures and irregular water escape pipes occur but are not common.

The sandstones are clean with sharp boundaries to the mudstones, and muddy sandstones are extremely rare (Figs. 5, 7, 10, 11 and 12). Fining/coarsening or thinning/thickening-upward successions are notably absent. Sandstone–mudstone boundaries are extremely irregular. The base of the sandstone bodies is always sharp, commonly loaded, flat and horizontal for up to a few metres, and rarely, if ever faulted. Some of the thicker sandstone bodies have vertical or even overhanging margins, and were deposited in steep-walled gullies eroded into the slope muds; the fill was commonly modified by loading of sand into the slope and basinal muds. The massive sands are interpreted as having been deposited from hyperconcentrated to concentrated sedimentary density flows, tapping a well-sorted

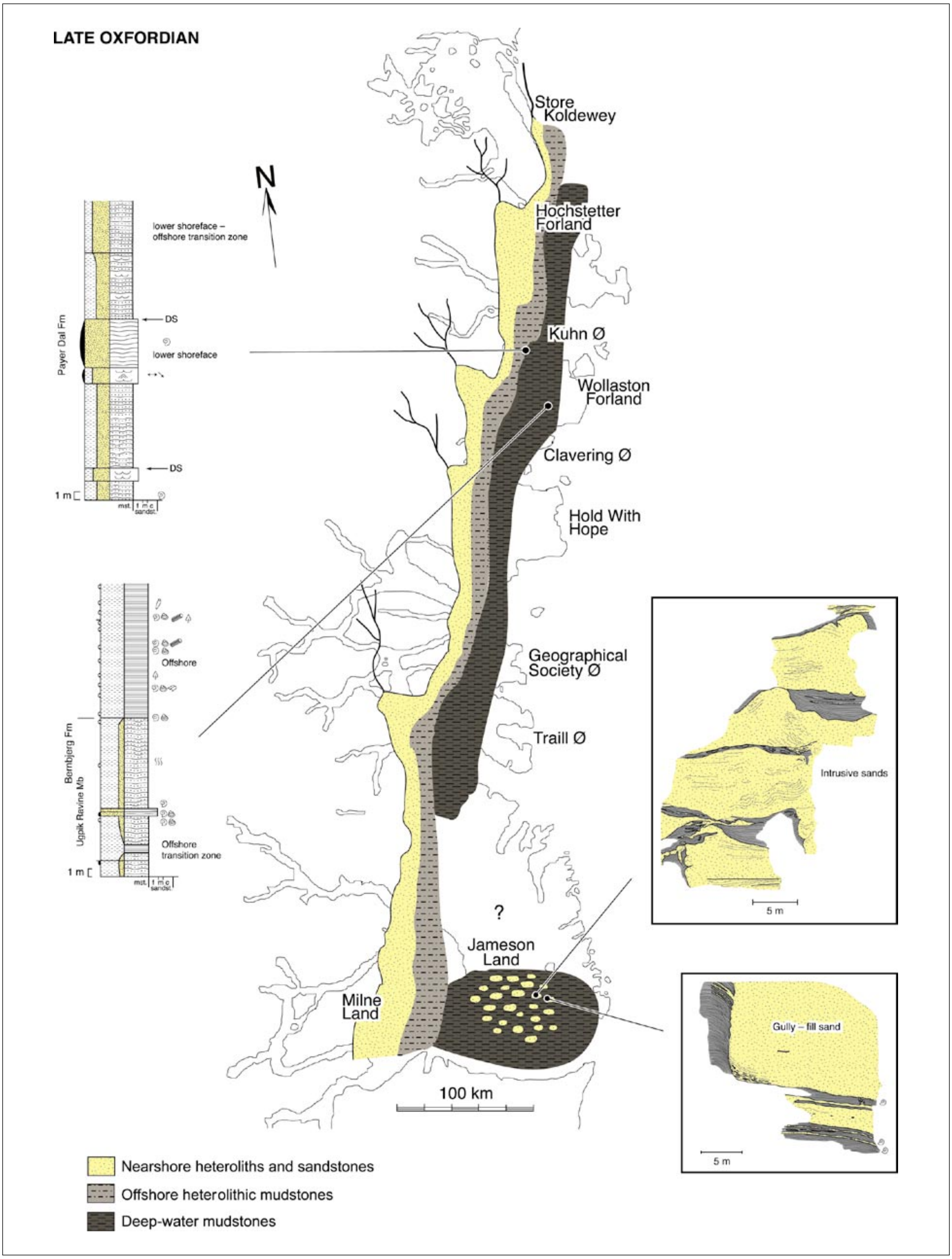

Fig. 2 Palaeogeographic map of East Greenland in the Late Oxfordian.

sand source formed by current and wave winnowing of sand-dominated delta front and shelf sediments (Figs. 3 and 4). A downslope transition from massive gully fill sandstones transported and deposited from confined flows, to sheet-like but still massive sandstones deposited at the base-of-slope from unconfined flows, occurs in the Lower–Middle Oxfordian Olympen Formation (LARSEN & SURLYK, 2003; BRUHN & SURLYK, in press), and has also been suggested for the Hareelv Formation (SURLYK, 1987). This indicates that trans-

