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New aspects of deformed cross-strata in fluvial sandstones: Examples from Neoproterozoic formations in northern Norway

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Abstract

Extensive (20–200 m long) exposures of tabular cross-sets in Neoproterozoic fluvial sandstone in Northern Norway demonstrate that deformed cross-strata, in the form of recumbently folded cross-strata with associated massive sand, are localized features passing in both up- and down-current direction into undeformed, concave-upward or sigmoidal cross-strata. The deformation occurs in down-current inclined, tangential wedge-shaped zones beneath reactivation surfaces, and less commonly as flat-topped lenticular zones. The localized nature of the sediment deformation is attributed to local liquefaction below the top of the bed in the case of the flat-topped lenses and at the dune front in the case of the more common tangential wedges. The position of the flat-topped lenses suggests deformation by the shear stress of high-velocity, suspension-laden currents. Although liquefaction of the dune front implies the action of gravity forces, it is argued that the fluvial currents were the main driving force at the instant of bed liquefaction. Post-folding gravitational shearing probably enhanced the deformation within the upper part of the wedges, with their long, flat-lying toeset resulting from redeposition of downslope-moving liquefied sand.

The down-current alternation of deformed tangential wedges and undeformed cross-strata suggests that the mechanism that triggered the liquefaction of the dune lee side was related to the fluvial system itself and hence was of autokinetic origin. The tabular cross-sets have previously been interpreted as a product of the dune upper-stage plane-bed flow regime. In this flow context, it can be speculated that the liquefaction and deformation occurred when the flow conditions approached the plane-bed phase, probably inducing a highly differential turbulent pattern and pressure fluctuations sufficient to liquefy the fine/medium sand. The small flat-topped deformation lenses also suggest liquefaction by cyclic loading, whereas the solitary nature of the large lenses may, alternatively, be the result of impulsive loading from bank collapse.

In less well-exposed fluvial successions, the auto- or allokinetic origin of recumbently folded cross strata may be difficult to determine. However, the common occurrence of recumbent folds in cross-stratified fluvial sandstones and their virtual absence in marine cross-stratified deposits suggests strongly that, in the majority of cases, the deformation was autokinetic, resulting from flow phenomena typical of river channels. This kind of deformation structure should thus not be attributed to an allokinetic seismic triggering mechanism unless independent evidence of fault activity can be documented.

Keywords: Fluvial sandstone; Soft-sediment deformation; Recumbent fold; Massive sandstone; Reactivation surface; Liquefaction

1. Introduction

Fluvial sandstones commonly show soft-sediment deformation structures in the form of solitary sets of

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recumbently folded cross-strata. The origin of these deformation features has been attributed variously to the drag force of a current flowing across the bedform (e.g., Rust, 1968; Allen and Banks, 1972; Allen, 1985; Hendry and Stauffer, 1975; Turner, 1981; Owen, 1987) or to the gravitational stresses acting on the bedform's steep front (e.g., Jones, 1962; Jones and Rust, 1983). Mc Kee et al. (1962a,b) reproduced similar structures in the laboratory by dragging a sandbag or injecting a slurry flow across the substrate of normally packed, cross-stratified sand. In the laboratory experiments of Owen (1996), simple recumbent folds formed when a current was flowing over a liquefied cross-stratified substrate. Allen and Banks (1972) proposed a physical model for the formation of such structures in the conditions combining liquidized (i.e., liquefied or fluidized) bed state and a tangential shear stress of a horizontal current.

Following the model of Allen and Banks (1972), most researchers of ancient fluvial deposits have thus assumed that the cross-stratified substrate was probably liquefied when being deformed. However, there has been little consensus as to the actual mechanism that might trigger the liquefaction. Liquefaction caused by earthquake tremors was favoured by Allen and Banks (1972), Turner

