Caledonian thrusting on Bjørnøya: implications for Palaeozoic and Mesozoic tectonism of the western Barents Shelf

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The late Proterozoic to Ordovician rocks on Bjørnøya, located on the western Barents Shelf, experienced significant contractional deformation during the Caledonian orogeny, contrary to some descriptions. Major thrust zones bound the various pre-Devonian basement units of the island, and the Upper Riphean-Vendian to Middle Ordovician rocks are stacked in a WNW-verging thrust pile. In detail, mesoscopic structures, such as ductile shear folds and fabrics, brittle faults with appropriate slip-lines, and stacked units, support a contractional nature of the deformation. An unconformity with overlying Upper Devonian sandstones truncates all the major basement thrusts, thereby indicating a Caledonian age for the major deformation of the basement units. Later, Palaeozoic normal faults dissect the basement units and upper Devonian to mid-Carboniferous cover rocks. During this faulting episode, all units were also folded into a monocline. A strong similarity in orientation of the basement- and cover-related fault populations indicates that these extensional faults were controlled by the Caledonian structural grain. The Palaeozoic normal faults have also utilized the Caledonian contractional fabric, supporting basement control on the Palaeozoic extension in the area. Using Bjørnøya as a guide, we discuss the importance of the Caledonian basement grain for Palaeozoic and Mesozoic extension of the western Barents Shelf.

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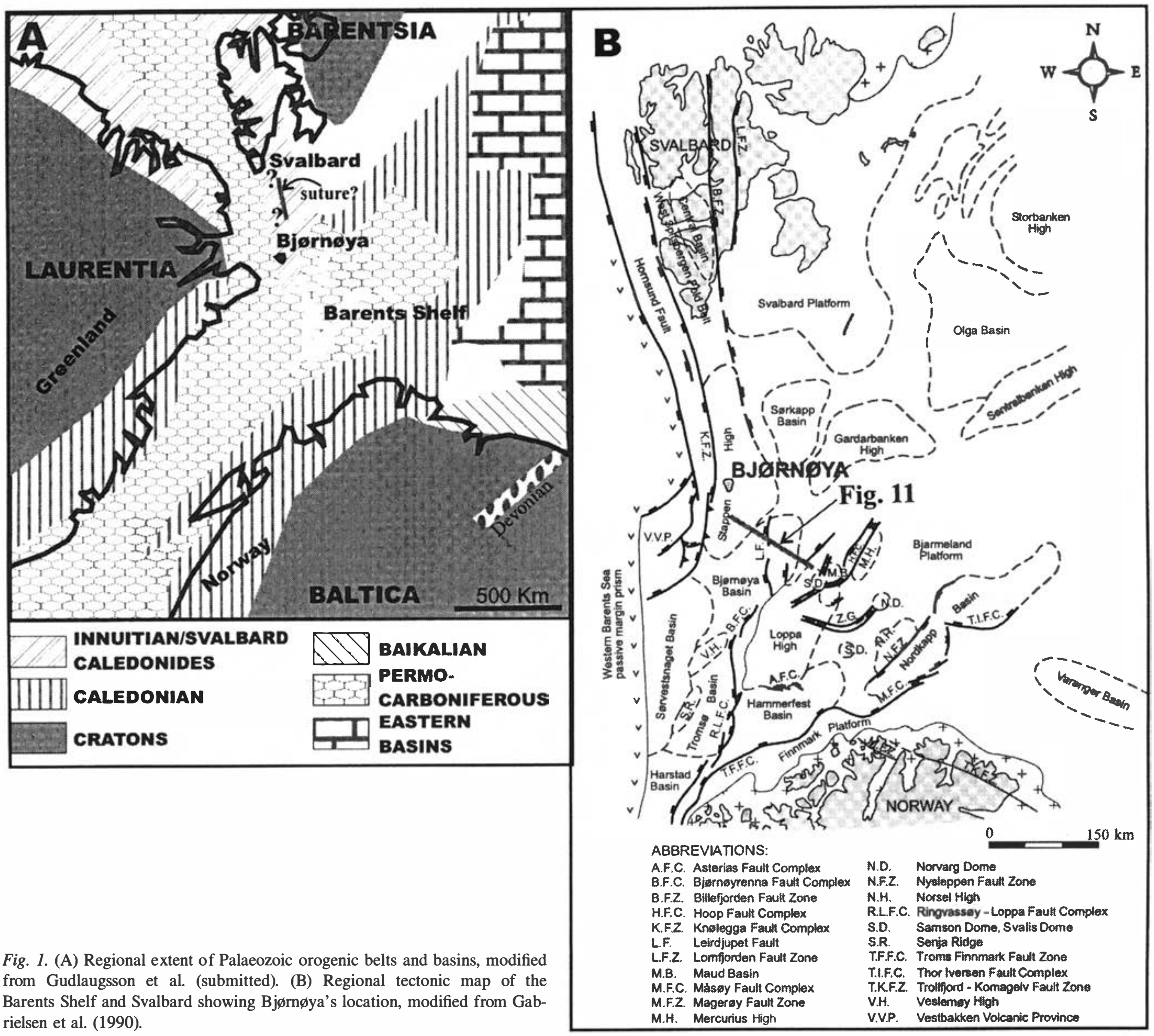
Introduction

Bjørnøya (Bear Island) is located midway between North Norway and Spitsbergen (Fig. 1), and as such represents a window into the western Barents Shelf, otherwise mainly known from drill cores and seismic sections. This island is thus an important location for analysing in detail the Caledonian and Palaeozoic stratigraphic successions and structural histories of one of the most prominent structural features of the region, the Stappen High (e.g. Holtedahl 1920; Horn & Orvin 1928; Harland & Wright 1979; Worsley et al., submitted). These topics are essential to hydrocarbon exploration of the extensive shelf area.