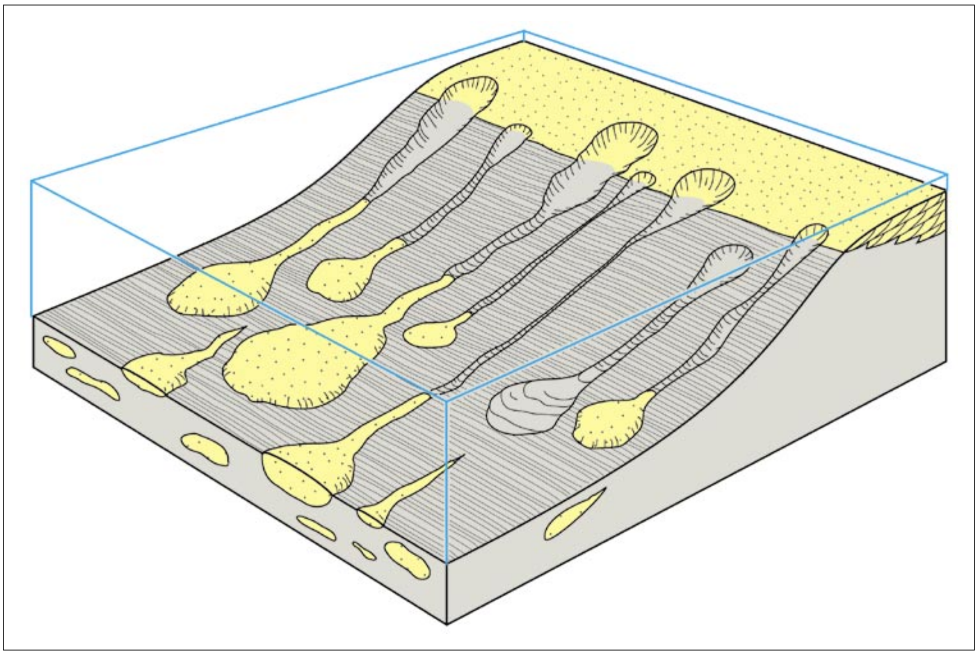

Fig. 3 Depositional model for the Upper Oxfordian–Kimmeridgian Katedralen Member of the Hareelv Formation.

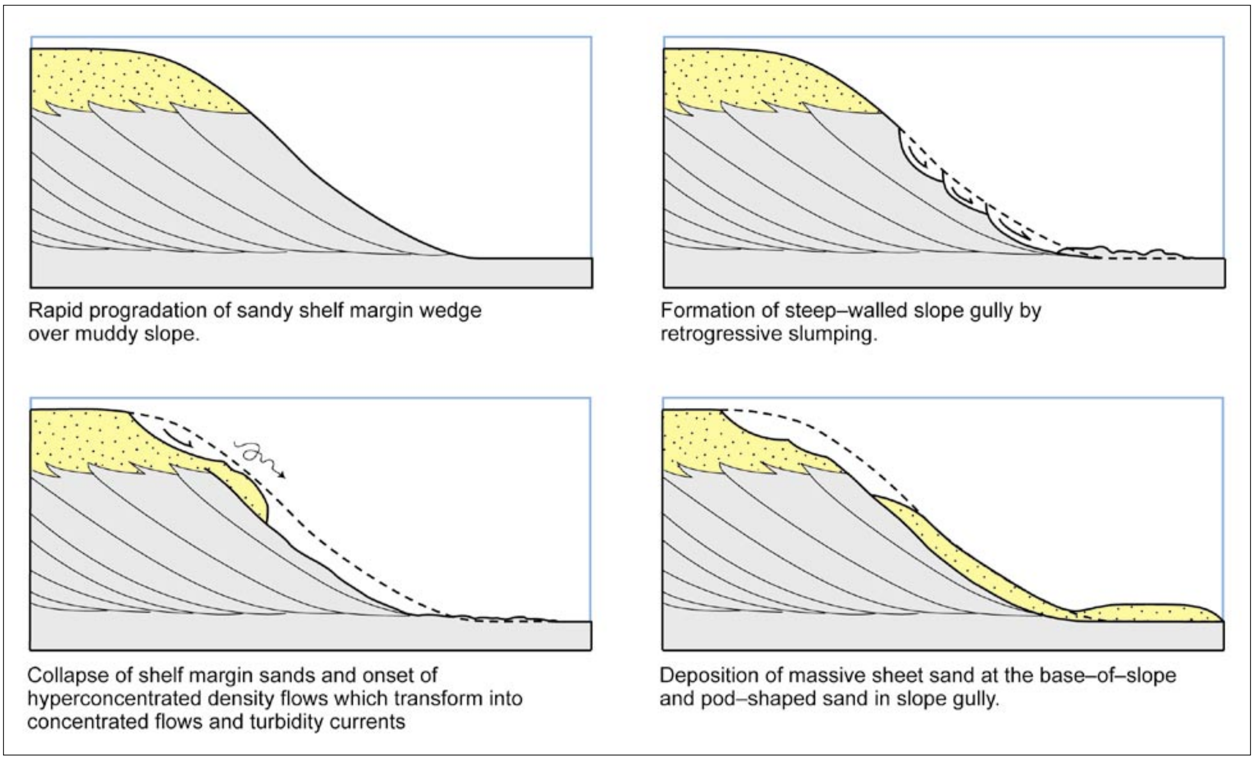

Fig. 4 Diagrams showing sandy progradation to the shelf edge, slope failure, gully formation by retrogressive slumping, imitation of hyper-concentrated to concentrated sandy density flows, and deposition of pod-shaped slope gully sands and sheet-like base-of-slope lobes.

port and deposition took place from sediment flows undergoing downslope transformation from hyperconcentrated to concentrated density flows.