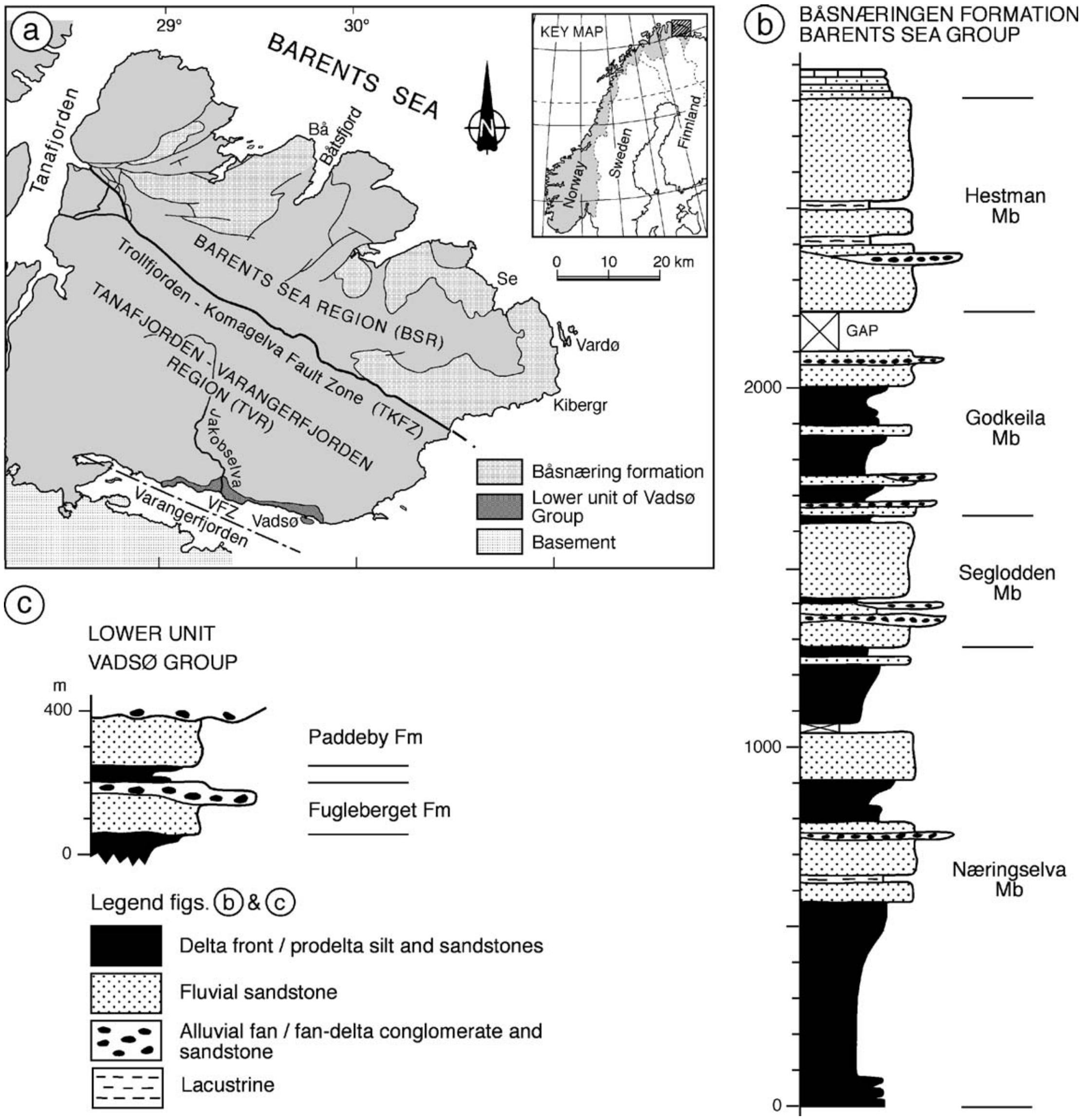

Fig. 1. (a) Map showing the lower allostratigraphic unit of the Vadsø Group (Tanafjorden–Varangerfjorden Region) and the Båsnæringen Formation of the Barents Sea Group (Barents Sea Region). (b) Stratigraphic setting of the Hestman Member. (c) Stratigraphic setting of the Fugleberget Formation.

(1981), Leeder (1987), and Ord et al. (1988), while others attributed liquefaction to hydraulic processes occurring within the depositional system itself (e.g., Røe, 1987; Jones and Rust, 1983; Røe and Hermansen, 1993; Wells et al., 1993). Leeder (1987) referred to the deformation structures caused by earthquake-induced stresses as "allokinetic" and those produced solely by sedimentation processes as "autokinetic."

The present paper is a detailed account of simple recumbently folded cross-strata and associated massive (structureless) elements in the Upper Riphean fluvial sandstones of the Fugleberget Formation and the Hestman Member of the Båsnæringen Formation on the Varanger Peninsula of Finnmark, northern Norway. Extensive outcrops of tabular cross-sets demonstrate that the deformed parts of the fluvial cross-sets are localized features of limited lateral extent, passing in both the up-palaeocurrent and the downcurrent direction into undeformed cross-strata, which allows the geometry of the deformed bed portions to be determined and the nature of the transition between the deformed and undeformed cross-strata to be analyzed. These aspects of hydroplastic deformation have drawn little attention in most previous publications, but as demonstrated by the present study have important implications for the nature of the deformation processes and their significance.

2. Stratigraphic setting

Deformed sets of cross-strata abound in the fluvial portions of the Late Riphean Båsnæringen Formation of the Barents Sea Group and in the broadly coeval, lower allostratigraphic unit of the Vadsø Group of the Varanger Peninsula. The Båsnæringen Formation is 2.5–3 km thick (Siedlecka and Edwards, 1980) and occurs to the north of the Trollfjorden–Komagelva Fault Zone (TKFZ) in the Barents Sea Region (Fig. 1). This sedimentary succession consists of marine basin-slope deposits overlain by eight vertically stacked, deltaic-fluvial sequences (Fig. 1b). The lower stratigraphic unit of the Vadsø Group, 300 m thick, occurs to the south of the TKFZ, in the Tanafjorden Varangerfjorden Region, and comprises only two deltaic-fluvial sequences (Røe, 2003). The successions were deposited in the extensional, NW–SE-trending, Timan–Varanger Basin (Olovyanishnikov et al., 2000; Roberts and Siedlecka, 2002) with the intrabasinal TKFZ probably acting as a down-to-the-north normal fault during Late Riphean sedimentation (Siedlecka, 1985; Drinkwater et al., 1996). The Varangerfjorden Fault Zone (VFZ, Fig. 1a), presently concealed, may have been active as the basin-margin fault at this time (Røe, 2003).