In Palaeozoic times, Bjørnøya was situated just north of the intersection of two major rift zones, a NE-SW trending one to the east, located over the Loppa High, and a N-S rift along the present-day shelf margin and the Stappen High, including Bjørnøya (Gudlaugsson et al., submitted). These major structural trends likely influenced the Mesozoic-Cenozoic tectonic development of the Barents Shelf (Fig. 1B), as seen by Late Mesozoic extension (e.g. Gabrielsen 1984; Gabrielsen et al. 1990) that faulted the shelf into basins and highs along these inherited trends. This pattern was further accentuated by differential Cenozoic uplift and basin formation that contributed to the present structural position of the Stappen High as an uplifted basement-cored block.

The Palaeozoic-Mesozoic structural trends in turn are subparallel to Caledonian ones. During the Caledonian orogeny two structural/geophysical lineaments or contractional belts existed: one striking N-S, continuing to Spitsbergen, where it forms the Svalbard Caledonides and Innuitian tectonic province, and a second lineament, trending NE-SW, forming the probable main continuation of the Scandinavian Caledonides (Fig. 1A; Harland 1978; Harland & Wright 1979; Harland et al. 1984; Birkenmajer 1981; Gudlaugsson et al., submitted). The eastern Bjørnøya Basin and the Loppa High follow the NE-SW trending arm of the mountain belt, whereas the Stappen High and the shelf margin follow the N-S striking belt. Despite the location of Bjørnøya near the intersection of the two Caledonian belts, Caledonian tectonism has by some been considered minor or non-existent (e.g. Harland & Wright 1979), thus disputing older work (Holtedahl 1920; Horn & Orvin 1928).

We will argue for significant Caledonian contractional deformation, accommodated by WNW-directed thrusting, on Bjørnøya. The main goals of this paper are: (1) to describe and document structures in support of a significant Caledonian contractional episode; (2) to discuss structures that indicate Palaeozoic reactivation of the thrusts as normal faults, thereby demonstrating reactivation of Caledonian structures during later regional extension; and (3) to discuss the implications of such



A.F.C.	Asterias Fault Complex	N.D.	Norvarg Dome
B.F.C.	Bjørnøyrenna Fault Complex	N.F.Z.	Nysleppen Fault Zone
B.F.Z.	Billefjorden Fault Zone	N.H.	Norsel High
H.F.C.	Hoop Fault Complex	R.L.F.C.	Ringvassøy - Loppa Fault Complex
K.F.Z.	Knølegga Fault Complex	S.D.	Samson Dome, Svalis Dome
L.F.	Leirdjupet Fault	S.R.	Senja Ridge
L.F.Z.	Lomfjorden Fault Zone	T.F.F.C.	Troms Finnmark Fault Zone
M.B.	Maud Basin	T.I.F.C.	Thor Iversen Fault Complex
M.F.C.	Måsøy Fault Complex	T.K.F.Z.	Trollfjord - Komagelv Fault Zone
M.F.Z.	Magerøy Fault Zone	V.H.	Veslemøy High
M.H.	Mercurius High	V.V.P.	Vestbakken Volcanic Province

Fig. 1. (A) Regional extent of Palaeozoic orogenic belts and basins, modified from Gudlaugsson et al. (submitted). (B) Regional tectonic map of the Barents Shelf and Svalbard showing Bjørnøya's location, modified from Gabrielsen et al. (1990).

reactivation during Palaeozoic and Mesozoic tectonism of the western Barents Shelf.

Bjørnøya's rock record

Bjørnøya comprises two main rock units separated by a major angular unconformity (Figs. 2, 3): the Caledonian basement (Hecla Hoek), exposed along the south and southeast cliffs of the island (Fig. 2), and the overlying Palaeozoic and Triassic cover succession (e.g. Andersson 1899; Horn & Orvin 1928; Dallmann & Krasil'šcikov 1996; Worsley et al., submitted). Three distinct basement units (Fig. 3), the Russehamna, Sørhamna and Ymerdalen formations (Krasil'šcikov & Livšic 1974), have a total thickness of 1200 m (Holtedahl 1920; Horn & Orvin 1928). The stratigraphically lowest, although structurally highest unit, the Russehamna Formation, consists of grey, massive dolomites, and local units with oolitic sandstone and stromatolites, the latter suggesting an Upper Riphean-Vendian age (Milstein & Golovanov 1979). Shales and quartzitic sandstones of the Sørhamna Formation are approximately 150 m thick with sandstone dominant to the east and shale to the west. A debatable correlation has been made with the Late Precambrian Tanafjorden-Varangerfjorden Group sediments, including Varangian glacial deposits (Vendian) of northern Norway and Spitsbergen (Harland & Gayer 1972; Harland 1978). The uppermost stratigraphic unit, the Ymerdalen Formation, is divided into a lower massive grey dolomite and overlying grey limestone, with a total thickness of 400 m, and an upper black limestone which is 240 m thick (Krasil'šcikov & Livšic 1974). Fossils present in the uppermost basement unit indicate a Middle Ordovician age (Nathorst 1910).

