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Middle Pennsylvanian megabreccia adjacent to the Odellfjellet Fault in Billefjorden, central Spitsbergen

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The Billefjorden Trough, a well studied onshore analogue to Carboniferous rift basins in the Ba-rents Sea, is bounded to the west by the Billefjorden Fault Zone. Structural field analysis of a mega-breccia and adjacent strata of the Minkinfjellet Formation in the hanging wall of the Odellfjellet Fault segment of the Billefjorden Fault Zone suggests that slope failure occurred along the basin-bounding fault in the Middle Pennsylvanian during the "through-going fault zones" phase of extension, i.e., during decreasing tectonic activity. Structural field data acquired in the megabreccia adjacent to the Odell-fjellet Fault using the scanline method show no relationship between fracture density and the presence and/or proximity to a major fault. In the early Cenozoic, mild reworking of Middle Pennsylvanian deposits, including plastic deformation within the megabreccia, reflects Eurekan strain partitioning and decoupling during reactivation of the Billefjorden Fault Zone. The study also reveals the occurrence of abundant WNW–ESE-striking faults in Middle Pennsylvanian sedimentary deposits, which probably formed parallel to the preexisting structural grain trending highly oblique to Grenvillian and Caledonian grains.
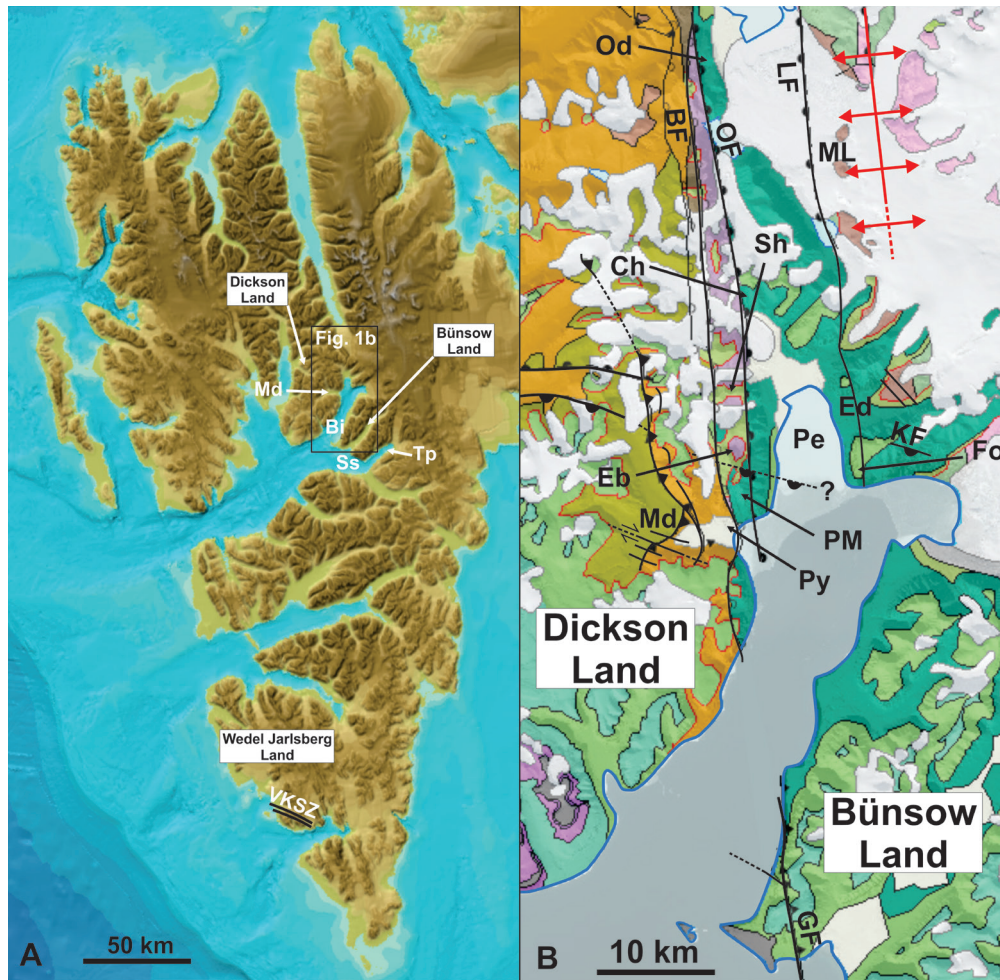
Introduction

The Billefjorden Trough in central Spitsbergen (see Fig. 1A for location) is a well-studied analogue to Carboniferous rift basins in the Barents Sea (Aakvik, 1981; Gjelberg & Steel, 1983; Gjelberg, 1983, 1984; Braathen et al., 2011). It is an asymmetric half-graben bounded to the west by a major east-dipping, long-lived fault, the Billefjorden Fault Zone (Harland et al., 1974). The main goals of the study have been to study fracture density and its relationship with the distance to the main basin-bounding normal fault,

Figure 1. (A) Topographic-bathymetric map around Spitsbergen modified after Jakobsson et al. (2012). Abbreviations: Bi – Billefjorden, Md – Mimerdalen, Ss – Sassenfjorden, Tp – Tempelfjorden, VKSZ – Vimsodden–Kosabapasset Shear Zone; (B) Geological map modified from svalbardkartet.npolar.no showing the main tectono-stratigraphic units and structures in the study area in central Spitsbergen. Abbreviations: BF – Balliolbreen Fault, Ch – Cheopsfjellet, Eb – Elsabreen, Ed – Ebbadalen, Fo – Fortet, GF – Gipshuken Fault, KF – Kampesteindalen Fault, LF – Løvehovden Fault, Md – Mimerdalen, ML – Mittag–Lefflerbreen, Od – Odellfjellet, OF – Odellfjellet Fault, Pe – Petuniabukta, PM – Pyramiden Mountain, Py – Pyramiden, Sh – Svenbrehøgda.

the Odellfjellet Fault, and to describe and characterise (stratigraphically) megabreccia outcrops located in the vicinity of the Odellfjellet Fault (see Fig. 1B for location) and discuss its implications on the tectonic evolution of the Billefjorden Trough. This contribution partly builds on previous studies in the area (Koehl et al., 2016) and refines their interpretation of structural field data. Broader implications of the study include a better understanding of tectonic and sedimentary processes along major border faults in rift basins in general.

Secondary goals have been to study potential Eurekan overprint structures within the studied rock units and briefly add to the tectonic context (fault reactivation and sediment reworking) in central Spitsbergen in the early Cenozoic by comparing our observations with those of other studies in Billefjorden (e.g., Ringset & Andresen, 1988; Harland et al., 1988; Koehl, 2021). In addition, the study reveals the presence of two dominant fault sets within the studied sedimentary deposits and discusses their relationship with known basement structural grains (inheritance) in Svalbard and the Barents Sea (e.g., N–S-trending Caledonian and WNW–ESE-trending Timanian grains).

Geological setting

The Billefjorden Trough consists of uppermost Devonian–lowermost Permian sedimentary rocks of the Billefjorden and Gipsdalen groups (Cutbill & Challinor, 1965; Cutbill et al., 1976; Dallmann et al., 1999) deposited unconformably over Proterozoic basement folded and thrusted during the Caledonian Orogeny (Gee et al., 1994; Witt-Nilsson et al., 1998) and over Devonian sedimentary rocks of the Mimerdalen Subgroup and Wood Bay Formation deposited during the collapse of the Caledonide Orogen (Friend et al., 1966; Friend & Moody-Stuart, 1972; Murascov & Mokin, 1979; Piepjohn & Dallmann, 2014; Fig. 2). The Billefjorden Trough is an asymmetric half-graben bounded by major, east-dipping, normal-fault segments of the Billefjorden Fault Zone in the west (e.g., Balliolbreen, Odellfjellet, and Gipshuken faults; Harland et al., 1974).