The deltaic-fluvial sequences in the two successions are remarkably similar, despite the large differences in their thickness (Fig. 1b and c) and their location on opposite sides of the TKFZ. The lower, progradational parts of the sequences are silt-dominated and suggest deposition as low-energy, fluvial- and tide-dominated deltas (Hjellbakk, 1993; Røe, 1995, 2003). Their upper, mainly aggradational parts consist of predominantly fine- to medium-grained sandstones deposited by relatively shallow, high-power braided rivers (Røe and Hermansen, 1993; Røe, 1995; Hjellbakk, 1997). Conglomerates and massive sandstones of alluvial fan or fan-deltaic origin locally cap, or are intercalated with, these sandy fluvial deposits.

Recumbently folded cross-strata with associated massive sandstone are the most common deformation feature in the upper part of all these deltaic-fluvial

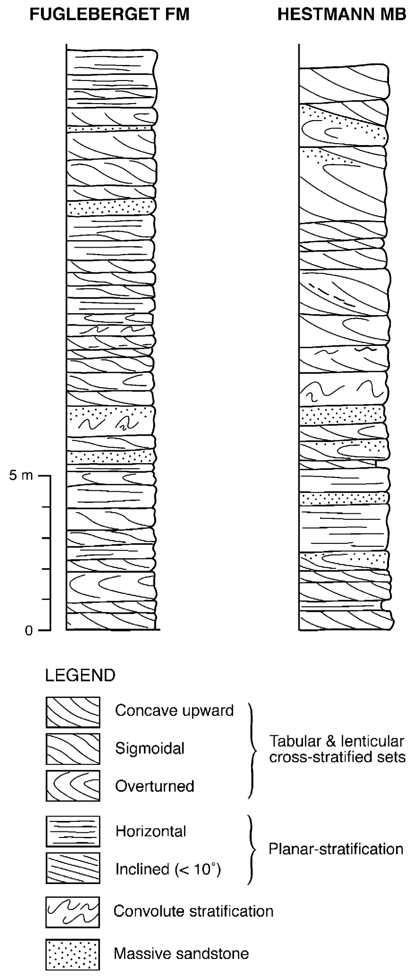

Fig. 2. Typical facies sequences in the sandy portion of the Fugleberget Formation and the Hestman Member. Note their similar, uniform fine grain sizes and stratification characteristics.

sequences. The field observations discussed are from the spectacularly exposed Hestman Member of the Båsnæringen Formation (Fig. 1b) and the Fugleberget Formation (Fig. 1c). Similar features also occur in the other fluvial formations of the Vadsø and Barent Sea Groups (Hjellbakk, 1993; Røe, 1995).

3. The fluvial sandstone

The fluvial sandstone deposits of the Fugleberget Formation and the Hestman Member have been discussed in detail by Røe (1987) and Røe and Hermansen (1993), and hence, only their attributes relevant to the present study are summarized here. These fine- to medium-grained sandstones consist of large- to very large-scale, tabular to lenticular sets of moderately inclined cross-strata, alternating with sets of upper-stage horizontal and low-angle planar parallel strata (Fig. 2). The cross-strata in both tabular and lenticular sets are tangential at the base and concave upward to sigmoidal in shape, with the latter locally passing into horizontal or low-angle topset strata in the up-palaeocurrent direction. Preserved form-sets have humpback geometries, with an offset of the bedform summit and brinkpoint. The cross-sets commonly show internal deformation, including recumbent folds and locally also large-scale convolutions or more complex folding (Fig. 2).

The characteristics of the cross-sets, particularly the common sigmoidal shape of cross-strata, the associated topsets of planar parallel strata (Figs. 2 and 3a and b)