The cover sequence starts with Upper Devonian to Lower Carboniferous sandstones, shales and coals of the Billefjorden Group (Horn & Orvin 1928; Cutbill & Challinor 1965; Worsley & Edwards 1974), followed by

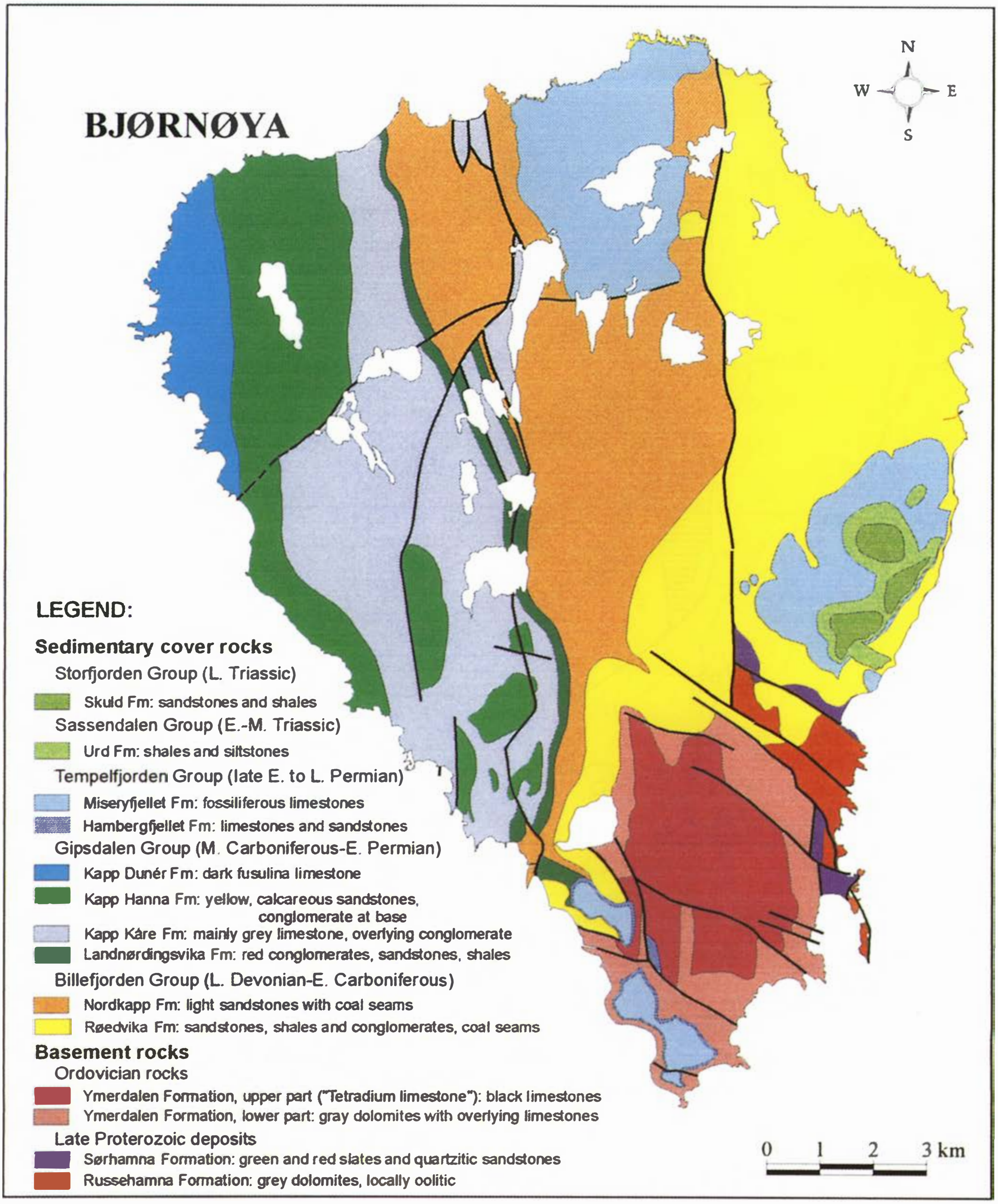


Fig. 2. Bjørnøya's bedrock geology, modified from Dallmann & Krasil'šcikov (1996). The stratigraphic section of the island is described in the legend.

the Middle Carboniferous to Lower Permian, carbonate-dominated Gipsdalen Group, which has subordinate conglomerate and sandstone units (Fig. 2). This series is involved in a west-verging monocline. An angular unconformity that truncates Palaeozoic normal faults separates the Gipsdalen Group from the succeeding Mid to Upper Permian Tempelfjorden Group, which is made up of silicified carbonates, sandstones and shales (Siedlecka