At the base of this rift basin, uppermost Devonian–Mississippian strata of the Billefjorden Group (Playford, 1962, 1963; Lindemann et al., 2013; Marshall et al., 2015) consisting of fluvial clastic- and coal-rich sedimentary rocks (Fig. 2) are thought to have been deposited broadly during a period of tectonic quiescence (McCann & Dallmann, 1996; Braathen et al., 2011; Smyrak-Sikora et al., 2018) or within widespread mini-basins (Cutbill & Challinor, 1965; Cutbill et al., 1976; Aakvik, 1981; Gjelberg, 1984; Koehl & Muñoz-Barrera, 2018).

In the Pennsylvanian, sediment deposition was localised east of the Billefjorden Fault Zone within the Billefjorden Trough. This was accompanied by kilometre-scale normal faulting along the Billefjorden Fault Zone and deposition of shallow-marine sediments of the Gipsdalen Group (e.g., Steel & Worsley, 1984; Braathen et al., 2011; Smyrak-Sikora et al., 2018; Fig. 2). These included (1) upper Serpukhovian red-grey beds of the Hultberget Formation deposited possibly as part of an alluvial fan (Playford, 1962, 1963; Cutbill et al., 1976; Johannessen, 1980; Gjelberg & Steel, 1981; Johannessen & Steel, 1992; Smyrak-Sikora et al., 2018), (2) Lower Pennsylvanian deposits of the Ebbadalen Formation including grey, yellow and red sandstone-conglomerate interbedded with green-grey shale in the lower part, and dolomite units interfingering with gypsum-anhydrite and dolomite-limestone in the upper part (Holliday & Cutbill, 1972; Johannessen, 1980; Johannessen & Steel, 1992; Braathen et al., 2011), (3) Middle Pennsylvanian limestones, dolomites, evaporites and karst/dissolution breccias of the Minkinfjellet Formation deposited in a relatively deeper marine system (McWhae, 1953; Cutbill & Challinor, 1965; Lønøy, 1995), and (4) uppermost Middle Pennsylvanian–lower Permian carbonate and evaporite deposits of the Wordiekammen and Gipshuken formations (Gee et al., 1952; Cutbill & Challinor, 1965; Keilen, 1992; Ahlborn & Stemmerik, 2015) deposited in a marine environment under limited tectonic activity (Braathen et al., 2011; Maher & Braathen, 2011). The Hultberget, Ebbadalen and Minkinfjellet formations are believed to reflect a (early) syn-rift tectonic setting in the Billefjorden Trough, whereas the Word kammen Formation and Gipshuken Formation are commonly associated with late-rift and post-rift settings, respectively (Cutbill & Challinor, 1965; Steel & Worsley, 1984; Braathen et al., 2011).

Stratigraphic units			Stratigraphic chart	Period/Epoch/Stage	
Gipsdalen Group	Gipshuken Fm			Cisuralian	
	Wordiekammen Fm			Gzhelian	Pennsylvanian
				Kasimovian	
	Minkinfjellet Fm	Fortet Mbr	Te Fo	Moscovian	
		Terrierfjellet Mbr			
		Carronelva Mbr			
	Ebbadalen Fm	Odellfjellet Mbr / Trikolorfjellet Mbr	Tr Od	Bashkirian	
		Ebbaelva Mbr			
	Hultberget Fm			Serpukhovian	Mississippian
Billefjorden Group	Mumien Fm	Birger Johnsonfjellet Mbr		Visean	
		Sporehøgda Mbr			
	Hørbyebreen Fm	Hoelbreen Mbr		Tournaisian	
		Triungen Mbr			
Andrée Land Group				Upper	Devonian
	Mimerdalen Subgroup			Middle	
	Wood Bay Fm			Lower	
	Red Bay Group		?		
	Siktefjellet Group		?	upper Silurian	
			? Scale break		
	Basement		+	Precambrian	

Legend

- Sandstone–conglomerate
- Sandstone and shale (redbeds)
- Coal seams and coaly shales
- Carbonate-dominated
- Dissolution breccias
- Evaporites
- Basement rocks

Figure 2. Litho-stratigraphic chart of late Paleozoic (uppermost Devonian–lower Permian) sedimentary rocks of the Billefjorden and Gipsdalen groups in central Spitsbergen. The chart is based on descriptions by Gee et al. (1952), McWhae (1953), Playford (1962), Cutbill & Challinor (1965), Holliday & Cutbill (1972), Cutbill et al. (1976), Johannessen (1980), Aakvik (1981), Gjelberg & Steel (1981), Lønøy (1981, 1995), Gjelberg (1983, 1984), Johannssen & Steel (1992), Dallmann et al. (1999), and Braathen et al. (2011).

The stratigraphic unit of interest to this study, the Minkinfjellet Formation, is divided into three members. The lower member (Carronelva Member) is composed of greenish to yellowish, very fine- to fine-grained sandstone, dolomite and evaporite (Cutbill & Challinor, 1965; Lønøy, 1981, 1995), whereas the upper member (Terrierfjellet Member) is dominated by limestone, dolomite and evaporite (Lønøy, 1981, 1995; Dallmann et al., 1999). The uppermost Fortet Member consists of relatively well sorted dissolution breccias (McWhae, 1953; Lønøy, 1981; Dallmann, 1993).

In the Paleocene, the opening of the Labrador Sea and Baffin Bay (Chalmers & Pulvertaft, 2001; Oakey & Chalmers, 2012) resulted in Eurekan contraction-transpression in Svalbard, during which east-verging thrusts formed in the West Spitsbergen Fold-and-Thrust Belt (Harland, 1969; Harland & Horsfield, 1974; Craddock et al., 1985; Dallmann et al., 1993) and thick sediment successions were deposited in the Central Tertiary Basin (Larsen, 1988; Petersen et al., 2016). In central Spitsbergen, local faults like the Billefjorden Fault Zone were mildly inverted as shown by the 200 metres top-west reverse offset of the Wordikammen and Gipshuken formations along the Gipshuken Fault (Harland et al., 1974; Ringset & Andresen, 1988; Dallmann et al., 2004; Bælum & Braathen, 2012).

Methods

The study presents field structural measurements and observations of brittle faults and bedding surfaces in the hanging wall of the Odellfjellet Fault in Pyramiden acquired in 2015 (Figs. 3, 4, 5, & 6). Measurements were taken in a megabreccia unit located just east of the presumed trace of the east-dipping Odellfjellet Fault, and within adjacent ESE-dipping strata of the Minkinfjellet Formation farther east for comparison.

Structural measurements in the megabreccia, which is presumed to be located in the damage zone of the Odellfjellet Fault, were acquired using the scanline method (Priest & Hudson, 1981) to assess fracture density (number of fractures per metre) and orientation with regards to major fault zones. The scanline trends E–W, i.e., perpendicular to the Odellfjellet Fault, and the results are shown in Fig. 3D. Strike and dip of fractures in the damage zone of the Odellfjellet Fault were used to infer the main stress orientation during rifting. Structural field measurements are plotted in lower-hemisphere, equal-area, Schmidt stereonets.

