Marine and Petroleum Geology 27 (2010) 2118–2140

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Mechanisms of collapse of the cretaceous helvetiafjellet formation at Kvalvågen, eastern Spitsbergen

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ARTICLE INFO

Article history:
Received 20 January 2010
Received in revised form
5 August 2010
Accepted 6 September 2010
Available online 17 September 2010

Keywords:
Spitsbergen
Helvetiafjellet
Kvalvågen
Delta collapse
Billefjorden fault
Kvalhovden
Svalbard
Paleolandslides

ABSTRACT

Coastal cliffs at Kvalvågen, eastern Spitsbergen, expose palaeolandslide blocks and related slope failure features that record local collapse of an otherwise undisturbed succession of paralic sediments. The collapse occurred along a shallow sloping shelf at the edge of an epicontinental sea in the Early Cretaceous. The event was coincident with a rise in relative sea level along a coast that had just previously experienced a major paralic regression across a muddy marine environment. The low relief environment in which the slope failure structures formed, as well as the timing of the collapse raise questions regarding the cause of the topographic instability and the possible influence of sea level changes or tectonic activity. These outcrops have been previously interpreted as the collapse of a deltaic system triggered by local seismic activity or collapse of a shelf break in the headwall regions of submarine canyons. This paper presents new structural and stratigraphic data that refine and adjust the previous interpretations through the evaluation of a variety of possible mechanisms for collapse based on the new data. Our data suggest that active delta deposition was not occurring at Kvalvågen at the time of collapse and that the collapse was likely due to allogenic forcing. Despite the possible influence of pore fluids and rheological controls on the collapse, we find that the geometry and kinematics of landslide slip planes, synsedimentary folds, and other slope failure related features require over-steepened topography and that these are most consistent with westward-directed collapse off of a north striking escarpment with elevated topography on the east side. Fault exposures, a large contrast in palaeo-elevation, and liquifaction features support previous interpretations of a tectonic cause for the collapse and suggest that this topographic feature may have been a fault or fold scarp. This study demonstrates the importance of combining stratigraphic and sedimentological data with structural data and kinematic analysis in the interpretation of sedimentary processes.

1. Introduction

The coastal areas of southeastern Spitsbergen are dominated by sedimentary strata that were deposited along the edge of an epicontinental sea in northern Pangea during the Mesozoic (Harland, 1997). These rocks have experienced relatively little deformation since their deposition and remain nearly horizontal in eastern Spitsbergen. The exceptions are where the units are deformed along three major deformation zones, the Billefjorden and Lomfjorden fault zones (Andresen et al., 1992a), the Tertiary fold and thrust belt in southern Spitsbergen (Steel and Worsley, 1984), and one anomalous locality where major disruptions are exposed in coastal cliffs at Kvalvågen (Fig. 1). At this location a variety of features record major disturbance of the Early Cretaceous Rurikfjellet and Helvetiafjellet Formations. The most striking of these features are large landslide blocks (ranging from 5 to 25 m across) composed of Helvetiafjellet Formation sandstone and underlying Rurikfjellet Formation sandstone and mudstone that were dropped down into Rurikfjellet mudstone along normal faults (Fig. 2) first described in detail by Nemec et al. (1988a). The Helvetiafjellet Formation sandstone is completely missing in some parts of the outcrop where the displaced beds have presumably slipped out of the present-day plane of exposure or below present-day sea level. Other disturbance-related features include smaller slide blocks, minor faults, folds, debris flows, and convoluted bedding. The timing of the collapse within the stratigraphic section suggests that this collapse occurred during a low to rising relative sea level following a period of regression in the region (Gjelberg

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doi:10.1016/j.marpetgeo.2010.09.004

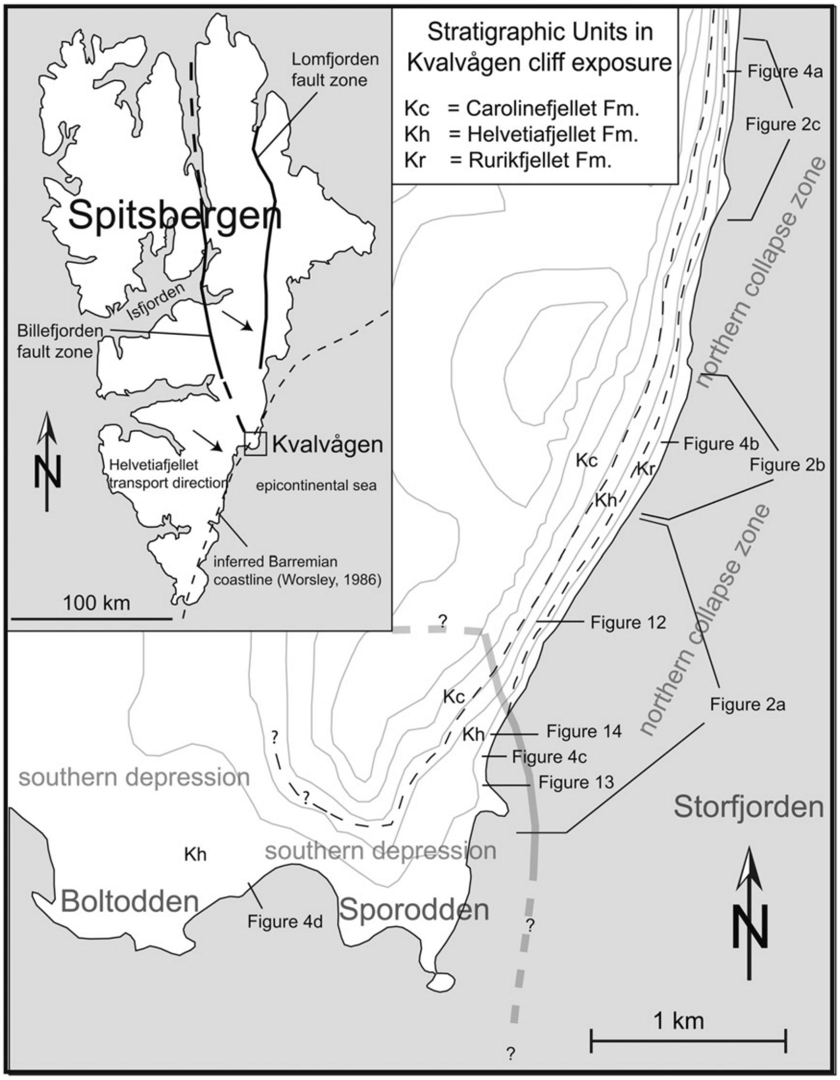

Fig. 1. Location map of the Kvalvågen area showing the collapse zone, approximate stratigraphic contacts exposed in the cliff face, and locations of photos. Inset map shows location of Kvalvågen on Spitsbergen relative to known fault lineaments and Early Cretaceous paleogeography.

and Steel, 1995; Steel et al., 2001; Midtkandal and Nystuen, 2009). This temporal relationship between sea level fluctuation and the disturbance of coastal strata raises questions regarding possible effects of sea level change on the stability of paralic sedimentary deposits due to changes in pore pressure, overburden, or hydrologic characteristics. However, this structural zone at Kvalvågen stands out as an anomaly in a largely undisturbed section of late Mesozoic strata in eastern Spitsbergen and similar collapse features have not been observed elsewhere in the region. It is therefore important to understand whether this spectacular deformation is due to a local isolated event (collapse of a shelf edge, an over-steepened delta front on the shelf, or a fault scarp) or a rare exposure of a regional process that accompanies sea level fluctuations on shallow sloping coastal environments (such as erosion of submarine canyons along a shelf edge or gravity gliding due to fluid overpressures).

Nemec et al. (1988a,b) presented the results of a comprehensive study of the Kvalvågen area and interpreted these outcrops to represent the collapse of an eastward prograding delta front triggered by seismic shaking. This model was based on the similarity of the slip planes and displaced blocks to those seen on active deltas, as well as the authors' interpretations of depositional environment both before and after the collapse.

A second hypothesis was suggested by Steel et al. (2001) who interpreted the collapse to be due to blocks sliding into the head of a submarine canyon that was eroding landward across the shelf edge. In this model, the canyon would be the areas where the lower Helvetiafjellet beds are missing in the outcrop. This model implies that these exposures are the easternmost limit of the paralic Helvetiafjellet strata.

Our recent work in the area has produced new structural and stratigraphic data that are not fully accounted for in the previous interpretations. In addition, since the work of Nemec et al. (1988a, b) was published, a large amount of research on overpressure, growth faulting, and gravity sliding on offshore areas has been presented that may lend new insights into the collapse at Kvalvågen. The goal of this paper is to build on the work of Nemec et al. (1988a,b) by evaluating the Kvalvågen outcrops in light of our new data and more recent developments in understanding slope failures in the nearshore environment.

We use the new data to test the previous models as well as several other hypotheses including slope failure due to hydrologic or lithologic weakening, and collapse of local relief created by faulting or local magmatic activity. If the collapse event were the direct result of faulting in the area, this would be the first evidence

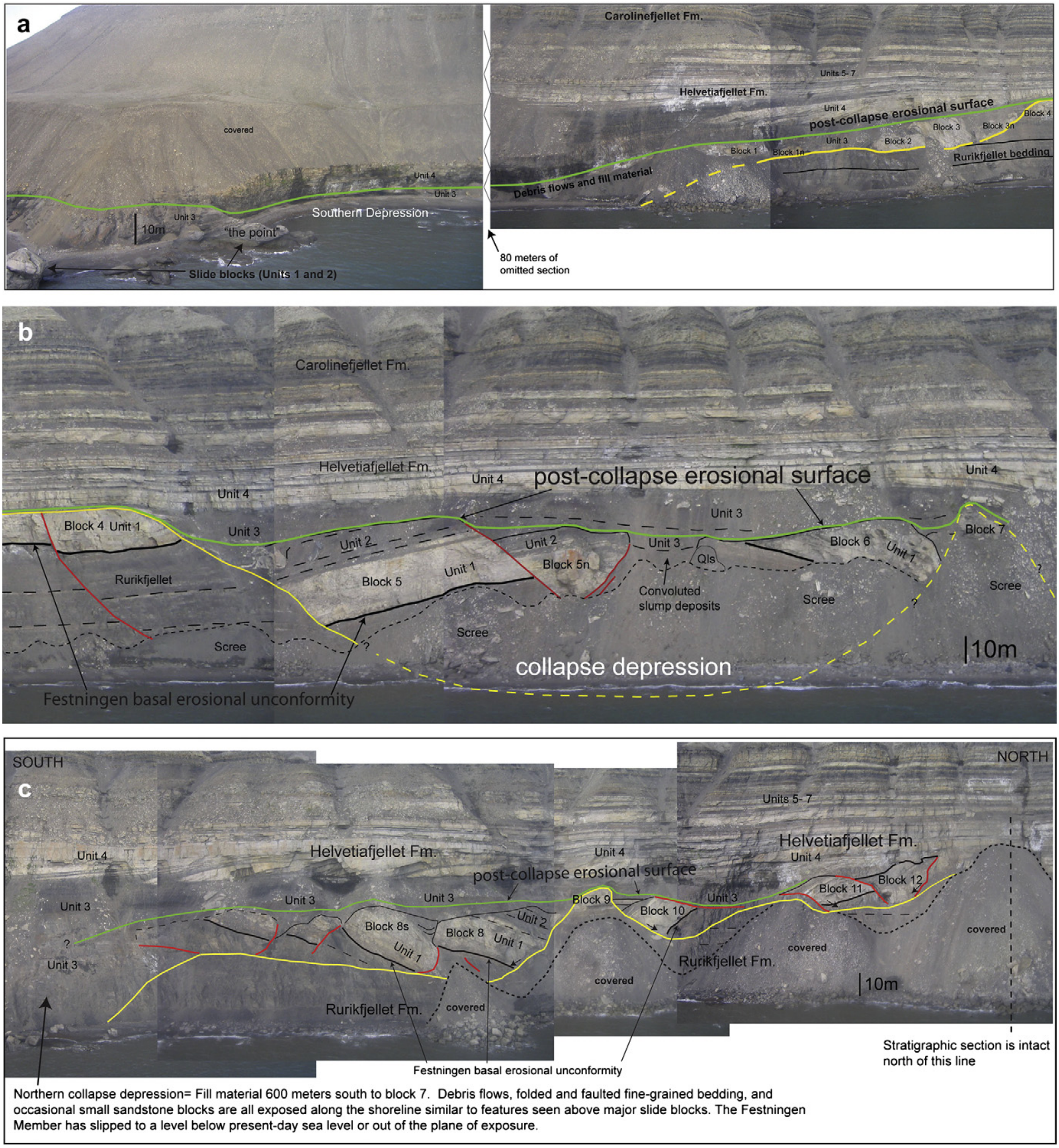

Fig. 2. Photomosaics of the eastern coastal cliff exposures at Kvalvågen. Black lines indicate bedding, red lines indicate faults, yellow lines indicate the base of the collapse zone, and green lines indicate the post-collapse erosional surface. a) The boundary between the Southern Depression and the northern collapse area. b) The central part of the northern collapse area. c) the northern part of the northern collapse area.

of Lower Cretaceous tectonic activity along the southeastern side of Spitsbergen and may require a revision to the inferred local structural framework and timing of activity on nearby structures such as the Lomfjorden and Billefjorden fault zones. The hypothesis of local magmatic activity as a mechanism for collapse is explored because the timing of the collapse at Kvalvågen is broadly coeval with emplacement of basaltic sills and flows in central and eastern Svalbard (Burov et al., 1977). Maher (2001) associated this magmatic activity with the High Arctic Large Igneous Province and suggested that this magmatism caused a widespread uplift event recorded by a regional erosional unconformity at the base of the Helvetiafjellet Formation (Worsley, 1986; Gjelberg and Steel, 1995).