The gullies probably originated as slides and the slide scars were subsequently modified by retrogressive slumping, which cut backwards into the front of the shelf-margin wedge where they acted as downslope conduits for a few sand flows, as indicated by the presence of amalgamation surfaces in the sandstone bodies (Figs. 3 and 4). Levee deposits are notably absent, indicating that the flows and the gullies are independent phenomena and that the latter did not serve as long-term transport conduits for the flows.

3. POST-DEPOSITIONAL REMOBILIZATION OF THE SANDS

The upper boundary of the more sheet-like sandstone bodies steps up and down on several scales ranging from

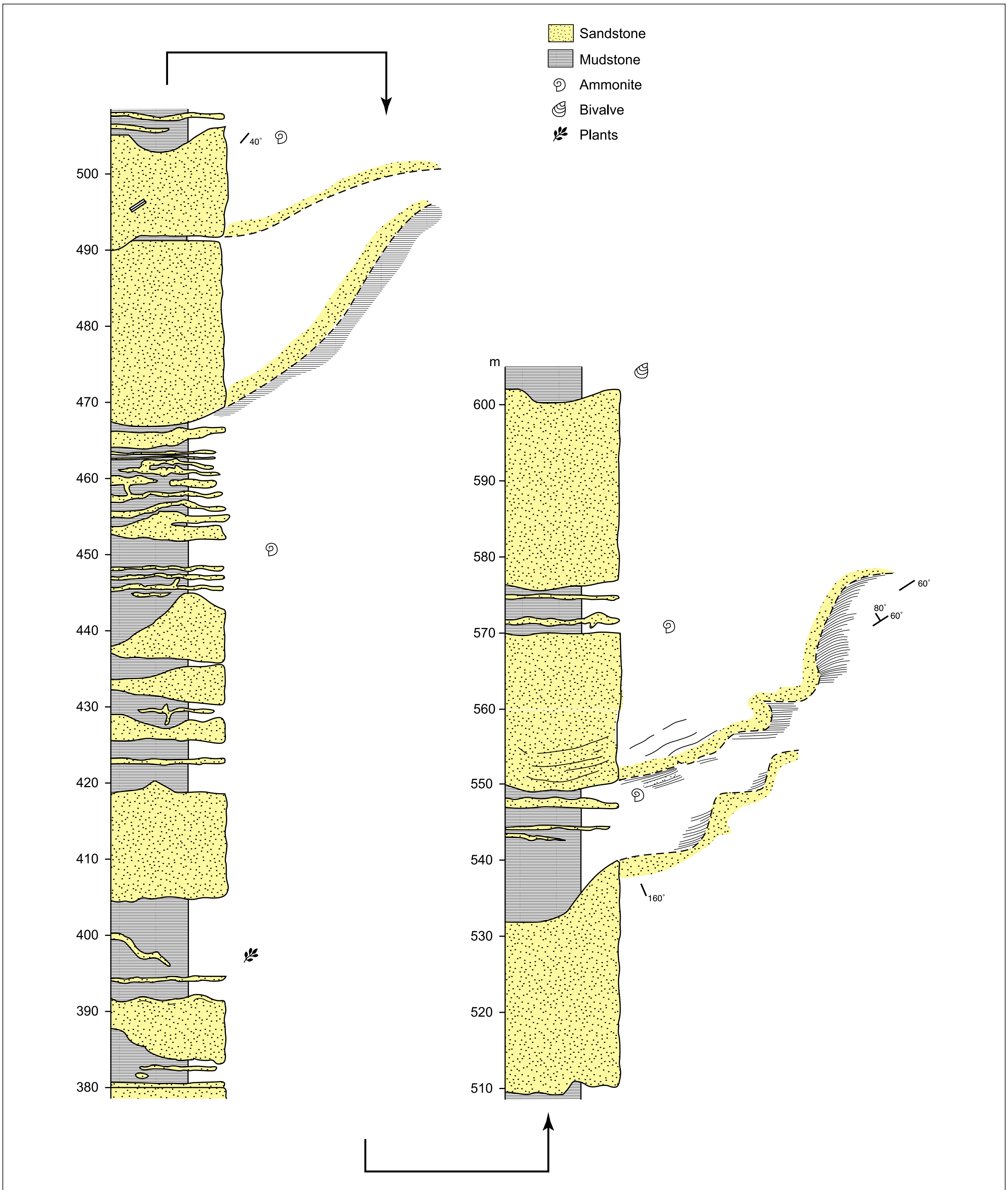

Fig. 5 Log through part of the Hareelv Formation (Katedralen Member) in southern Jameson Land. Note the disorganised nature of the member, the stacked gully fill sandstones at 470–505 m, and mounded top of sandstone beds at 532 m. All sand bodies have undergone remobilization and injection, and all the thin sandstone beds are sills.

millimetres to metres (Figs. 6 and 7). Many of the larger sandstone bodies have a ridge-like or mounded upper surface, quite commonly with a dip of up to 60º (Figs. 5, 9 and 12).