High-resolution versions of the figures can be found at https://doi.org/10.18710/UFUYIC and the whole dataset of outcrop photographs at https://doi.org/10.18710/NARMZS on DataverseNO. In addition, this electronic dataset includes photographs of the entire beach transect we analysed as it was in August 2015, starting from the megabreccia in the west to ESE-dipping strata of the Minkinfjellet Formation in the east.
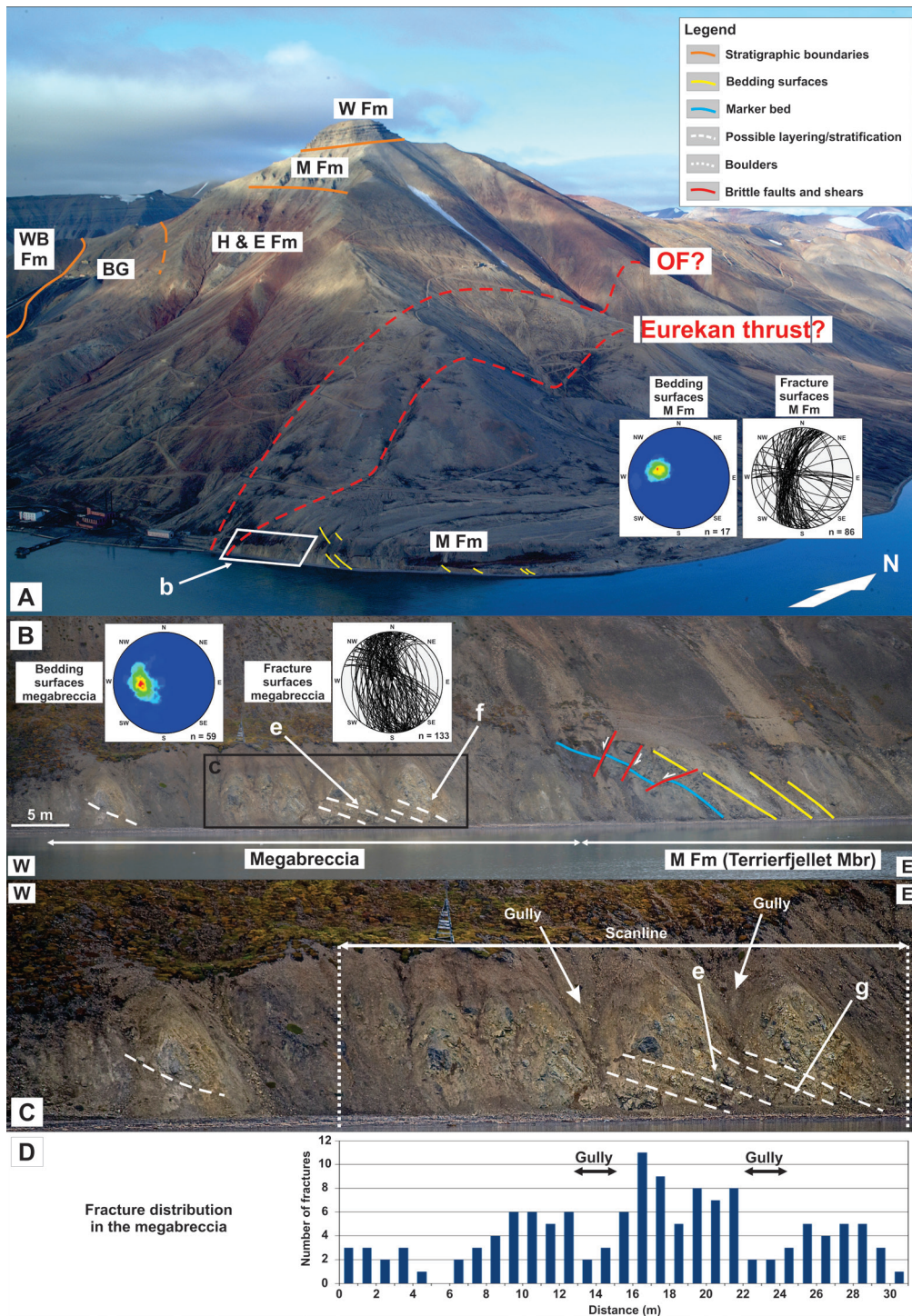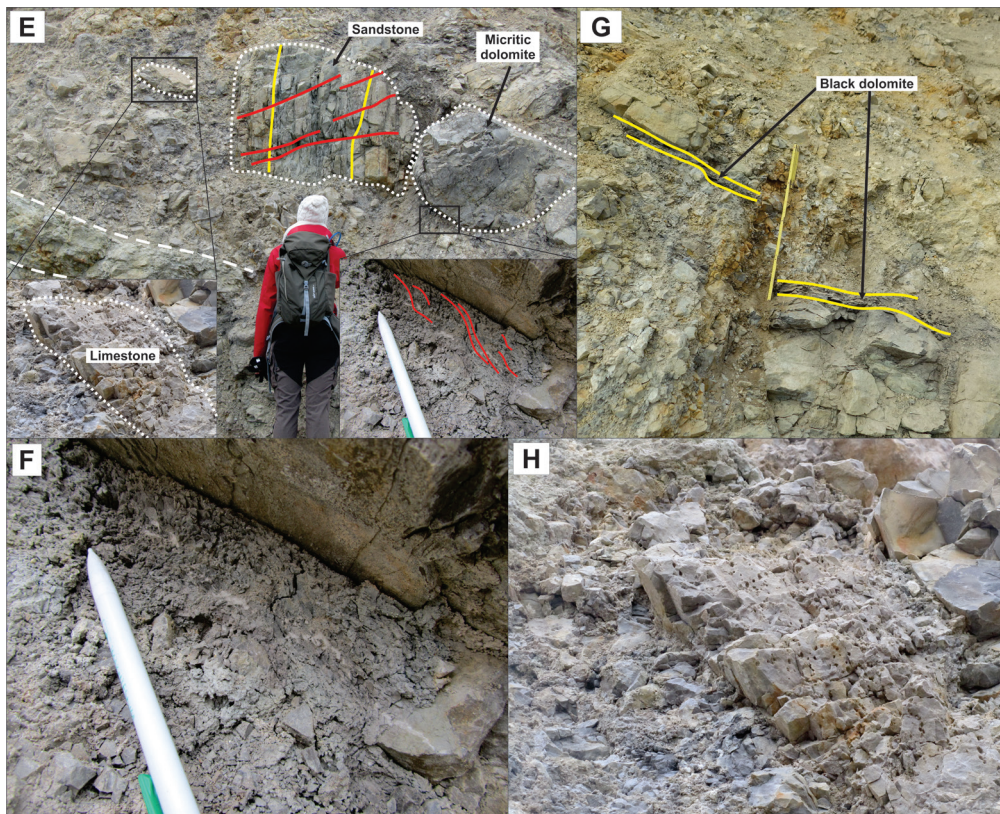
Figure 3. (A) Aerial photograph of the Pyramiden Mountain viewed from the southeast (see Fig. 1B for location) showing major stratigraphic units and the location of the megabreccia, and of the Odellfjellet Fault segment of the Bille-fjorden Fault Zone and a possible Eurekan thrust. Schmidt stereonets show bedding and fracture surfaces, respectively, as gradient shader and great circles. Photo by Åsle Strøm. Abbreviations: BG – Billefjorden Group, H & E Fm – Hultberget and Ebbadalen formations, M Fm – Minkinfjellet Formation, OF – Odellfjellet Fault, W Fm – Wordie-kammen Formation, WB Fm – Wood Bay Formation. (B) Panorama showing the megabreccia east of Pyramiden with possible stratification/layering, and the relationship of the megabreccia with nearby ESE-dipping strata of the Minkin-fjellet Formation to the east. Schmidt stereonets show bedding and fracture surfaces, respectively, as gradient shader and great circles. Bedding surfaces are from within the boulders, whereas fracture surfaces are both from the matrix and the boulders. See legend in (A). (C) Zoom in the megabreccia outcrop showing possible stratification (dashed white lines) and the location and extent of the scanline of structural measurements, and of two topographical gullies. See legend in (A) and location in (B). (D) Fracture density graph extracted from the scanline in the megabreccia showing the variations in the number of fractures in one-metre intervals (total of 31 intervals). Note the correlation between the two fracture density lows within the megabreccia and two topographic (erosional) gullies. Location of the scanline in (C). (E) Outcrop photograph showing boulders (dotted white lines) of greenish–yellow sandstone (Carronelva Member of the Minkinfjellet Formation) and of limestone (with dissolution features) and micritic dolomite (Terrierfjellet Member of the Minkinfjellet Formation) in the megabreccia. Note the Z-shaped shear fabrics (red lines) below the boulder of micritic dolomite (lower right inset) and the high dip angle of bedding surfaces and low dip angle of fractures surfaces within the boulder of greenish–yellow sandstone. See legend in (A) and location in (B). (F) Zoom in Z-shaped structures below large boulders in the matrix of the megabreccia. (G) Outcrop photograph of black bituminous dolomite possibly belonging to the Carronelva–Terrierfjellet members of the Minkinfjellet Formation within the megabreccia with possible primary bedding surfaces (yellow lines). Vertical yellow wooden metre stick for scale. See legend in (A) and location in (C). (H) Zoom in a limestone boulder within the megabreccia showing dissolution holes.