2. Stratigraphy at Kvalvågen

The cliffs at Kvalvågen expose Early Cretaceous sedimentary rocks of the upper Rurikfjellet Formation, the Helvetiafjellet Formation, and the lower Carolinefjellet Formation (Fig. 3). All of

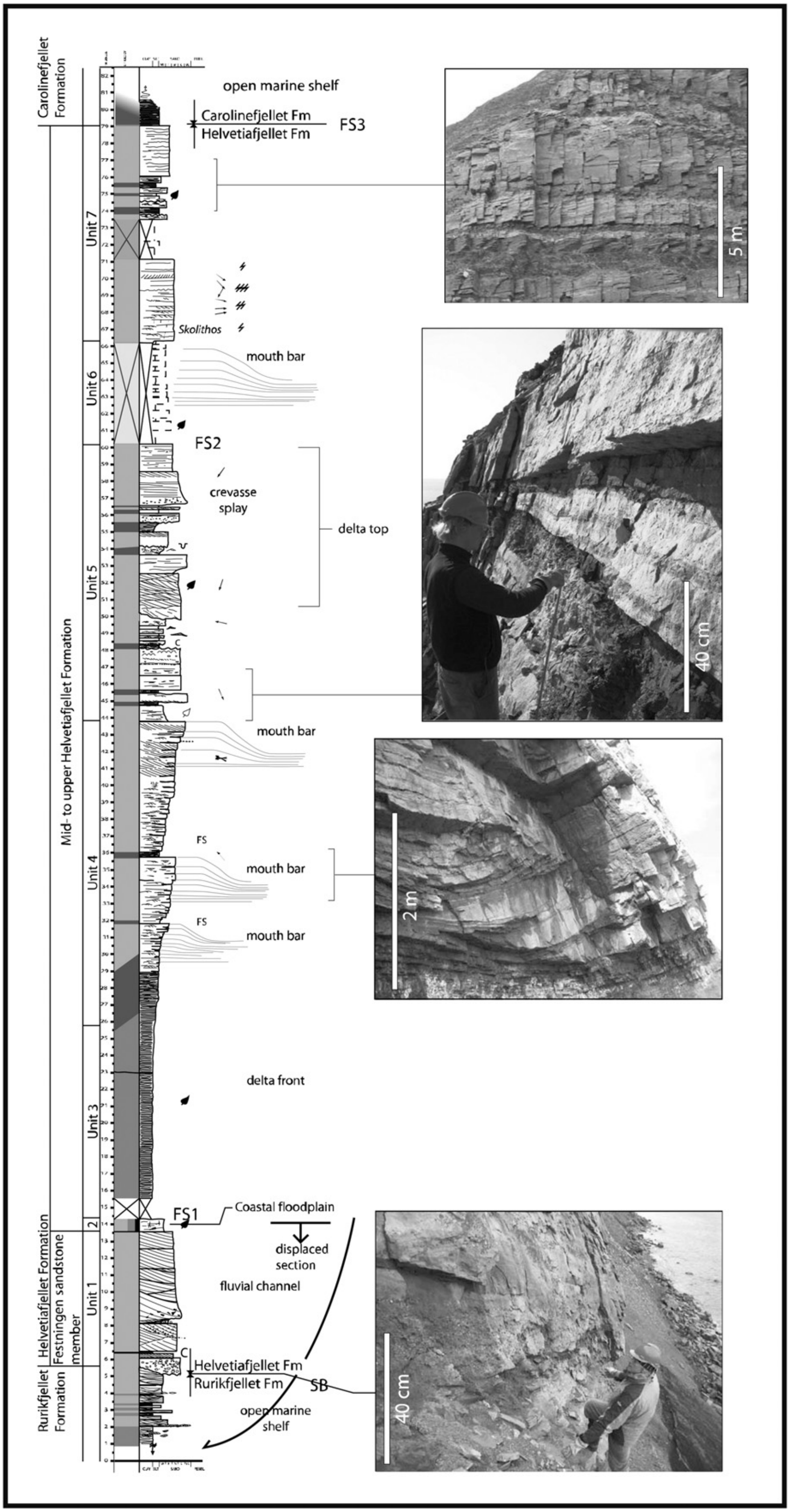

Fig. 3. Detailed stratigraphic log from the Kvalvågen cliffs (reproduced from Midtkandal, 2007). The displaced blocks have been re-attached to illustrate undisturbed state. Note that the displaced section occurs after deposition of fluvial channels and floodplain deposits and that the delta sedimentation postdates the collapse event and fills in the space created by collapse.

these units were deposited along a gently sloping shelf at the edge of the Boreal Basin, an epicontinental sea that existed in northern Pangea during the Cretaceous (e.g., Harland et al., 1984; Steel and Worsley, 1984; Torsvik et al., 2001).

2.1. Rurikfjellet formation

The oldest unit exposed at Kvalvågen is the Rurikfjellet Formation (Parker, 1967). The Rurikfjellet Formation is a shallow regressive shelf succession in eastern Spitsbergen that prograded towards the southeast (Dypvik, 1980; Dypvik, 1985; Dypvik et al., 1991). Frequency and thickness of silt- and sandstone beds increase upwards, and in many outcrops fine-grained sandstone beds and individual upward-coarsening distal prodelta, shoreface or open shelf sand deposits form distinct progradational parasequence sets (Edwards, 1976; Dypvik, 1980, 1985; Mørk et al., 1999). This stratigraphic and sedimentary pattern is also present in the Kvalvågen area, as well as along Kvalhovden, an extensive cliff section directly north of Kvalvågen.

Only the uppermost Rurikfjellet Formation is exposed in the cliff section at Kvalvågen, and consists of five individual upward-coarsening parasequences (Fig. 3). Clay-rich mudstone dominates the Rurikfjellet Formation but coarser beds are also present. Grain size increases upwards from thin-bedded coarse-grained siltstone in the lower part to medium sand in the uppermost sandstone body just beneath the Helvetiafjellet Formation where the bed thickness reaches up to 1 m.

The upper contact of the Rurikfjellet Formation is an erosional unconformity where a conglomerate bed at the base of the overlying Helvetiafjellet Formation (Parker, 1967) scoured into the Rurikfjellet beds. A similar erosional contact at the base of the Helvetiafjellet Formation is present throughout many areas of Spitsbergen (e.g., Worsley, 1986; Gjelberg and Steel, 1995; Midtkandal, 2007; Midtkandal and Nystuen, 2009) and has been interpreted to record a regional uplift event in the Barremian (Steel and Worsley, 1984; Maher, 2001).

2.2. Helvetiafjellet formation

The Helvetiafjellet Formation is a sandstone-dominated paralic succession that interrupts the shallow marine, open shelf conditions that existed throughout most of the Cretaceous in eastern Spitsbergen.

2.2.1. The lower boundary of the Helvetiafjellet Formation and the Festningen sandstone member (Unit 1)

In the Kvalvågen area, the Helvetiafjellet Formation lies on an erosional unconformity. This unconformity has relief of up to 1.5 m cut into mudstone and hummocky cross-stratified sandstone beds of the Rurikfjellet Formation. This surface is present within the slide blocks as well as along the undisturbed cliff section north of the collapse zone. The unconformity is in most places overlain by a 30 cm thick, matrix-supported fluvial conglomerate with extrabasinal clasts. Above this is a 10–12 m thick fining upward sandstone succession composed of predominantly tabular and trough cross-stratified sandstone. Shale clast conglomerate, plane-parallel stratified sandstone, current ripple laminated sandstone and structureless sandstone are also present. Palaeocurrent directions indicate flow towards SSE, and downstream accretionary bars tens of meters in length and up to 3 m high are well developed within the unit.

This lower section of the Helvetiafjellet Formation is herein defined as Unit 1 (Fig. 3) and is interpreted to represent braided fluvial channel deposits. The lack of fine-grained sediment in this unit suggests highly mobile braided channels that eroded fine-grained backwater accumulations of mud or silt, and any vegetation that may have formed on emerged channel bars at the time (Nemec, 1992). This unit corresponds lithostratigraphically to the Festningen Member of Parker (1967). This interpretation differs from some previous work at Kvalvågen. Nemec et al. (1988a,b) interpreted these fluvial deposits at the base of the Helvetiafjellet to be "…the product of a laterally migrating fluvial channel, probably the distributary channel of a prograding delta." (p. 459–460). No lateral equivalent delta mouth bars or delta front deposits are exposed at Kvalvågen though they are well described from other locations in southern Spitsbergen (Gjelberg and Steel, 1995). Because the outcrops are located at the eastern coast of Spitsbergen, the eastward continuation of the strata may have been eroded. In their interpretation, the erosional unconformity at the base of the sandstone succession, preserved within the displaced sandstone slide blocks, represents the base of fluvial feeder channels of a delta that prograded across delta front and prodelta transitional facies of the underlying Rurikfjellet Formation. Steel et al. (2001) interpreted these basal sandstones to be a fluvial channel belt (p. 994).

The boundary between the Rurikfjellet Formation and the Helvetiafjellet Formation has been described as a subaerial erosional unconformity throughout Spitsbergen (e.g. Mørk et al., 1999; Midtkandal and Nystuen, 2009). Our interpretation of the Kvalvågen exposures does not differ from this view and we see no evidence requiring the existence of a delta at the Kvalvågen locality at this specific stratigraphic level. Our alternative interpretation of a fluvial conglomerate followed by a thick fluvial sandstone succession resting directly on open marine shelf deposits is significant in that it does not imply that the collapse occurred in a deltaic environment (Nemec et al., 1988a,b) and instead suggests that any corresponding delta or shelf edge (Steel et al., 2001) may have been located significantly farther southeast at the time of collapse.

2.2.2. Unit 2: Coastal floodplain

Unit 2 occurs above the Festningen Member in the undisturbed part of the succession in the Kvalvågen area, as well as within the detached fault blocks of the collapse zone. Unit 2 consists of beds of plane-parallel stratified sandstone, current ripple laminated sandstone and structureless sandstone beds embedded in mudstone and coal (Fig. 3). Stratigraphically above the lower fluvial sandstone body of the Festningen Member, brown to black sandstone and mudstone beds with coal fragments and a high content of organic matter occur with conformable contact to Festningen sandstone strata. The sandstone beds are penetrated by vertical root structures, are 15–30 cm thick, and thin to the south. The unit is 2–4 m thick, with no apparent overall upward fining.

Unit 2 is interpreted as representing *coastal floodplain deposits*. A decrease in fluvial channel mobility or channel avulsion may have provided the opportunity for preservation of fine-grained river-sourced sediments and peat (coal). The sandstone thinning direction suggests crevasse splays and crevasse sheets that were introduced into this part of the basin by a channel system somewhere to the north of the Kvalhovden area. The unit was deposited before the basin succession was disrupted by collapse.

2.2.3. Unit 3: Delta front and collapse scar fill strata

Unit 3 is restricted to the collapse zone, occurring within half-grabens between the rotated slide blocks and within the extensive down-dropped area that makes up the exposures at Sporodden and Boltodden (Figs. 1 and 2). We refer to this area as the "southern depression". Unit 3 does not occur on the relatively intact horsts between the half-graben depressions (Fig. 2) and varies in thickness, ranging from about 50 cm to more than 20 m in the areas where the removal of the Festningen Member created deep depressions. Unit 3 consists of two parts separated by an erosional unconformity. The lower part is a mixture of gravity slide deposits mixed with mudstones with lesser amounts of sandstone beds. The gravity slide deposits consist of debris flows, small (cm to m scale) sandstone slide blocks, and disrupted sandstone and mudstone strata. Along the beach cliff between "the point" and Block 1 (Fig. 2a) these collapse scar infill strata in Unit 3 are well exposed and were described in detail by Nemec et al. (1988a). The discrete sandstone bodies are clearly separated from the surrounding mudstone by sharp lithologic boundaries. The lower boundaries of the sandstone bodies are erosive. They are typically 1–2 m thick as maximum thickness and taper out laterally to form lens-shaped cross sections of 5–6 m wide. No internal structures or grading are recorded in the sandstone beds. Lamination in mudstone adjacent to the sandstone bodies is disturbed.