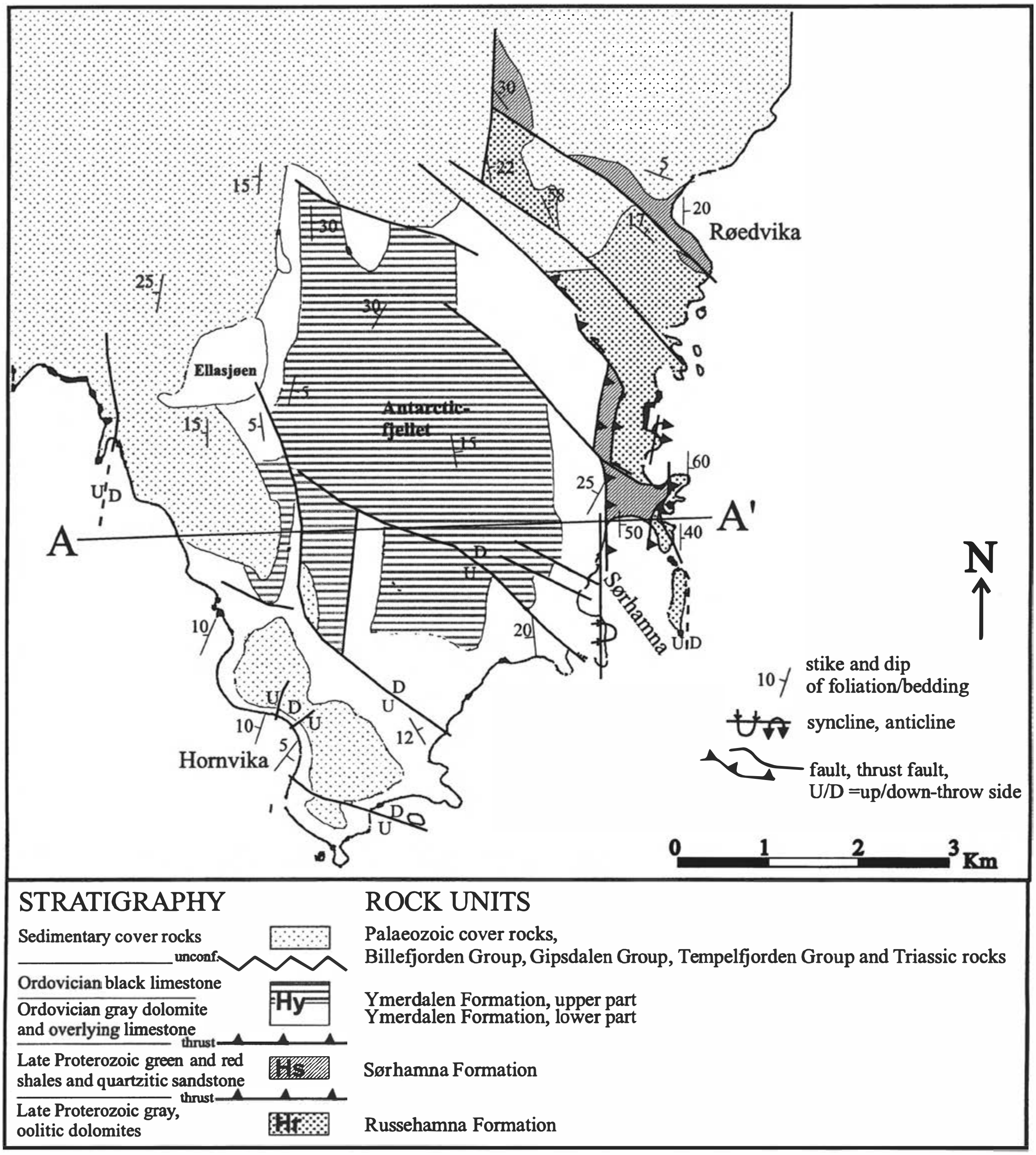


Fig. 3. Detailed bedrock map of the southern part of Bjørnøya. The stratigraphic section with location of major thrusts separating the basement units is described at the base of the figure.

1975). The uppermost exposed strata consist of erosional remnants of Triassic shales and sandstones of the Storfjorden Group (Mørk et al. 1990).

Basement structures

Differing opinions exist as to the extent and character of Caledonian tectonism preserved in the basement units of Bjørnøya. Krasil'šcikov & Livšic (1974) argue that the Russehamna and Sørhamna formations suffered weak late Precambrian, Baikalide deformation, whereas Harland & Wright (1979) favour a minor Cambrian folding event, predating deposition of the subhorizontal Ymerdalen Formation. In contrast, Holtedahl (1920) and Horn & Orvin (1928) invoked the existence of a thrust between the

