Geol. Mag. **148** (*1*), *2011, pp. 154–170.* © *Cambridge University Press 2010*
doi:10.1017/S0016756810000567

Løvehovden fault and Billefjorden rift basin segmentation and development, Spitsbergen, Norway

H. D. MAHER, JR* & A. BRAATHEN†

*Department of Geography and Geology, University of Nebraska at Omaha, Omaha, NE 68182-0199, USA
†Arctic Geology Department, UNIS, 9171 Longyearbyen, Norway

(*Received* 24 June 2009; *revised version received* 7 March 2010; *accepted* 23 March 2010; *first published online* 27 July 2010)

Abstract – The Carboniferous Billefjorden rift basin is a well-known example of a suite of Carboniferous basins on the Barents Shelf and NE Greenland. The basin has a clastic, carbonate and evaporite fill with complex and disputed stratigraphic relationships, especially regarding the Ebbadalen and Minkinfjellet formations. Geometrically, the basin is considered a simple half-graben. A N–S-trending fault and monocline structure within the northern portion of the basin, the Løvehovden fault, has lithological and thickness differences across it within the Minkinfjellet and possibly Ebbadalen formations. The fault shows W-side-down movement, defining a sub-basin within the larger half-graben. Significant along-strike changes occur. Down-throw to the west is at least 150 metres and possibly 400 metres, as shown by across-fault thickness differences of Ebbadalen and/or Minkinfjellet formations. To the east of the fault, the contact between the Ebbadalen and Minkinfjellet formations is a disconformity with significant local relief, and is interpreted to represent exposure from footwall uplift, and associated near- or at-surface solution, producing basal stratiform breccias. A similar contact is not exposed west of the fault. Monoclinal deformation and thickening of the younger Wordiekammen Formation above and across the monocline constrain a later movement component. Kinematic data and the structural style clearly indicate the Løvehovden fault is a normal fault with associated tri-shear zone development, consistent with the regional Carboniferous rift setting. Earlier interpretations describe the Løvehovden fault and monocline as Tertiary contractional features. In contrast, our work advocates that they are an important architectural basin element, defining a sub-basin within the Billeforden Trough during Minkinfjellet Formation deposition, with insignificant, if any, Tertiary reactivation. The Løvehovden fault is aligned with and represents the southern termination of the Lemströmfjellet fault to the north. Thus, the Billefjorden basin changes from a narrow graben to a broader half-graben to the south. These along-strike changes have important implications for the stratigraphic architecture of the basin, and for palaeogeographic reconstructions. These results and application of 3-D models for extension related tri-shear zones may help inform interpretation of other Carboniferous basins on the Barents Shelf.

Keywords: Svalbard, Carboniferous, Billefjorden, rift, fault-propagation, Minkinfjellet.

1. Introduction

The Billefjorden trough (Fig. 1) is the best exposed and studied Carboniferous basin on Spitsbergen and is typically described as a classic half-graben developed against a steeply E-dipping Billefjorden fault zone (Steel & Worsley, 1984; Johannessen & Steel, 1992). The basin hosts mixed clastic, evaporite and carbonate fill (e.g. Gjelberg & Steel, 1981; Worsley & Aga, 1986; Lonoy, 1995; Pickard *et al.* 1996; Eliassen & Talbot, 2003*a*). To the west is the St Jonsfjorden trough, where W-dipping Carboniferous faults associated with half-graben fill were reactivated and played a role in the development of the thick-skinned, basement-involved, portion of the western Tertiary fold-and-thrust belt on Spitsbergen (Maher & Welbon, 1992; Braathen & Bergh, 1995). Carboniferous normal faulting is also evident along the Lomfjorden lineament to the east of Billefjorden (Harland, 1997), with evidence of subsequent Tertiary contractional inversion (Bergh, Braathen & Maher, 1994). Similar Carboniferous basins are widespread on the Barents Shelf and are significant exploration targets (Stemmerik & Worsley, 2005). One is well exposed on Bjornoya (Worsley *et al.* 2001). The basins appear to have been most active in the Bashkirian and Moscovian (e.g. Worsley *et al.* 2001), but accommodation space development persists into the Permian (Stemmerick & Worsley, 2005). Debate exists as to the overall tectonic setting for Barents Shelf Carboniferous rifting, specifically as to whether there was a significant strike-slip component (e.g. Haszeldine, 1984; Torsvik, Lovlie & Sturt, 1985; Ziegler, 1988; McCann & Dallmann, 1996). Due to excellent exposures and proximity to Longyearbyen as a logistical base, the Billefjorden Trough is routinely visited by petroleum industry geologists, and also serves as a field classroom for UNIS (University Centre in Svalbard), making it the most visited and well-known Barents Shelf Carboniferous basin.

The Billefjorden rift fill consists of the Hultberget, Ebbadalen and Minkinfjellet formations (Fig. 2). The total rift fill is typically described as approximately

*Author for correspondence: harmon_maher@mail.unomaha.edu

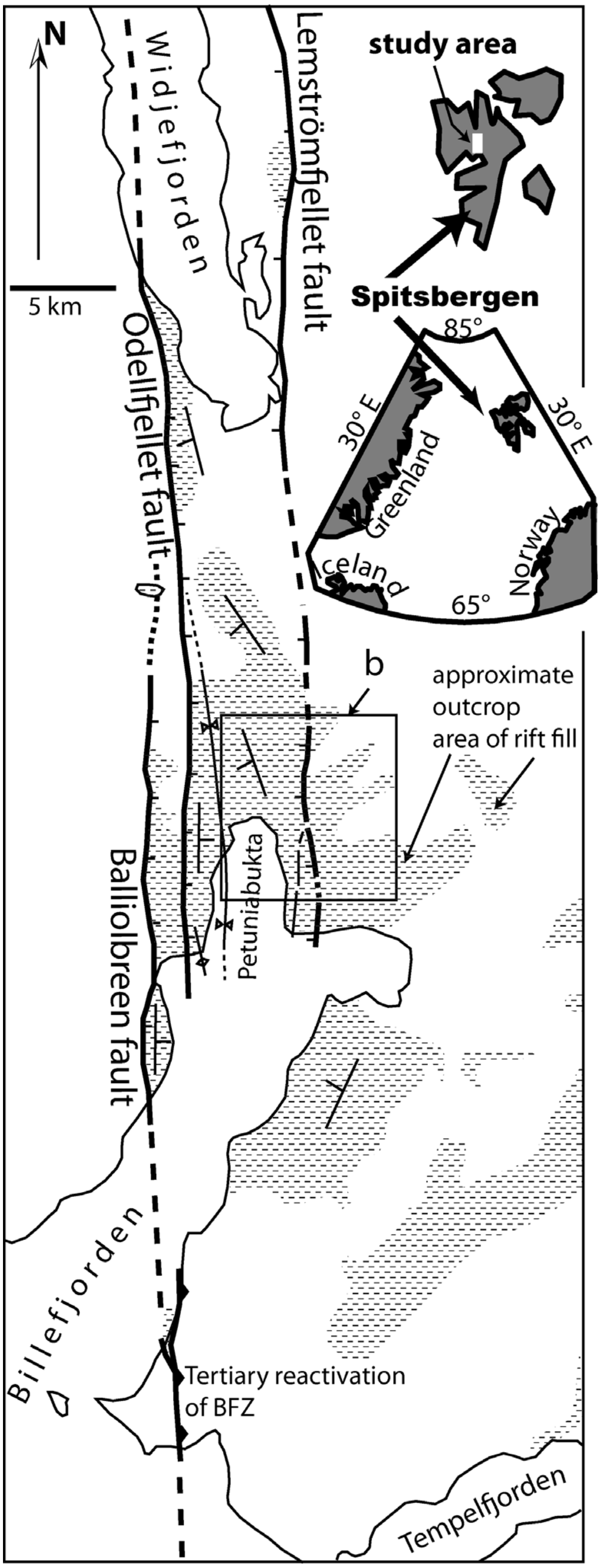

Figure 1. Overview map of Billefjorden fault zone. Inset box ‘b’ is map area of Figure 3.

1 km thick. As part of its complex history, Tertiary reactivation with a reverse component also occurs along the Billefjorden fault zone (McCann & Dallmann, 1996; Haremo *et al.* 1990). In addition, along the east limb of the half-graben, a fault that is well exposed at Løvehovden is described as a steep, Tertiary reverse fault-controlled monocline (McCann & Dallmann, 1996; Manby *et al.* 1994). Tertiary tectonism on Svalbard was related to the evolution of a complex right-lateral transform involving NE Greenland and linking opening of the Norwegian–Greenland Sea and the Eurasia Basin (e.g. Harland, 1969; Mosar *et al.* 2002). An earlier phase of Tertiary transpression was followed by Oligocene transtension and the development of extensional structures exposed along the west coast of Spitsbergen (e.g. Dallmann, 1992; Gabrielsen *et al.* 1992). In this context, the Løvehovden fault and monocline is associated with Tertiary transpression. Our observations indicate otherwise.

Detailed mapping described herein has traced the Løvehovden fault northward, where it is aligned with the Lemströmfjellet fault (Fig. 1). The Løvehovden fault is associated with monoclines and subsidiary faults, and more distributed and ductile deformation in adjacent evaporites. This paper is a description and discussion of evidence that the Løvehovden lineament was an eastern sub-basin bounding normal fault during part of Minkinfjellet Formation deposition, with continued fault-related monocline development during Wordiekammen Formation times, and with insignificant, if any, Tertiary reactivation. Implications for along basin-strike sediment fill architecture and palaeogeography are also explored, as are similarities of the Løvehovden feature with known extensional fault-propagation fold geometries.

2. Regional stratigraphy

A basic stratigraphic framework for the area was initially developed by Cutbill & Challinor (1965). To the east of the Billefjorden fault zone, metamorphic basement rocks known as the Hecla Hoek sequence underlie a pre-rift sequence of fluvial orthoquartzites and coal-shale sequences collectively comprising the Billefjorden Group. To the west of the Billefjorden fault zone, deformed Devonian rock locally underlies either Billefjorden Group strata or younger Wordiekammen Formation strata (Fig. 2). The Hultberget Formation, the lowest part of the Billefjorden rift basin fill, is characterized by terrestrial red clastics, and has a variable thickness of up to 120 m. The overlying Ebbadalen Formation has highly variable facies (Dallmann, 1999), and is cast by Eliassen & Talbot (2003*b*) as ‘clastic wedges shed from the Nordfjorden High, which laterally interfinger with a basin-centre gypsum-dominated succession’ (p. 301). The study area is somewhat east of the basin depocentre. The Ebbadalen Formation is split into the lower and thinner Ebbaelva Member, consisting of near-shore marine sandstones and shales, and the overlying Trikolorfjellet Member, which is dominated by well-bedded evaporites in the study area. Most of the evaporite material in the Billefjorden basin stratigraphy is gypsum, but

https://doi.org/10.1017/S0016756810000567 Published online by Cambridge University Press