Figure 4. (A) Interpreted and (B) uninterpreted photograph of part of the megabreccia unit showing the subtle layering consisting of alignments of the long axes of boulders and/or the long edges of boulders within the megabreccia.
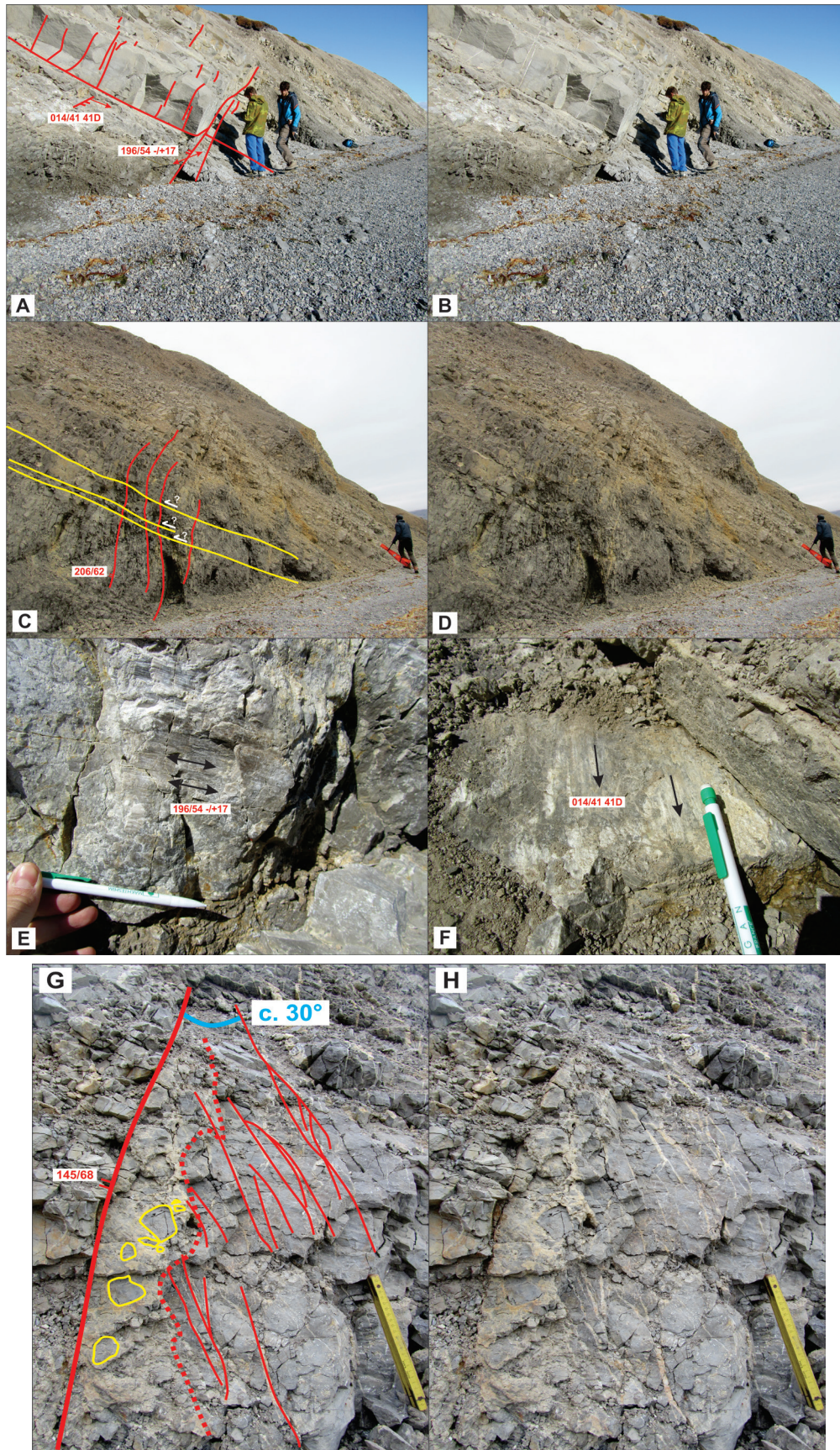
Figure 5. Examples of fracture geometries in the study area, including planar (A, B) and undulating/bending fractures (C, D), some of which display fault striations suggesting strike-slip to dip-slip sense of shear (E, F) and some involving calcite cement and calcite-filled crackle breccia (G, H). Note the undulating character and S-shaped geometry of subvertical, NNE–SSW-striking fractures across bedding-parallel fracture surfaces, thus suggesting a formation of the former as shear fractures during top-west contraction (C, D). Also note the c. 30° angle between major fractures associated with crackle breccia and swarms of minor calcite-filled fractures, which suggests a formation as tensile cracks (G, H).
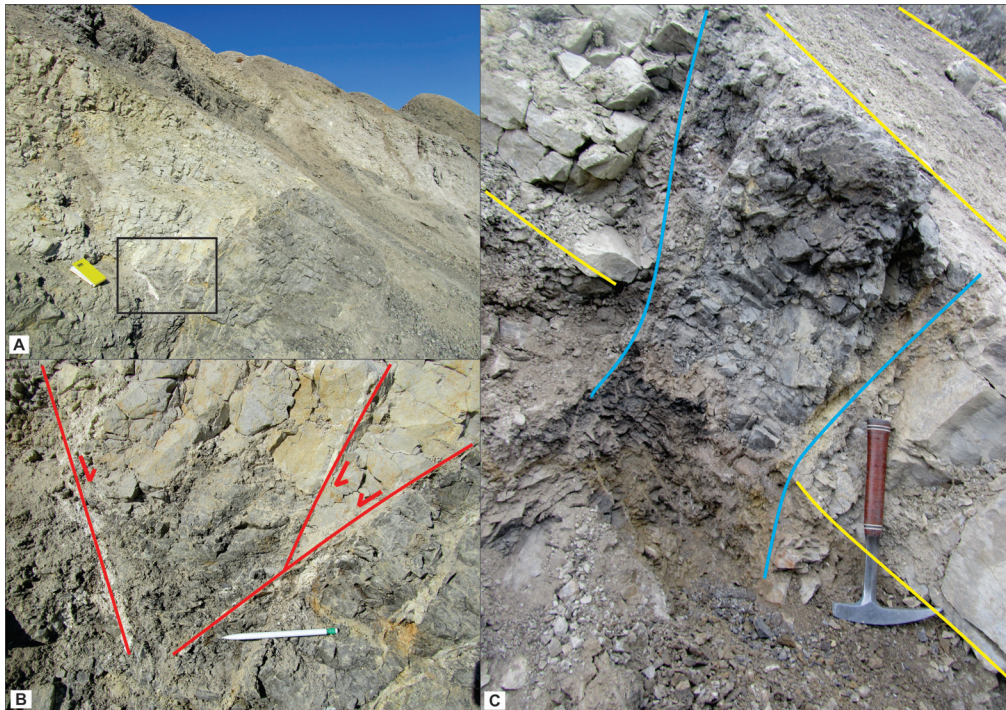
Figure 6. (A) Field photograph and (B) zoom in decimetre-scale graben structures displaying V-shaped geometries and possibly representing V-structures related to cave roof collapse during the dissolution of evaporites at depth. (C) Abrupt interuption of ESE-dipping bedding surfaces (yellow lines). Dark micritic dolomite is found seemingly as a column (blue lines) within a bed of light-coloured limestone. The micritic dolomite shows limited deformation, including mild brecciation to the left, but is massive with a few minor fractures showing no offset in the central and right parts of the potential pipe, which suggest either limited or no transport of the dolomite.