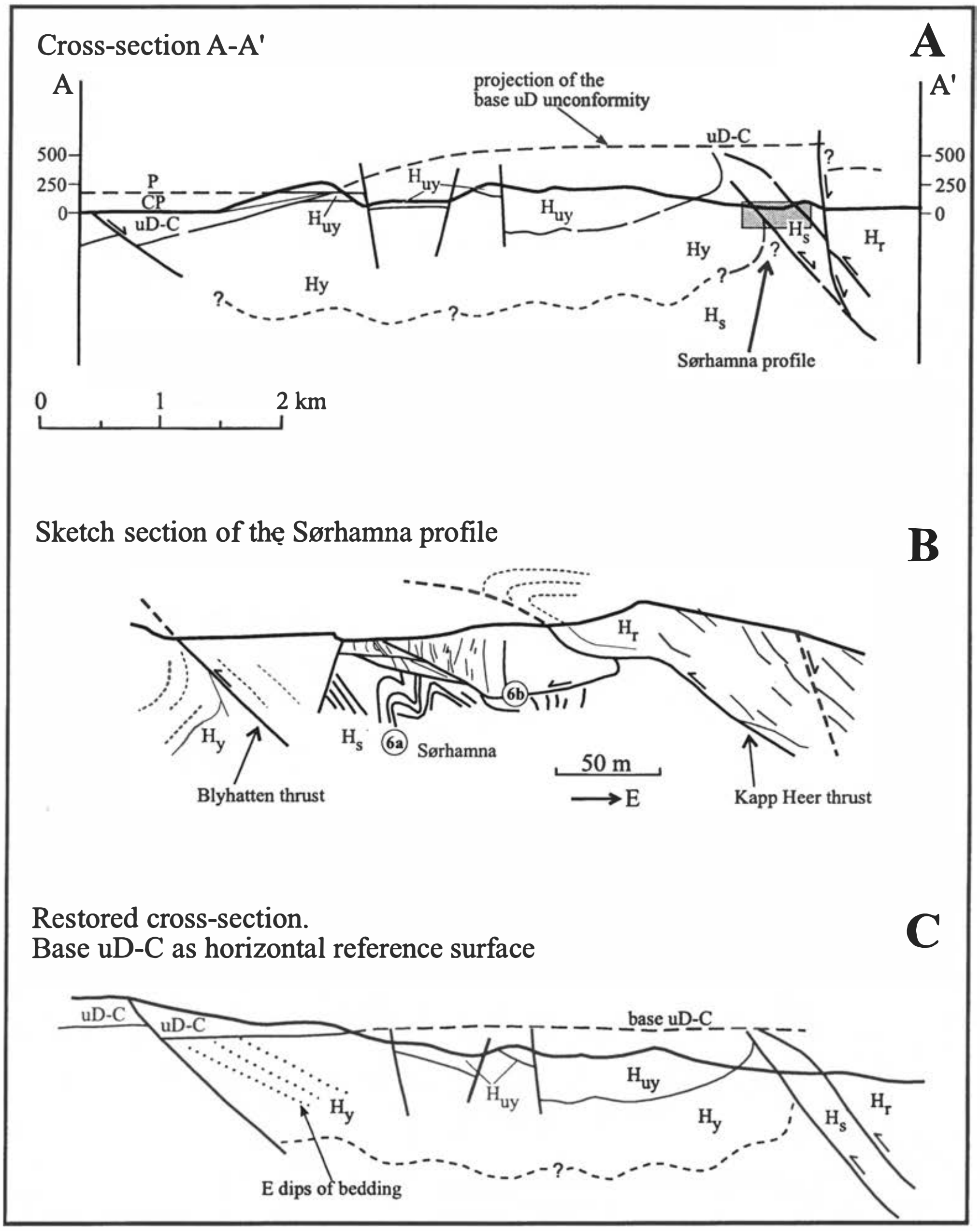


Fig. 4. E-W cross-section of the Caledonian basement in Bjørnøya. The section line A-A' is located in Fig. 3. (A) The constructed cross-section. (B) A close-up sketch of the former in the Sørhamna profile. Locations of photographs in Figs. 6A and 6B are specified in the profile. (C) The cross-section after restoration of the basement-cover contact to a horizontal position. Hr = Russehamna Formation; Hs = Sørhamna Formation; Hy = Ymerdalen Formation; Huy = upper part of Ymerdalen Formation; uD-C = Upper Devonian-Carboniferous rocks; base uD-C = base of cover rocks; P = Permian rocks.

Sørhamna and Ymerdalen formations, as indicated from intensive folding and faulting in both units near their contact. Given an Ordovician age for the Ymerdalen Formation, this thrust would be a Caledonian feature. The apparently almost flat lying nature of the Ymerdalen Formation carbonates has led many to conclude that Bjørnøya was not affected by, or suffered only minor Caledonian tectonism. In the following sections we will present evidence that challenges this interpretation.

Basement rocks are overlain to the north and west sides by Billefjorden Group cover strata (Fig. 3). The basal unconformity and overlying sandstone dip approximately 5° to the north in the eastern area, whereas 15–25° westward dips occur to the west. Thus, the overall structure of the basal unconformity and cover rocks is an open, west-verging and north-plunging monocline (Fig. 4A). This flexure is influenced by map-scale faults that both displace and truncate the basal unconformity. Two fault orientations dominate, N-S and NW-SE striking (Fig. 2). An E-W orientation is present as a subordinate population. All three fault orientations are found in both the cover and basement rocks (see below).

Major thrusts are located along the contacts between the three basement formations (Figs. 3, 4B). The best example is seen in the cliff sections of Sørhamna (Fig. 5), at the contact between the Russehamna and Sørhamna formations. There, the Russehamna Formation is emplaced westward over the Sørhamna Formation by a moderately east-dipping reverse fault, the Kapp Heer thrust. Bedding in the hanging wall strikes N-S and dips moderately east, but changes to a vertical and overturned orientation further north along strike, where an open to tight, west-verging anticline dominates the map pattern (Fig. 3; Dallmann & Krasil'ščikov 1996). Sandstone beds of the footwall (Sørhamna Formation) strike N-S, have a near vertical to overturned position, and display tight chevron folds. They are successively truncated by the Kapp Heer thrust that climbs to the west (Fig. 4B). The thrust displacement is a minimum of 150 m, the length of the exposed part of the thrust in the Sørhamna section, but associated deformation suggests it exceeds this minimum.

The contact between the Sørhamna and Ymerdalen formations shows a similar thrust relationship (the Blyhatten thrust, Figs. 4B, 5). The Ymerdalen dolomite in the footwall is openly to gently folded to the west. However, bed attitudes change from an overall subhorizontal orientation to a N-S striking, subvertical and partly overturned position when approaching the thrust contact (Figs. 3, 4A, 4B; Holtedahl 1920). In contrast, a well developed cleavage in shales of the hanging wall (Sørhamna Formation) strikes N-S and dips moderately to the east, an orientation that is subparallel to the faulted contact. The Sørhamna Formation clearly overlies the subvertical beds of the lower Ymerdalen Formation, revealing a minimum thrust displacement of approximately 100 m. Again, the severity of deformation suggests significantly greater displacements.

Mesoscopic structures that support major thrusting in the basement are well displayed in the Sørhamna area. Dolomites of the Russehamna and Ymerdalen formations show extensive cataclasis, thrusts with meter scale displacement, and spaced ESE-dipping cleavage near the formation-bounding major thrusts. The Sørhamna Formation suffered a different style of deformation due to its variable lithologic character. The sandstone dominated eastern part is extensively folded into tight, elliptical to chevron shaped folds (Figs. 4B, 6A) with subhorizontal fold-axes and steeply ESE to SE dipping axial surfaces (Fig. 7A). A well-developed crenulation cleavage, dipping moderately to steeply to the ESE, is present in the hinge zones, and in shale dominated layers (Fig. 7B). This cleavage contains quartz and oriented, fine-grained white mica and chlorite, indicating lower greenschist facies metamorphic conditions during deformation.