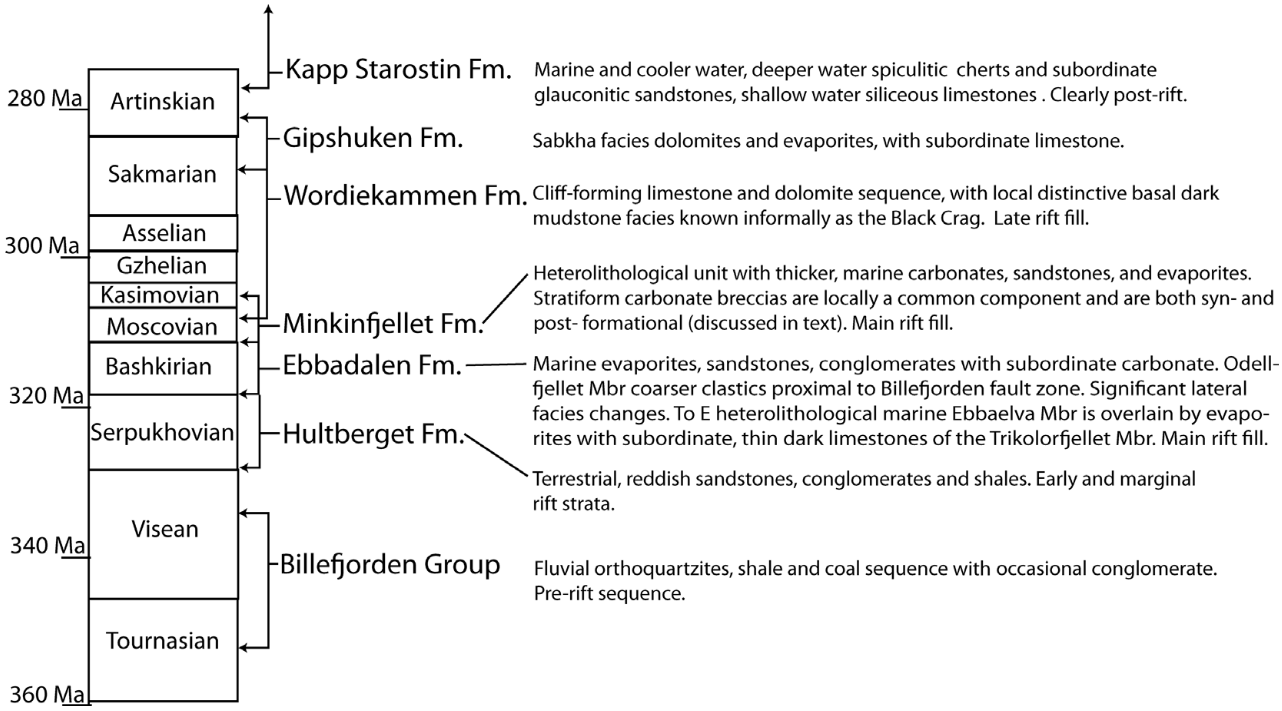

Figure 2. Stratigraphic units of the Billefjorden basin.

significant anhydrite also occurs, and so the term 'evaporite' is used throughout this report.

The Ebbadalen–Minkinfjellet formations contact is defined by the first appearance of a significant carbonate-dominated section (Dallmann, 1999) and is associated with a transgression (Eliassen & Talbot, 2003*a*). Carbonates, sandstones, evaporites and breccias exist in different proportions within the Minkinfjellet Formation. Evaporite beds are characterized as being rare in the lower part of the Minkinfjellet Formation, while stratiform breccia beds are common, with the proportion of evaporite increasing to the south (Eliassen & Talbot, 2003*a*). Significant lateral facies changes are consistent with the narrow rift setting (Dallmann, 1993), active fault margins, a shallow marine setting, and Carboniferous sea-level changes. Breccias may be both syn- and post-depositional (discussed in Section 6.b), and thus care must be taken with stratigraphic assignment. Significant breccia bodies are involved in the deformation at Løvehovden.

The contact with the overlying Wordiekammen Formation is well defined throughout the area. The distinctive Fortet breccias (Dallmann, 1999) of the upper Minkinfjellet Formation are overlain by cliff-forming Wordiekammen Formation carbonates. Pipe breccias extend through the contact and are clearly palaeokarst features (Eliassen & Talbot, 2003*a*). Low-angle truncation surfaces observed in the Wordiekammen Formation carbonates suggest that platform emergence during lowstands occurred. Pickard *et al.* (1996) indicate that a low-relief Campbellryggen marine basin continued to exist during deposition of the lower Cadellfjellet Member of the Wordiekammen Formation. The Gipshuken Formation (Fig. 2) is not exposed in the study area, but can be found in Bunsow Land to the south (Fig. 1). It is dominated by carbonates, but contains significant evaporite facies to the south. The overlying Kapp Starostin Formation marine strata have a regionally uniform character, and post-date any tectonism.

3. Structural character of the Løvehovden fault

The faults and monoclinal structure found at the west end of the Løvehovden ridge (Figs 4, 5) are mapped and described in McCann & Dallmann (1996), Dallmann, Piepjohn & Blomeir (2004) and Dallmann *et al.* (2004) as Tertiary reverse faults and are projected to continue to the northwest across the mouth of Ragnardalen and then die out. Detailed mapping shows them to instead continue across Ragnardalen with an almost due-north trend and to link with a previously mapped normal fault (Fig. 3). This more northerly fault trend is oblique to the NW-trending, shallowly dipping, east limb of the large asymmetric syncline that involves Wordiekammen Formation strata and has its axial trace along the west side of Petuniabukta (Fig. 1), herein referred to as the Petuniabukta syncline. The age of the substantial tilt the Wordiekammen Formation strata displayed as part of the Petuniabukta syncline (Fig. 2) is relatively unexplored in the literature, with McCann & Dallmann (1996) suggesting it has a Tertiary age. A significant part of the syncline expression may reflect Permian development (discussed in Section 6.b). The Løvehovden fault's more northerly trend across Ragnardalen is closely parallel to the Billefjorden fault

https://doi.org/10.1017/S0016756810000567 Published online by Cambridge University Press

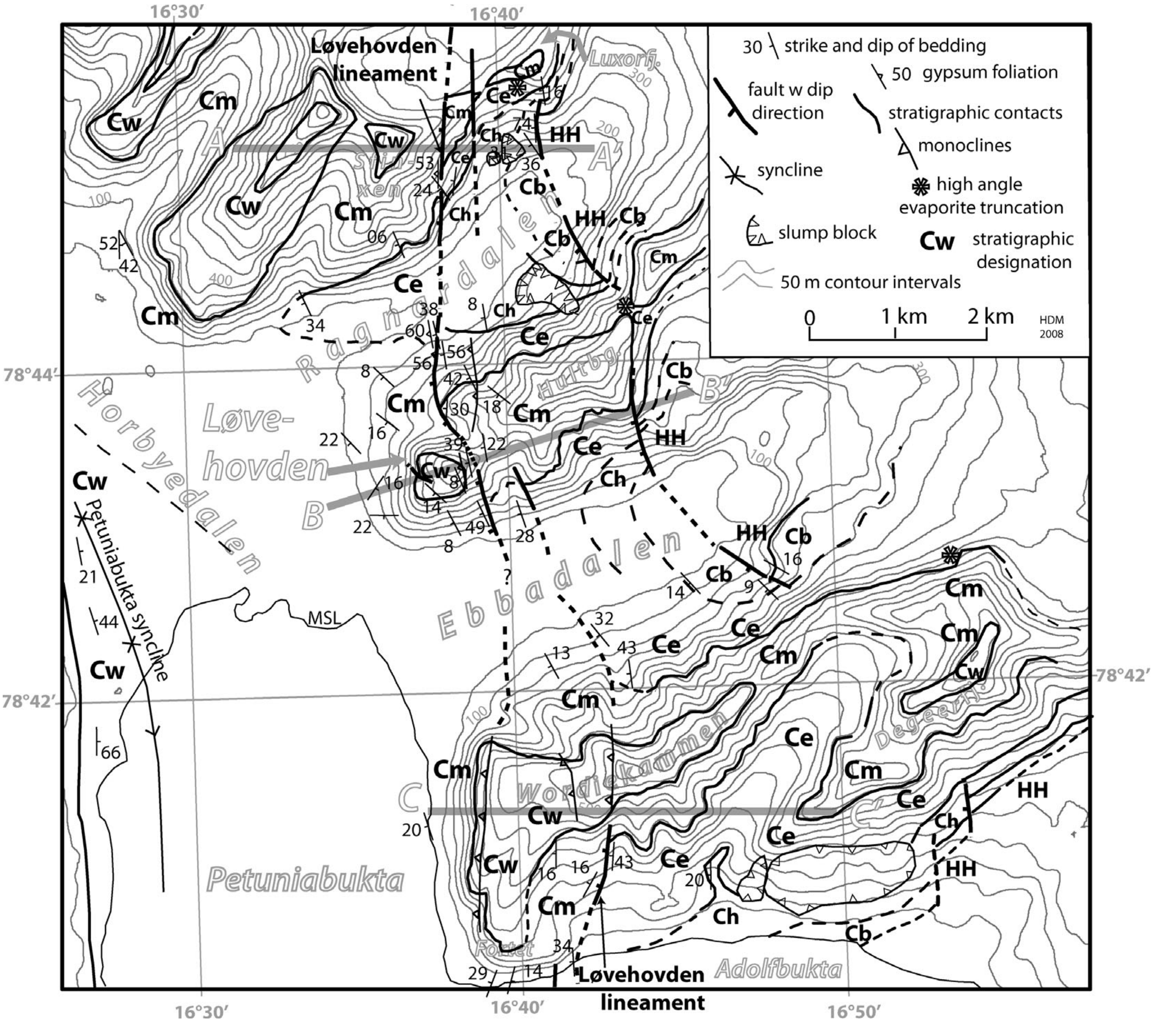

Figure 3. Geological map of study area. Grey lines are traces of cross-section profiles in Figure 5. Stratigraphic symbols: HH – Hecla Hoek sequence (basement rocks), Cb – Billefjorden Group, Ch – Hultberget Fm., Ce – Ebbadalen Fm., Cm – Minkinfjellet Fm., Cw – Wordiekammen Fm.

zone. It is also parallel to and in line with the Lemströmfjellet normal fault to the north, which juxtaposes Billefjorden Group strata against basement rocks, but the intervening Mittag-Leffler glacier prevents a direct connection from being established (Fig. 3).

A normal fault and associated deformational features very similar to the structures at Løvehovden are well exposed in Minkinfjellet and Ebbadalen formations strata on the south slopes of Wordiekammen (Figs 3, 6). An overlying monocline in the Wordiekammen Formation strata above can be traced to the north across the top of the mountain. Below the monocline on the south slopes of Ebbadalen are outcrops of sheared and tilted evaporites that represent the more poorly exposed continuation of this fault feature. These structures project towards the Løvehovden monocline, and this is the fault trace made by McCann & Dallmann (1996). To the west a monocline parallels the west face of Wordiekammen, and a poorly exposed fault of unknown but limited offset lies below. Thus the Løvehovden fault may have two branches as it crosses Ebbadalen, with one taking a more northwesterly turn as traced to the south across Ebbadalen (Fig. 2).

The following is a description of the Løvehovden lineament starting from the south slopes of Løvehovden, where it is best exposed. The lineament is then traced northward, to the south slopes and then the north slopes of Ragnardalen, and then southward, to the north and then south slopes of Wordiekammen.