Results

Lithological description of the megabreccia

We investigated ESE-dipping limestone-dominated strata of the Minkinfjellet Formation and a chaotic, heterogeneous, poorly sorted, possibly stratified, *c.* 30 metre-wide conglomeratic unit (Fig. 3B) east of Pyramiden and referred to as megabreccia due to the size (>1 metre) of some of the boulders (see Figs. 1B & 3A for location). The megabreccia consists of a fine-grained clayey, calcareous matrix wrapped around angular clasts of various size, ranging from pebbles to boulders. The matrix is partly lithified (small blocks disintegrating upon pick-up), but does not seem to contain any fossils. In places, the fine-grained clayey matrix shows Z-shaped sigmoidal features below some large boulders (Fig. 3E, F). These features are subtle but discrete surfaces that resemble ductile fabrics within shear zones in that they represent small deformation surfaces seemingly bending partly consolidated blocks of matrix. The surfaces do not show any striation.

Clasts within the megabreccia display four discrete lithologies. First, a yellowish to greenish, very fine to fine-grained sandstone (Fig. 3E), which is abundant within the Carronelva Member of the Minkinfjellet Formation (Lønøy, 1981, 1995; Eliassen & Talbot, 2003). Second, black bituminous dolomite and limestone (Fig. 3G) that are relatively common in the Carronelva and Terrierfjellet members of the Minkinfjellet Formation (Lønøy, 1981), e.g., in Bünsow Land (Gobbett, 1963; Lønøy, 1995) and along the eastern shore of Petuniabukta (Fig. 1B). Third and fourth, micritic dolomite and limestone displaying millimetre- to centimetre-scale rounded holes possibly representing dissolution features (Fig. 3E, H), which most likely belong to the upper part of the Minkinfjellet Formation because of their close similarities to dominant lithologies within adjacent, gently ESE-dipping strata of the Terrierfjellet

Member of the Minkinfjellet Formation in the east (Fig. 3B; Koehl et al., 2016) and with contemporaneous rocks in Bünsow Land (Gobbett, 1963; Lønøy, 1995). This suggests that the megabreccia is contemporaneous or younger than the Minkinfjellet Formation. However, no clasts of the overlying Wordiekammen Formation (Ahlborn & Stemmerik, 2015) were encountered in the megabreccia, which possibly implies that it formed before lithification of the Wordiekammen Formation.

Potential internal layering within the megabreccia appears as subtle alignments of the long axes of blocks and alignments of the long edges of boulders (Figs. 3B, C & 4). This may indicate a formation in several pulses or episodes, and the high level of mixing of clasts within the megabreccia suggests that boulders from both the lower and the upper parts of the Minkinfjellet Formation were reworked simultaneously (Fig. 3E, G).

The megabreccia is located 15–20 metres west of outcrops consisting of gently ESE-dipping strata of the (upper part of the) Terrierfjellet Member of the Minkinfjellet Formation. The imaginary prolongation of these ESE-dipping strata to the west appears to extend above the megabreccia outcrop (Fig. 3B) and the megabreccia boulders all consist of lithified material from the Minkinfjellet Formation (Fig. 3E, G; Gobbett, 1963; Lønøy, 1981, 1995; Eliassen & Talbot, 2003). Therefore, if the megabreccia is depositional, it is possibly contemporaneous with and part of the stratigraphy of the Minkinfjellet Formation.

Fracture and bedding surfaces in strata of the Minkinfjellet Formation and the megabreccia

The scanline taken in the megabreccia shows an overall increase of fracture density towards the centre of the megabreccia, including three peaks with high fracture density (≥4 fractures per metre) separated by two lows (<4 fractures per metre; Fig. 3D and Electronic supplement 1). The two lows correlate with topographic gullies and limited outcrop exposures (Fig. 3B, C). From the centre of the megabreccia outcrop, fracture density decreases both westwards towards the presumed trace of the Odellfjellet Fault and eastwards towards ESE-dipping strata of the Minkinfjellet Formation (Fig. 3D). In both directions, fracture density decrease is accompanied by gradually more limited outcrop exposures and outcrops of lower quality (Fig. 3B, C and Electronic supplement 1).

Structural measurements in gently ESE-dipping sedimentary strata of the upper part of the Minkinfjellet Formation east of the megabreccia show two dominant sets of discrete, planar to undulating (e.g., S-shaped, subvertical, NNE–SSW-striking) fracture surfaces striking dominantly N–S to NNE–SSW with *c.* 50–80° dip angles and subsidiarily WNW–ESE to NW–SE with dip angles in the range of *c.* 70–90° (Fig. 5A–D). These fractures are intra- to inter-strata, though they seem to die out relatively quickly upwards and downwards in the stratigraphy. A handful of fractures displayed striations suggesting strike-slip to dip-slip movements (Fig. 5E, F). However, the low number of fault lineations and uncertainties in the sense of shear do not allow us to discuss the kinematic history confidently. The two fracture sets appear to cross-cut one another, thus suggesting a coeval formation. However, the limited quality and/or extent of the outcrops and the limited number of instances in which the cross-cutting relationships were observed call for caution. Some of the fractures involve crackle breccia consisting of angular to sub-rounded clasts of limestone and micritic dolomite in a calcite cement showing limited to no offset (Fig. 5G, H), while others form mini-graben structures with tens of centimetre- to metre-scale normal offsets of the stratigraphy (see offset marker bed — blue line in Fig. 3B). The undulating to planar geometries of the fractures, the arrangement of some fractures into swarms striking oblique (*c.* 30°) to major fracture surfaces, and the bending of some fractures across bedding surfaces suggest a formation both as shear and tensile cracks (Fig. 5A–D, G, H; Einstein & Dershowitz, 1990).

Similar fracture sets were recorded in the megabreccia, both in the matrix and in boulders, where N–S- to NNW–SSE-striking fractures show a broader spread in both strike (NNW–SSE to NNE–SSW) and dip angle (*c.* 40–90°; Fig. 3B), whereas WNW–ESE- to NW–SE-striking fractures show only minor or no change in strike and dip range (65–90° instead of 70–90°). Knowing that the fractures within the megabreccia's boulders do not propagate into the matrix (i.e., formation of the fractures prior to formation of the boulders), the presence of similarly striking fracture sets both within the megabreccia and adjacent strata of the Minkinfjellet Formation suggests a common tectonic history for these stratigraphic units.

Bedding surfaces within megabreccia boulders display significant variations in trend (dominantly NE- to SE-dipping) and dip angle (*c.* 20–60°; Fig. 3B), whereas they consistently dip (*c.* 30–40°) gently to the east-southeast in adjacent strata of the Minkinfjellet Formation (Fig. 3A). Such variations in trend, strike and dip angle for bedding surfaces and N–S- to NNE–SSW-striking fractures but not for WNW–ESE-striking fractures suggest that, during transport, boulders experienced rotation along an axis (sub-)parallel to the trend of ESE-dipping bedding surfaces and to the strike of N–S- to NNE–SSW-striking fractures, and (sub-)orthogonal to WNW–ESE- to NW–SE-striking fractures, i.e., most likely along a (N–S- to) NNE–SSW-trending axis.