The upper part above the unconformity consists primarily of mudstones with smaller amounts of plane-parallel stratified sandstone, current ripple laminated sandstone, and structureless sandstone with bioturbation. The upper fine-grained beds of Unit 3 are warped down against the flanks of the small half-grabens and drape the upper surface of the fault blocks. Disturbed lamination is recorded near the axis of some of the half-grabens, however, these strata are not rotated like the underlying strata of the fault blocks.

The intervening erosional unconformity undulates with lows over the centre of the half-grabens and highs along the half-graben margins. A slight change in mudstone color is also apparent across the surface; red-brown mudstone is present below the unconformity, whereas the mudstone above is black.

Unit 3 is interpreted to represent *gravity slide debris mixed with delta front deposits that included thin turbidites*. The depressions and half-grabens that formed due to the collapse event were filled with debris derived from the sides of the depressions and mixed with fine sandstone and mudstone that was deposited as thin turbidites from a river-dominated delta. As the depressions filled and the walls become more stable, the amount of debris falling into the depressions decreased and the upper parts of the depression were filled with the delta front deposits. The unconformable surface within Unit 3 is interpreted to represent a flooding surface because of the abrupt change from collapsed slide blocks and debris flows below to deeper-water turbidite succession above. The undulation of the surface is attributed to the filling of topography following the collapse and some differential compaction of the mudstone sediments due to varied thickness within the half-graben segments.

2.2.4. Unit 4: Delta mouth bars

Unit 4 conformably overlies the delta front deposits of Unit 3 and comprises a significant portion of the Helvetiafjellet Formation in this area (Fig. 3). In a generalized ascending order, Unit 4 is composed of a structureless, trough cross-stratified, tabular cross-stratified and plane-parallel stratified sandstone set. The unit occurs stratigraphically above the collapse zone and consists of 4–7 m high clinothems made of sandstone beds 10–50 cm thick. The lowermost set of clinoforms terminates distally into fine-grained mud- and siltstone beds that form a conformable boundary to the underlying Unit 3. In the roughly north-south oriented cliff section at Kvalvågen, both northerly and southerly progradation directions are recorded within discrete sandstone beds.

Unit 4 is interpreted to represent *delta mouth bars* of a prograding delta or delta lobe. The apparent opposing directions of sediment transport are interpreted as lateral deposition from prograding 3D delta lobes, filling in an interdistributary bay. A detailed study of the mouth bar deposits exposed in the Boltodden locality is included in Nemec et al. (1988a).

2.2.5. Unit 5: Progradational delta plain parasequence set

Unit 5 is composed of 2 upward-thickening sandstone-dominated intervals bounded by relatively thin silt- and mudstone beds. The dominant facies are 40–120 cm thick planar-bedded sandstones interbedded with 10–30 cm thick silt- and mudstones. The upper of the two units contains a 40–60 cm horizontally bedded interval of mud-, siltstone and coal. Palaeocurrent directions vary, but are generally confined within 90°–180°.

Unit 5 is interpreted as *progradational delta plain* deposits formed landward of a prograding delta front. Each set boundary is suggested to represent a minor flooding surface, formed during a high-frequency rise in relative sea level. The relatively low divergence in palaeocurrent directions compared to Unit 4 indicates deposition inland from the delta front deposits in shallow distributary channels.

2.2.6. Unit 6: Progradational delta mouth bar and delta top

Unit 6 is a sandstone-dominated unit with an apparently abrupt lower boundary to the underlying fine-grained interval. The unit is about 2 m thick where it is exposed north of the collapse zone, and thickens abruptly to more than 4 m directly above the northernmost slide block. The lower sandstone body is composed of a single clinothem set spanning the entire unit thickness, with 10–30 cm high foresets with mud drapes that increase in thickness towards the upper boundary. Dip direction is broadly southerly.

Unit 6 is interpreted to represent a renewed delta mouth bar progradation, with a similar setting to what has been suggested for units 4 and 5.

2.2.7. Unit 7: Aggradational to retrogradational parasequence set

A 30–40 m interval of repeated sets of fine-grained sandstone and siltstone with upward-coarsening motifs mark the uppermost deposits belonging to the Helvetiafjellet Formation in the Kvalvågen area (Fig. 3). The deposits rest conformably on the underlying strata, and no internal erosional surfaces are recorded. The upper boundary is a transitional interval of sand- and silt-dominated sediments that gradually grade upward into siltstone and mudstone and constitute the conformable boundary between the Helvetiafjellet Formation and the Carolinefjellet Formation. The Carolinefjellet Formation (Parker, 1967) consists of shale and sandstone deposited on an open shelf and represents a rise in relative sea level and return to dominantly marine deposition (Mørk et al., 1999).

Unit 7 is interpreted as *stacked aggradational to retrogradational parasequences.* The depositional environment was probably nearshore, shallow water environment some distance offshore or alongshore from the main delta feeding sediment into the basin. Vertically, these deposits pass conformably into open shelf mudstone that formed during the overall regional rise in relative sea level that ended the paralic environment of the Helvetiafjellet Formation in the Spitsbergen area.

2.3. Disrupted stratigraphy and spatial relationships

The succession of units presented above is not uniform throughout the Kvalvågen area due to disruption by the collapse event and resultant differences in topography and local environment. The Kvalvågen area can be divided into 3 distinct zones that expose different stratigraphic sections. These zones consist of a large (>4 km^2) depression (which we refer to as the "southern depression") that makes up the southern exposures in the area around Sporodden and Boltodden (Figs. 1, 2a, 4c,d), a northern section of intact strata that extends to the north well beyond the Kvalvågen area (Fig. 4a), and a transitional collapse zone in between in which large slide blocks that slipped into smaller depressions are exposed (Figs. 2b,c, 4b).

In the northernmost part of the Kvalvågen area, the stratigraphy described in the previous section is undisturbed and all the units

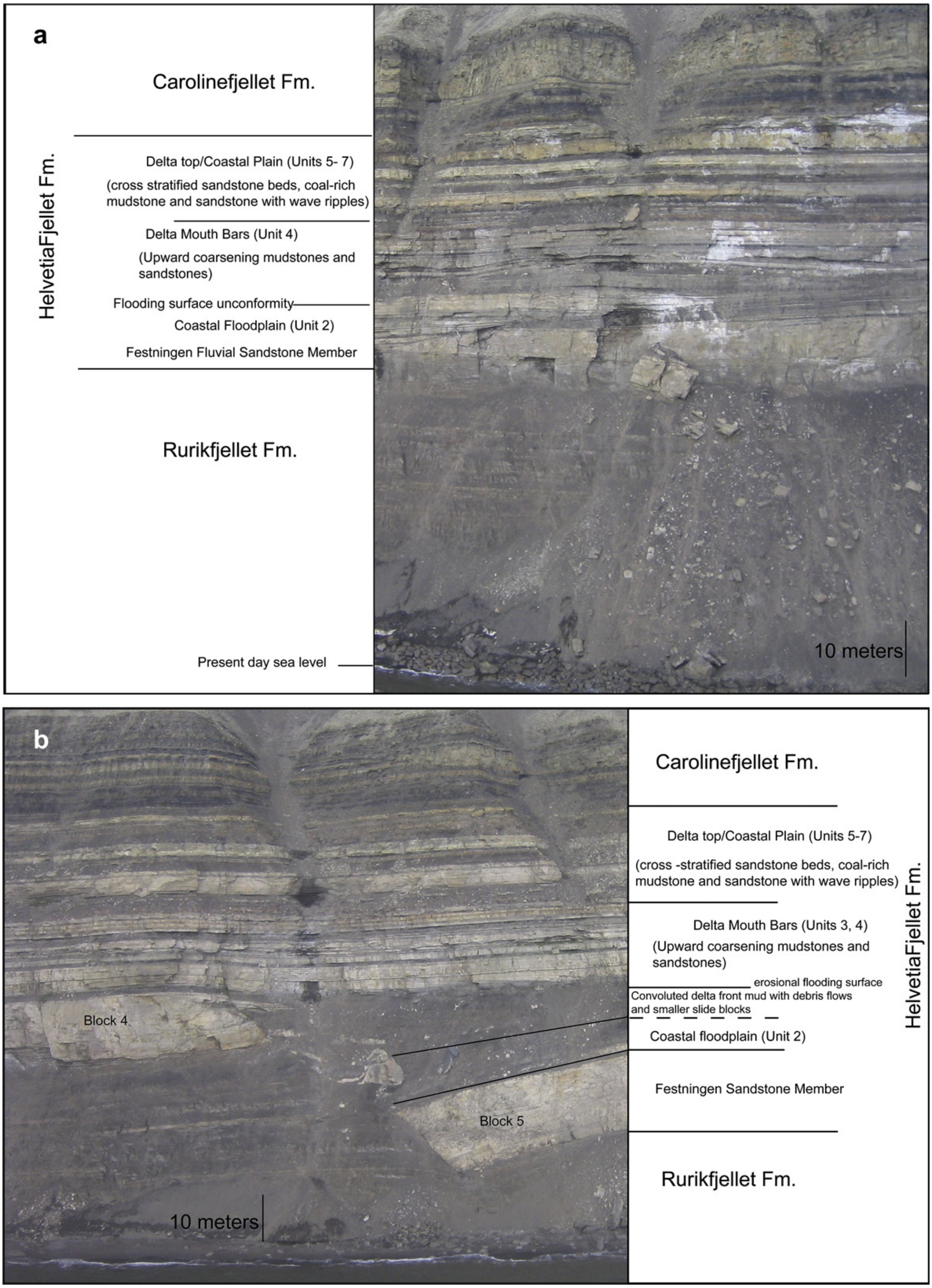

Fig. 4. Stratigraphic sections from different parts of the Kvalvågen area to illustrate stratigraphic differences (locations shown in Fig. 6). a) undisturbed section north of the northern collapse zone. b) section from the northern collapse zone. c) section from the eastern exposed part of the southern depression (same beach cliff shown in Fig. 2a). d) section from the east side of Boltodden (Fig. 1) within the southern depression.

are present except Unit 3 (Fig. 4a), which was only deposited within the depressions and half-grabens created by the collapse.

The northern collapse zone is characterized by displaced blocks of the lower Helvetiafjellet Formation that slid down into depressions that range from tens of meters to 100s of meters across. A large amount of the lower Helvetiafjellet Formation is absent and must have slipped out of the plane of exposure, or below the level of exposure in order to create these depressions. The stratigraphy

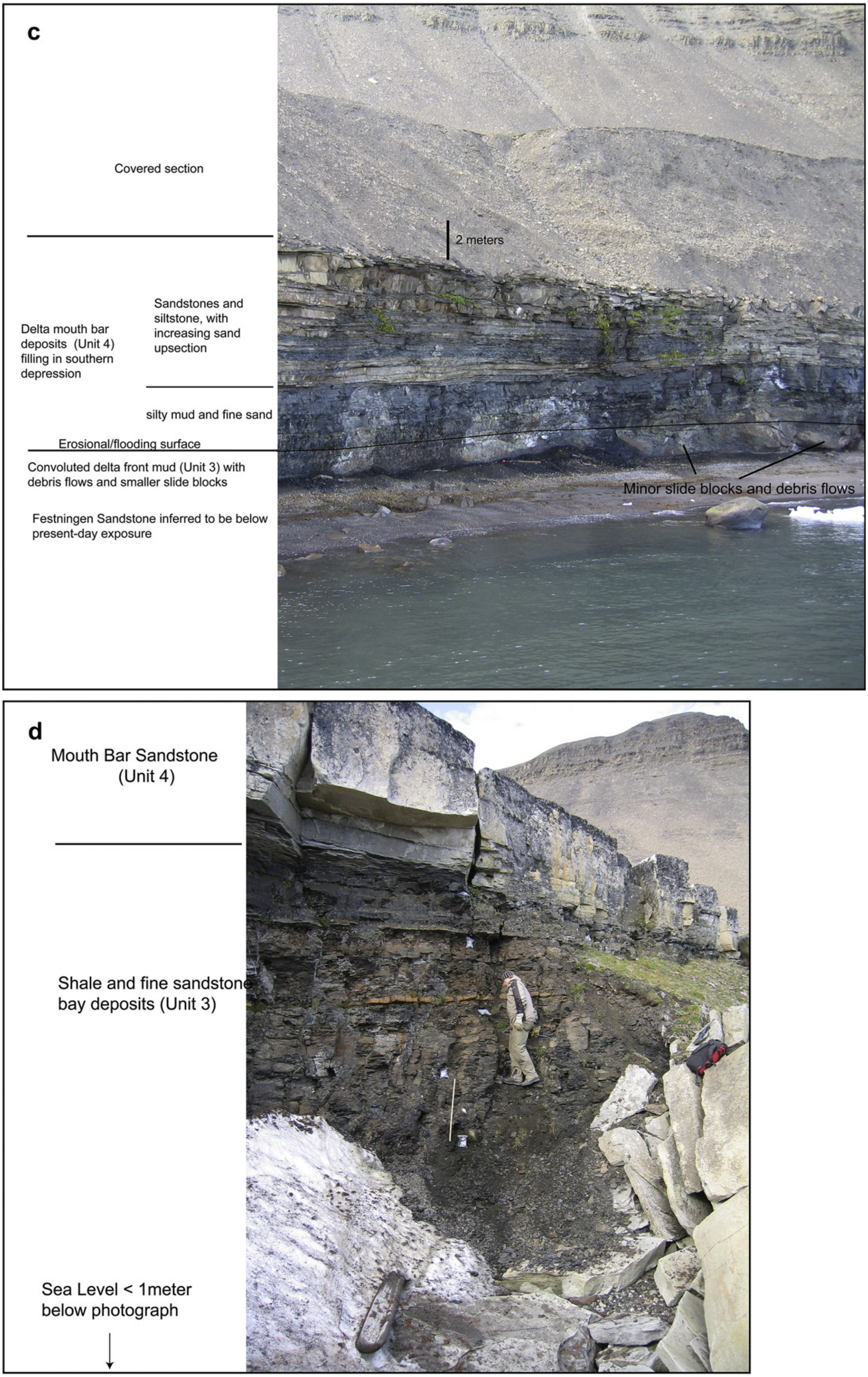

Fig. 4. (*continued*).

here is disrupted by the collapse, but all the units are represented. The erosional flooding surface within Unit 3 removed several meters of material off the top of the horsts, such that the upper Festningen Member sandstone and overlying floodplain deposits are missing at these locations (Fig. 5).