The mounded tops were formed by intrusive diapirism, as the original depositional upper surface of the sands was undoubtedly flat, reflecting their density flow origin. The bedding in the mudstones is dominantly horizontal except for layers immediately adjacent to the larger sandstone bodies. Faults have not been observed along the steeply dipping sandstone–mudstone boundaries and the mudstones did not slide off the mound along any type of detachment plane.

Sandstone dykes and sills occur throughout the formation, commonly in great density and showing a high degree of complexity (Figs. 11–14). The sills are com-

Fig. 6 Large pod-shaped sandbody composed of several amalgamated massive deep-water sandstone units. The sands underwent post-burial remobilisation and liquefaction and were intruded into adjacent mudstones. The sandstone body to the upper left is about 50 m thick. Upper Oxfordian, Katedralen Member, Hareelv Formation, southern Jameson Land.

Fig. 7 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 reflects post-depositional remobilisation, liquefaction, fluidization, and injection of the original density flow deposit. Katedralen Member, Hareelv Formation, southern Jameson Land.

Fig. 8 Thick, massive sandstone body showing consolidation lamination. This facies is typical of the Katedralen Member, Hareelv Formation. Southern Jameson Land.

Fig. 9 Massive sandstone body of the type commonly showing a mounded top. Person at the base for scale. Katedralen Member, Hareelv Formation, southernmost Jameson Land.

monly transgressive on all scales, and they vary in thickness from millimetres to many metres. Thicker sills are transitional to remobilized sandstone bodies and there is no clear distinction between the two groups (Figs. 11 and 12). Dykes and sills may occur in such a high density that they occupy the bulk of the sediment volume, so that the host mudstone is only represented by displaced and irregular, sometimes folded laminae and lamina sets (Fig. 12, lower part).

Sandstone dykes are commonly ptygmatically folded, due to post-intrusive compaction of the surrounding mudstones, which were only slightly compacted at the time of intrusion (Figs. 12 and 14). Other intrusions are completely irregular, winding and curved, also reflecting intrusion in a poorly consolidated mudstone under shallow burial. Some dykes and sills show roughly orthogonal relations where the sills follow bedding planes in the mudstones, whereas the dykes are subvertical, showing that the mudstones were sufficiently compacted at the time of intrusion to allow development of joints (Figs. 11 and 13). Extremely variable intrusion geometries commonly occur at the same stratigraphic level, reflecting repeated intrusive events under different depths of burial. This is also shown by cross-cutting relationships and different degrees of compaction folding (Figs. 12 and 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 thus not been observed.

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 occasional presence of water escape structures indicate that the sands of the Hareelv Formation have been remobilized and liquefied subsequent to deposition.

The liquefaction process included fluidization resulting from pore fluid movement, liquefaction caused by cyclic shear stress, and shear liquefaction resulting from the application of a shear stress across a sand body (cf. NICHOLS, 1995). These processes interact in the natural environment and cause the sands to become more susceptible to liquefaction (NICHOLS, 1995).

The importance of large-scale loading in the deformation of the Hareelv sandstone bodies indicates that liquefaction was caused by shock or vibration. Liquefaction by fluidization played an additional, albeit minor role in additions to shocks. 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 in most cases it is extremely difficult to impossible to distinguish primary, massive sands, from sands which have undergone in-place liquefaction followed by only minor remobilization and injection, or from completely remobilized and far-travelled intrusive sands (Figs. 5, 10, 11 and 12). Even apparently subhorizontal, thick massive beds, looking like normal primary beds, can commonly be shown to be of an intrusive nature when traced laterally (Figs. 11 and 12).

The lack of injection complexes above mounded sand bodies show that breakage of the mudstone seal and outflow of liquefied sand on the seafloor did not take place. Liquefaction, remobilization and injection of sand into the surrounding mudstones thus always took place after burial, ranging from several metres to tens of metres (Fig. 15). The regular, platy shape of most mud-