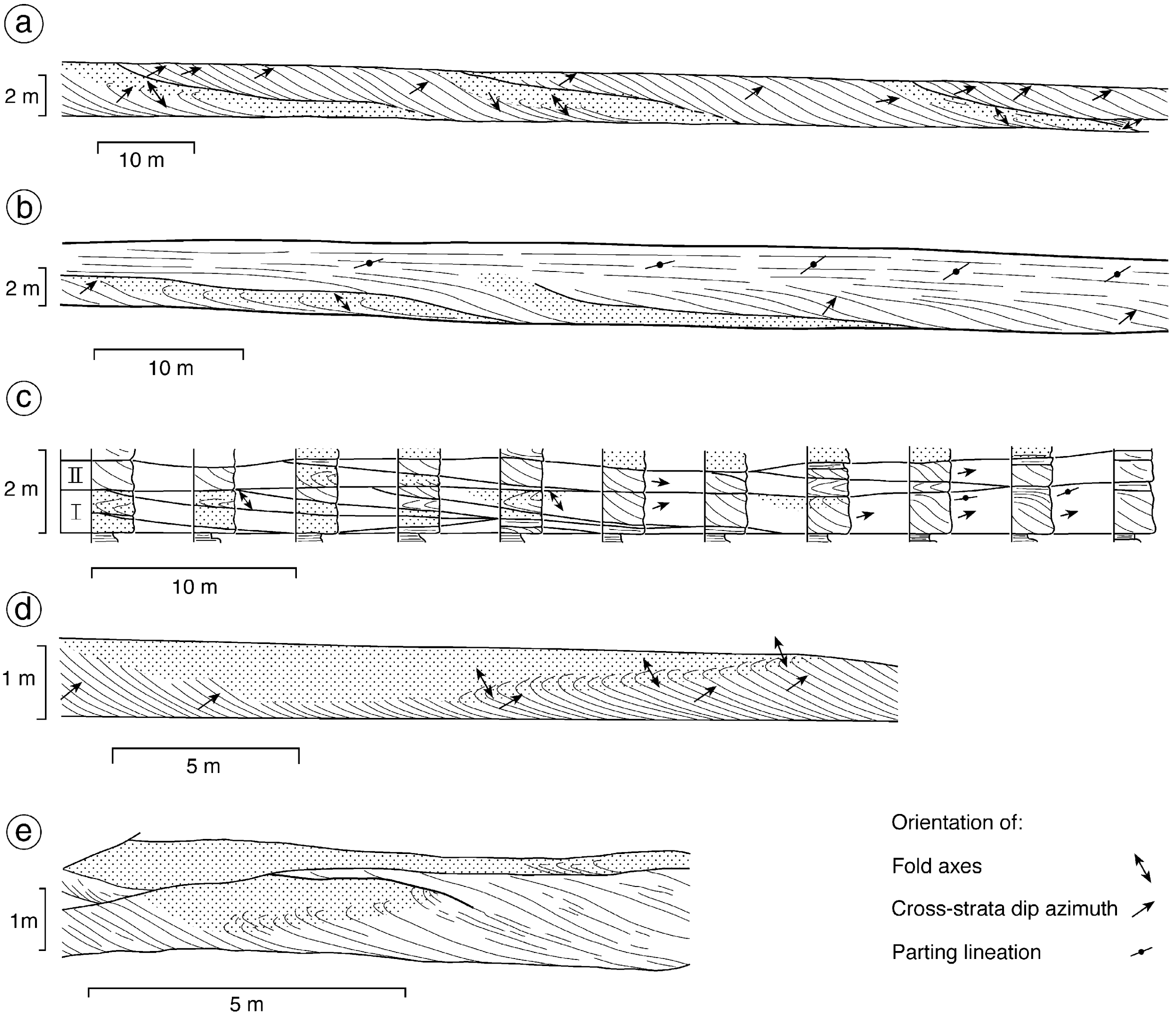

Fig. 3. Internal architecture of tabular cross-sets. (a–c) Tangential wedge-shaped zones of deformed sediments in alternation with undeformed, concave-up and sigmoidal cross-strata. Note the close spacing of the wedges in (c) and the small deformation lenses downcurrent. (d) Flat-topped lenticular zones of deformed sediments. (e) Lens-shaped deformation zone overlain by a wedge of deformed sediments.

and the humpback form-set geometry suggest deposition from high-velocity currents heavily laden with suspended sand at or near the dune/plane-bed hydraulic transition. The vertical and lateral passing of the cross-strata into planar to gently inclined strata suggests a temporal and spatial alternation of the transitional and upper flow-regime conditions. The thicknesses of composite bar forms (Røe and Hermansen, 1993) suggest flood-stage flow depths greater than 4 m in the deeper parts of the Fugleberget rivers and in excess of 6 m in the Hestman rivers.

Recumbently folded cross-strata associated with massive sand are common in both lenticular and tabular sets. The lenticular cross-sets are generally deformed throughout their downcurrent extent. The tabular cross-sets, in contrast, show a transition from undeformed to deformed strata and are thus to be discussed in more detail below.

4. Internal architecture of tabular cross-sets

The tabular cross-sets in the Fugleberget Formation are 0.2 to 2 m thick, with exposed downstream lengths up to 100 m. In the Hestman Member, the cross-sets are up to 4 m thick and exposed over downstream lengths up to 200 m. The majority of these cross-sets are locally deformed into recumbent folds with associated massive sandstone components. The undeformed cross-strata are inclined at an angle of 17–23°, commonly alternating between concave upward and sigmoidal in shape within a single cross-set.

A conspicuous feature of the tabular cross-sets is the occurrence of gently inclined (5–10°) reactivation surfaces that are concave upward or virtually planar (Figs. 3a–c and 4). These surfaces separate packets of strata that are herein referred to as “intrasets.” The intrasets typically show a down-palaeocurrent transition from largely undeformed to overturned cross-strata and/or a massive deposit. The reactivation surfaces generally have a wide downcurrent spacing (Fig. 3a), but some are so close to each other that the associated intraset comprises little more than the overturned cross-strata and a massive sandstone (Fig. 3c). There is a range of intermediate cases between the isolated reactivation surfaces and the closely spaced, multiple ones. The dip azimuths of the reactivation surfaces are parallel or somewhat oblique (at up to 30°) to the modal direction of foreset dip measured in the corresponding undeformed cross-strata.