The "southern depression" is a large area (>4 km^2) that includes Sporodden and Boltodden in the southern part of the study area. It is defined by the lack of exposure of the upper Rurikfjellet and lower Helvetiafjellet formations in the coastal outcrops and the presence of delta front mudstone and turbidites (Unit 3) and prograding point bars (Unit 4) that apparently filled a large depression (Fig. 4c and d).

Comparison of the stratigraphy at different locations along the coastal outcrops at Kvalvågen (Fig. 4) shows that large contrasts exist between the present-day elevation of stratigraphic units along strike due to the vertical displacement of units during collapse. The most significant structural feature in the area is the stark contrast in stratigraphic level between the northern collapse zone and the large southern depression. Fig. 6 illustrates these contrasts using the base of the Helvetiafjellet Formation and the flooding surface within Unit 3 that postdated the collapse as markers. A difference of 40–50 m occurs at the northern edge of the "southern depression" where the level of collapse drops sharply to the south (Fig. 7). Any interpretation of the collapse at Kvalvågen must account for the development of this large depression and the associated removal of material.

3. Structural data and observations

A variety of structural features are present in the Kvalvågen area that record disturbance to the stratigraphic section. The most obvious structural features are the large (tens of meters across) slide

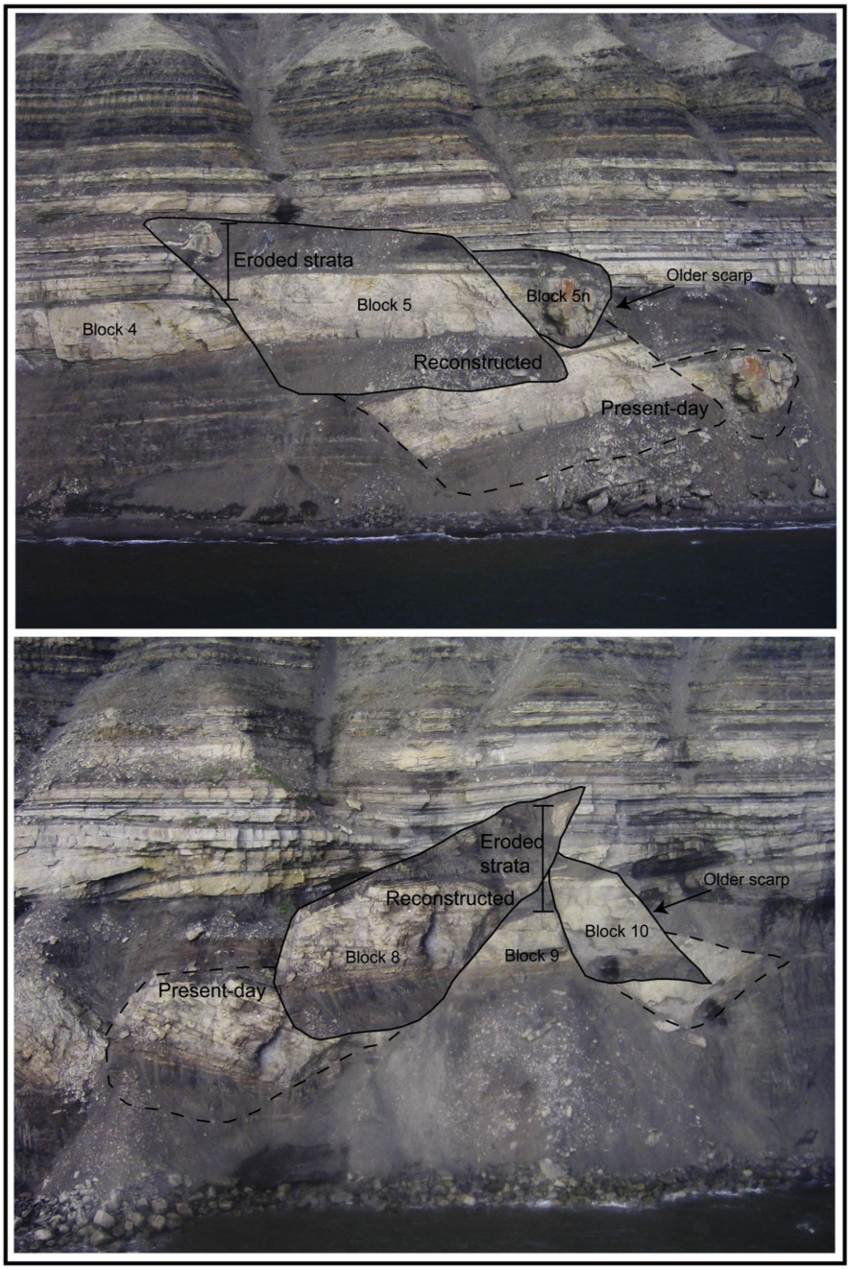

Fig. 5. Reconstructions of slide blocks against un-moved horsts. Blocks 4, 5, and 5-north on the top; Blocks 8, 9, and 10 on the bottom.

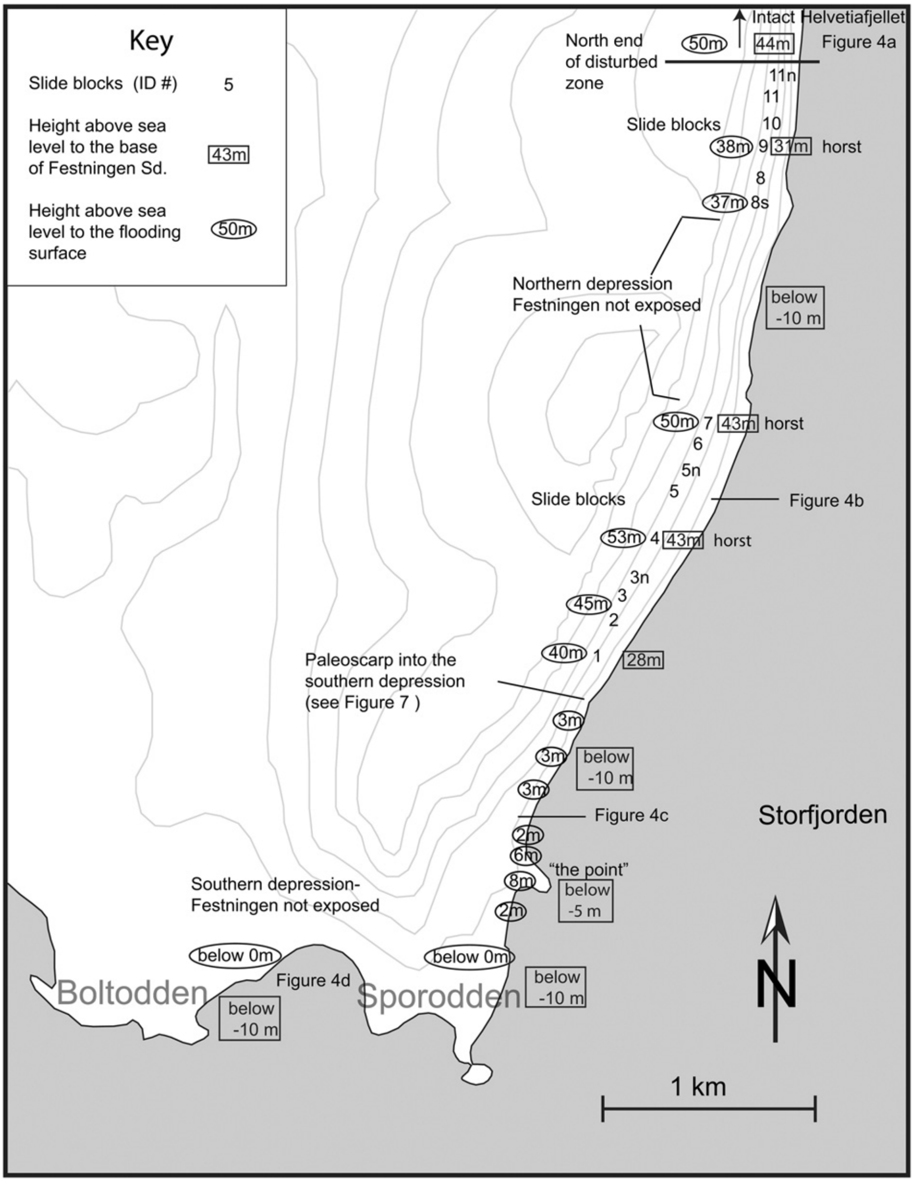

Fig. 6. Map showing elevations of the base of the Helvetiafjellet Fm. (in boxes) and elevations of the flooding surface (in ovals). The positions of the numbered slide blocks are shown for reference. The flooding surface marks the base of the delta front deposits (south of the paleoscarp) or the base of the delta mouth bars (north of the paleoscarp). The locations of the strat columns in Fig. 4 are also shown.

blocks of the Helvetiafjellet Formation and uppermost Rurikfjellet Formation that have slipped down into the underlying muddy strata (Fig. 2). In addition to the large slide blocks, other structural features in the Kvalvågen area include smaller slide blocks, minor faults, folds, and discontinuities in stratigraphic level. Local buttress unconformities are also present in the cliff exposure due to the removal of material out of the plane of exposure along faults and subsequent deposition in the depressions that were left behind. There is a range of time in which these deformational features were developed and they will be described here oldest to youngest. To identify the larger slide blocks in the following section we largely retain the numbering system applied by Nemec et al. (1988a).

3.1. *Pre-Festningen faults*

The earliest structural features present are small-displacement faults in the Rurikfjellet strata that do not cut the Festningen Member that was deposited unconformably on the Rurikfjellet beds (Fig. 8). The displacements range from a few centimeters to over two meters with sense of slip being both normal and reverse. Some of the normal faults die out downward in the Rurikfjellet Formation and may be synsedimentary growth faults from sediment loading. In Block 1 the Festningen Member sandstone was deposited against a fault buttress formed in the underlying Rurikfjellet beds (Fig. 9) with no observable breccias, suggesting the possibility of growth faulting at this location. However, most of the faults within the Rurikfjellet strata do not offset or deform the basal contact of the Festningen Member and the deposit does not thicken across them, indicating that they occurred prior to deposition of the Festningen Member. The orientation of these small faults varies between the individual blocks and because the degree of vertical-axis rotation during movement of the slide blocks cannot be determined in some cases, the original orientations of some of the faults are unknown. However, where vertical-axis rotation of the blocks is minimal, these faults are typically north-south striking normal faults or east-west striking reverse faults.