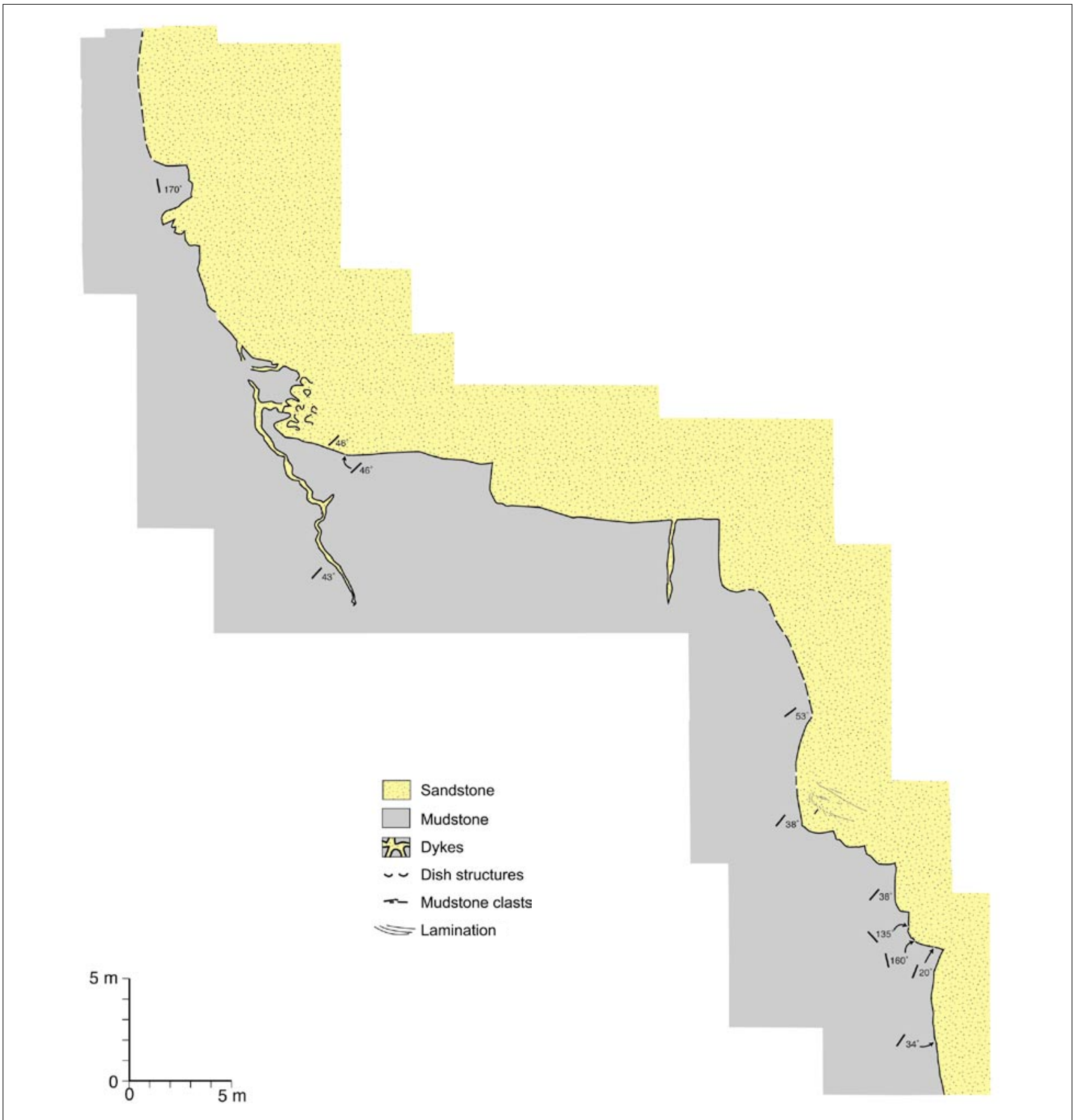

Fig. 10 Massive, gully-fill sandstone showing stepped margin modified by loading. Katedralen Member, Hareelv Formation, southern Jameson Land.

stone clasts shows that the surrounding mudstones had undergone substantial compaction at the time of remobilization. The ubiquitous presence of load structures, compaction folded dykes, flow marks on sandstone–mudstone interfaces, and the occurrence in some sand bodies of plastically deformed and sheared mudstone clasts, indicate on the other hand that liquefaction and injection also took place at shallower depths.

The fact that all sandstone bodies in the formation have undergone remobilization, liquefaction, and injection and the common presence of cross-cutting dykes and sills show that liquefaction took place throughout deposition of the formation, i.e. from the Late Oxfordian through the Volgian. Remobilization, liquefaction and injection were caused by shocks and vibrations and to a lesser degree by fluidization: it is not possible to directly prove the influence of gravitational shear stress.

The triggering processes were active more or less continuously over a time interval of at least 10 million years in the Late Jurassic, corresponding to the climax phase of the main Mesozoic rift event in the North Sea–North Atlantic region. In East Greenland, rifting was initiated in Mid Jurassic time, and the rift climax seems to have occurred in the Late Oxfordian–Kimmeridgian, whereas Volgian deposition was dominantly shallow marine, reflecting a reduced subsidence rate and infilling of the basin (SURLYK & NOE-NYGAARD, 1991; SURLYK, 2003).