The deformation zones beneath the reactivation surfaces are wedge shaped and inclined in the down-palaeocurrent direction, thinning downdip, and are generally tangential with respect to the cross-set lower boundary (Fig. 3a–c). These tangential wedge-shaped zones of deformed sediment extend from the base to the top of the parent cross-set, although their flat-lying toe parts vary considerably in downcurrent length. The sediment deformation wedges are found in virtually all tabular cross-sets in the fluvial deposits studied. Deformed sediments are, in addition to the tangential wedges, present within flat-topped lenses below the top of a cross-set (Fig. 3c–e). These lens-shaped zones of deformation have concave-upward bases and a symmetrical to somewhat asymmetrical shape in sections parallel to the palaeocurrent direction. The lenses vary from 3 to 40 m in downcurrent length and from 0.3 to 2 m in thickness. In contrast to the tangential deformation wedges, the flat-topped lenses occur only spo-

Fig. 4. Downcurrent transition from a tangential wedge-shaped zone of deformed sediments to undeformed concave-up and sigmoidal cross-strata within a tabular cross-set of the Hestman Member. Note the concave-upward shape of the reactivation surface on top of the deformation wedge and the sigmoidal shape of undeformed cross-strata.

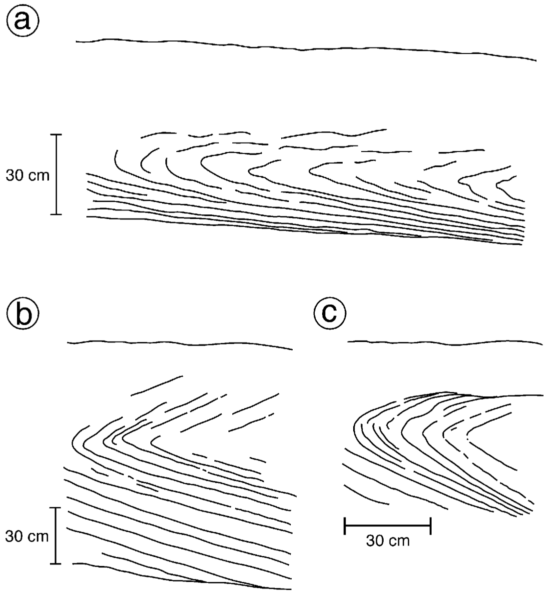

Fig. 5. Styles of soft sediment deformation in the tangential wedges. Note the gradual transition between the folded cross-strata and the massive sand in (a, b) and the minor slip surface above the fold hinge zone in (c). (a) Fugleberget Fm.; (b, c) Hestman Mb.

radically in the tabular cross-sets, although more than one of the smaller lenses can be found at the top of the same cross-set (Fig. 3c I).

5. The tangential wedge-shaped zones of deformation

Massive sandstone is the dominant facies in the majority of the tangential wedges. Below the steeper updip segment of a reactivation surface, the massive sandstone passes downwards into recumbently folded cross-strata or there is an abrupt transition of the homogeneous sandstone into undeformed foreset strata below (Fig. 3a–c). In a few cases, faint parallel-lamination caps the massive sandstone directly beneath the inclined part of the reactivation surface (Fig. 3a, right wedge), and there are also a few cases where the folded foreset strata are directly truncated by a reactivation surface, with no intervening layer of massive sand (Fig. 3c II). The horizontal toe parts of the deformation wedges are mainly massive. Some upstream-dipping diffuse surfaces occur sporadically in the downstream part of longer toesets.

The fold axes are sub-horizontal and generally perpendicular to the dip azimuth of the undeformed foreset strata (Fig. 3a–c), although oblique orientations (at up to 20°) are also observed. The traces of the fold axial planes in flow-parallel vertical sections are overall inclined down-palaeocurrent at 3–6° but may locally show smaller scale secondary undulations. The folds have mainly rounded hinge zones (Figs. 5 and 6), but angular, chevron-type folds are also present. The primary stratification is always well-defined within the fold's lower limb, where the inclination of strata outside the hinge zone is similar to that of the undeformed cross-strata. The stratification within the overturned upper limb is diffuse, with a downflow transition into massive sandstone. The fold upper limbs locally show low-amplitude undulations (Figs. 5a and 6) but in many cases lamination is practically lacking above the hinge zone. In a few instances, there is a subhorizontal surface of local discontinuity, separating the folded and the massive part of the sandstone bed (Fig. 5c).

Fig. 6. Recumbent fold passing upward into massive sandstone in a tangential wedge of the Fugleberget Formation. Note the wavy nature of the upper fold limb laminae. Scale to the right ca. 15 cm.

6. The flat-topped lenticular zones of deformation

The flat-topped lenses of sediment deformation at a cross-set upper boundary are similarly dominated by massive sandstone. In a flow-parallel vertical section, the base of the lens-shaped deformation zone corresponds to the abrupt, non-erosional transition between undeformed cross-strata and massive sandstone, whereas evidence of recumbent folding along this contact is recognizable only in the downcurrent part of the lens (Figs. 3d,e and 7). The axial plane traces of these relic folds are slightly inclined in the up-palaeocurrent direction, which contrasts with their overall downcurrent inclination in the tangential wedge-shaped deformation zones. However, the fold axes are nearly perpendicular to the dip direction of undeformed foreset strata, as in the tangential wedges. Likewise, the folds have mainly rounded hinges and their faintly stratified upper limbs pass rapidly into homogeneous sandstone (Fig. 7). Placers of heavy minerals, in the form of small tear-shaped pockets or sag-like lenses, occur locally isolated near the flat top of the lenticular deformation zone. In a few places, a reactivation surface caps the down-palaeocurrent part of the lenses (Fig. 3e).