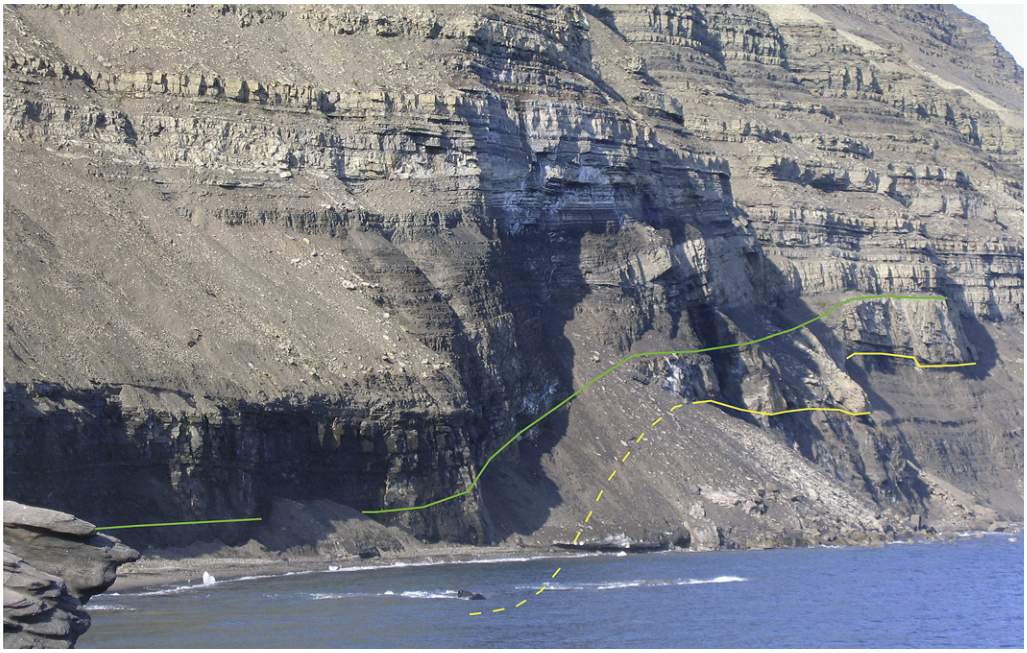

Fig. 7. Sharp contrast in collapse level at the north end of the southern collapse zone (also shown in Fig. 2a and labeled as "Paleoscarp" in Figure 6). Yellow line is the base of the Helvetiafjellet and the green line is the flooding surface within Unit 3 that postdates the collapse episode.

3.2. Main slide blocks

The major slide blocks exposed at Kvalvågen are coherent landslides that were displaced downward into the underlying muddy strata. Most of the slide blocks include the upper Rurikfjellet Formation, the Festningen Member and the overlying floodplain deposits (Unit 2). Some of the smaller blocks consist entirely of the Festningen Member sandstone.

The slide planes along which these blocks moved are brittle structures that cleanly cut the strata (Fig. 10). Many of the slip planes are delineated by proto-gouge or sheared mudstone derived from the mudstone beds of the Rurikfjellet unit in the footwalls but there is no mixing between the sandstone blocks where they are juxtaposed against shale (Fig. 10). However, along several of the fault planes, the Festningen Member sandstone is deformed by small ripples that suggest small-scale folding of the hangingwall

Fig. 8. Small-displacement faults in the Rurikfjellet Formation that do not cut the base of the Helvetiafjellet Formation.

Fig. 9. Festningen Sandstone deposited against a buttress developed in the upper Rurikfjellet beds.

block during transport (Fig. 10). Prestholm and Walderhaug (2000) described the slip planes in detail and concluded that the rare intra-fault sandstone layers they observed suggest fluidization occurred during displacement along some of the slip planes.

The geometry and orientation of the slide planes vary. The slide planes typically dip steepest in the upper parts, particularly adjacent to the intact horsts (Fig. 2). Where the lower parts of the slide planes are exposed, they are listric and decrease in dip down section indicating that most of the big slide blocks moved as rotational landslides. In the northernmost collapse zone (blocks 8 through 12) most of the blocks moved along planes that strike roughly east-west and dip north and south, whereas most of the slide blocks to the south (blocks 1–3n, Block 5n) moved along slide planes that strike north-south and dip to the west (Fig. 11). The orientations of the basal slide planes, and striations that are present along some of the planes can be used to infer the direction of block transport. Where slide planes at the base of the blocks are exposed, the blocks are assumed to have moved in a down-dip direction along the slide plane. Tilting of the bedding within the blocks has occurred due to horizontal-axis rotation of the bedding as the slide blocks moved down listric slide planes. Fig. 11 shows that the tilt of the bedding in the blocks consistently strike within a few degrees of the slide plane strike in most cases, showing that relatively little vertical-axis rotation of the blocks has occurred during movement. In the few locations where the slide planes are not exposed ("the point" and Block 6), the tilt of the bedding within the slide blocks is used to infer the dip direction of the underlying slide plane and hence the direction of movement down slope. However, there are uncertainties at these locations due to the possibility that an unknown amount of vertical-axis rotation has occurred during sliding. Other elements that are used to infer movement direction include the lateral extent of the blocks along and into the cliff exposure and deformation of sediments in front of the blocks (Fig. 12). The transport directions of the blocks indicate the direction of collapse and distribution of paleotopography. Fig. 11 shows the structural data collected from the individual blocks and the inferred direction of block movement and associated paleotopography.

In most places the slide planes of the blocks corresponds with the base of the collapse zone (Fig. 2). The dip angle and dip direction of this basal collapse surface vary widely in the plane of the cliff exposure with dip directions that alternate 180° from north to west to south. This large change in dip direction suggests that the surface actually curves in and out of the plane of exposure with an average strike that is roughly parallel to the present-day cliff exposure. The small horsts, labeled as blocks 4 and 9 (Fig. 2), were most likely not isolated "peaks" but were attached to an intact continuation of the strata that extends either into the cliff to the west, or out of the cliff to the east. Measurements from the slide planes on either side of Block 9 indicate that the surface curves into the cliff around the west side of this horst. This geometry agrees with the observations that many of the slide blocks sit on slide surfaces that dip to the west and indicates that the basal slide surface generally dips to the west. Some of the large apparent variations in the dip of the surface are the result of a highly oblique view of the surface due to the orientation of the cliff exposure.

The slide blocks exposed in the cliff are only a small percentage of the lower Helvetiafjellet Formation that must have once extended across the disrupted area at Kvalvågen. Most of the uppermost Rurikfjellet beds, the Festningen Member, and the floodplain deposits were displaced out of the plane of present-day exposure, or below present-day sea level. The general westward dip of the basal collapse surface where it can be measured means that any missing material would have been displaced down slope along the basal slide surface, and hence would have moved out to the west. In the large "southern depression" the only occurrence of the Festningen Member sandstone and overlying floodplain deposits (Unit 2) are two large isolated blocks at "the point" (Figs. 1, 2, and 11). The base of these blocks is not exposed but the strata are tilted towards the east, which suggests they slid down to the west if they moved as rotational landslides like most of the slide blocks to the north.

3.3. Late-stage collapse and scar infill

The lower topographic areas created by the collapse event at Kvalvågen were filled with debris flows, slump deposits, small slide blocks and turbidites described as Unit 3 above. The largest scar that was created was the "southern depression" (Figs. 6, 11). Only the northeastern edge of this depression is exposed in the cliff face (Figs. 2a, 7). The edges and aerial extent of this depression cannot be evaluated because it extends beyond the present-day outcrops

Fig. 10. a) Slide plane at base of Block 5 (crouching person for scale). b) Slide plane between blocks 5 and 5 n. c) Ripple features on the slide plane at the base of Block 2. d) Proto-gouge along a basal slide plane.

in the area. The eastern and southern extents must lie beyond the current coastline, although the presence of the slide blocks exposed at "the point" suggests that the eastern boundary was not far (assuming the blocks did not slide more than a few meters to tens of meters) to the east of the present-day coast. This inference is based on the observation that most of the other exposed slide blocks have not moved very far from their source, and the lack of any slide blocks to the south or west of this location. These slide blocks are the only occurrences of the Festningen Member within the southern depression. More than 20 m of debris flows and fill shale was deposited on top of the slide blocks at "the point" and were subsequently tilted by approximately 15° to the south in the immediate area above the slide blocks. This is contrary to the slight west to northwest dip of the Unit 3 strata documented by Nemec et al. (1988a) in the eastern exposed portion of the "southern depression". The local tilt suggests that multiple episodes of displacement occurred at this location. The fill deposits above the slide block are cut by several normal faults that strike south and dip steeply to the west. One of these faults completely truncates the slipped block and formed a buttress against which later delta strata were deposited (Fig. 13). In the cliff exposure north of "the point" the Unit 3 slump deposits contain syndepositional folds whose axes

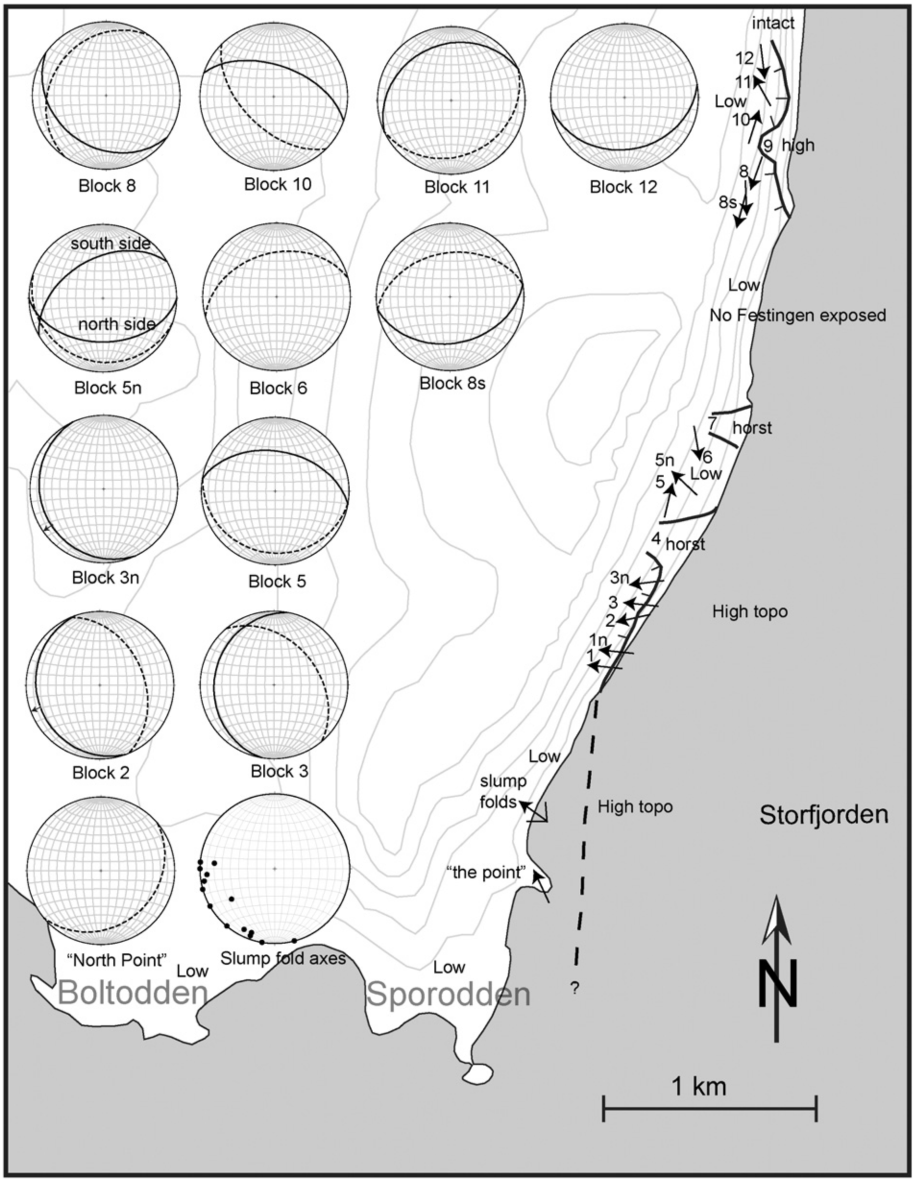

Fig. 11. Map showing location and slip direction of collapsed blocks. Corresponding stereonet plots show bedding (dashed plane), basal slip surface (solid plane) and striations (arrows on slip surface) where present. The "folds" are synsedimentary folds showing top-to-the-west shear due to material slipping down from the high topo to the east. Paleotopography (high topo and low topo) is based on slip directions of the collapsed blocks. The inferred scarp trace is shown in red and one strand is exposed at "the Point" in the southern part of the study area.

are consistently trending south to west and show top-to-the-west displacement (Fig. 11). This supports the interpretation that material was sliding into the hole from the east-southeast and suggests the presence of higher topography in this direction. The western edge of the "southern depression" is also unexposed, but a sharp discontinuity in the stratigraphic level across an unexposed section about 1 km west of Boltodden suggests the western edge lies between these two exposures and Nemec et al. (1988a) suggested that this discontinuity may be a older fault across which the post-collapse delta prograded (p. 473, Nemec et al., 1988a).