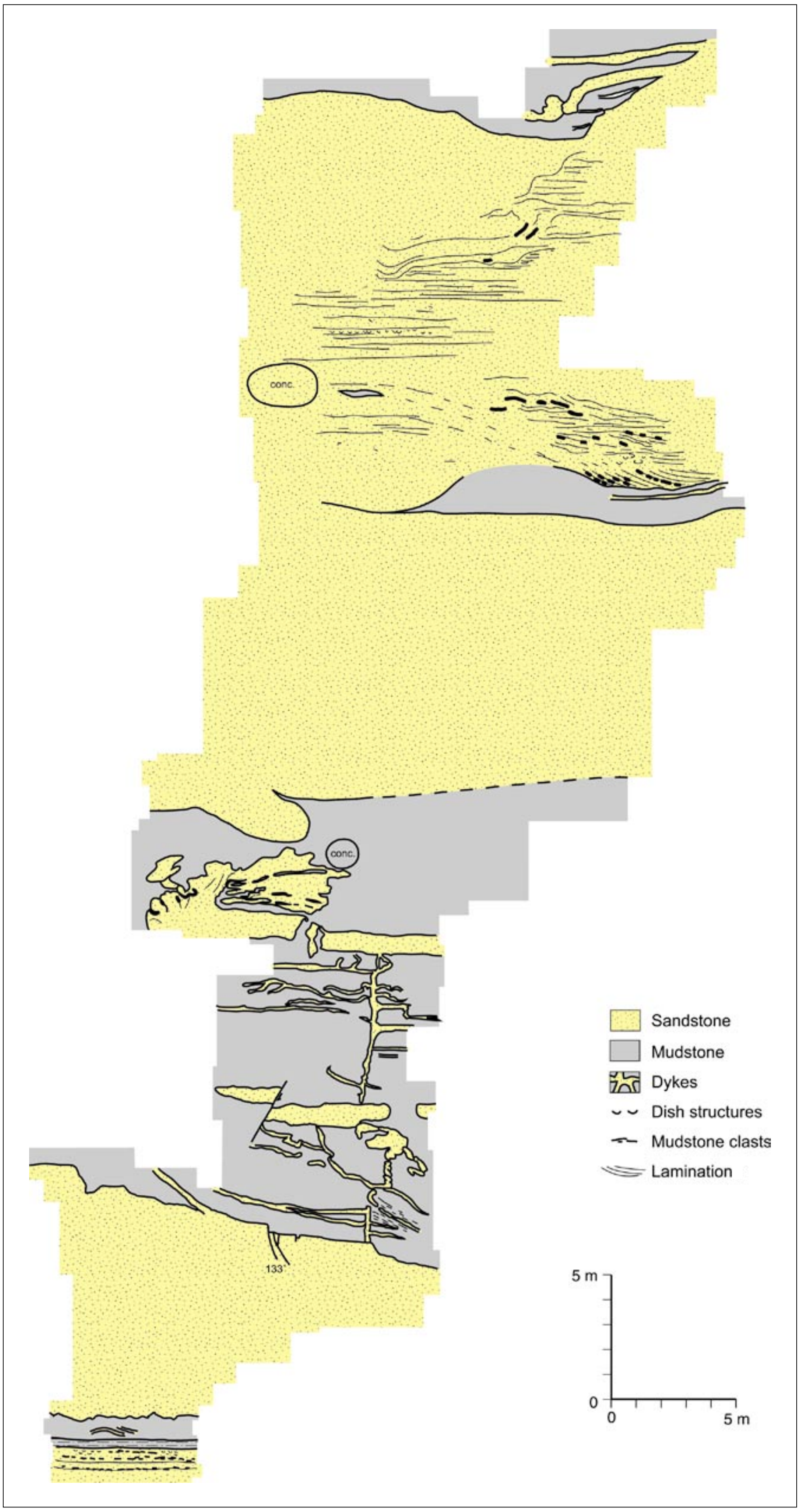

Fig. 11 Thick massive sheet sandstones modified by remobilisation and intrusion. The upper sheet shows preserved consolidation lamination in the central part and to the lower right, indicating only minor remobilisation of this bed. The mudstone unit in the lower part of the section shows a complex network of thin sandstone dykes and sills. The roughly orthogonal relationships indicate that intrusion in this part took place after burial and compaction of the mudstone. The top of the lower sandstone sheet steps up and down and shows small faults. Katedralen Member, Hareelv Formation, southern Jameson Land.

The pervasive liquefaction of all sand bodies in the Hareelv Formation is thus interpreted as having been caused by cyclic earthquake shocks during an extended period of intensive rifting. Additional important factors were the buildup of pore pressure, upward movement of pore waters expelled from the compacting muds, presence of mudstone seals, and slope shear stress. There is no evidence for migration of hydrocarbons generated in older rocks in Jameson Land, and the lack of faults cutting the Mesozoic succession, and the relatively great thickness of the Hareelv Formation indicate that the migration of gas to shallow levels along fault conduits