Discussion

Relationship between fracture density and presence or proximity to a major fault

Both westwards and eastwards, fracture density decreases (i.e., away from the centre of the megabreccia outcrop) and the two density lows within the megabreccia might be related to outcrop collapse in areas with relatively higher degree of fracturing (perhaps reflecting the presence of major faults). However, the lack of fault rocks such as fault gouge or cataclasite, and lack of consistent fracture density increase on the edges of density lows and areas with lower fracture density suggest otherwise. The Odellfjellet Fault is believed to be a major fault with km-scale displacement (i.e., large amount of clast transport; Braathen et al., 2011). Therefore, if the megabreccia were to correspond to the fault core zone, the clasts within the megabreccia should be well-sorted, rounded to sub-rounded, and major grain cominution should be observed. None of this is the case. Since apparent fracture density highs seem to match outcrop availability and quality, it is more likely that low fracture density reflects a higher degree of erosion of the studied megabreccia outcrop, whereas high fracture density occurs in well (better) preserved portions of the outcrop (Fig. 3C, D and Electronic supplement 1). Despite the continuous character of the base of the megabreccia outcrop, there is no obvious relationship between fracture density and the presence or proximity to major faults like the nearby Odellfjellet Fault. Such a relationship should appear in the areas with sufficient outcrops (e.g., overall increase to fracture density from east to west instead of largest fracture density in the central part of the megabreccia; Fig. 3D). Should the gullies be related to large faults, such faults would appear at the base of the outcrop, which is continuous, and the fracture density should increase accordingly towards the edges of the gullies. None of this is the case.

Origin of the megabreccia east of Pyramiden

Boulders within the megabreccia east of Pyramiden originate from both the Carronelva and the Terrierfjellet members of the Minkinfjellet Formation (Gobbett, 1963; Lønøy, 1981, 1995; Eliassen & Talbot, 2003) and appear to be located stratigraphically below the upper(most) part of the Terrierfjellet Member of the Minkinfjellet Formation, which consists of ESE-dipping strata (Fig. 3A, B). No clasts of

the Wordiekammen Formation were encountered in the megabreccia, which suggests that the mega-breccia was deposited before lithification of the Wordiekammen Formation, i.e., most likely during the Middle Pennsylvanian, shortly after lithification of the lower part of the Terrierfjellet Member of the Minkinfjellet Formation.

Bedding and fracture surfaces within boulders constituting the megabreccia east of Pyramiden show significant variations and include sub-horizontal brittle faults and sub-vertical bedding surfaces (Fig. 3A, B, E). Such variations in trend, strike and dip imply that both bedding and fracture surfaces experienced significant rotation during transport, possibly when the blocks were detached, fell and/or slid and were deposited, most likely along a (N–S- to) NNE–SSW-trending axis. If the megabreccia were to represent a recent (Quaternary) landslide, bedding and fracture surfaces within boulders of the mega-breccia would show rotation along an axis (sub-) parallel to the current topography, i.e., along an E–W-trending axis. This further supports the interpretation that this megabreccia is part of the stratigraphy of the Minkinfjellet Formation.

In Billefjorden, the dissolution of evaporites (e.g., of the Ebbadalen and Minkinfjellet formations) at depth is thought to be responsible for the formation of a relatively well-sorted karst breccia of the Fortet Member of the Minkinfjellet Formation, e.g., in Fortet (Fig. 1B; McWhae, 1953; Dallmann, 1993; Dallmann et al., 1999; Eliassen & Talbot, 2003, 2005; Nordeide, 2008). Such a breccia occurs as pipes and as stratabound deposits interbedded with undeformed carbonates of the Minkinfjellet Formation (Eliassen & Talbot, 2005). It is possible that the boulders of Minkinfjellet Formation in the megabreccia east of Pyramiden represent a karst breccia (Koehl et al., 2016, fig. 4B). However, the megabreccia shows a poorly sorted (several metres' wide boulders to microscopic matrix), polymictic facies (Fig. 3B) that is significantly different from both columnar and stratabound, monomictic, relatively well-sorted karst breccias, which are generally dominated by 1–10 cm-wide clasts and show reverse grading, i.e., increasing clast size upwards (Eliassen & Talbot, 2005). Moreover, the high level of mixing of clasts from the lower (Carronelva Member) and upper part (Terrierfjellet Member) of the Minkinfjellet Formation suggests a more abrupt trigger mechanism for the deposition of the megabreccia. Notably, clasts from lower stratigraphic intervals (e.g., greenish-yellow sandstone of the Carronelva Member) could not have been moved upwards if the megabreccia formed as a karst breccia.

Although the megabreccia does not conform to typical dissolution breccias in Billefjorden, it should be noted that dissolution of gypsum and formation of dissolution breccia are thought to occur at depth farther east, below strata of the Minkinfjellet Formation adjacent to the megabreccia. This is suggested by the presence of fractures showing no to limited offset filled with crackle breccia (see Fig. 5G, H), which is typical in areas where gypsum dissolution occurred, e.g., in eastern Billefjorden (Eliassen & Talbot, 2005), and by abrupt but local interruptions of bedding in places by small faults, which might define V-structures reflecting cave roof-collapse (Fig. 6A–C). However, the rocks within the potential V-structures are not brecciated (Fig. 6A–C), which is not in line with cave roof collapse. Therefore, although an interpretation of the megabreccia as a stratabound dissolution breccia might seem possible, it is not the interpretation most favoured by our data.

The poorly sorted megabreccia is also very different from relatively well sorted, pebbly, Pennsylvanian sedimentary breccias described between the Odellfjellet and Balliolbreen faults in Pyramiden (Braathen et al., 2011). Furthermore, if the megabreccia represented a reworked fault breccia, it would show, at least in places, blocks of cataclastic fault rock and/or fault gouge and the planar surfaces within the megabreccia would dip just as steeply as the fault. This is not the case.

Another possiblity is that the investigated megabreccia formed as a syn-tectonic, fault-growth deposit during Carboniferous normal faulting along the Odellfjellet Fault (Koehl et al., 2016, fig. 4A). Such an interpretation may explain the presence of boulders of greenish-yellow sandstone and

bituminous dolomite-limestone originating from the footwall and/or hanging wall of the fault, and the apparent rotation of boulders of the megabreccia along a (N–S- to) NNE–SSW-trending axis by slope failure along the Odellfjellet Fault paleotopography. Boulders cross-cut by N–S- to NNE–SSW-striking fractures (e.g., Fig. 3E) may have fallen and/or slid into the hanging wall of the Odellfjellet Fault and experienced rotation along a (N–S- to) NNE–SSW-trending axis, i.e., (sub-) parallel to the fractures strike, i.e., mass wasting deposit (Fig. 3A, B). This interpretation explains most of our observations. First, it accounts for the broad variation in dip angle of N–S-striking fractures within the megabreccia (*c.* 40–90°) and the difference in dip-angle range with similarly striking fractures within adjacent ESE-tilted strata of the Minkinfjellet Formation (*c.* 50–80°). Second, it explains the much smaller variations in dip angle of WNW–ESE-striking fractures within boulders of the megabreccia (*c.* 65–90°) and a smaller difference in dip angle range with similarly striking fractures in adjacent ESE-tilted strata of the Minkinfjellet Formation (*c.* 70–90°) since these were oriented (sub) orthogonal to the axis of rotation during fall (Fig. 3A, B.). Third, it provides a reasonable explanation for the significant variations in trend (NE- to SE-dipping) and dip angle (20–60°) of bedding surfaces within the megabreccia (Fig. 3A, B). This interpretation is supported by the location of the megabreccia in the proximal hanging wall of the east-dipping Odellfjellet Fault (Fig. 3A) and by the presence of Z-shaped sigmoidal shear fabrics in the megabreccia's clayey matrix below some of the boulders (Fig. 3E), which possibly correspond to soft-sediment deformation features reflecting the sliding and/or fall and (re-) deposition of blocks of Minkinfjellet Formation into a matrix of unconsolidated sediments, e.g., in shallow water. The potential internal, ESE-dipping stratification within the megabreccia (i.e., parallel to stratification within the Minkinfjellet Formation adjacent to the megabreccia; Fig. 3B) suggests that the megabreccia was deposited through several successive episodes of slope failure (though relatively quickly because it sits within a discrete stratigraphic level of the hangingwall section), which is reasonable considering the hundreds of metre-scale normal movement inferred along the Billefjorden Fault Zone during Pennsylvanian times (e.g., Johannessen & Steel, 1992; Braathen et al., 2011). The high level of mixing of the megabreccia may be explained by mixing of boulders both from the footwall and hanging wall, with some boulders may from the hanging wall remaining partly attached to the footwall at fault asperities. This is supported by the gently curving geometry of the Odellfjellet Fault in map view (Dallmann et al., 2004). Yet, another possibility might be a composite between a syn-tectonic growth deposit and a dissolution breccia. Based on the evidence favouring a formation as a fault-growth deposit (previous paragraph) and on hints of evaporite dissolution at depth (e.g., Fig. 6), it is possible to suggest a formation of the megabreccia as a fault-growth deposit in the Middle Pennsylvanian, and partial reworking as a stratabound dissolution breccia. The main arguments against reworking due to evaporite dissolution are (1) the high level of mixing of the clasts of all members of the Minkinfjellet Formation, (2) the absence of reverse grading, and (3) the size of many of the clasts (boulders ≥1 m wide) in the megabreccia.