In addition to the large "southern depression", the collapse event at Kvalvågen created two smaller depressions that are present in the northern collapse zone. One is located between Block 5n and Block 6 where a 10 m thick section of debris flows and convoluted mudstone is exposed (Fig. 2b). The spatial relationships in the cliff face show that the blocks on either side fell into space that was created when the missing Festningen Member strata that would have existed between the blocks was displaced out of the plane of exposure. The second depression is more than 500 m long and stretches from Block 7 at its southern end to Block 8s at its northern end. This depression is represented by the absence of the Festningen Member and the presence of Unit 3 scar infill deposits exposed in the cliff from sea level 50 m up to the erosional surface that marks the top of Unit 3. The basal collapse surface is inferred to be below present-day sea level along this stretch of the cliff. Much of this section is covered by present-day debris falling off the cliffs above. However, exposed sections at the bottom of the outcrop near sea level and at the northern end show that the lower section of the cliff is a mixture of debris flow deposits, small slide blocks, and severely folded and faulted sandstone and mudstone layers. These folded and faulted layers are interpreted to be slump deposits that were deformed as they slid into the space created by the earlier stages of collapse. The absence of the Festningen Member along this stretch implies that it was displaced out of the plane of exposure or

Fig. 12. Slide blocks 1 and 1 n with deformed scar fill sediment in front of the blocks that indicate emplacement from the east (right side of picture).

below present-day sea level. At the northern edge of this depression, Blocks 8 and 8n, along with several smaller slide blocks, are on top of the Unit 3 fill. This relationship indicates that some of the collapse happened in stages, as these blocks did not slide in until the depression had been partly filled with Unit 3 fill strata.

The smaller half-grabens that developed above the slide blocks in the northern collapse area were also filled with slump deposits, debris flows, and shale. In some places (Block 5, Block 10) sand bodies can be seen flowing off the un-slipped horsts and down into the half-grabens. Displacement of one of these sandstone beds at the north edge of Block 4 indicates that some reactivation of the slip planes occurred after the main slip event.

3.4. Post-collapse erosional event

Reconstructions of the slipped blocks against the horsts show that approximately 5–6 m of the un-slipped strata was eroded off the horsts before the overlying beds were deposited (Fig. 5). On top of these horsts, as well as the slide blocks and half-grabens, a distinct erosional surface is present within Unit 3 that is marked by a thin (10–60 cm) black shale layer. This erosional surface dips into the smaller depressions in the northern and central part of the collapse zone and climbs over the tops of the intact horsts indicating that some relief still existed despite the erosion. The surface descends to a lower level in the “southern depression” where it is observed in the lower part of the beach cliff truncating debris flows and slump deposits below (Fig. 14). This surface is interpreted to represent a flooding surface eroded by wave action as a result of sea level rise during or immediately after the main collapse event.

3.5. Delta propagation and difference in collapse elevation

After the half-grabens and depressions in the northern collapse area were filled and then truncated by the erosional unconformity, a delta prograded across the area. Delta sediments also prograded across the “southern depression” but the present-day contrasts in elevation of these delta sediments (about 60 m difference) indicate that a significant topographic contrast still existed at the time and that the “southern depression” was filled with delta sediments before the higher northern collapse area was buried. Nemec et al. (1988a) describe these sediments in detail and show that delta propagation occurred towards the northeast across the “southern depression”. Small (approximately 1 m diameter) depressions, or sinkholes, are present along the upper surface of the delta sandstones that Nemec et al. (1988a) attributed to liquifaction due to

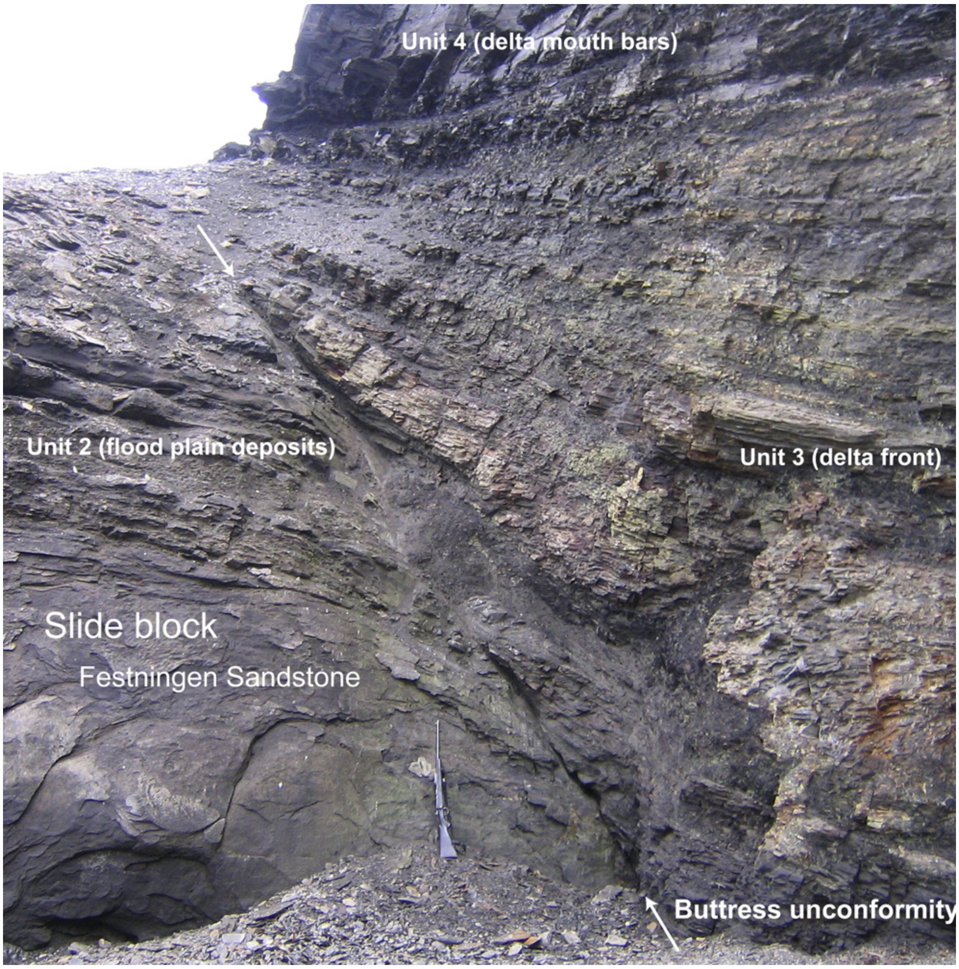

Fig. 13. Contact that marks the west side of "the point" slide block. The contact is a fault buttress that was overlapped by collapse scar fill deposit (right side of contact).

seismic shaking. Nemec et al. (1988a) noted that these liquefaction features occur on first-order bounding surfaces, which they suggested indicate discrete episodes of sagging and bay deepening triggered by seismic tremors. Small-displacement west-dipping normal faults are also developed in the sandstone beds. These faults and a gentle semi-circular dip of the delta sandstones to the northwest attest to local subsidence after deposition of the delta sediments.

4. Evaluation of hypotheses and discussion

The new stratigraphic and structural data presented in this paper are not fully satisfied by previously published interpretations of the collapse of Cretaceous strata at Kvalvågen and call for a re-evaluation of the cause of the collapse. Determining the mechanisms of this collapse is not only important for evaluating the regional tectonic and depositional environments at the time, but may also demonstrate an inherent form of sediment disruption of coastal environments due to sea level fluctuations. The Kvalvågen outcrops record details of structural re-arrangement at the edge of an epicontinental sea during a cycle of sea level fall and rise. The possibility that this disruption may have been due to an inherent instability in the depositional environment called for further investigation in case there were autogenic disturbances that influenced the patterns of sediment transport and deposition. Such autogenic causes for local collapse may include commonplace sediment loading and oversteepening of delta lobes, excess relief caused by patterns of avulsion, pore pressure changes caused by sea level rise or fall, and variations in compaction. In the discussion that follows, we first summarize the depositional and structural history of the collapse area and then evaluate possible mechanisms of collapse in light of the new data presented in this paper.

4.1. General review of depositional history (sequence stratigraphy)

The relationships between the depositional environments, structural features, and erosional episodes recorded at Kvalvågen are key to evaluating the mechanism of collapse and we therefore summarize the history here:

1. A shallow, muddy marine shelf (upper Rurikfjellet Formation) was subaerially exposed due to a regionally significant fall in relative sea level. The shelf was subject to erosion, creating local relief. This is also evident elsewhere on Spitsbergen (e.g., Midtkandal, 2007; Mørk et al., 1999; Midtkandal and Nystuen, 2009; but see also Gjelberg and Steel, 1995). Small north-south striking normal faults and east-west striking reverse faults developed in the upper Rurikfjellet during this time.
2. The Festningen sandstone was deposited across this surface as a fluvial braidplain at Kvalvågen. Some of the faults in the Rurikfjellet strata were active at this time where the Festningen Member sandstone was draped across small scarps.
3. A coastal floodplain (Unit 2) developed as the fluvial channels became restricted or migrated out of the outcrop area.

Fig. 14. The post-collapse erosion surface truncating debris flows and small slide blocks at the northern edge of the "southern depression".

4. The main collapse event occurred. The "southern depression" was formed along with small depressions in the northern collapse area. Large blocks were displaced as rotational and translation slides to the south, north, and west along an undulating slide surface that cuts across strata. This collapse was roughly coincident with a low but rising relative sea level. The newly formed depressions became the focus of sedimentation in the area.
5. Subsequent collapse followed as the depressions and half-grabens were filled with turbidites, debris flows, small slide blocks, and slump deposits derived from the higher topography. By this time, sea level had risen enough to cover the entire area and the upper parts of the depressions were filled with delta front mud that mixed with the debris falling in.
6. The horsts and un-slipped parts of the coastal plain were eroded (most likely by wave action) with at least a few meters thickness of material removed.
7. A delta prograded across the area, filling in the "southern depression" and then subsequently expanding over the northern collapse area. Continued collapse created minor faults in the delta sediments and may also have re-activated larger structures at depth that control delta lobe deposition.
8. Sea level continued to rise and the coast transgressed westwards as sandy shelf strata were deposited.

4.2. Mechanisms of collapse

4.2.1. Delta front collapse and submarine slides

The interpretation that the Kvalvågen outcrops represent a collapsed delta front (Nemec et al., 1988a,b) is not supported by the data presented here. The first discrepancy is that the data presented here indicate that there was no delta prior or during the collapse event at Kvalvågen. We agree, however, that delta sediments were present and were deposited after the collapse event, filling the depressions that formed as a result of the collapse. The model of Nemec et al. (1988a,b) was partly based on their interpretation of the Festningen Member in the Kvalvågen area as a distributary channel on a prograding delta. They also interpreted the upper Rurikfjellet strata underneath the Festningen Member as delta slope deposits. This led to their depiction of the collapse occurring shortly after the deposition of a prograding delta across a shelf slope. They note, however, that the delta was not undergoing active deposition at the time of collapse (based on their observations that the floodplain strata were being deposited over the Festningen Member sandstone prior to the collapse) and therefore did not collapse by sediment loading. The observations presented here and in previous studies (Nemec et al., 1988a,b; Prestholm and Walderhaug, 2000) demonstrate that the slip planes that underlie the displaced blocks are not growth faults as seen in other geologic and modern examples of delta failures (e.g., Bhattacharya and Davies, 2001; Maestro et al., 2002; Lopez, 1990). Nemec et al. (1988a,b) instead hypothesized nearby seismic activity as the trigger for the gravitational sliding. They also noted that slope oversteepening directly due to crustal tectonism was possible, but they deemed this mechanism unlikely due to the location with respect to known faults and the lack of evidence for syndepositional warping. In contrast to the hypothesis of Nemec et al. (1988a,b), we interpret the Festningen Member to be a braided fluvial channel fill as it has been interpreted throughout Spitsbergen (e.g., Midtkandal and Nystuen, 2009) and show that there is no evidence for an active delta before or during the collapse in the immediate area.

A second problem with the delta collapse hypothesis is the orientation and geometry of the fault planes. The direction of collapse, as indicated by the structural data (Fig. 11), is in contrast with what would be expected from an eastward building delta front. Although failure of a delta front could involve outwardly radial orientations, or even slides back towards the coast in sinuous delta lobe geometry, the dominant direction of collapse would be expected to occur in the same direction as the delta was prograding. However, the current data suggest that none of the exposed blocks at Kvalvågen were derived from the west and many of the displaced blocks and slump folds were emplaced from east to west and require higher topography to the east at the time of collapse.

In addition to the orientation of the slide planes being problematic, the dips of the exposed slip planes are significantly steeper than those associated with slides on many present-day deltas. In the offshore Mississippi delta Prior and Coleman (1982) report scarps that typically dip between 1° and 4° and are only 3–8 m in height. Larger slides on continental slopes exhibit slide planes that rarely exceed 30° and typically occur on the lower slope-upper rise area, rather than adjacent to the shelf edge (e.g., Prior et al., 1986; Locat et al., 2009; Twichell et al., 2009). In contrast, the slip planes that accommodated the slides at Kvalvågen range from 70° to 15° with an average of about 40°. Although the overall angles of the Cretaceous slope in eastern Spitsbergen are slightly steeper (steepest = 3°; Steel et al., 2001) than those of the Mississippi delta (0.5–1.5° degrees; Prior and Coleman, 1982), this difference is unlikely to account for the large disparity in dip angles of the slip planes. Even in steeper offshore slopes, such as those off the coast of Israel where slopes reach a maximum angle of 18°, the steepest slide scars are approximately 20° (Almagor and Wiseman, 1982). One difficulty with comparing the slides at Kvalvågen to modern-day submarine slides is the large difference in size due to the fact that modern slides must be studied with seismic and bathymetric data that may not image slides as small as those seen at Kvalvågen. Another aspect is that a more appropriate modern analog for the slides at Kvalvågen would be slides in the lower-relief environments of Hudson Bay or the Persian Gulf because the study area was at the edge of the an epicontinental sea at the time of the collapse.