3.a. North slopes of Ebbadalen

The south slopes of Løvehovden contain the clearest exposures of the Løvehovden fault (Fig. 4). A distinctly brittle fault that dips 70° westward truncates footwall Ebbadalen and lower Minkinfjellet Formation strata. Footwall strata steepen in dip with approach to the fault, and Minkinfjellet Formation thick evaporites and carbonate units in the hanging-wall are subparallel to the fault in its lower section, that is, they

https://doi.org/10.1017/S0016756810000567 Published online by Cambridge University Press

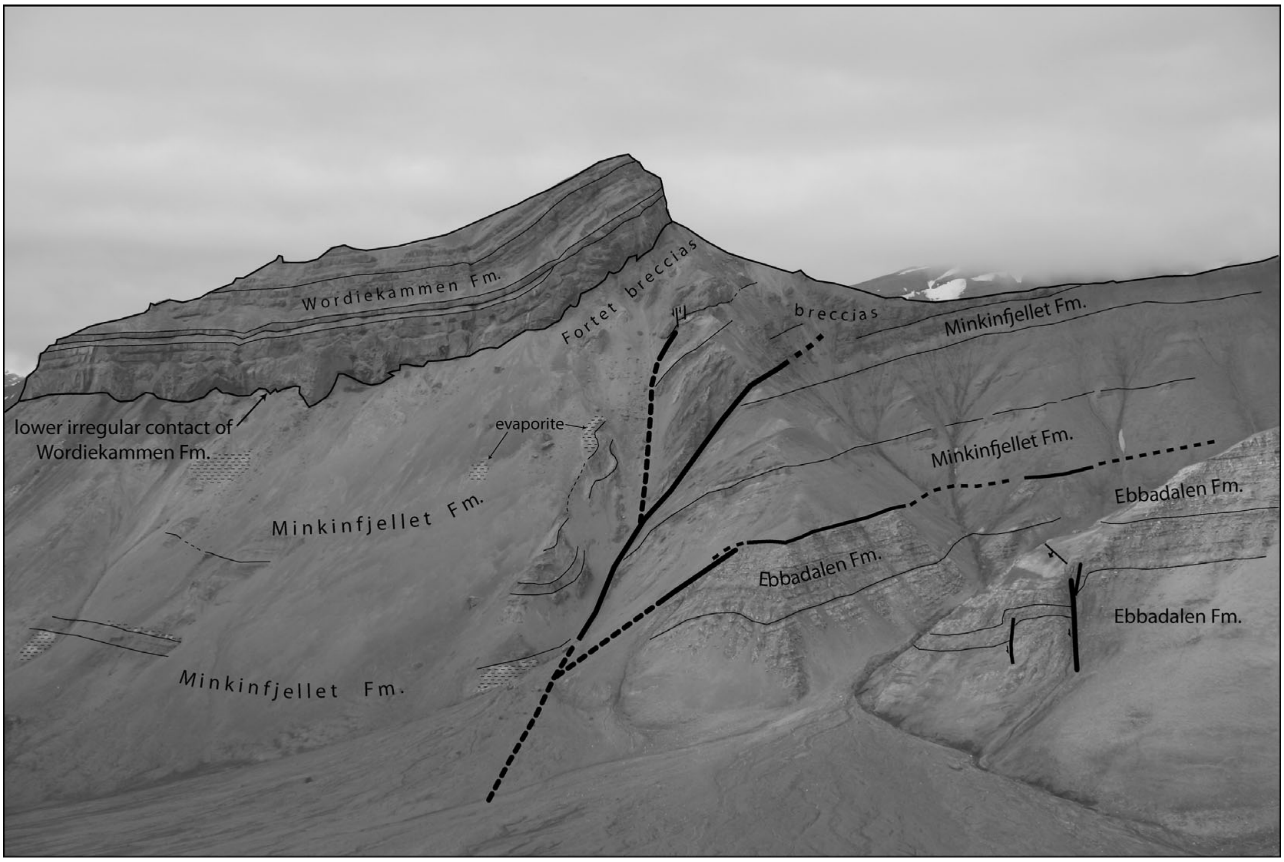

Figure 4. Photograph and interpretative line drawing of west end of Løvehovden ridge where the Løvehovden lineament is well exposed. View to north along fault trace and peak is at 610 m.

form an approximate hanging-wall flat for several hundred metres. They also show considerable internal deformation and the stratigraphic packet thins. As these hanging-wall beds are traced upwards along the fault, the proportion of breccia distinctly increases, while that of evaporite decreases. At the ridge line, dipping, thick horizons of carbonate breccia dominate. Some breccia beds appear to be semi-continuous across the faults, although the lack of distinctive marker horizons makes this difficult to ascertain. The breccia beds are distinctly petroliferous at this position.

A distinctive W-side-down subvertical fault with 50 metres or so of offset occurs east of the Løvehovden monocline, juxtaposing redder strata of the lower Ebbadalen Formation against evaporites with thin dark limestone layers to the west of the upper Ebbadalen Formation (Figs 4, 5). Two smaller faults occur to the east and west of this fault. The upper smaller fault in its present orientation is a subvertical reverse fault, but this does not consider post-fault rotation. With ascent, the larger fault transitions into a small monocline within the evaporite-dominated section. The monocline can be traced horizontally for a short distance and has a somewhat NW trend, anticlockwise of the Løvehoveden lineament. The fault and monoclinal structure do not deform overlying Minkinfjellet Formation strata, a short distance along its projection (Figs 4, 5). If the overlying Wordiekammen Formation strata are restored to horizontal then this fault dips steeply west, and is a normal fault. The more northwesterly trend is similar to that of the Løvehovden lineament to the south as it crosses Wordiekammen (Fig. 2).

3.b. South slopes of Ragnardalen

The fault and monocline can be traced continuously northward for roughly 1 km from the Løvehovden ridge line down to the outwash plain for Ragnarbreen, both as a brittle fault that truncates thick limestone units in Minkinfjellet Formation strata of the hanging-wall and as steep (60°) dips and significant ductile deformation within more steeply inclined upper Ebbadalen Formation evaporites of the footwall. The ductile deformation extends over a zone about 100 metres wide, and is marked by all transitions from pinch-and-swell structures to boudinage of limestone layers within evaporites. The evaporites display a well-developed fabric that is sub-parallel to oblique to bedding (Fig. 6). The fabric consistently dips less steeply than associated bedding. Boudins vary in size from metres in thickness to a bit less than a centimetre, are both symmetric and asymmetric in character, and are often blocky and brittle in style. Both microfaults and evaporite veining contributed to carbonate layer extension. Evaporite foliation shows evidence of flowage into the necking area between boudins (Fig. 6). Asymmetric boudins and small-scale faults show geometries that consistently indicate a

https://doi.org/10.1017/S0016756810000567 Published online by Cambridge University Press

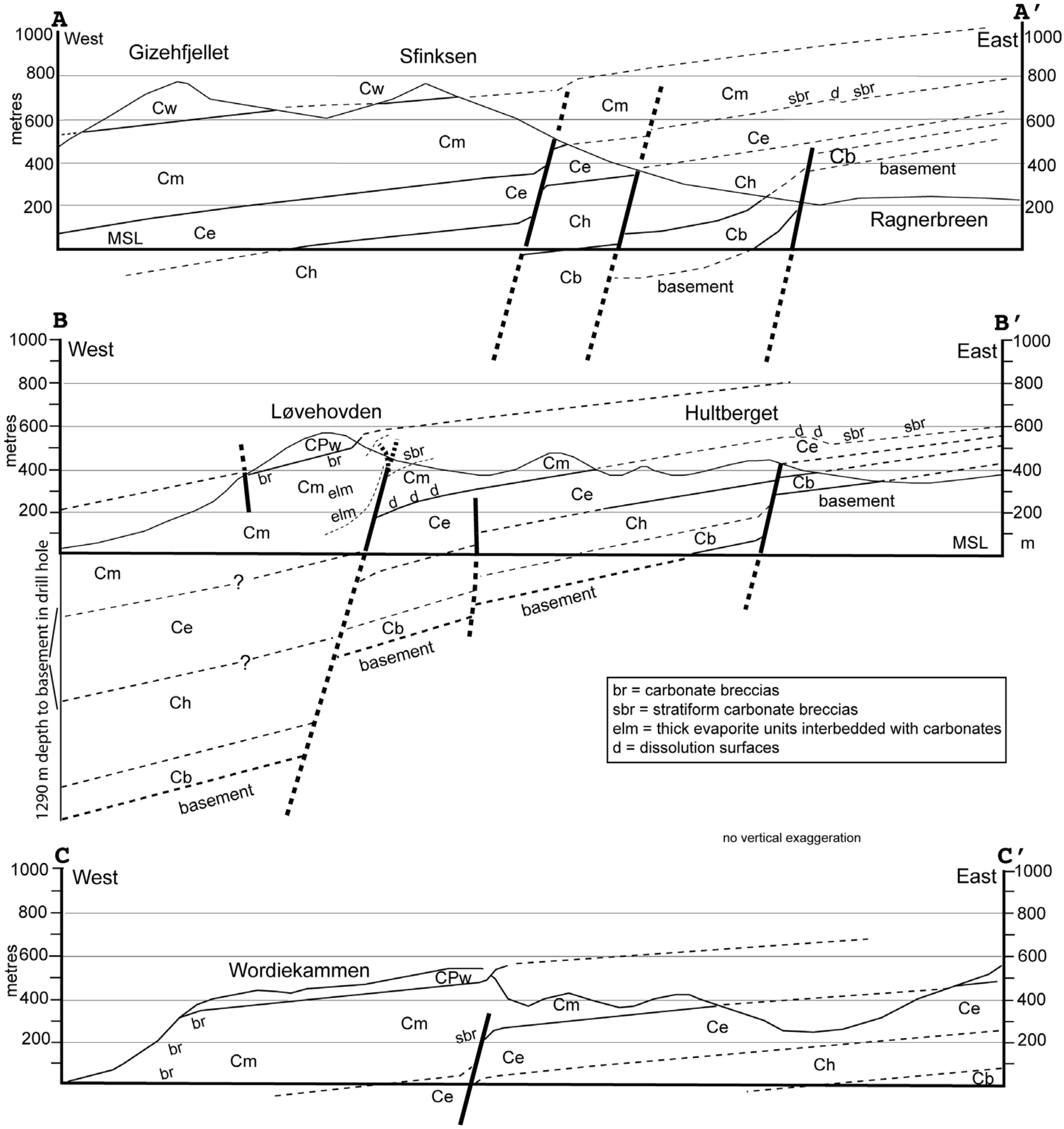

Figure 5. Cross-sections through: (A–A′) Sfinksen to Luxorfjellet, (B–B′) Løvehovden to Hultberget and (C–C′) Wordiekammen, Sfinksen. Stratigraphic symbols as for Figure 3.

hanging-wall and W-side-down movement component. Boudin separation indicates localized bedding-parallel elongations that exceed 100 %. Thin-sections indicate that intracrystalline glide and recrystallization were involved in the evaporite deformation (Nanfito, Maher & Braathen, 2008). Angular clasts of bedded carbonate within evaporite occur in positions consistent with brittle plucking of carbonate clasts by the ductilely flowing evaporite.

In the very eastern margin of the high strain zone, an area of folding and microfaulting with asymmetries suggesting up-dip (to the east) shear exists (Fig. 6d). These structures are subordinate to the much more common and extensive boudinage and small-scale faulting. More importantly, the bedding oblique foliation in evaporites was folded, indicating that this folding post-dated fabric development in the evaporite.

3.c. North slopes of Ragnardalen

Directly on line with the above described outcrops and across the Ragnardalen valley floor and marginal moraines is a well-exposed normal fault (Figs 4, 5). Minkinfjellet Formation strata in the hanging-wall are brittlely truncated with little deformation. A brittle breccia zone about 70 cm thick is locally

https://doi.org/10.1017/S0016756810000567 Published online by Cambridge University Press

preserved. Ebbadalen Formation beds in the footwall show significant steepening (up to 65°) and internal deformation, including boudinage similar to that seen to the south. However, the thickness of the zone of ductile deformation is narrow, 10–20 m wide, significantly less than to the south. Recorded fault striae of subsidiary faults in the shear zone indicate dip-slip movement. Another normal fault with less offset occurs along the ridge to the east, offsetting the Minkinfjellet–Ebbadalen formations contact.

Even further to the east, close to the present terminus of Ragnarbreen, is a normal fault that offsets basement and the overlying Billefjorden Group and Hultberget Formation strata. However, overlying Ebbadalen evaporites are not affected by the faulting. In addition, Hultberget Formation red-beds thicken significantly across the fault (Fig. 5). These relationships constrain the age of faulting, with the easternmost normal fault active prior to the Løvehovden fault.