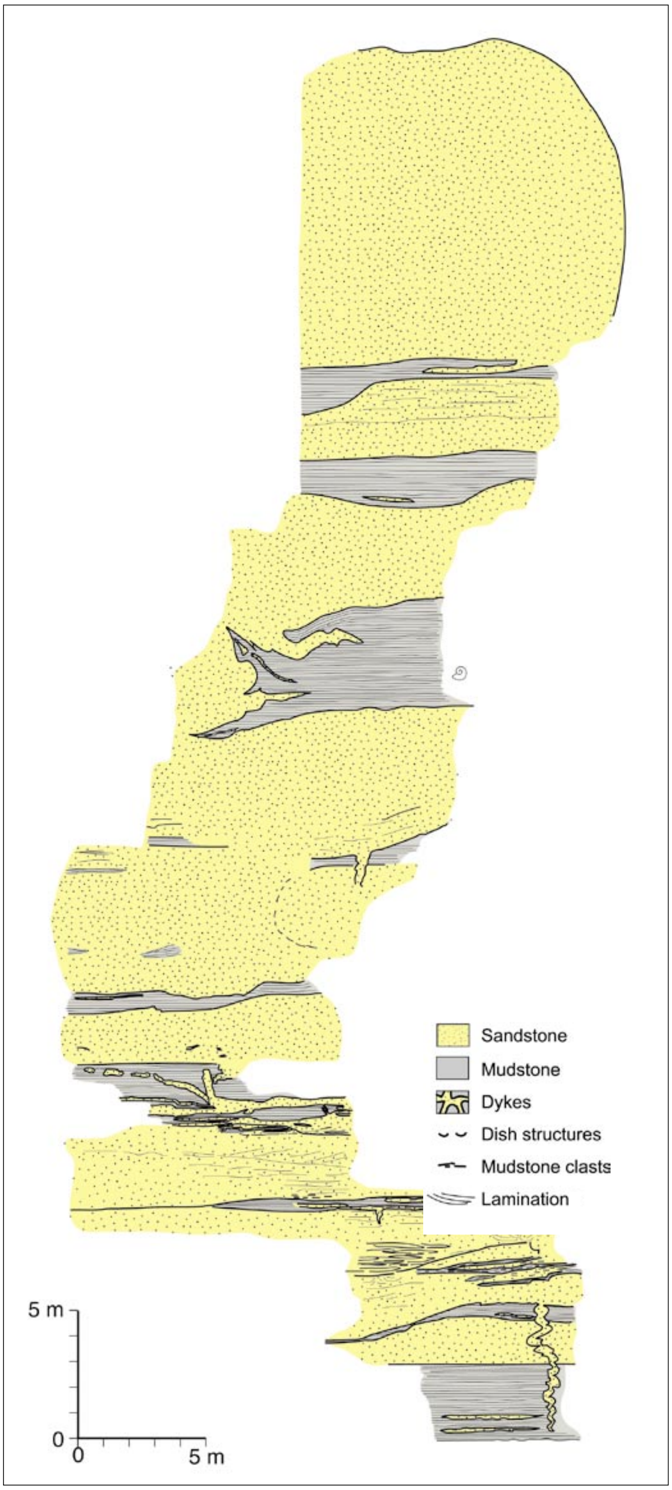

Fig. 12 Intruded massive sandstones formed by complete remobilisation and relatively long distance injection. The lowermost sheets show preserved consolidation lamination indicating relatively minor remobilisation. The subvertical dyke to the lower right is folded due to compaction of the mudstones. Katedralen Member, Hareelv Formation, southern Jameson Land.

was unlikely. Degradation of gas hydrates as a possible cause has not yet been tested, but the fact that liquefaction took place throughout a long period of time characterized by high sea-level stand argues against it.

4. FIELD ANALOGUE FOR HYDROCARBON RESERVOIRS

The Hareelv Formation is an excellent field analogue for deeply buried hydrocarbon reservoirs of unusual shapes. Thus 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. These reservoir sands have been variously interpreted as turbidite fills of elongate erosional gullies, as convex-upward debrites or as remobilized and injected sands (DIXON et al., 1995, and references therein). The latter explanation is receiving increasing support by improved seismic resolution data and retrieval of additional cores, and not least by the increasing attention paid to the relatively few field analogues such

Fig. 13 Sandstone sills in mudstones below thick massive sandstone. Katedralen Member, Hareelv Formation, southern Jameson Land.

as the Hareelv Formation. The Forth Fields area is similar to the Hareelv Formation as regards the depositional model and post-depositional remobilization and injection. The interpretation of the Gryphon/Harding Field involved the 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 much smaller conjugate faults, with throws of a few tens of centimetres commonly intersecting the top of sheet-like sandstones.

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 (Figs. 6, 9 and 11). They may be difficult to locate and interpret correctly because of their extremely irregular shape and occurrence 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 connectivity, and they may form pathways for hydrocarbon migration into shallower, regular and more predictable sand bodies such as shelf-margin wedges. Sandstone dykes and sills are commonly observed in cores and if correctly identified, suggest the presence of larger sand bodies in adjacent strata. Vertical or steeply dipping intrusions may not be visible on seismic data, but their possible presence may be inferred from the irregular or mounded shapes of the reservoirs.

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 a strong similarity to a massive sandstone turbidite. Katedralen Member, Hareelv Formation, southern Jameson Land.

5. CONCLUSIONS

The Upper Oxfordian–Volgian Hareelv Formation of Jameson Land, East Greenland is probably the World's largest sediment injection complex. It represents a common but somewhat overlooked class of a line-sourced, disorganized sandy density flow system derived from the collapsing fronts of shelf-margin wedges. The formation is 200–400 m thick and the sand occurs as large massive bodies tens of metres thick, hundreds of metres