4.2.2. *Submarine canyon erosion*

The interpretation that the Kvalvågen outcrops represent a shelf break and collapse of fluvial shelf sediments into the heads of submarine canyon walls or gullies (Steel et al., 2001) is easier to justify than delta collapse, but is still not fully supported by the data presented here.

The stratigraphic relationships presented above indicate that just prior to the collapse, the area was a coastal braidplain during a falling to lowstand in sea level. Any submarine canyons that may have developed during this lowstand would have been located further to the east or southeast beyond the corresponding shoreline. The collapse event occurred during a dramatic rise in relative sea level as indicated by the presence of delta front mudstone and turbidites mixed with debris (Unit 3) that filled the collapse scars. This was accompanied by an erosion event that leveled off the high-standing horsts between the depressions that was most likely the result of wave action as sea level rose. The abrupt transition between subaerial deposition (Unit 2) and deeper-water deposition (Unit 3) without any intervening deposits indicates that flooding occurred quickly. Very rapid development and headward erosion of submarine canyons would be required at this time and would need to keep up with sea level rise for the collapse to be due to canyon formation. The data, however, do not allow for a calculation of the rate of sea level rise to fully evaluate whether or not canyon headward erosion could keep pace.

Comparing the geometry and orientations of the slide planes at Kvalvågen with the submarine canyon erosion model yields mixed results. The steep slopes of the slide planes exposed at Kvalvågen are still steeper than most submarine canyon slide scars (e.g., Embley, 1982; Twichell and Roberts, 1982; Twichell et al., 2009), but unlike scarps on active deltas, similar headscarp angles have been documented in the headward eroding areas of some active submarine canyon systems (e.g. Green and Uken, 2008).

As with the delta collapse hypothesis, however, unique conditions are required to justify the submarine canyon interpretation with the orientation of the slide planes. Submarine canyons or gullies that may have formed along the margin of the epicontinental sea would have been oriented roughly east-west according to the regional depositional trends and inferred location of the shelf edge (Steel et al., 2001). Most submarine canyons develop by headward erosion due to the progressive failure of material down the canyon in the form of mass-movement such as landslides, debris flows, and slumps (e.g., Shanmugam, 2006; Green and Uken, 2008). If the collapse depressions at Kvalvågen were canyons or the heads of developing canyons, the direction of collapse should be from the north, south, and west. Although many of the exposed slides did come in from the north and south, none were observed from the west and many came from the east, which would require up-slope movement of material. The direction of slumping, as indicated by the slump folds in the "southern depression", is also from the south and east. To fit the data to the submarine canyon interpretation would require a canyon that was oriented roughly north-south and located to the west of the present-day cliff. The "southern depression" would then represent the canyon itself and the collapse blocks and depressions in the northern collapse zone would be landslides falling off a highly sinuous canyon wall westward into the canyon. This configuration does not conflict with the slide plane geometry, however, the north-south orientation would be unusual as it would be roughly parallel to the inferred shelf edge (Steel et al., 2001). Although we consider this highly unlikely, it cannot be directly refuted from the structural data and limited exposure.

4.2.3. *Possible hydrologic/stratigraphic causes for collapse related to sea level rise*

The basic requirement for slope failure is topographic instability and both the above interpretations were hypothesized because they are environments that can develop over-steepened slopes. It is possible, however, to produce slope failures in lower than expected topographic gradients with certain hydrologic and/or lithologic conditions. These include factors such as high pore pressures, the presence of gas-charged sediments, and weak or lubricated slide planes inherent in the subsurface stratigraphy that can act as detachments for gravity gliding. For example, Maestro et al. (2002) reported relatively steep slip planes from the Ebro delta in Northeast Spain that are close to or the same as those reported here from Kvalvågen. These slip planes are soled in gas-charged sediments and slipping on a basal detachment. Modeling studies (e.g., Mourgues and Cobbold, 2006; Mourgues et al., 2009) have shown that gravitational gliding can occur on very low-angle slopes if fluid overpressures are present in the subsurface. These types of conditions might be expected on a prograding delta where sands are deposited over mud or other environments that produce similar stratigraphic relationships. In the Kvalvågen area, the presence of the Rurikfjellet mudstone layers under the Festningen Member sandstone presents a potential for overpressure and sliding along a weak layer in the Rurikfjellet Formation. This stratigraphic relationship, along with the observation that the collapse event occurred roughly coincident with a relative rise in sea level leads to the question as to how rising sea level (and associated rising water table, pore pressure, overburden) may have contributed to the collapse of the Kvalvågen area. Could marine flooding of the area have induced increases in pore pressure and the addition of overburden that caused weak layers in the Rurikfjellet Formation to act

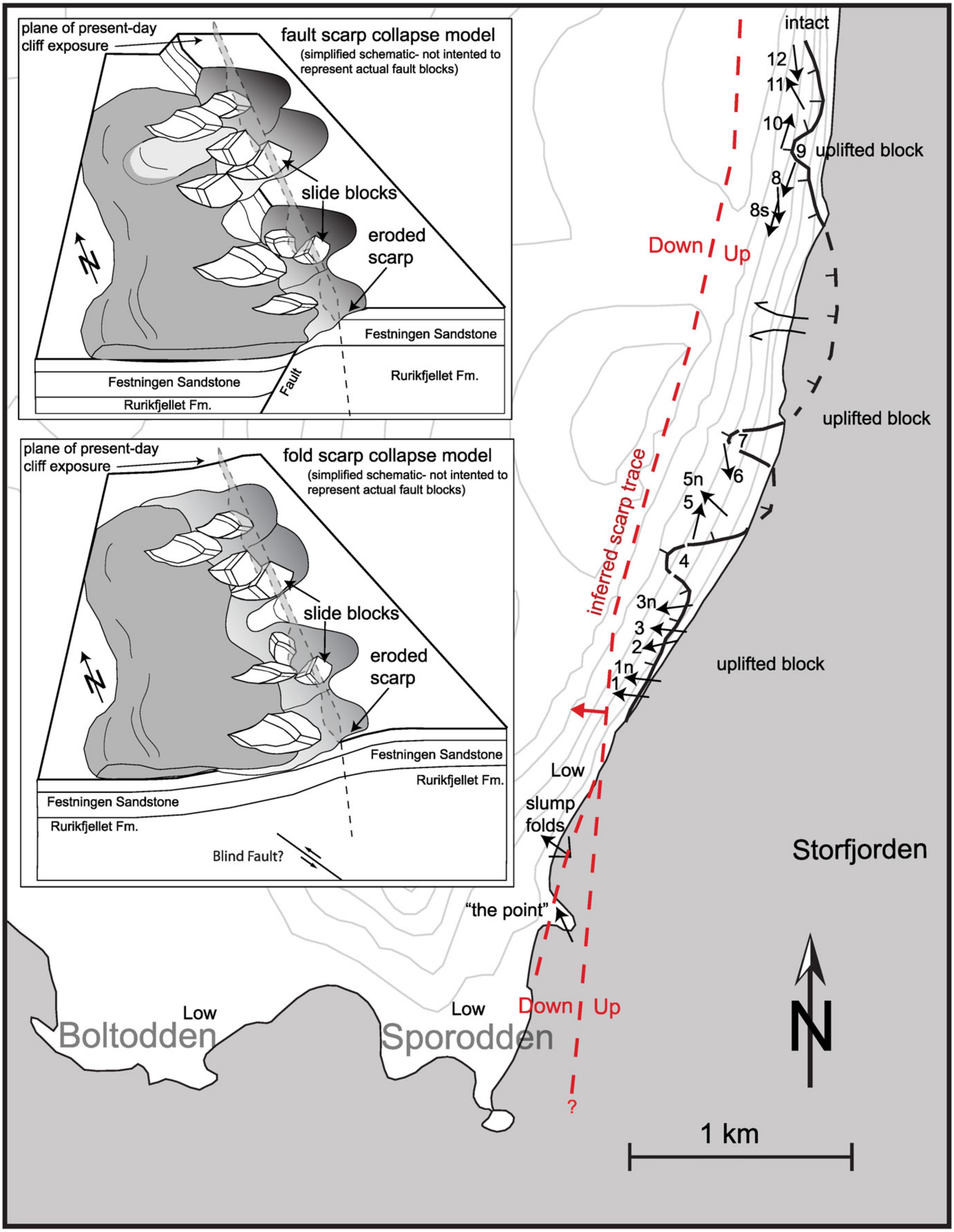

Fig. 15. Map of Kvalvågen area with movement of slide blocks and inferred location of the paleo fault/fold scarp. Inset figures illustrates the fault and fold scarp collapse models and show large landslides and flows developing in the uplifted topography on the east side of the lineament.

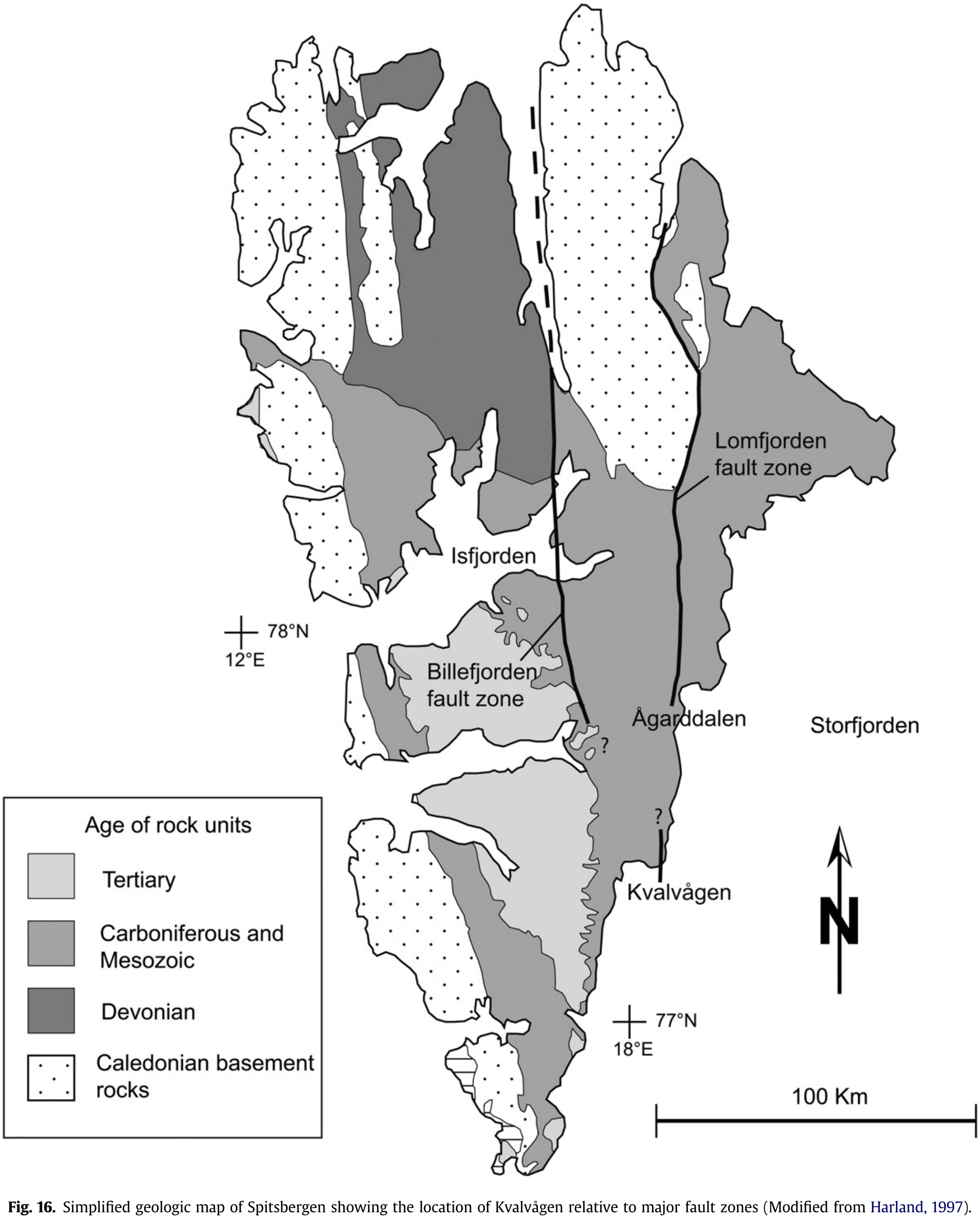

Fig. 16. Simplified geologic map of Spitsbergen showing the location of Kvalvågen relative to major fault zones (Modified from Harland, 1997).

as detachment surfaces? Studies of slope failures associated with high pore pressures (e.g., Morley and Guerin, 1996; Trincardi et al., 2004; Mourgues and Cobbold, 2006; Mourgues et al., 2009) report distinctive characteristics such as the presence of fluid escape pipes, mud volcanoes, toe thrusts structures, and faults that sole into a basal detachment that corresponds with a weakened layer in the stratigraphy. Although Nemec et al. (1988a) inferred that high pore pressures contributed to the collapse, none of the common fluid escape features are present in the outcrops at Kvalvågen and the basal sliding surface at Kvalvågen does not correspond with a single stratigraphic layer or level. The exposed part of the basal slide surface undulates dramatically (see structural data section above) and cuts across both sandstone and shale and mudstone lithologies. In addition, where the attitude of the basal slide surface can be measured, it typically exhibits measurable dip angles and shallows out at various stratigraphic levels rather than soling into specific horizontal stratigraphic surface like has been observed in sediments that failed due to fluid overpressure (e.g., Trincardi et al., 2004; Mourgues and Cobbold, 2006; Mourgues et al., 2009). It is therefore unlikely that marine flooding alone could have induced the observed collapse features through the introduction of high pore pressure and increased overburden and a source of topographic relief is still required. However, the overall lithologic character of the collapse zone, the timing relationship between the collapse and sea level changes, and the presence of some indicators of fluidization along some of the slip planes (Prestholm and

Walderhaug, 2000) and liquifaction (Nemec et al., 1988a,b) suggest that hydrologic factors may have played a role in weakening the elevated areas that were subjected to slope failure.