7. Bed rheology

The general dominance of massive sandstone within both the tangential wedges and the flat-topped lenses suggests a fluid-like or liquidized (sensu Allen, 1985) bed rheology during deformation, because such a bed state facilitates intergranular shear of sufficient magnitude to destroy the lamination completely. In the flume experiments of Mc Kee et al. (1962a,b) with normally packed sand and where the forces applied were either slurry-like sediment mass or the drag of a sandbag, folds developed near the top of the bed and structureless sand were not extensively formed.

The gradual upward transition of folded cross-strata into massive sand suggests that the former were also liquidized, or at least partly liquidized, when being deformed. The absence of oversteepened foreset strata below the fold hinge zones indicates that the liquidized bed state extended not far below this level. In the case of the chevron-type folds, the change from liquidized rheology to normally packed sand probably coincided with the axial plane, whereas in the case of the rounded forms, it probably corresponded to the fold inflection point. The down-palaeocurrent-inclined bases of the tangential wedges and the concave upward bases of the flat-topped lenses thus probably reflect the differential depth of the liquidized bed state.

Liquidized conditions in sand can be achieved either by liquefaction or by fluidization. Fluidization occurs when a fluid force acting vertically through loose sediment exerts a fluid drag on the grains that balances their weight (e.g., Lowe, 1975). In the present case, a fluidization mechanism is not likely because of the absence of fluidization channels (pillars sensu Lowe, 1975) in the deformed zones as well as in the underlying undeformed cross-strata.

Sand with free connection to the water column above becomes liquefied when the grain fabric is destroyed as a consequence of impulsive or cyclic stresses. Under these circumstances, pore pressure increases as a consequence of the progressive collapse of the grain fabric (Allen, 1985). However, the liquefaction susceptibility of fine sand will increase if the pore pressure is initially high (e.g., Hendry and Stauffer, 1975). These authors suggested that high-velocity current and a considerable water flux through the sand could create such a condition. Alternatively, variation in permeability within the cross-set, and hence, variation in flow rate of the fluid percolating through it, could cause relatively high pore pressure in the bed prior to its liquefaction. In particular, the humpback geometry

Fig. 7. Part of the flat-topped lens-shaped zone in Fig. 3d. Note the up-current dipping axial surface trace of the folds and the abrupt, nonerosive transition between the undeformed low-angle inclined cross-strata and the deformed zone. Scale to the right ca. 15 cm.

(Fig. 8a) of transitional regime bedforms and their horizontal to low-angle inclined topset strata (Saunderson and Lockett, 1983; Røe, 1987) suggest an upward and down-palaeoflow decline in permeability, corresponding to the transition from loosely packed cross-strata (e.g., Allen, 1985) to closer packed topset strata. The mechanism that triggered the liquefaction will be discussed in a subsequent paragraph.

8. The driving forces

The position of the flat-topped lenses below the horizontal top of the cross-sets (Fig. 3c and d) or below their gently upstream-inclined top surfaces (Fig. 3e) implies deformation by currents flowing across the bedform. Allen and Banks (1972) demonstrated that currents with velocities of the order of 1 m/s were sufficient to deform a liquefied cross-set. In the present case, the dominance of massive sand within the lenses, and the position of the folds at the base of the liquefied zones suggest, however, that the magnitude of internal shear and hence the current drag were much greater than in the theoretical model of Allen and Banks (1972). Based on the nature of the primary stratification, Røe (1987) and Røe and Hermansen (1993) have suggested deposition by high-velocity currents, heavily laden with sand in suspension. The internal characteristics of the lenses are consistent with such flow conditions. The heavy mineral sags and droplets present near the top of some of the lenses are attributed to a reverse density gradient and hence deformation by vertical forces. The preservation of these features implies their formation subsequent to the horizontal or subhorizontal grain translation indicated by the fold geometry.

The deformed cross-strata within the tangential wedges may be a result of not only water currents, but also of gravitational forces. Liquefaction of sediment below a slope inevitably leads to sediment col-