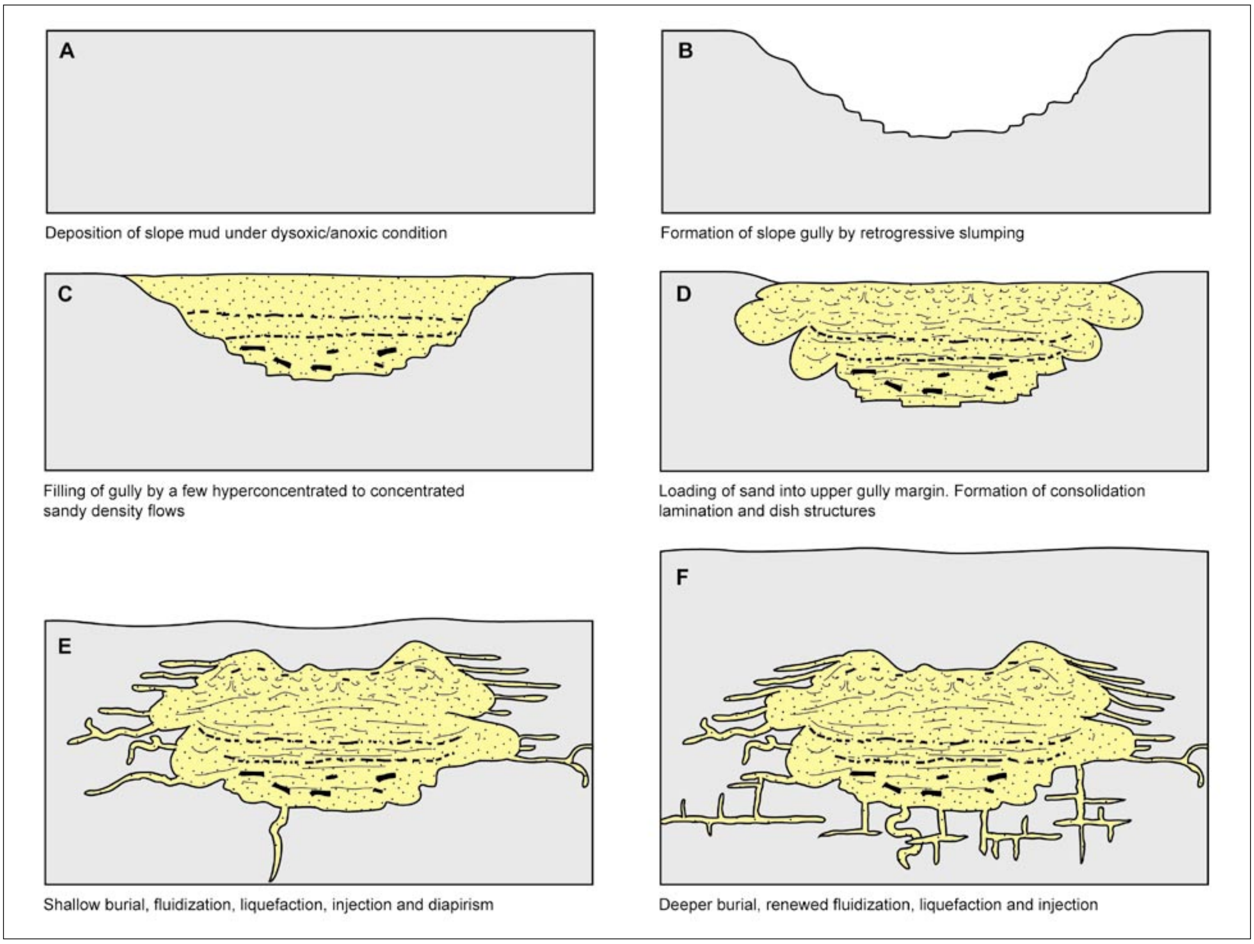

Fig. 15 Model for the remobilisation, fluidization, liquefaction, intrusion and diapirism of sandstones in the Hareelv Formation, Jameson Land, East Greenland. A and B show deposition of black mud under dysoxic to anoxic conditions and formation of a slope gully by retrogressive slumping (cf. Figs. 3 and 4). The gully walls are commonly stepped with subvertical segments (cf. Fig. 10). In C the gully is filled by a few sand flows 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 the sandbody and injection of sand dykes and sills after shallow burial (cf. Figs. 9, 13 and 14). 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 (cf. Figs. 12 and 13) and cross-cut by later intrusions and the consolidated lower part of the mudstone succession has developed regular orthogonal vertical and horizontal joints which are intruded by sand (cf. Fig. 13). The indicated depth of burial is schematic and probably amounted to several tens of metres.

wide and in some cases of kilometre length. The sandstone bodies are randomly distributed throughout the formation and consist of well-sorted fine-to-medium-grained sand. The sand was deposited in steep-sided erosional slope gullies, and as more sheet-like bodies at the base-of-slope and in the basin. Transport and deposition was from hyperconcentrated density flows passing down-slope into concentrated flows. The travel distance of the flows ranged from a few tens of metres to several tens of kilometres..

Post-depositional remobilization, liquefaction and subsequent injection of sand into surrounding mudstones, strongly modified the density flow system and resulted in the formation of a complex of highly irregular, interconnected sand bodies, dykes and sills on all scales. Remobilization took place repeatedly over more than 10 million years and ranged from almost syndepositional to rather deep burial, in scales ranging from a few centimetres to hundreds of metres. The formation was deposited during the main Mesozoic rift phase in East Greenland and remobilization was caused by earthquakes combined with the effects of overpressure induced by rapid burial, hydrocarbon migration and slope shear stress.

The Hareelv Formation provides an excellent field analogue for complex subsurface Jurassic and Cenozoic hydrocarbon reservoirs in the North Sea, the Cretaceous of the Norwegian shelf and many other areas. The excellent exposures allow study of sand body size, geometry and interconnectedness, and 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, and may act as a migration route to shallow, well organized shelf-margin sandstone wedges, which form a more obvious exploration target.

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