3.d. North slopes of Wordiekammen

A well-developed, W-facing monocline in the cliff-forming Wordiekammen Formation strata has some 50 m of structural relief. Exposures of the underlying Ebbadalen Formation are not as good as elsewhere, with some complication by small slumps. However, brittle boudinage of the carbonate layers and foliation development in the adjacent evaporites exist. In addition, steeper northwesterly dips that are inconsistent with a slump origin are consistent with fault deformation. To the west the exposures are poor, but significant carbonate subcrop that exists lower down on the slopes is consistent with Minkinfjellet Formation strata occurring west of the fault, in a manner similar to that found at Løvehovden across the valley.

3.e. South slopes of Wordiekammen

At lower elevations the evaporite-rich Ebbadalen Formation strata in the footwall to the east can be traced towards a fault, becoming progressively more deformed and tilted with proximity. The monocline in the overlying cliff-forming Wordiekammen Formation strata overlies the fault tip. Boudinage of carbonate interlayers, distributed small normal faults, and foliation development are all common in Ebbadalen Formation evaporites within tens of metres of the fault trace (Fig. 6). As on Ragnardalen's north slope, the hanging-wall Minkinfjellet Formation carbonate, sandstone and evaporite horizons appear to truncate against the fault with little deformation. A distinct and very petroliferous stratiform breccia horizon within the Minkinfjellet Formation with abundant dead oil truncates against the deformed evaporite material in the footwall, suggesting the deformed evaporites provided an up-dip seal.

Figure 7 plots poles to bedding from along the length of the Løvehovden fault. The distribution is that of a W-facing monoclinal flexure where bed rotation very closely approaches parallelism with the 70° dip of the major brittle fault. The best-fit girdle axis of 171–1 parallels the average orientation of the lineament trace. Intersections between paired readings of bedding and the oblique deformation fabric within evaporite beds (Fig. 6) are mostly shallowly plunging to the NNW. Plots of small-scale fault planes and associated fault striae associated with the lineament document that normal fault kinematics dominate. Only one fault had a reverse offset. Kinematic indicators were consistent along the length of the fault.

4. Stratigraphic differences across the Løvehovden lineament

The Ebbadalen to Minkinfjellet formations contact on the east side of Ragnardalen is sharp and well defined (Dallmann, 1999; Eliassen & Talbot, 2003*a*). The well-bedded and evaporite-dominated section of the Ebbadalen Formation, with subordinate, dark interbeds of limestone typically a metre thick or less, is overlain in sharp contact by a variety of bedded, largely micritic carbonates, stratiform carbonate breccias, yellowish coloured sandstones, and infrequent evaporites. The latter beds belong to the lower Carronelva Member of the Minkinfjellet Formation (Figs 8, 9). The contact is also a slope break and is easily traced along the mountain sides, especially in photo-textured laser scans. Evidence for significant relief on the formational contact with local truncation of the underlying evaporite beds is described in Section 5. No significant facies changes were observed as the upper Ebbadalen Formation strata approach the Løvehovden fault, and individual beds can be traced for over one kilometre. Significantly, a similar sharp contact and disconformity is not exposed to the west of the Løvehovden fault in Ragnardalen.

The most convenient candidate for top of the Ebbadalen Formation on the west side of the Løvehovden fault crops out in the lower north slopes on the north side of Ragnardalen (Fig. 8). The formational boundary with the Minkinfjellet Formation is taken as the base of a thick limestone unit. Overlying strata consist of micritic carbonate units (mixed limestone and dolostone) that are metres to over 15 metres thick, with abundant sabkha textures, interbedded with evaporite beds of similar thickness, with occasional yellowish sandstone units. They differ substantially from the lower Minkinfjellet Formation strata (Carronelva Member) on the east side of the fault in that on the west side carbonate breccias are absent to much less common, evaporite horizons are more common and much thicker, and bedding overall is thicker. No bed sets can be matched across the fault despite excellent exposures. Further, beds equivalent to the uppermost Ebbadalen Formation evaporites and thin dark limestones found immediately on the west side are not exposed on the western side of Løvehovden fault at the base of Løvehovden (Fig. 3). The lowest

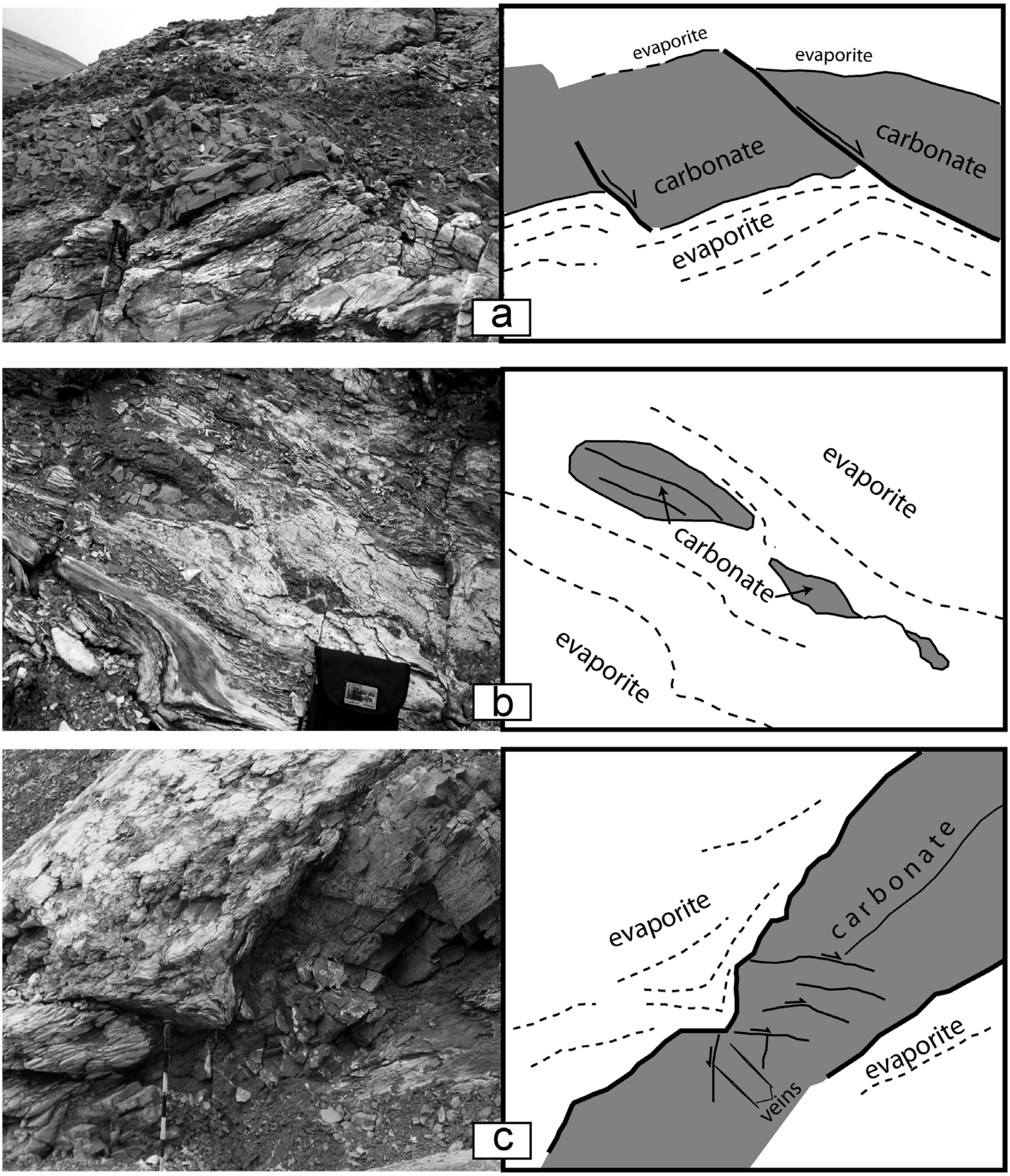

Figure 6. Photographs and line drawings of outcrops. From the south slopes of Ragnardalen. (a) View to south of brittle faults transgressing a carbonate layer with ductile flowage of the surrounding evaporite. Dashed lines represent evaporite fabric. Bars on walking stick are 10 cm each. (b) View to south of boudinage of carbonate layers within the evaporite. Small angular clasts of carbonate in the evaporite matrix are due to brittle plucking by the ductilely flowing evaporite. Smaller boudin is transgressed by several evaporite veins. The object in the lower right is a note case 17 cm in width. (c) Thicker limestone layer showing pinch and swell (incipient boudinage) by veining and distributed small-scale faults accomodating layer-parallel extension. The inverted teepee-like structure in the evaporite suggests ductile flow of the evaporite into the intervening gap. Walking stick for scale.

units at the base of the mountain are thick (5–10 m) limestone units which can be traced around the base of much of the mountain, indicating they are within the Minkinfjellet Formation. This interpretation, that the Ebbadalen Formation is not exposed in the lower slopes of Løvehovden, differs from previous mapping (e.g. Dallmann *et al.* 2004). A very gentle regional southern dip of platform strata on Svalbard occurs in this region, so that younger units are exposed to the south. Given both this regional dip, the NW strike and SW dip of

https://doi.org/10.1017/S0016756810000567 Published online by Cambridge University Press