Sandstone beds (Sørhamna Formation) proximal to and in the footwall of the Kapp Heer thrust show subvertical dips (Figs. 4B, 5). Mesoscopic faults, dipping moderately to the WNW, cross-cut and displace various beds, showing a consistent downdip, top-to-the-WNW sense of slip (Fig. 6B). In that they repeat strata, these faults are contractional in nature. When traced to the west, they have subhorizontal and then moderate ESE dips and become west-directed thrusts in their present orientation. There, they also truncate/decapitate mesoscopic folds in the central part

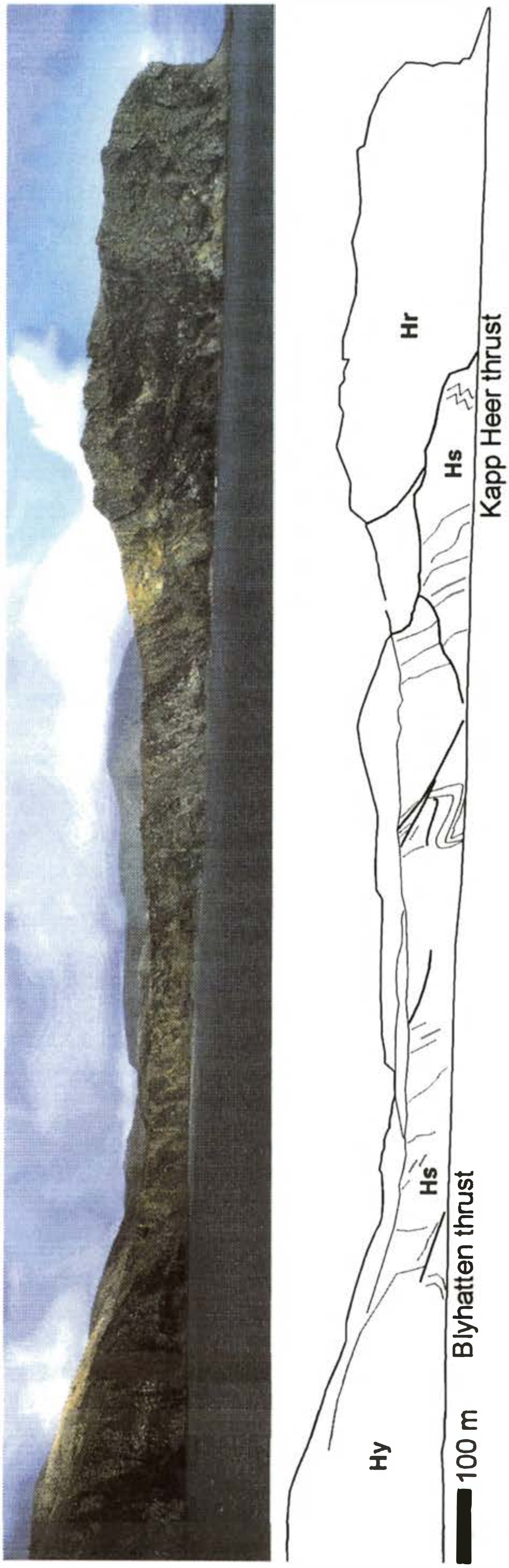


Fig. 5. Photo-mosaic and sketch profile of the Sørhamna section. The view is from the SSE.