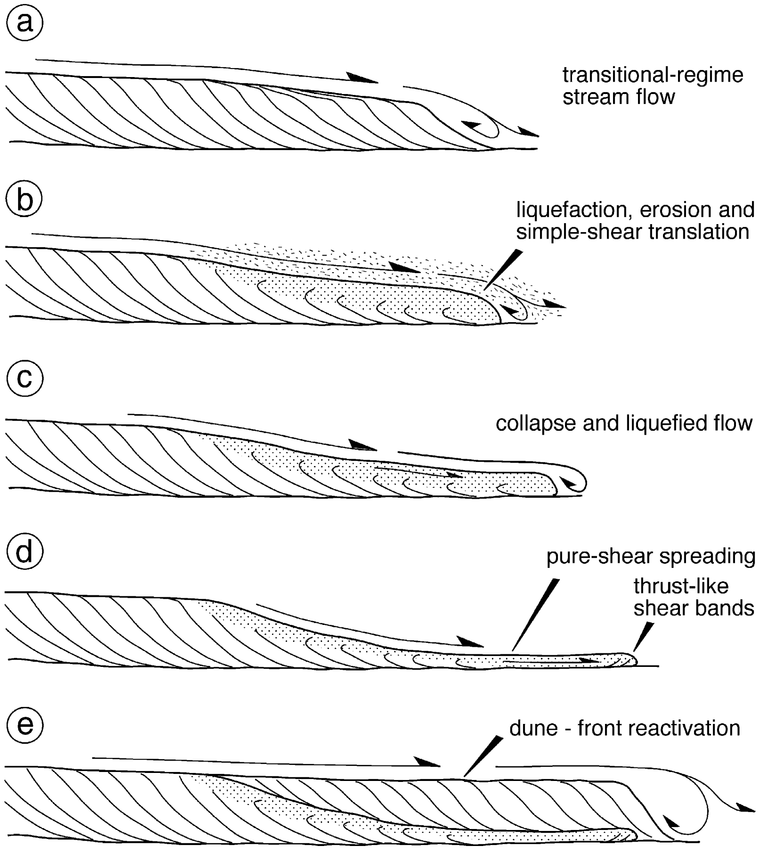

Fig. 8. Inferred stages in the development of the tangential wedges of deformed cross-strata. (a) Concave upward and sigmoidal cross-strata formed in the dune-plane bed transition. The downcurrent shortening of the foreset strata and development of low-angle topset strata indicate the flow-regime approaching plane-bed stage. (b) Liquefaction of the dune front and deformation by the tangential shear imposed by the current drag (simple-shear translation). The upper part of the liquefied sediments is eroded and brought into turbulent suspension. (c) Collapse and liquefied flow, with deformation driven by both sediment gravity and the suspension-laden currents. (d) Downcurrent spreading by pure-shear translation results in long massive toeset. (e) Reactivation of the dune-front and deposition of concave-up and sigmoidal cross-strata.

lapse and lateral spread (e.g., Allen, 1985; Owen, 1996). The down-paleocurrent-inclined bases of the liquefied dune front also seem to suggest mass movement down these low-angle (3–6°) lee slopes.

Deformation due to liquefaction and failure of the bedform front, combined with sediment mass flow down a slope much gentler than the foreset angle of repose, was favoured by Jones and Rust (1983) in their interpretation of the down-palaeocurrent-inclined wedges of recumbently folded cross-strata and massive sand in thick fluvial cross-sets of Triassic age. The recumbent folds were located directly below slip planes (decollement surfaces) and hence attributed to gravitational slip. The massive character of the overlying sand was attributed to intergranular shear within a downslope-moving liquefied sand flow. The possible impact of the accompanying water currents was virtually ignored in their study.

In the present case the majority of the recumbent folds pass transitionally upwards into massive sandstone (Figs. 3a-c, 5a,b and 6), which suggests that the folding could not have been produced by gravitational slip, contrary to the suggestion of Jones and Rust (1983). It is also unlikely that the folds in the lower part of the wedges were produced by gravitational shearing in a liquefied sand flow. The similarity of fold shape and orientation in the deformation lenses and tangential wedges suggests broadly comparable velocity profiles in these liquefied portions of the bed and hence similar dominant driving forces. Therefore, it is suggested that the liquefied dune front was folded by the shear stress of the river currents at the instant of bed liquefaction and prior to the shear effect from the gravity forces (Fig. 8a and b). It is also likely that during the process of liquefaction and deformation, the upper section of the liquefied sediments was eroded and transported in turbulent suspension by the high-velocity stream flow (e.g., Hendry and Stauffer, 1975 and Fig. 8b).

It has already been argued that the drag exerted by the turbulent current flow was sufficient to destroy the lamination completely, and hence, the sedimentary evidence of post-folding deformation by gravitational shearing is limited. However, the exceptionally long, bottomset part of some of the wedges (Fig. 3a and b) is probably a result of sand redeposition from the downslope-moving liquefied sand (Fig. 8c, d). The sporadic evidence of up-flow dipping diffuse surfaces in the "distal" downstream part of the wedges is interpreted as listric shear bands suggestive of thrust-like internal shearing in the frontal portion of a freezing liquefied flow.

The presence of discontinuity surfaces above a few of the fold hinge zones (Fig. 5c) suggests local post-folding gravitational slip. The wavy shape of the upper fold-limb laminae (Figs. 5 and 6) is attributed to vertical water escape during resedimentation. The local presence of faint parallel lamination between the massive sandstone and inclined portion of the reactivation surface (Fig. 3a, right wedge) indicates turbulence and tractional grain segregation in the uppermost part of the liquefied sediment, probably due to interaction with the overriding stream flow. The parallel attitude of the lamination and the reactivation surface suggest that at least the shape of the reactivation surfaces was mainly a consequence of the dune front liquefaction and deformation, and not the result of subsequent erosion.

9. The triggering mechanism

The localized nature of the cross-strata liquefaction and deformation within the tabular cross-sets suggests that the liquefaction was caused by processes related to the fluvial system itself (Røe, 1987: Hermansen, 1989) and thus of autokinetic origin (sensu Leeder, 1987). The alternative that the localized liquefaction was caused by textural variation within the cross-sets (e.g., Allen and Banks, 1972) can be ruled out because there is no apparent difference in grain-size and sorting between their deformed and undeformed parts. The high-angle discordant relationship between the abrupt, non-erosional boundary of the deformed zones and the stratification in the underlying undeformed sediment also preclude a major change in the susceptibility of the sediment to liquefaction across this boundary. Furthermore, the lateral alternation of undeformed cross-strata and the tangential wedges of deformed sediments suggests that the time span of each liquefaction event was much less than might be expected if earthquake tremors were involved.