Implications for post-Caledonian extension in central Spitsbergen

Such large megabreccia deposits are common in late-rift sedimentary deposits and generally reflect steepening (in time) of the main fault and resulting slope failure (critical wedge taper; e.g., Blair & McPherson, 1994; Andric et al., 2018) once the dip angle of the slope is high enough. In addition, the studied megabreccia did not contain any clasts of formations stratigraphically older or younger than the Minkinfjellet Formation. This indicates that younger formations were not yet lithified and that older formations were not exposed or not uplifted high enough in the footwall of the Odellfjellet Fault to be involved in slope failure. This suggests that the Minkinfjellet Formation and associated megabreccia east of Pyramiden were probably deposited during reduced fault activity, during a late episode of normal faulting along the Odellfjellet Fault in the Middle Pennsylvanian (late–latest syn-rift), i.e., during the "through-going fault zones" phase of Gawthorpe & Leeder (2000). This interpretation contrasts with that of Braathen et al. (2011) who ascribed the Minkinfjellet Formation to the syn-rift stage (equivalent to the "linkage and interaction" phase of Gawthorpe & Leeder, 2000).

A deposition of the Minkinfjellet Formation and associated megabreccia east of Pyramiden during the "through-going fault zones" phase of Gawthorpe & Leeder (2000) is also supported by the overall thickness variations of the Minkinfjellet Formation in the Billefjorden area (Dallmann, 1993). The Minkinfjellet Formation gradually thins westwards towards the Billefjorden Fault Zone, thus suggesting passive infill in a late-rift setting (i.e., "through-going fault zones" phase of Gawthorpe & Leeder, 2000) with limited tectonic activity along a few major faults, such as the Odellfjellet Fault (present study), the Gipshuken Fault segment of the Balliolbreen Fault in southern Billefjorden (Harland et al., 1974; Ringset & Andresen, 1988; Dallmann et al., 2004; Dallmann, 2015; see Fig. 1B for location), and the Løvehovden Fault (Braathen et al., 2011; Maher & Braathen, 2011; see Fig. 1B for location).

Alternatively, the lack of paleotopography along the Odellfjellet Fault in Pyramiden might be related to fault relay (Braathen et al., 2011). However, the presence of a fault relay zone at this locality during formation of the megabreccia should be reflected in the rotation of the fracture and bedding surfaces within the megabreccia boulders with sedimentary input (clasts) coming from the north. This does not seem to be the case since both the intra-boulder fractures and bedding surfaces show a simple rotation along a NNE–SSW-trending axis. Based on the isochore and isopach maps by Braathen et al. (2011), the potential relay between the Odellfjellet and Balliolbreen faults was mostly active during deposition of the Ebbadalen Formation in the Early Pennsylvanian, i.e., prior to the formation of the megabreccia in the late Middle Pennsylvanian.

Potential Eurekan reactivation of the Billefjorden Fault Zone and reworking of the megabreccia

In the area of Pyramiden, Elsabreen and Svenbrehøgda (and all the way to Cheopsfjellet), the top-basement unconformity and sedimentary strata of the Ebbadalen Formation (Braathen et al., 2011) and of the Minkinfjellet Formation (Fig. 3A; see also Koehl et al., 2016) dip gently to the east-southeast to southeast, and graben structures within the Minkinfjellet Formation just east of Pyramiden (Fig. 3B) are tilted east-southeastwards to southeastwards. Braathen et al. (2011) ascribed this southeastward to east-southeastward dip-tilt and displacement gradients along the Balliolbreen and Odellfjellet faults to the presence of a SE- to SSE-dipping relay zone between the Balliolbreen and Odellfjellet faults in Pyramiden–Elsabreen, possibly including the Pyramiden Fault (Smyrak-Sikora et al., 2018). However, the dip of strata of the Ebbadalen Formation does not appear to change across (i.e., because of) this fault (Smyrak-Sikora et al., 2018, fig. 7). Should the relay fault have been active at the time of deposition of the Ebbadalen Formation (Braathen et al., 2011), bedding surfaces of the associated deposits must have been somewhat tilted towards the normal (relay) fault. The lack of change of strike and dip across the postulated relay fault suggests that the east-southeastern dip of the sedimentary strata in the area is related to other factors.

The ESE-dip of Pennsylvanian sedimentary strata in Pyramiden, Elsabreen and Svenbrehøgda might be related to the actual strike of fault segments of the Billefjorden Fault Zone being NNE–SSW instead of N–S to NNW–SSE (see stereonets in Fig. 3A showing the dominance of NNE–SSW-striking fracture within the Minkinfjellet Formation), and to tilting of the strata during Eurekan inversion of NNE–SSW-striking faults segments of the Billefjorden Fault Zone (and minor folding; Fig. 7). This is supported by a similar ESE-dip of uppermost Devonian–Mississippian sedimentary strata of the Billefjorden Group, by the dominant top-WNW sense of shear of early Cenozoic Eurekan contractional duplexes and thrust faults within this stratigraphic unit in Pyramiden (Koehl, 2021), and by the presence of an Eurekan thrust in the area along the eastern slope of Pyramiden, Mumien and Svenbrehøgda (Dallmann et al., 2004).
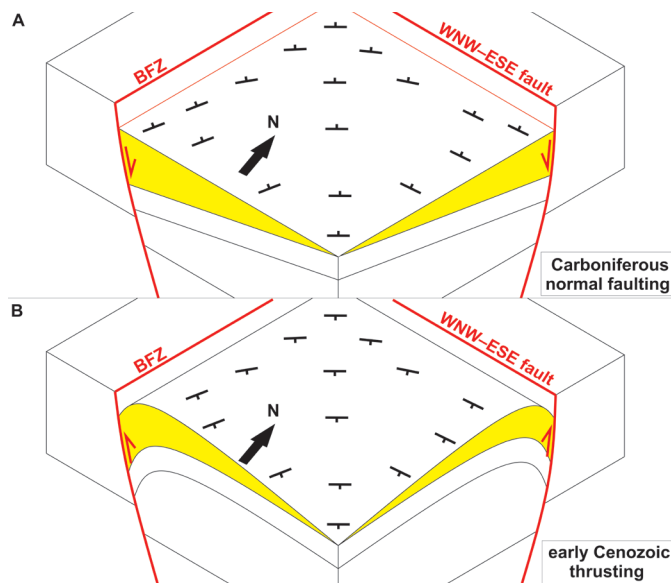
Figure 7. Schematic sketches showing (A) tilting of late Paleozoic sedimentary strata along coeval ESE- and SSW-dipping normal faults (red lines), and (B) back-tilting overall to the east-southeast due to inversion of post-Caledonian normal faults during early Cenozoic Eurekan deformation. Abbreviation: BFZ – Billefjorden Fault Zone.