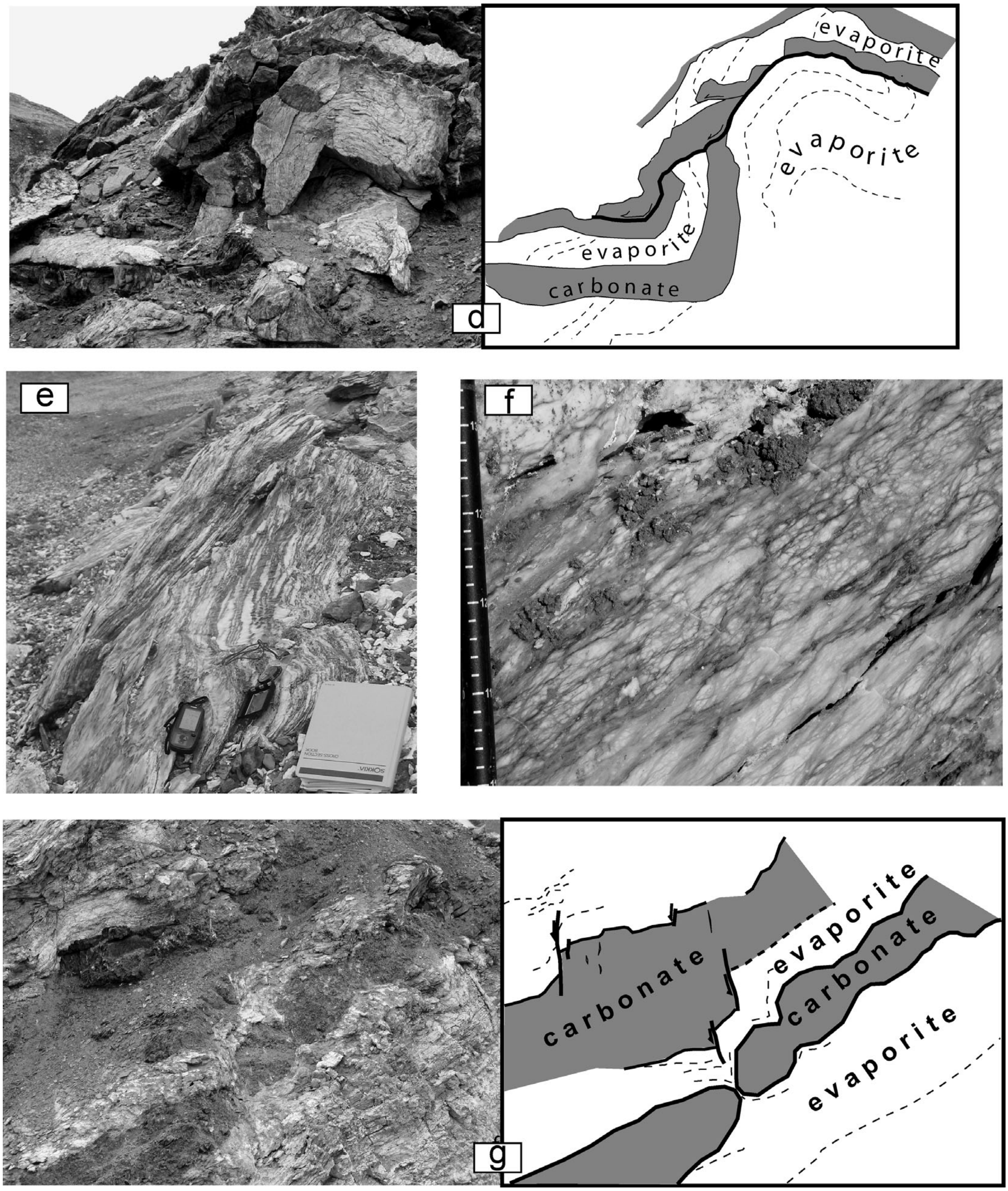

Figure 6. (Continued) (d) Up-dip (eastward) verging fold with associated small-scale thrust faults. An earlier oblique fabric in the evaporite is reoriented by the fold, and hence pre-dates it. This earlier fabric is consistently anticlockwise of bedding in this southerly view. (e) Progressive development of fabric in evaporite increasing in intensity toward the trace of the brittle fault just to left (which truncates a thick Minkinfjellet carbonate unit out of view). From the south slopes of Wordiekammen. The field notebook in the lower right is 17 cm in width. (f) Composite shear fabric in evaporite–anhydrite, with brittle microboudinage of carbonate material in band in upper left portion. Scale to left in centimetre markings. View to north. (g) Boudinage and extension of carbonate layers within evaporite–anhydrite layers. Lower layer about 1 m thick. View to the north.

the eastern limb of the Petuniabukta regional syncline, and the position of this stratigraphic contact on the north side of Ragnardalen, the underlying evaporites of the Ebbadalen Formation exposed on the north side of Ragnardalen project into the subsurface in the Løvehovden region. In cross-section reconstructions (Fig. 5) the Minkinfjellet Formation strata on the west side of the lineament are at least 150 m thicker than on

https://doi.org/10.1017/S0016756810000567 Published online by Cambridge University Press

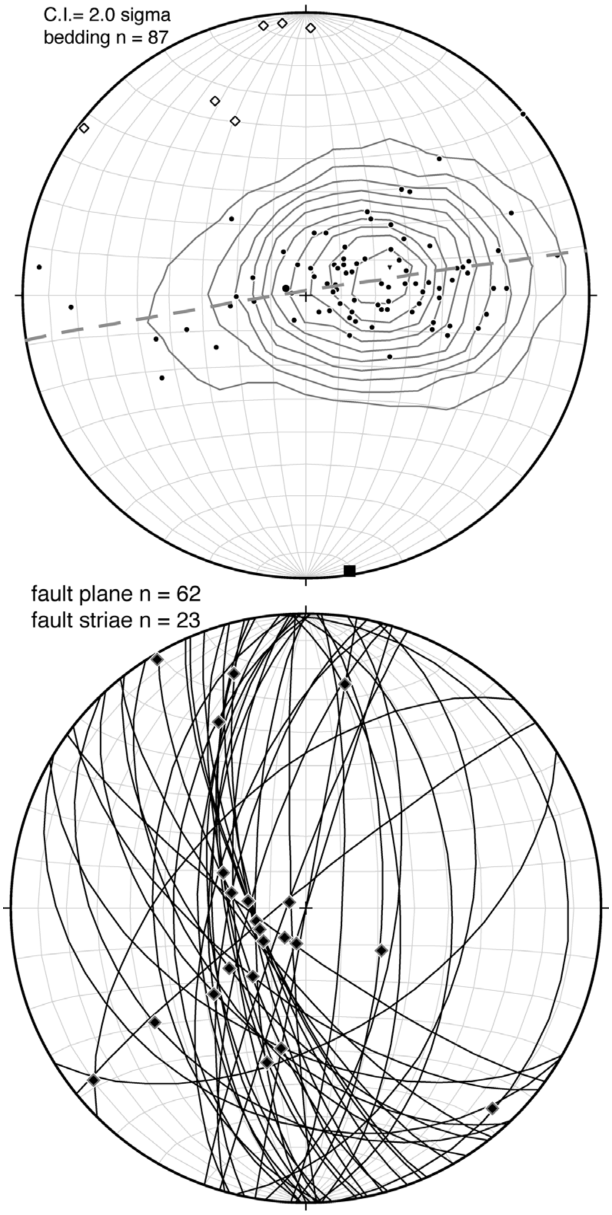

Figure 7. Stereoplots of structural elements associated with the Løvehovden fault. (a) Contoured (Kamb plot) poles to bedding, with a statistical best-fit girdle axis of 171–1. Diamonds represent intersections between bedding and shear fabric in deformed evaporites. (b) Lower hemisphere stereonet plot of fault planes with fault striae marked.

the east side. Stratigraphic sections from DeGeerfjellet and Fortet from Eliassen & Talbot (2003*a*) and from our work also show substantial differences across the fault (Fig. 8), especially in the Carronelva Member. Further, at Wordiekammen a well-defined break that exists between the Ebbadalen and Minkinfjellet Formation strata can be traced into the Løvehovden fault from the east, but is not exposed on the west side.

Lidar (Light Detection And Ranging) data was collected from the slopes of Wordiekammen, Løvehovden and Hultberget, and the north slopes of Ragnardalen (Buckley *et al.* 2008). Derived photo textured digital elevation models clearly indicate that Wordiekammen Formation units thicken across the monocline that overlies the lineament (Fig. 9d). A substantial portion of the thickening is accommodated by the basal massive, cliff-forming unit, but thickening is also seen in overlying layering. A similar, but more subtle thickening of higher units is also visible on Løvehovden, but here only the lower portion of the monocline involving Wordiekammen Formation strata is preserved.

5. Truncation surfaces at the top of the Ebbadalen Formation

The Ebbadalen–Minkinfjellet formational boundary is sharply defined to the east of the Løvehovden lineament. Tracing the formational contact on the north and south sides of Ebbadalen demonstrates that the contact cuts significantly down-section into the underlying evaporites as it approaches the Løvehovden fault (Fig. 9b). In addition, abrupt local relief and truncation of greater than 10 metres of Ebbadalen evaporites can be seen on Luxorfjellet 1 km east of the lineament (Fig. 9a). The relief is associated with a lateral transition from bedded carbonates to massive breccias in the overlying Minkinfjellet Formation strata. The formational contact thus cuts down-section to the east. Significantly, beds overlying the breccias do not show evidence of collapse at this location even though they overlie the transition from breccias to bedded carbonates. In addition, low-angle truncation of underlying bedding in evaporites is seen immediately to the west (Fig. 9a), where well-bedded carbonate of the Minkinfjellet Formation rests directly on the contact. These Minkinfjellet Formation carbonate beds are in turn truncated above by another low-angle disconformity, with overlying carbonate breccias (Fig. 9a).

Similar relationships are clearly seen on both Hultberget and Wordiekammen ridges to the south, forming a NW-trending feature some 6 km long (Fig. 3, asterisks). At Hultberget more than half the Ebbadalen Formation evaporites have been removed (visual estimate > 40 m). On the east side of the truncation surface the massive, basal, carbonate breccias some 15–20 metres thick are overlain by bedded carbonate breccias, and then a sequence of carbonate micrites and yellowish sandstones. These beds project into the Ebbadalen Formation evaporite beds to the west. Unfortunately, the truncation surface itself is not exposed. In the Lidar data the stratiform breccia horizons can be traced to about 1.5 km to the east along the northern slopes of easternmost Hultberget, where they appear to transition to better bedded, reddish material. However, this transition has not been confirmed by detailed outcrop studies.

At the east end of Wordiekammen a very similar feature exists (Fig. 9c); however, the relief on the truncation surface appears even greater. Here, as at Hultberget, the basal breccias transition into well-bedded strata that clearly project into the truncation surface (Fig. 9c), so that accommodation space for sediments

https://doi.org/10.1017/S0016756810000567 Published online by Cambridge University Press

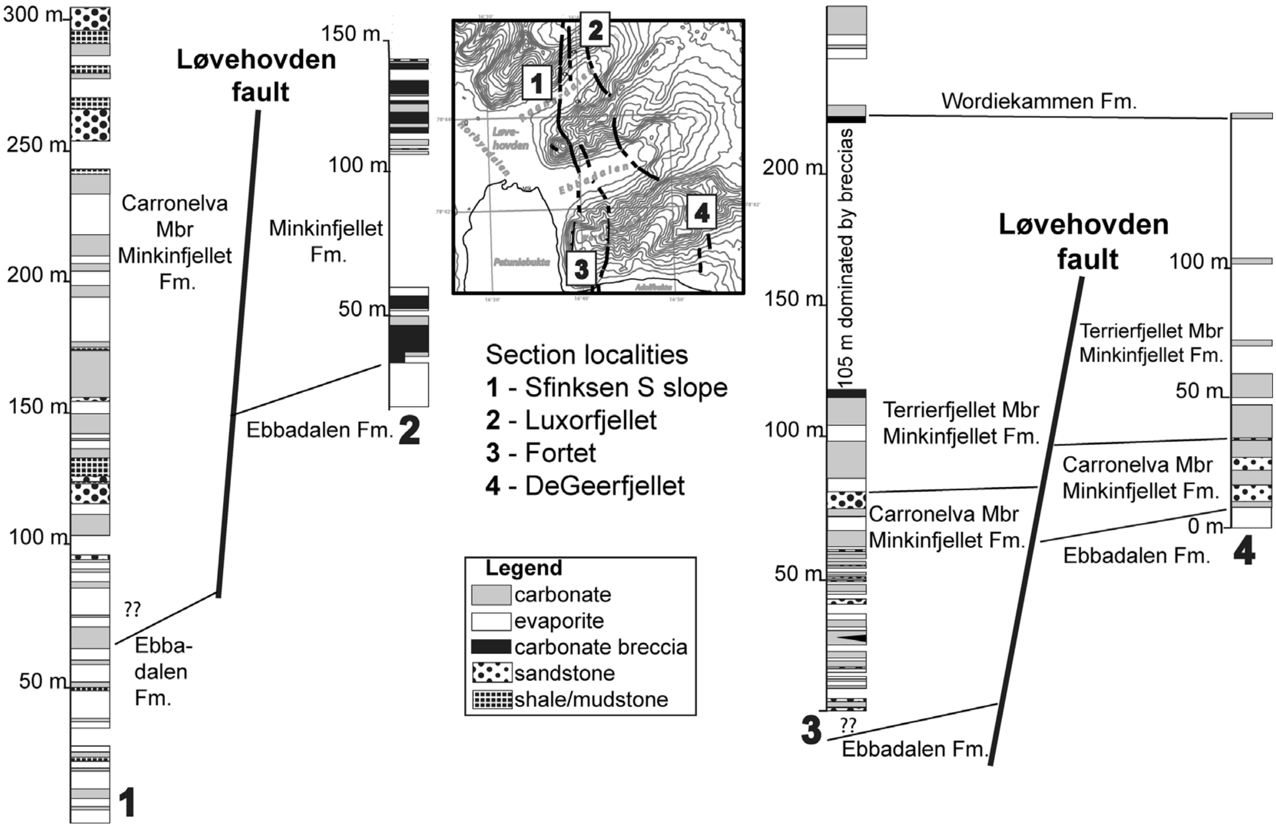

Figure 8. Lithological columns from Sfinksen (1) and Fortet (3) on the west side of the Løvehovden fault, and Luxorfjellet (2) and DeGeerfjellet (4) on the east side. All but the Luxorfjellet section modified and simplifed from Eliassen & Talbot (2003*a*).

was developed during Minkinfjellet Formation times in association with the surface. The underlying evaporite beds are unfaulted, and overlying beds do not show sign of collapse. Eliassen & Talbot (2003*a*) describe subsurface evaporite dissolution fronts associated with stratiform breccias in the Minkinfjellet Formation. We focus on the cause of these truncation surfaces below.