The repetitive occurrence of the tangential deformation wedges within the tabular cross-sets suggests that liquefaction of the bedform front was caused by intermittent changes in the flow structure, rather than by erratic phenomena, such as channel bank collapses (cf. Jones and Rust, 1983). The notion that the tabular cross-sets were deposited in the dune-plane bed transition during one flood cycle (Røe, 1987; Røe and Hermansen, 1993) implies that the liquefaction, degradation and deformation of the bedform front were related to flow phenomena in this transition. Observations on transitional flows suggest that they are highly erratic, with the water surface both in phase and out of phase with the bedforms (Saunderson and Lockett, 1983). In the lower part of the transitional regime, the bedforms and flow have attributes similar to those of the lower flow regime, whereas the dune slipface shortens and the length of the low-angle topsets increases as the upper flow-regime is approached (Fig. 8a). The increased bed shear stress in the latter condition may also cause dune-front erosion.

Accordingly, it is suggested that the original, undeformed and relatively long cross-strata formed in the lower or middle part of the dune-plane bed regime, whereas the liquefaction and deformation of the dune front (forming the tangential wedges) occurred when the flow conditions approached the plane bed phase (Fig. 8a and b). Fluctuations in the flow velocity and/or depth during flood or falling-flood stages (e.g., flood surges caused by heavy, short-lived rainfall) may have contributed to the somewhat variable flow in the transitional regime. It can be speculated that the remoulding of dunes into an upper stage plane-bed may involve flow conditions that induce a highly differential turbulent pattern and cause pressure fluctuations at the bedform front sufficient to liquefy the fine sand, particularly if the initial pore pressure is high and increases further by cyclic loading.

The evidence that the flat-topped lenses, like the tangential wedges, formed during migration of the bedforms (Fig. 3e), and the similar degree of deformation between the two geometrically different zones, suggests that the liquefaction of the lenses was also caused by turbulent pressure fluctuations in the transition to upper flow regime. In particular, the smaller lenses which in places are repeated along the length of the bed (Fig. 3c) favour turbulence and hence, cyclic loading, as a triggering mechanism. The solitary and rare occurrences of the larger lenses may alternatively suggest liquefaction by impulsive loading from bank collapse during falling flood stages similar to the mechanism proposed by Jones and Rust (1983).

10. Conclusions

Extensive tabular cross-sets in the Neoproterozoic fluvial sandstone of northern Norway show deformed cross-strata, in the form of recumbent folds and associated massive sandstone that occur as localized features passing in both up- and down-palaeocurrent direction into undeformed, concave-up and sigmoidal cross-strata. The deformation occurs as either tangential wedge-shaped zones or flat-topped lenticular zones, with the former being the most common type.

The flat-topped deformation lenses suggest partial liquefaction below the sub-horizontal bed top and deformation by a high-velocity, suspension-laden water current. The inclined tangential wedges suggest liquefaction of the dune front and hence deformation by gravity forces in addition to the shear stress exerted by the current. It is argued that the dune-front strata were deformed by tangential current shear at the instant of bed liquefaction and prior to the shear effect of gravitational sand flow. The exceptionally long, massive bottomset part of some of the tangential deformation wedges may be a result of sand redeposition from subsequent liquefied sand flow. The wavy appearance of upper fold limb laminae is attributed to vertical water escape during resedimentation of the liquefied sediments.

The downcurrent alternation of the deformation wedges and undeformed cross-strata within a cross-set suggests that the liquefaction and deformation of the dune front was caused by intermittent changes in the flow conditions. In the context of the flow regime of the dune/upper-stage plane-bed transition, the liquefaction and deformation could have occurred when the flow conditions approached the plane-bed phase, inducing a highly differential turbulence pattern and pressure fluctuations sufficient to liquefy the fine sand. The liquefaction associated with the flat-topped lenses is also attributed mainly to cyclic loading by the current, although the rare solitary occurrences of the largest lenses may alternatively suggest liquefaction by impulsive loading from channel bank collapse.

In the present study, the inference that the bed liquefaction was generated autokinetically by the current is based on the evidence that only a part of the bed was liquefied when being deformed and on the repetitive occurrence of deformed and undeformed cross-strata along the length of the bed. In cases where the cross-stratified bed is deformed throughout its exposed downcurrent length, it may be difficult to determine whether the deformation was autokinetic or allokinetic. However, since the formation of recumbent folds requires relatively small drag force (Allen and Banks, 1972), the common occurrence of such features in cross-stratified fluvial sandstones and its virtual absence in marine cross-stratified deposits suggests strongly that the deformation in the majority of cases is autokinetic, resulting from flow phenomena typical of river channels. Contrary to the opinions of Allen and Banks (1972) and Leeder (1987), this kind of deformation structure is thus of little value in palaeotectonic analysis unless independent evidence of an allokinetic origin can be documented.

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