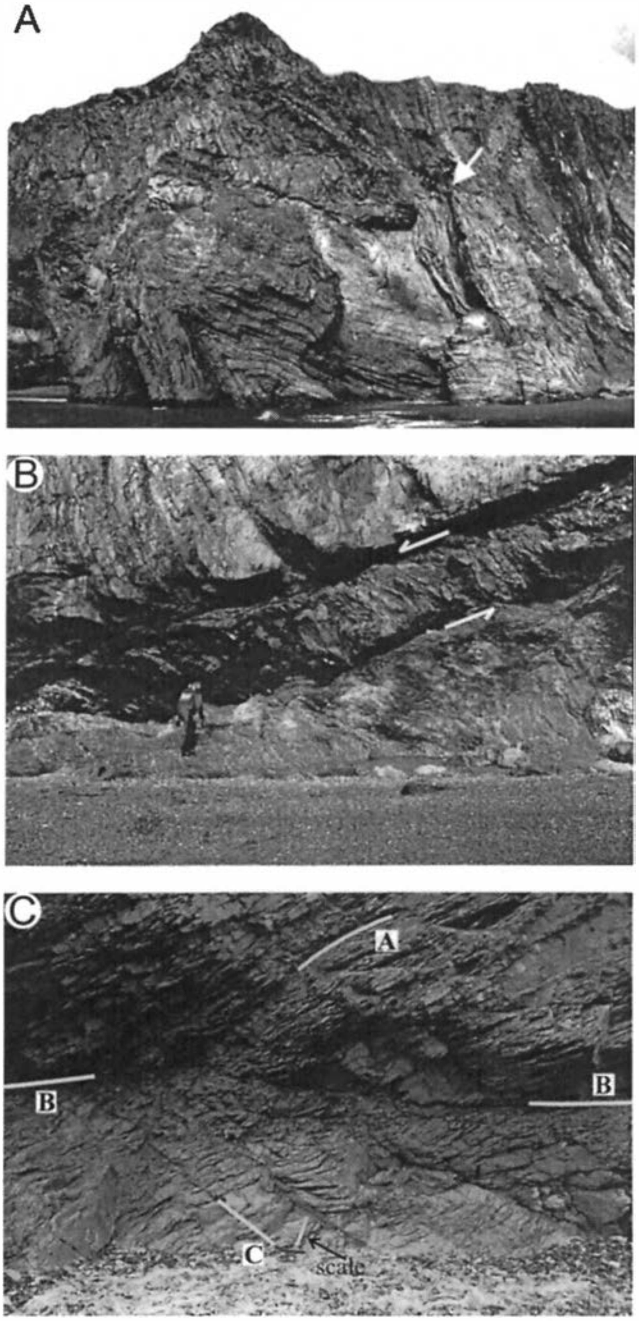


Fig. 6. Examples of mesoscopic contractional structures in the Caledonian basement. (A) Intraformational folds in the Sørhamna Formation. The view is from the south. Note the cleavage along the axial planes and the decapitation of the folds in the upper part (arrow). Fig. 4B locates the folds in the larger structural picture. (B) Duplex in the Sørhamna shale and sandstone unit, viewed from the south. See Fig. 4B for location and structural position of the duplex. (C) Cleavage and shear-bands in the Sørhamna Formation shale, viewed from the north. The three structures present at this location are labelled A, B and C, as discussed in the text.

of the Sørhamna profile (Figs. 4B, 6A). Thus, we interpret these mesoscopic thrust faults to be progressively folded proximal to the Kapp Heer thrust to the east.

Further west, in the shale-dominated eastern part of the Sørhamna Formation, the rocks are highly tectonized, and primary features, such as bedding, are almost entirely overprinted by a penetrative to subpenetrative cleavage. This deformation is well expressed by fractured sandstone

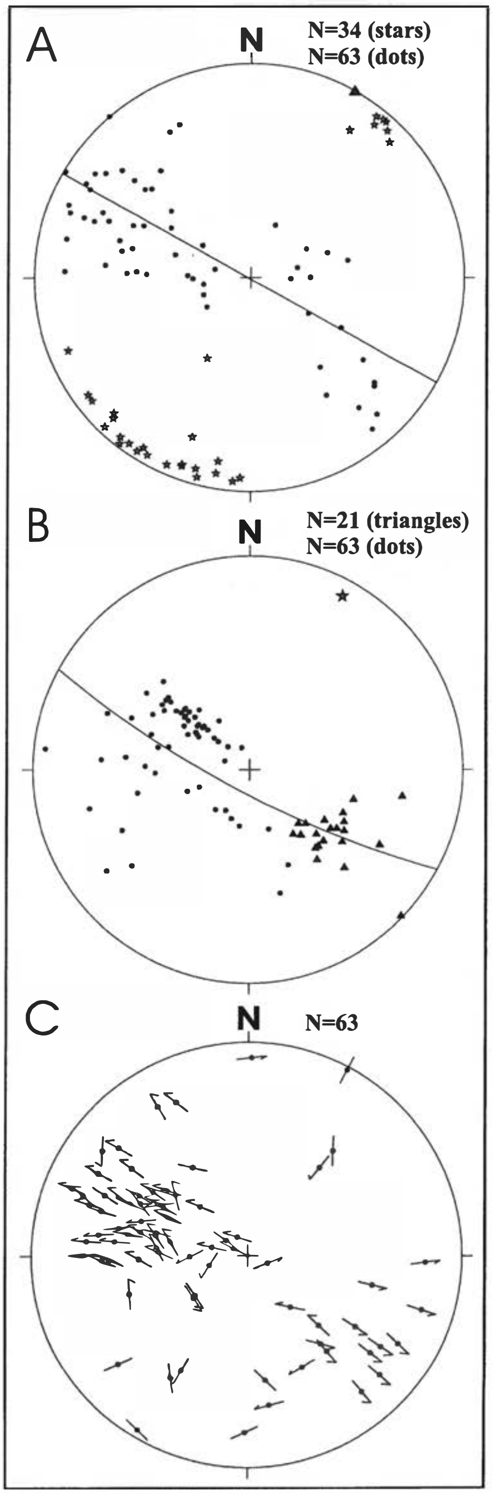


Fig. 7. Stereoplots (equal area, lower hemisphere, Schmidt net) of mesoscopic Caledonian structural data. (A) Poles to bedding in the basement rocks (dots) and measured fold axes (stars). Note the best-fit fold axes of the bedding readings (triangle). (B) Poles to cleavages in the basement rocks. Dots locate the penetrative cleavage (*A* in Fig. 6C), whereas the ESE-verging kink-bands (*C* in Fig. 6C) are plotted as triangles. See the text for further description. (C) Slip-linear plot of faults with slip-lines. WNW-directed fore-thrusts are identified by arrows pointing toward the WNW, whereas back-thrusts have arrows pointing toward the ESE. The 'slip-linear' plots, as described by Aleksandrowski (1985) and Goldstein & Marshak (1988), present the pole to the fault plane represented by a line/arrow, which indicates the direction and sense-of-slip of the hanging wall. The arrow is parallel to the horizontal trace of a plane (M-plane), which is defined by the pole to the fault and the slip-line.