6. Discussion

6.a. Løvehovden lineament kinematics

The above analysis substantiates that the movement along the lineament is west-side-down. Where it is well defined, the brittle fault core dips 70 to 80° to the west. The Wordiekammen Formation strata of the east limb of the Petuniabukta syncline dip consistently 10–20° to the west. Restoring these strata to horizontal results in the fault dipping roughly 60° during Minkinfjellet Formation times, a typical near-surface orientation for a normal fault. Subsidiary faults hundreds of metres to the west of the main Løvehovden fault, which are exposed on the south slopes of Løvehovden (Figs 2, 3), are presently sub-vertical. In a restored position they also dip to the west, and restore as more steeply dipping normal faults. Further, fault striae and slickensides are consistent with predominantly west-side (hanging-wall) down-dip movement (Fig. 7).

Associated development of monoclines and fault proximal deformation can be associated with fault zone tri-shear development (e.g. Hardy & McClay, 1999). The array of microfaults, boudinage and fabric development indicates significant layer-parallel extension and hanging-wall down-shear in the tri-shear zone. The evaporite fabric, which is oblique and dips more shallowly than bedding, is consistent with hanging-wall-down, layer-parallel shear. It is not of an orientation or association that would be consistent with it forming as an axial planar fabric, and encompassing folds are typically absent here. It is interpreted as a shear fabric that developed in the incompetent evaporites. Observed asymmetric boudinage is consistent with such kinematics. A similar fabric and suite of structures exists in deformed evaporites associated with the Billefjorden fault zone along the western rift margin, and is interpreted to reflect Carboniferous normal movements (Nanfito, Maher & Braathen, 2008).

This assemblage and geometry of structures is consistent with tri-shear zone deformation associated with a normal fault (Hardy & McClay, 1999). Distributed deformation is mainly concentrated in the Ebbadalen Formation footwall evaporites, and varies along strike, with its greatest width at Løvehovden. The increase in breccia development and concurrent decrease in evaporite beds in hanging-wall strata with proximity to and within the tri-shear zone on the Løvehovden ridge (Fig. 4) suggests that solution and breccia development contributed to the tri-shear zone deformation. Solution may have been an additional

https://doi.org/10.1017/S0016756810000567 Published online by Cambridge University Press

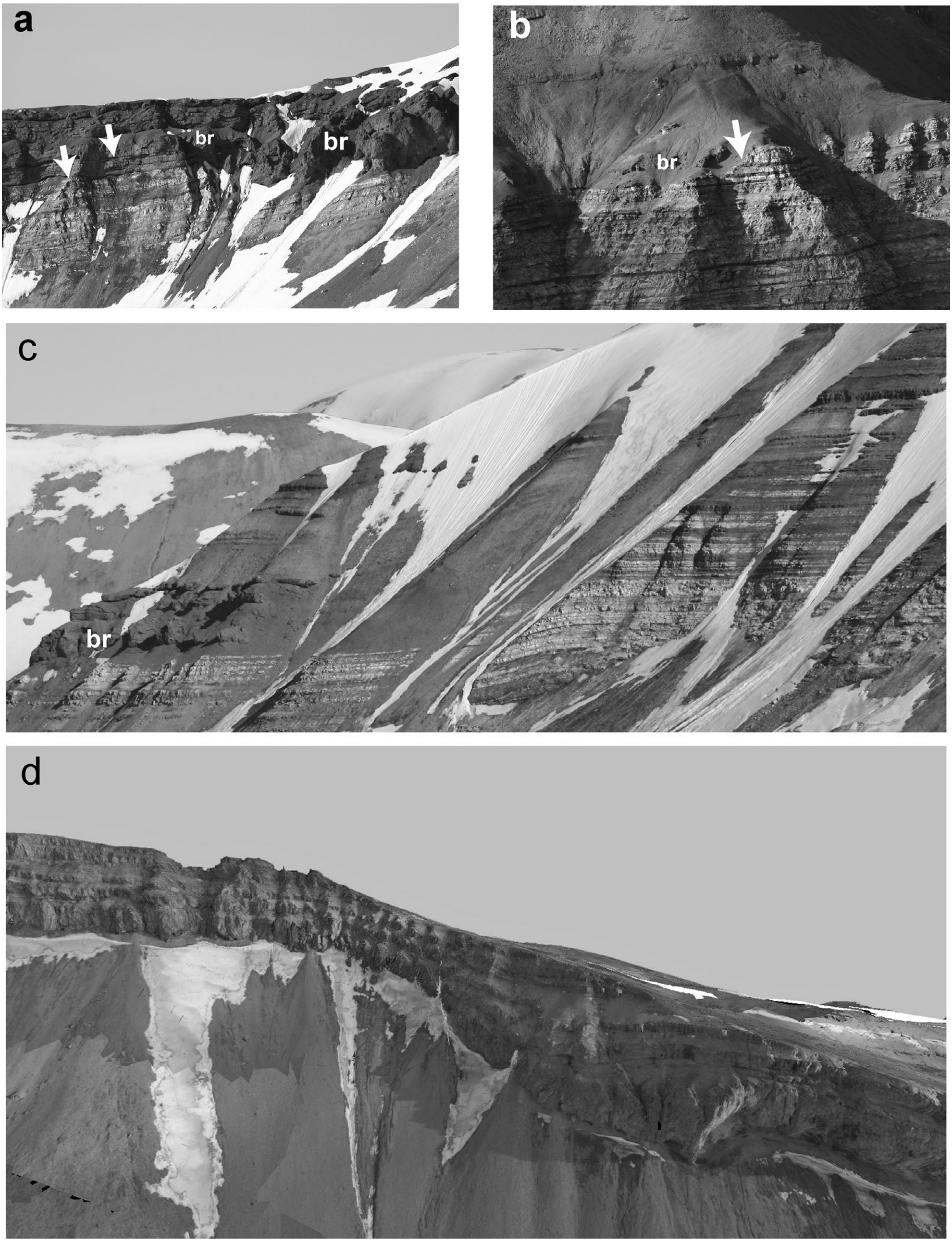

Figure 9. Field images of the Ebbadalen–Minkinfjellet Formation contacts on the east side of the Løvehovden fault. (a) Photograph of Ebbadalen–Minkinfjellet Formation contact on Luxorfjellet looking northward. Low-angle truncation of Ebbadalen Formation strata associated with undulating relief and overlying well-defined carbonates of the Minkinfjellet Formation (lower arrow) changes to a zone of high-angle truncation and thick, carbonate breccias to the right. Another low-angle truncation of carbonate layers occurs above (upper arrow). (b) Low-angle and stepwise truncation (arrow) of bedding in underlying Ebbadalen evaporites seen in southern slopes of Hultberget west of the Løvehovden fault. (c) Photograph of the very west end of Wordiekammen (looking south) showing truncation of Ebbadalen evaporites on the right, replaced by basal breccias and overlying stratified material of the Minkinfjellet to the left. Photo taken from Hultberget where very similar relationship exists. Underlying strata are continuous. (d) Lidar data screen capture image looking south of Wordiekammen Formation strata involved in the monocline above the Løvehovden fault. Note the clear thickening of several Wordiekammen Formation units on the west side of the monocline.

https://doi.org/10.1017/S0016756810000567 Published online by Cambridge University Press

stratal thinning mechanism that operated in the tri-shear zone.

The significant role that thick ductile layers, such as provided by the upper Ebbadalen Formation evaporites, play in monocline development associated with basement-involved normal faulting is described by Sharp *et al.* (2000) for the Suez rift, which involved a mixed carbonate, clastic and evaporite fill with high competency contrasts similar to that in the Billefjorden basin. From the fault monoclines in the Suez rift, Jackson, Gawthorpe & Sharp (2006) describe layer-parallel slip in weak mudstone units with block rotation of more competent sandstone layers that are similar to structures in evaporite–limestone layers in the Løvehovden tri-shear zone (Fig. 6). Modelling by Finch, Hardy & Gawthorpe (2004) demonstrates that weak layers increase the width of the associated monocline, while an increase in fault dip decreases it. The greater Ebbadalen Formation evaporite thickness to the north may thus be associated with the better development of the associated monocline structure at Løvehoveden, while a steeper fault dip may explain a more limited development in the north slopes of Ragnardalen. The cross-section and along-strike geometries of the Løvehovden fault are consistent with those of a normal fault tri-shear zone.

6.b. Amount and timing of movement

The limited structural relief on the monocline involving the Permian Wordiekammen Formation strata on Wordiekammen constrains the amount of post-Carboniferous throw on the Løvehovden fault to be on the order of 50 m. The stratigraphic throw on the lower Minkinfjellet Formation boundary in Ragnardalen is minimally 150–200 m (Fig. 3), indicating a minimum of 100–150 m of additional Minkinfjellet Formation fill to the west of the Løvehovden lineament. These estimates are complicated by the likely stratal removal by both footwall exposure and erosion (discussed in Section 5), and by possible subsurface stratiform solution of the evaporites. Both are concentrated in the eastern footwall block, and inclusion of their effects would therefore serve to increase the amount of throw.

A Russian drill hole west of Løvehovden that encountered basement rocks at 1290 metres below sea-level (Dallmann *et al.* 2004) is consistent with the western thickening of the Minkinfjellet Formation fill across the Løvehovden lineament (Fig. 5, cross-section B–B′), and/or across additional faults to the west in the subsurface. With exposed Minkinfjellet Formation carbonates and evaporites at the drill hole surface, cross-section reconstruction suggests a stratigraphic thickness of pre-Wordiekammen Formation fill is 400 m greater than to the east of the lineament. While some 150 m of the increase in stratigraphic thickness across the fault must involve the Minkinfjellet Formation, the remaining amount could also involve an increase in Ebbadalen and/or Hultberget Formation strata.

As discussed, the sharply defined boundary between the Ebbadalen and Minkinfjellet formations on the east side of the Løvehovden lineament is associated with significant truncation of underlying evaporite beds (Fig. 9). Locally this contact has significant relief along a 'palaeovalley' feature to the east (Fig. 3). Well-bedded carbonates and sandstones in the accommodation space associated with the truncation surface are consistent with Minkinfjellet Formation sediment infilling of palaeo-relief associated with the surface. In this case, the overlying stratiform breccias can be associated with near- or at-surface karst, dissolution and erosional processes that produced the relief (Fig. 10). The lack of collapse features in higher strata that overlie the lateral transition from evaporites to stratiform breccia is consistent with such a scenario. The existence of a slightly higher local high-angle truncation surface overlain by breccias at Luxorfjellet (Fig. 9a) suggests multiple exposure and stratiform breccia events. Breccias bodies in the Billefjorden basin in general are thus polygenetic with some lower Minkinfjellet Formation stratiform breccias being syn-formational and significantly earlier than the well-developed, cross-cutting pipe breccias such as can be found at Fortet (Eliassen & Talbot, 2003*a*). Other pipe and stratiform breccias in higher stratigraphic levels of the Minkinfjellet Formation to the west of the lineament are associated with breccia pipes that cut up into the Wordiekammen Formation strata and are thus distinctly younger in age.