4.2.4. Magmatic activity

Another potential source of topography may be relief created by local intrusive volcanic activity. Volcanic detritus in the Helvetiafjellet Formation (Edwards, 1979; Worsley, 1986) and the coeval emplacement of basaltic sills and flows in central and eastern Svalbard (Burov et al., 1977) indicate that a large amount of magmatic activity occurred at the same time as the deposition of Lower Cretaceous sedimentary strata in and around Spitsbergen (Maher, 2001). The unconformity that marks the base of the Helvetiafjellet Formation may be due to uplift associated with the intrusion of shallow sills (Maher, 2001). Since the collapse at Kvalvågen closely postdates the initial deposition of the Helvetiafjellet Formation, the possibility of local topographic disturbance due to a volcanic event must be considered. However, the orientation and size of the structural features at Kvalvågen do not seem to match any expected patterns that might be created by surficial eruptions. In addition, thin-sections of samples taken from fill sediments in the half-grabens show no evidence of a local volcanic source. Dolerite sills are exposed at the surface in nearby locations along the east coast of Spitsbergen and topographic development in the area related to magmatic intrusions at depth, although considered here to be unlikely, is not precluded by the available exposures and data.

4.2.5. Tectonic activity

Previous studies have hypothesized that the collapse at Kvalvågen might have been related to seismic activity or tectonic lineaments in the area (Nemec et al., 1988a,b; Gjelberg and Steel, 1995) and we evaluate that interpretation in light of the new data. Tectonic activity can lead to the development of sharp topographic differences that induce local collapse and the structural data presented above are consistent with a tectonic cause for the collapse at Kvalvågen. First, the abundance of minor faults, both before and after the main collapse episode, indicates the presence of local tectonic stresses over a prolonged period of time in the area. These structures include dominantly north-south striking faults developed in the upper Rurikfjellet Formation that predate the deposition of the Festningen Member, as well as north-south striking faults that exhibit west side down displacement within Units 2 through 4 of the Helvetiafjellet Formation. Liquifaction features present in the area may also attest to local tectonic activity. Circular depressions in the post-collapse delta sediments are attributed to liquifaction resulting from local seismic shaking (Nemec et al., 1988a). Nemec et al. (1988a) also report that probable seismite horizons coincide with periods of renewed subsidence in the post-collapse strata that suggest these vertical movements were seismically induced.

The geometry and orientation of the main slide planes can be explained with an interpretation involving tectonically created topography. The steep dip angles of many of the slide planes would be expected from collapse of a high-relief feature such as a fault or fold scarp. If this scarp was oriented in a roughly north-south orientation (parallel to the tectonic lineaments present throughout Spitsbergen) the westward movement documented for some of the slide blocks is not problematic as it was with previous interpretations. Fig. 11 shows that the slide blocks exposed in the area slid to the north, west, and south. The paleotopography inferred from these data (as well as from slump folds) would be consistent with a roughly north-south trending lineament that was elevated on the east side. This topographic lineament would intersect the modern-day cliff at the north edge of the large “southern depression” where a 40 m difference in the paleotopography is visible in the cliff exposure (Figs. 6 and 7). We infer this elevation difference to be the location of a degraded fault scarp or fold scarp that was quickly eroded after development. The exposures to the north of this location are in the uplifted block, and the exposures to the south and southwest (the “southern depression”) are the upper part of the down-dropped block, which was covered by debris flows, slumps, and mud partially derived from erosion of the uplifted side. After the collapse and coeval rise in sea level, a delta prograded across the down-dropped area and filled this depression before continuing across the uplifted eastern side of the escarpment. The delta lobe sediments in the “southern depression” are significantly thicker, and at a lower elevation than the stratigraphically equivalent strata above the northern collapse area and delta front strata in the “southern depression” onlap onto the paleoscarp at the edge of the down-dropped block (Figs. 2a, 7). Due to limited exposure, it is unclear whether this linear escarpment was a fault scarp created by surface rupture along a fault, or a subtle fold scarp created by warping of the surface due to fault displacement at depth. Both models (illustrated in Fig. 15) satisfy the structural and stratigraphic data presented in this paper. If the feature was a fault scarp, any fault plane that may have intersected the surface was most likely buried by collapse and erosion of the fault scarp shortly after the ground rupture as the fault plane itself is not exposed. At the northeastern edge of the “southern depression” where the paleoscarp intersects the modern-day cliff exposure, the stratigraphic contrast in the Rurikfjellet Formation is buried beneath debris that was generated by the erosion of the scarp (Figs. 2a, 7). The amount of vertical offset along the inferred scarp exposed in the cliff is estimated to be about 40 m (Figs. 6 and 7). This amount suggests that a fault-created scarp would have been the result of multiple slip events. The fault that truncates the west side of the slipped block at “the point” may be a strand of a north-south trending fault zone. This fault scarp at “the point” later acted as a buttress against which the delta front sediments above the collapse zone were deposited. In the northern half of the collapse zone, blocks were sliding into steep-sided holes from the north, south, and east. These depressions were most likely created by large landslides that developed in the uplifted side of the scarp and moved the missing material out to the west across the topographic gradient (Fig. 15). All of the major slide blocks have slip planes that sole within the weaker Rurikfjellet strata, which would have been exposed in a fault scarp and subsequent landslide scars (Fig. 15). Reconstruction of the slipped blocks reveals the steep-sided nature of these depressions that they fell into (Fig. 5). The steep scarps at the north ends of blocks 5n and 11 suggest that the edges of the major landslides that created these holes may have been defined by secondary faults splaying off a main fault zone to the west. The lack of exposure of the southern and western extents of the “southern depression”, and the disappearance of the disturbance zone to the south and west below the level of present-day exposure, support the idea that this area is just a small exposed portion of the down-dropped western side of the fault zone. The absence of the Festningen sandstone in the hillsides north and northwest of Sporodden (Fig. 1) suggest that the “southern depression” extends some distance inland to the north and northwest. However, Nemec et al. (1988a) note that the delta succession in the “southern depression” is cut off from its source to the west and on the other side of a 65 m gap in exposure is an older (deeper) section. Although they did not observe any direct evidence of faulting, they hypothesized that this contrast may be an older fault. This stratigraphic contrast may represent another strand of the fault zone or the western side of a small graben created by movement along the fault zone.

We infer that the major elevation difference observed in the cliff at Kvalvågen is a regional feature that was covered by subsequent deposition of the Carolinefjellet Formation in the Early Cretaceous. The structural data and relationships suggest that this feature was a north-south trending fault scarp or fold scarp whose development was directly responsible for the collapse features observed at Kvalvågen.

4.3. *Regional significance*

The regional tectonic cause of the Kvalvågen fault zone cannot be fully evaluated due to the lack of exposures to the north and south along the fault. Since the exact dip of the fault at Kvalvågen cannot be determined, nor can the amount of possible strike-slip displacement, the precise kinematics of the movement that created the scarp is unknown. However, its possible relation to two major structural features in east Spitsbergen is evaluated here. Gjelberg and Steel (1995) hypothesized that the collapse at Kvalvågen was related to the progradation of the Helvetiafjellet Formation over the southern extension of the Lomfjorden fault zone. The Kvalvågen area is on strike with the Lomfjorden fault complex to the north that is inferred to have developed as early as the Cretaceous and was active in the Tertiary (Andresen et al., 1992a). Deformation along this zone has been documented as far south as Ågarddalen (Fig. 16) where the zone is expressed as an east-facing anticline inferred to be developing over a west-dipping reverse fault at depth (Andresen et al., 1992a). Although the Kvalvågen area is on strike with the southern end of the Lomfjorden fault, and the fault orientations and timing are similar, the sense of displacement along the Lomfjorden fault during the Cretaceous is opposite to that reported here at Kvalvågen. If the scarp collapse at Kvalvågen were related to the Lomfjorden fault, it would require that either the sense of displacement or the dip of the fault has changed along strike. This is commonly seen along strike-slip faults but no evidence of major strike-slip displacement has been reported from the Lomfjorden fault.

The Billefjorden fault zone is another major structural feature that has had a prolonged and complex kinematic history (eg., Harland et al., 1974; Steel and Worsley, 1984; Haremo et al., 1990, 1993; McCann and Dallmann, 1996). Thickness variations in Mesozoic strata across the Billefjorden fault zone (Fig. 16) have been interpreted to be the result of west side down displacement along the fault zone during the Early Cretaceous (Harland et al., 1974). This mode of displacement and timing is consistent with the observations at Kvalvågen where the abundance of minor faults showing normal displacement both before and after the main collapse event suggests that the primary mode of faulting was extensional. The Kvavågen area is slightly east of the southern projection of the Billefjorden fault zone and correlation would require an eastward bend or stepover in the fault zone (Fig. 16). Haremo et al. (1990, 1993) argued against significant normal displacement across the Billefjorden fault zone during the Mesozoic and inferred that the thickness variations were due to Tertiary contractional deformation along decollement zones. Their work in the Kjellstromdalen area revealed a variety of structural features, some of which are consistent in orientation and sense of displacement with structures at Kvalvågen. Despite Haremo et al. (1990, 1993) interpretation that most of the structural features within the Jurassic-Cretaceous strata along the Billefjorden fault zone south of Isfjorden are Tertiary in age, the similarity between structural elements at Kvalvågen and those observed along the Billefjorden fault zone (Haremo et al., 1990, 1993; Andresen et al., 1992b) make it our preferred candidate for the cause of deformation at Kvalvågen. The structural observations at Kvalvågen would thus record west side down separation along the Billefjorden fault zone during deposition of the Helvetiafjellet Formation. This holds implications for the history of the Billefjorden fault zone in terms of timing of displacement and southern extent of the fault zone.

5. Conclusion

The anomalous collapse of Lower Cretaceous strata at Kvalvågen occurred during relative sea level rise that followed a period of regionally significant sea level fall and shelf emergence. The Helvetiafjellet Formation is probably one of the world's most spectacular forced regressions of fluvial sandstones out across offshore mudstones. The evaluation of multiple hypotheses for the mechanism of collapse suggests that the event was solely the result of allogenic disturbances and a source of forced topographic relief is necessary. The orientation and style of structural elements exposed in the Kvalvågen area are most consistent with a collapse due to topographic development along a fault or fold scarp. This scarp is inferred to be the result of movement along a fault zone that strikes approximately north and exhibited west side down displacement. The large displaced blocks exposed in the cliffs at Kvalvågen are rotational and translation landslides that slid off this scarp, or into scars in the uplifted block from larger slides as the scarp quickly collapsed and eroded. Minor normal faults that developed both before and after the main scarp formation suggest that the area was extending at the time. The stratigraphic make-up of the area along with high pore pressures due to sea level rise may have contributed to the collapse but was not the primary cause. The faulting at Kvalvågen is tentatively correlated with the Billefjorden fault zone and may be a southeastern extension of the fault zone that was active during the Early Cretaceous. The uppermost Helvetiafjellet Formation is undisturbed and indicates that activity ceased by that time.

Acknowledgements

We gratefully acknowledge J. Ahokas for tremendous help in the field and J. Nystuen for valuable discussion over the past few years. We also thank R. Steel, P. Plink-Bjorklund, J. Gjelberg, and an anonymous reviewer for excellent reviews that greatly improved the manuscript. This work was partially funded by a Norwegian Science Foundation grant to the Physics of Geological Processes research center at the University of Oslo.

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