Furthermore, it is possible that Z-shaped shears within the clayey matrix of the megabreccia east of Pyramiden (Fig. 3E) actually formed during top-west to top-WNW early Cenozoic Eurekan deformation (Fig. 7). Strain partitioning and decoupling in early Cenozoic times may have resulted in plastic deformation within sedimentary layers made up of similarly weak material, e.g., coals-coaly shales of the Billefjorden Group in Odellfjellet (Koehl & Muñoz-Barrera, 2018) and Pyramiden (Koehl, 2021), and evaporites of the Ebbadalen Formation in eastern Billefjorden (Ringset & Andresen, 1988; Harland et al., 1988) and of the Gipshuken Formation in Sassenfjorden–Tempelfjorden (Koehl, 2021). Noteworthy, potential shear fabrics related to the fall and re-deposition of boulders of the Minkinfjellet Formation from the footwall of the Odellfjellet Fault into unconsolidated sediments within a shallow sea would probably display S-like geometries indicating down-east transport rather than the observed Z-like geometries. Hence, it is more probable that the Z-shaped shears in the clayey matrix of the megabreccia east of Pyramiden reflect top-WNW movements during early Cenozoic Eurekan tectonism (Figs. 3E & 7). Top-west to top-WNW Eurekan contraction would also explain the undulating to bending character (S-shaped geometry) of subvertical, NNE–SSW-striking fractures across ESE-dipping, bedding-parallel, fracture surfaces (Fig. 5C, D).

Possible origin of WNW–ESE-striking faults in Billefjorden

The study area shows two dominant fault sets striking N–S to NNE–SSW and WNW–ESE, the former of which parallels N–S-trending Caledonian (Gee et al., 1994; Witt-Nilsson et al., 1998) and Grenvillian structural grains in northeastern and central Spitsbergen (Johansson et al., 2004, 2005), whereas the latter is highly oblique to the Caledonian and Grenvillian trends.

Recent studies of seismic, magnetic and gravimetric data in the northern Barents Sea, Storfjorden and central Spitsbergen have revealed the presence of deep, crustal-scale, WNW–ESE- to NW–SE-striking shear zones and thrust systems that merge with Timanian faults in northwestern Russia (Klitzke et al., 2019; Koehl, 2020; Koehl et al., 2022). These thrust systems appear to have controlled the strike and geometry of subsequent, late Paleozoic normal faults and early Cenozoic thrusts (Klitzke et al., 2019; Koehl, 2020, 2021; Koehl et al., 2022).

Onshore Svalbard, these regional thrust systems correlate with discrete major WNW–ESE-striking structures, e.g., the Vimsodden–Kosibapasset Shear Zone in southwestern Spitsbergen (southern Wedel Jarlsberg Land; see Fig. 1B for location; Mazur et al., 2009). These structures are associated with late Neoproterozoic, amphibolite-facies metamorphism and geochronological ages typical of the Timanian Orogeny (Gayer et al., 1966, their samples 49 and 50, and their hypotheses 1 and 2 also discussed in Harland et al., 1966; Manecki et al., 1998; Majka et al., 2008; Faehnrich et al., 2020, their sample 16-73A).

In addition, a few occurrences of WNW–ESE-striking faults were reported in the field in Billefjorden. These include high-angle basement-seated faults in Ebbadalen and Adolfbutka (Christophersen, 2015), the Kampesteindalen Fault, which accommodated c. 50 metres of down-SSW normal displacement in the Early Pennsylvanian (Smyrak-Sikora et al., 2018), and WNW–ESE-striking faults in Proterozoic basement rocks in Mittag–Lefflerbreen and possibly related Carboniferous normal fault overprints in adjacent rocks of the Billefjorden Group and Hultberget Formation (e.g., the NNE-dipping Overgangshytta fault in Odellfjellet; Koehl & Muñoz-Barrera, 2018).

Since meso- to micro-scale WNW–ESE-striking faults in the Minkinfjellet Formation and related syn-tectonic megabreccia east of Pyramiden (see stereonets in Fig. 3A, B) align with and strike parallel to the main Timanian thrusts and shear zones mapped in northern Storfjorden and Sassenfjorden–Tempelfjorden (Koehl, 2021; Koehl et al., 2022), it is possible that they formed along comparable, inherited, basement-seated fault systems. Such a fault may either occur at depth (i.e., buried by subsequent Permian sedimentary rocks) or be located in deeply eroded areas like Mimerdalen.

Thus, another possibility to explain the observed dip and/or tilt is related to early Cenozoic inversion of N–S- and WNW–ESE-striking faults such as the east-dipping Billefjorden Fault Zone and a potential, WNW–ESE-striking, SSW-dipping, previously unrecognised fault. For example, early Cenozoic reverse reactivation of the east-dipping Billefjorden Fault Zone may have tilted Pennsylvanian sedimentary strata of the Ebbadalen and Minkinfjellet formations (dominantly) to the east and super imposed (preceding, simultaneous or subsequent) reverse movement along a previously unrecognised SSW-dipping fault at depth would have resulted in an overall east-southeastward to southeastward tilt of the strata and graben structures (Fig. 4A, B).

Conclusions

1) Analysis of fracture density using the scanline method did not show any relationship with the presence or proximity to major faults because fracture density variations seem to correlate with the quality and extent of the available outcrop exposures.

2) The megabreccia was deposited in the Middle Pennsylvanian after lithification of most of the sediments of the Minkinfjellet Formation but prior to lithification of those of the uppermost Middle Pennsylvanian–lowermost Permian Wordiekammen Formation.

3) Comparison of the orientation of fracture and bedding surfaces within clasts of the megabreccia and adjacent, gently ESE-dipping strata of the Minkinfjellet Formation suggest that the megabreccia reflects repeated slope failures during fault steepening processes along the Odellfjellet Fault segment of the Billefjorden Fault Zone.

4) Evidence for evaporite dissolution at depth might suggest partial reworking of the megabreccia as a stratabound dissolution breccia.

5) The megabreccia in the hanging wall of the Odellfjellet Fault east of Pyramiden represents a late-rift, syn-tectonic deposit reflecting the "through-going fault zones" phase of Carboniferous normal faulting in central Spitsbergen.

6)   The ESE-dipping character of potential stratification within the megabreccia and of adjacent strata of the Minkinfjellet Formation east of Pyramiden, together with Z-shaped shear fabrics within the megabreccia's clayey matrix suggest top-west-northwest, early Cenozoic Eurekan thrusting along the Billefjorden Fault Zone and related strain partitioning in weak sedimentary units (e.g., megabreccia's clayey matrix).

7)   WNW–ESE-striking faults in the Minkinfjellet Formation and associated megabreccia east of Pyramiden may have formed along a preexisting Timanian basement grain.

Future work

A potential aspect for future work may be to focus on tracking the possible presence of fossils within the megabreccia matrix. Although the present study did not reveal the presence of any fossil remains, it is possible that small fossils and/or fossil clasts may have been overlooked and/or are buried in the megabreccia unit. The presence and level of preservation of fossils (if any) may have implications for the formation mechanism of the megabreccia unit.

Another item that may be the focus of future studies would be to confirm the coeval character of the two fractures sets and their kinematics using cross-cutting relationships in the field, fault offsets and occurrences of fault lineations, though the limited extent and, in places, the limited quality of the exposures will anyway impede potential future work. A potential idea would be to combine this approach with other methods, such as U–Pb geochronology of the calcite fault cement (e.g., Roberts & Holdsworth, 2022).

Further consideration should also be given to features indicating dissolution of evaporites at depth such as crackle breccia (Fig. 5G, H) and potential V-structures (Fig. 6A–C), and further exploration of a possible reworking (formation?) of the megabreccia as a stratabound dissolution breccia should be emphasised.

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