In contrast, the possible Ebbadalen–Minkinfjellet formation's contact on the hanging-wall (west side) of the Løvehovden fault in Ragnardalen, though not extensively exposed, shows a transition from Ebbadalen evaporites to thicker bedded limestones, marine sandstones, and evaporites without stratiform breccias. The Ebbadalen to Minkinfjellet Formation transition is either unexposed or distinctly less obvious on the west side of the lineament. Further, the Minkinfjellet Formation is thicker to the west (Fig. 8). We interpret this formational contact to mark a movement phase on the Løvehovden fault, with footwall uplift exposing the evaporite-dominated footwall and submerging the hanging-wall basin fill to form a narrower sub-basin (Fig. 8). Minor Løvehovden fault footwall uplift and/or eustatic changes could have produced a low relief emergent area consisting primarily of Ebbadalen evaporites and carbonates that favoured shallow karst formation of the stratiform breccias (Fig. 10). Other stratiform breccia horizons in the lower Minkinfjellet Formation may have formed in a similar way, dissolving evaporites deposited during a previous high-stand to form the breccia beds.

Scholz & Contreras (1998) describe a model for rift development from a cross-section perspective where rifts initiate as more narrow symmetric graben, but one fault dominates in the evolution towards a wider half-graben. The history of the Løvehovden fault sub-basin is broadly consistent with this model, and similar sub-basins may be sought in other Barents Shelf Carboniferous basins. Given broadly similar stratigraphy

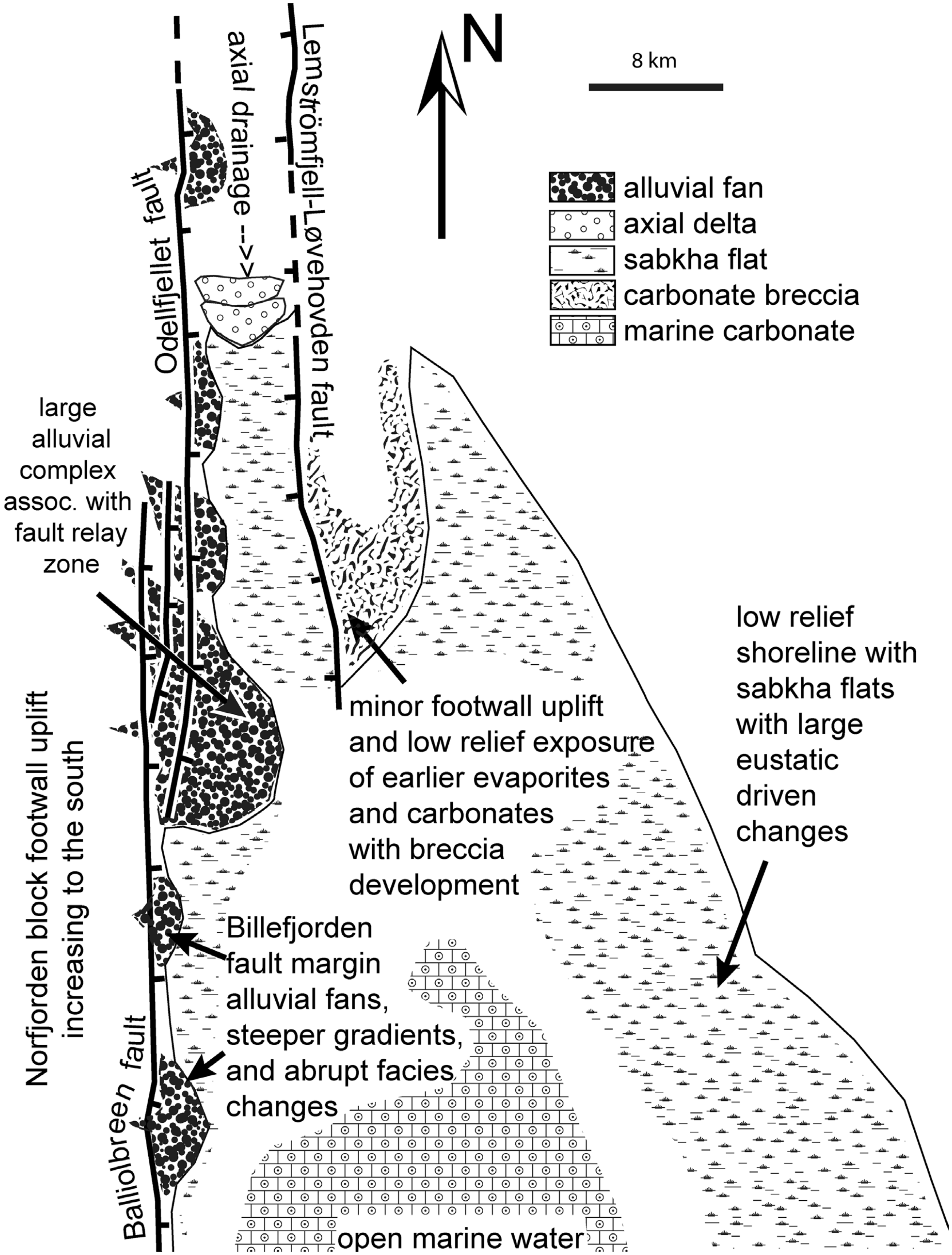

Figure 10. Schematic model (map view) for palaeogeography of Billefjorden fault basin during lowstand.

(Stemmerik & Worsley, 2005), with relatively low relief, the footwalls of these sub-basin bounding faults may be good localities for local karst development, as the interplay between faulting and sea-level changes caused intermittent periods of sabkha deposition and emergence.

The monocline in Wordiekammen Formation carbonates along and above the Løvehovden fault suggests

https://doi.org/10.1017/S0016756810000567 Published online by Cambridge University Press

that some post-Carboniferous normal fault movement occurred. The timing is constrained to be partially syn-Wordiekammen Formation times by the development of accommodation space geometries on the west side (Fig. 9d). However, it is difficult to rule out any post-Wordiekammen, west-side-down movements. Such movement may correlate with the extensive karst and pipe breccias development in the Wordiekammen Formation, which may have been Permian in age (Eliassen & Talbot, 2003*a*). The idea that differential compaction, diagenesis and solution across the fault contributed to the monocline development is attractive, but hard to evaluate without substantial subsurface data.

A major unknown about the timing of Billefjorden rift basin structural architecture is related to the development of the Petuniabukta syncline, which has over 700 m of structural relief of Wordiekammen Formation strata in the Pyramiden area, given outcrops of this unit both on the top of Pyramiden and along the shore (Dallman *et al.* 2004). Remove this deformation and much of the half-graben tilt of the basin is undone. McCann & Dallmann (1996) speculate that the syncline is Tertiary in age. However, where the Billefjorden fault zone is exposed along-strike in Bunsow Land just to the south across Billefjorden (Fig. 1), there is not only a lack of evidence of east-side-down normal offset of younger Permian strata (specifically the Kapp Starostin Formation strata) that would be consistent with Tertiary syncline development. Instead, there is clear evidence of east-side-up reverse fault motions associated with Tertiary contractional reactivation. This, coupled with other observations (Nanfito, Maher & Braathen, 2008; Maher, Braathen & Bælum, 2009), suggests that a later Permian phase of normal movement may exist on the Billefjorden fault zone. Khalil & McClay (2002) describe how large hanging-wall synclines are a consequence of tri-shear zone development in the Suez rift area. Thus, a late phase of monocline development above the Løvehovden fault may be associated with Petuniabukta syncline development and late phase basin development.

Only one locality of small up-dip and contractional features was found in the deformed evaporites in the Ragnardalen area (Fig. 6). These folded the oblique evaporite fabric that is consistent with hanging-wall-down kinematics. These contractional structures are consistent with very minor and localized Tertiary reactivation along the Løvehovden fault. Movement is hanging-wall east-side-up, opposite of the general sense of Tertiary movement proposed by McCann & Dallmann (1996), but consistent with minor Tertiary contractional reactivation of an older W-dipping normal fault.

The steeper, apparent reverse faults within the footwall of the main Løvehovden fault (Fig. 4) may reflect a combination of later rotation and their position at a convex-into-the-footwall fault trace (Fig. 3). At such a position, more steeply dipping normal, and even reverse, faults occur in the Suez Rift (Jackson, Gawthorpe & Sharp, 2006), reflecting the importance of along-strike changes in local strain. These faults do not affect overlying Minkinfjellet Formation strata, helping to constrain their age, and are consistent with an early phase of Ebbadalen Formation tri-shear zone development along the Løvehovden structure.

Haremo *et al.* (1990) describe Tertiary contractional features along the Billefjorden fault zone to the south of the study area where younger strata are exposed, as interplay between more pervasive thin-skinned, E-directed structures in Mesozoic strata and thick-skinned east-side-up reactivation of the fault zone. Tertiary basement-involved reactivation may have been limited to the Billefjorden fault zone due to its greater continuity, whereas the Løvehovden fault dies out to the south. The basin fill evaporites of the Carboniferous basin would not be in an appropriate position or depth to be involved in the E-directed, thin-skinned deformation.

6.c. Billefjorden basin segmentation

The Lemströmfjellet fault along the east side of Widjefjorden dips steeply west and has west-side-down throw that juxtaposes Billefjorden Group strata against basement rocks (Dallmann *et al.* 2004). The fault is parallel to and on the margin of steeply dipping foliations in the basement rocks, with shallower dips just to the east. The parallel Odellfjellet fault within the Billefjorden fault zone on the west side of the basin (Fig. 1) clearly reactivated a mylonitic basement foliation, and the Lemströmfjellet fault appears to be localized along the edge of a thick, steeply dipping basement shear zone. The elevation of the base of the Billefjorden rocks up to the top of the preserved basement to the east constrains the Lemströmfjellet throw to be at least 700 m. A nunatak along the connection between the Lemströmfjellet fault and Løvehovden fault has a lithological contact mapped with a strike parallel to the inferred fault trace and with a western dip of 60° (Dallmann *et al.* 2004). The alignment and similar kinematics suggest that the Lemströmfjellet fault and Løvehovden fault are linked beneath the intervening glacier. Given the greater offset to the north, and the lack of a Løvehovden linement continuation in Bunsow Land to the south, it is likely that the Løvehovden fault in the study area represents the southern termination of the combined Lemströmfjellet–Løvehovden fault complex.

On the west side of Petuniabukta, within the Billefjorden fault zone, Carboniferous movement from the Balliolbreen fault, that terminates to the north, was transferred to the Odellfjellet fault in a right-stepping geometry (Fig. 1). This transfer zone, coupled with the presence of the Løvehovden fault on the east side as the southern termination of the Lemströmfjellet fault, suggests that palaeogeographic and facies patterns in the Petuniabukta are not those typically associated with a simple half-graben. Instead, a more narrow graben in the Petuniabukta area, with along-basin-axis facies changes, likely deepening and widening to the south

(Eliassen & Talbot, 2003*b*), may have existed during Ebbadalen and Minkinfjellet Formation times (Fig. 10). The pattern in Bunsow Land along-strike to the south appears to fit a simple half-graben model better.

The more northwesterly strike of the W-dipping Wordiekammen Formation strata between the Odellfjellet fault and the Løvehovden fault (Fig. 1) is part of the east limb of the Petuniabukta syncline, which plunges gently southward. This geometry is consistent with increased dip-slip movement along the Billefjorden fault complex to the south, suggesting that the Petuniabukta area may be related to a transfer zone during the later phases of rift development.

7. Conclusions

The structures exposed on the west end of Løvehovden are part of a roughly N–S-trending fault zone that has been mapped in detail for a 10 km length in the study area, and which are interpreted as the southern extension of the Lemströmfjellet fault to the north, for a total fault complex length in excess of 25 km. Similar to the Odellfjellet and Balliolbreen faults within the Billefjorden fault zone, the Lemströmfjellet fault, and likely the Løvehovden fault, parallel a steep well-developed fabric in the basement rocks, and represent basement reactivation. Fault kinematics consistently indicate a W-side-down normal movement. The geometry is consistent with that of a tri-shear normal fault zone, where Ebbadalen Formation evaporites played a crucial role in strain accommodation. Stratigraphic differences across this fault indicate that it was active during deposition of the Minkinfjellet Formation, and at times defined a narrow sub-basin within the Billefjorden Trough. A disconformable surface between the Ebbadalen and Minkinfjellet formations on the east side of the Løvehovden fault is related to fault movement, exposure, and associated near- or at-surface evaporite dissolution that locally produced stratiform breccias. Multiple episodes of stratiform breccia formation occurred. Recognizing the existence of this sub-basin bounding fault is crucial to stratigraphic correlations and palaeogeographic exploration models. A concentration of shallow karst processes on the low-relief footwall block of the subsidiary conjugate fault in the early history of a half-graben may produce highly porous breccia reservoirs. Along-strike changes in basin architecture included a narrower basin between the Billefjorden fault zone and the Lemströmfjellet–Løvehovden fault in the Petuniabukta area and likely northwards, and a wider half-graben to the south as the eastern border fault complex died out to the south, and offset was concentrated on the Billefjorden fault zone. The Petuniabukta area is the transition between two very different segments of the Billefjorden basin. A capping monocline in Wordiekammen Formation strata with thickening of units on the west side indicates late-phase syn-depositional movement as part of a growth anticline. Subsequent minor late phases of basin development are also possible. Tertiary compressional reactivation is very minor to absent along the Løvehovden fault, contrary to prior reports. Models developed in the literature for normal-fault-related tri-shear zones and associated fault-propagation folds and for basin segmentation can be successfully employed to generate a more detailed understanding of the Billefjorden basin and other Carboniferous rifts on the Barents Shelf. Evaporite horizons may play a particularly important role in the basin architecture due to their weakness and solubility.

Acknowledgements. The Norwegian Research Council Petromaks project 176132 to the Center for Integrated Petroleum Research at the University of Bergen, the University Centre of Svalbard, and the University of Nebraska at Omaha are thanked for their support.

References

Bergh, S. G., Braathen, A. & Maher, H. D. Jr. 1994. The Lomfjorden fault zone; basement-controlled Carboniferous subsidence and Tertiary contractional reactivation in the Svalbard Foreland, East Spitsbergen. *Tectonics and Structural Geology Studies Group of Norwegian Geological Society*, Tromso, 10–11.

Braathen, A. & Bergh, S. 1995. Kinematics of Tertiary deformation in the basement-involved fold-thrust complex, western Nordenskiøld Land, Svalbard: tectonic implications based on fault-slip data analysis. *Tectonophysics* **249**, 1–29.

Buckley, S., Howell, J., Vallet, J., Wheeler, W. & Braathen, A. 2008. Oblique helicopter-mounted lidar combined with multiresolution modelling for the creation of high resolution, wide-area virtual geological outcrops. *American Association of Petroleum Geologists Annual Convention Abstracts*. San Antonio, Texas.

Cutbill, J. L. & Challinor, A. 1965. Revision of the stratigraphical scheme for the Carboniferous and Permian Rocks of Spitsbergen and Bjornoya. *Geological Magazine* **102**, 418–39.

Dallmann, W. K. 1993. Notes on the stratigraphy, extent and tectonic implications of the Minkinfjellet Basin, Middle Carboniferous of central Spitsbergen. *Polar Research* **12**, 153–60.

Dallmann, W. K. 1992. Multiphase tectonic evolution of the Sørkapp-Hornsund mobile zone (Devonian, Carboniferous, Tertiary) Svalbard. *Norsk Geologisk Tidsskrift* **72**, 49–66.

Dallmann, W. K. 1999. Upper Paleozoic Lithostratigraphy. In *Lithostratigraphic Lexicon of Svalbard* (ed. Winfried Dallmann), pp. 25–126. Norsk Polarinstitutt. Tromsø, Gjøvik Trykkeri As.

Dallmann, W. K., Ohta, I., Birjukov, A. S., Karnoušenko, E. P., Sirotkin, A. N. & Piepjohn, K. 2004. *Geological map of Svalbard 1:100,000, sheet C7G Dicksonfjorden*. Norsk Polarinstitutt Temakart No. 35, 1 sheet, 1:100,000.

Dallmann, W. K., Piepjohn, K. & Blomeir, D. 2004. *Geological map of Billefjorden Central Spitsbergen, Svalbard with geological excursion guide*. Norsk Polarinstitutt Temakart Nr. 36, 1 sheet, 1:50,000.

Eliassen, A. & Talbot, M. R. 2003*a*. Diagenesis of the mid-Carboniferous Minkinfjellet Formation, Central Spitsbergen, Svalbard. *Norwegian Journal of Geology* **83**, 319–31.

Eliassen, A. & Talbot, M. R. 2003*b*. Sedimentary facies and depositional history of the mid-Carboniferous

Minkinfjellet Formation. *Norwegian Journal of Geology* **83**, 299–318.

FINCH, E., HARDY, S. & GAWTHORPE, R. 2004. Discrete-element modeling of extensional fault-propagation folding above rigid basement fault blocks. *Basin Research* **16**, 489–506.

GABRIELSEN, R. H., KLØVAN, O. S., HAUGSBØ, H., MIDBØE, P. S., NØTTVEDT, A., RASMUSSEN, E. & SKØTT, P. H. 1992. A structural outline of Forlandsundet Greben, Prins Karls Forland, Svalbard. *Norsk Geologisk Tidsskrift* **72**, 105–20.

GJELBERG, J. G. & STEEL, R. J. 1981. An outline of Lower–Middle Carboniferous sedimentation on Svalbard: effects of tectonic, climatic and sea level changes in rift basin sequences. *Canadian Society of Petroleum Geologists Memoir* **7**, 543–62.

HARDY, S. & MCCLAY, K. 1999. Kinematic modeling of extensional fault-propagation folding. *Journal of Structural Geology* **21**, 695–702.

HAREMO, P., ANDRESEN, A., DYPVIK, H., NAGY, J., ELVERHØI, A., EIKELAND, T. A. & JOHANSEN, H. 1990. Structural development along the Billefjorden Fault Zone in the area between Kjellstromdalen and Adventdalen/Sassendalen, central Spitsbergen. *Polar Research* **8**, 195–216.

HARLAND, W. B. 1969. Contribution of Spitsbergen to understanding of the tectonic evolution of the North Atlantic region. In *North Atlantic Geology and Continental Drift* (ed. M. Kay), pp. 817–51. American Association of Petroleum Geologists, Memoir no. 12.

HARLAND, W. B. 1997. Chapter 17: Carboniferous–Permian history of Svalbard. In *The Geology of Svalbard* (ed. W. B. Harland), pp. 310–39. Geological Society of London, Memoir No. 17. Oxford: Alden Press.

HASZELDINE, R. S. 1984. Carboniferous North Atlantic palaeogeography: stratigraphic evidence for rifting, not megashear or subduction. *Geological Magazine* **121**, 443–63.

JACKSON, C. A. L., GAWTHORPE, R. L. & SHARP, I. R. 2006. Style and sequence of deformation during extensional fault-propagation folding: examples from the Hammam Faraun and El-Qaa fault blocks, Suez Rift, Egypt. *Journal of Structural Geology* **28**, 519–35.

JOHANNESSEN, E. P. & STEEL, R. J. 1992. Mid-Carboniferous extension and rift-infill sequences in the Billefjorden Trough, Svalbard. *Norsk Geologisk Tidsskrift* **72**, 35–48.

KHALIL, S. M. & MCCLAY, K. R. 2002. Extensional fault-related folding, northwestern Red Sea, Egypt. *Journal of Structural Geology* **24**, 743–62.

LONOY, A. 1995. A Mid-Carboniferous, carbonate dominated platform, central Spitsbergen. *Norsk Geologisk Tidsskrift* **75**, 48–63.

MAHER, H. D. JR, BRAATHEN, A. & BÆLUM, K. 2009. Implications of the Petuniabukta syncline for the timing of Billefjorden basin development on Spitsbergen, Norway. *Geological Society of America Abstracts with Program* **41**(6), 52.

MAHER, H. D. JR & WELBON, A. 1992. Influence of Carboniferous structures on Tertiary tectonism at St. Jonsfjorden and Bellsund, Western Svalbard. *Norsk Geologisk Tidsskrift* **72**, 67–75.

MANBY, G. M., LYBERIS, N., CHOROWICZ, J. & THIEDIG, F. 1994. Post Caledonian tectonics along the Billefjorden fault zone, Svalbard, and implications for the Arctic Region. *Geological Society of America Bulletin* **105**, 201–16.

MCCANN, A. J. & DALLMANN, W. D. 1996. Reactivation history of the long-lived Billefjorden Fault Zone in north central Spitsbergen, Svalbard. *Geological Magazine* **133**, 63–84.

MOSAR, J., TORSVIK, T. H. & BAT TEAM. 2002. Opening the Norwegian and Greenland Seas: plate tectonics in Mid Norway since the Late Permian. In *BATLAS Mid Norway plate reconstruction atlas with global and Atlantic perspectives* (ed. E. A. Eide), pp. 48–59. Trondheim: Geological Survey of Norway.

NANFITO, A., MAHER, H. D. & BRAATHEN, A. 2008. TI: Timing of evaporite deformation and diagenesis along the Billefjorden fault zone of Spitsbergen. *Eos Transactions American Geophysical Union*, Fall Meeting Supplement, **89**(53), Abstract T21B-1965.

PICKARD, N. E., EILERTSEN, F., HANKEN, N.-M., JOHANSEN, T. A., LØNØY, A., NAKREM, H. A., NILSSON, I., SAMUELSBERG, T. J. & SOMERVILLE, I. D. 1996. Stratigraphic framework of Upper Carboniverous (Moscovian–Kasimovian) strata in Bunsow Land, central Spitsbergen: paleogeographic implications. *Norsk Geologisk Tidsskrift* **76**, 169–85.

SCHOLZ, C. & CONTRERAS, J. 1998. Mechanics of continental rift architecture. *Geology* **26**, 967–70.

SHARP, I. R., GAWTHORPE, R. L., UNDERHILL, J. R. & GUPTA, S. 2000. Fault-propagation folding in extensional settings; examples of structural style and synrift sedimentary response from the Suez Rift, Sinai, Egypt. *Geological Society of America Bulletin* **112**, 1877–99.

STEEL, R. & WORSLEY, D. 1984. Svalbard's post-Caledonian strata – an atlas of sedimentational patterns and palaeogeographic evolution. In *Petroleum Geology of the North European Margin* (eds A. M. Spencer, E. Hotter, S. O. Johnsen, A. Mork, E. Nysxther, P. Songstad & Å. Spinnangr), pp. 109–35. London: Graham & Trotman.

STEMMERIK, L. & WORSLEY, D. 2005. 30 years on – Arctic Upper Palaeozoic stratigraphy, depositional evolution and hydrocarbon prospectivity. *Norwegian Journal of Geology* **85**, 151–68.

TORSVIK, T. H., LOVLIE, R. & STURT, B. 1985. Palaeomagnetic argument of a stationary Spitsbergen relative to the British Isles (Western Europe) since Late Devonian and its bearing on North Atlantic reconstructions. *Earth and Planetary Science Letters* **75**, 278–83.

WORSLEY, D. & AGA, O. J. 1986. *The Geological History of Svalbard*. Den norske stats oljeselskap, 121 pp.

WORSLEY, D., AGDESTEIN, T., GJELBERG, J. G., KIRKEMO, K., MØRK, A., NILSSON, I., OLAUSSEN, S., STEEL, R. J. & STEMMERIK, L. 2001. The geological evolution of Bjørnøya, Arctic Norway: implications for the Barents Shelf. *Norsk Geologisk Tidsskrift* **81**, 195–234.

ZIEGLER, P. A. 1988. *Evolution of the Arctic–North Atlantic and the Western Tethys*. American Association of Petroleum Geologists, Memoir no. 43, 198 pp. Tulsa, Oklahoma.