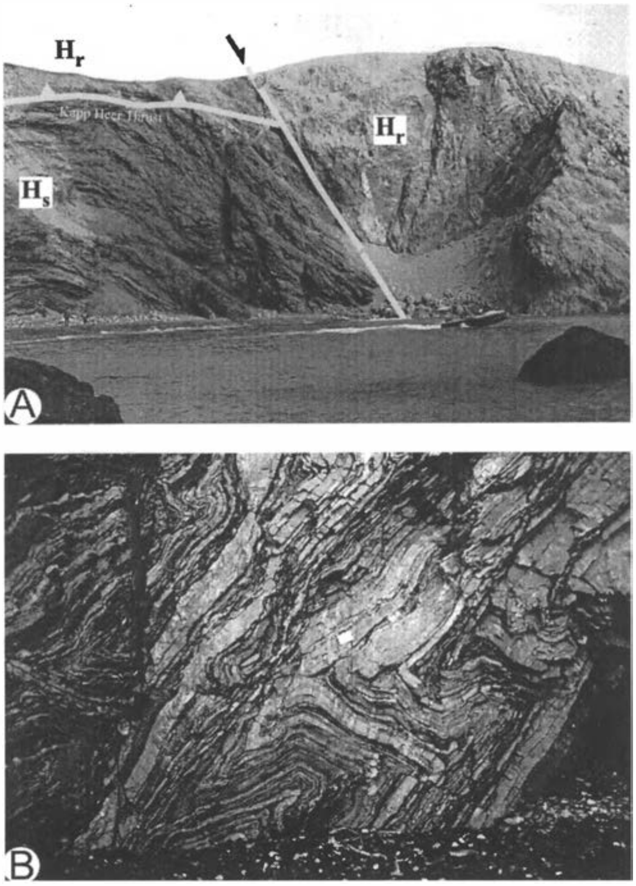


Fig. 8. Examples of mesoscopic extensional structures in the Caledonian basement. (A) Normal fault truncation of the Kapp Heer thrust at the contact of the Sørhamna (Hs) and Russehamna formations (Hr). The view is from the southeast. (B) Late, interformational, down-to-the-ESE verging folds and associated faults in the Sørhamna Formation, viewed from the north.

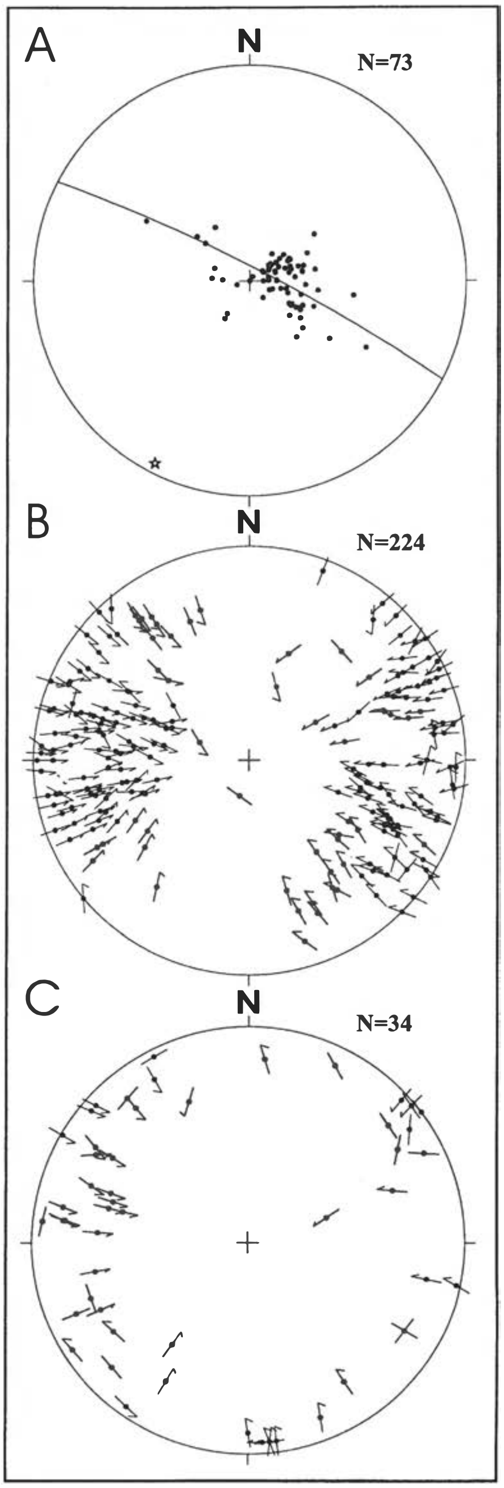


Fig. 9. Stereoplots (equal area, lower hemisphere, Schmidt net) of mesoscopic structures from the post-Caledonian cover rocks. (A) Poles to bedding (dots), where the data are gathered from the entire cover section. Note the overall fold axis for the data-set (star). (B) Slip-linear plot of faults in the cover rocks. (C) Slip-linear plot of late normal faults that are observed in the basement rocks.

lenses, locally containing primary bedding, in the foliated shale. The intensity of deformation in the shale suggests that this part of the basement section accumulated most strain during contraction.

Three mesoscopic structural fabrics (labelled A, B, and C) have been observed within the most deformed part of the Sørhamna Formation (see Fig. 6C). The most prominent, cleavage A, is the ESE-dipping penetrative foliation (Fig. 7B) in the shales. Within sandstone layers it is present as a spaced cleavage (Powell 1979; Groshong 1988), at some localities with cm-scale displacement of bedding. Where such offsets can be seen, these features likely represent shear-bands or, alternatively, the cleavage was reactivated as small reverse faults. Thin shear-bands (B in Fig. 6C) with associated cm-scale shear-folds locally truncate or fold cleavage A. The shear-folds verge consistently to the WNW, whereas the shear-bands change from moderate eastward dips to the west to subhorizontal orientations further east. These orientations are similar to the population of partly rotated mesoscopic faults described above. At some localities, the shear-bands (B) are characterized by growth of fibrous quartz and chlorite with a preferred WNW-ESE-oriented long axis. The third type of mesoscopic structures, observed as distinct kink-bands or spaced cleavage (fabric C, Fig. 6C), strikes NNE-SSE and dips moderately WNW, whereas the kink-folds verge to the ESE (Fig. 7B).

The overprinting relationships of the structural fabrics, where kink-bands (C) commonly fold the shear-bands (B),

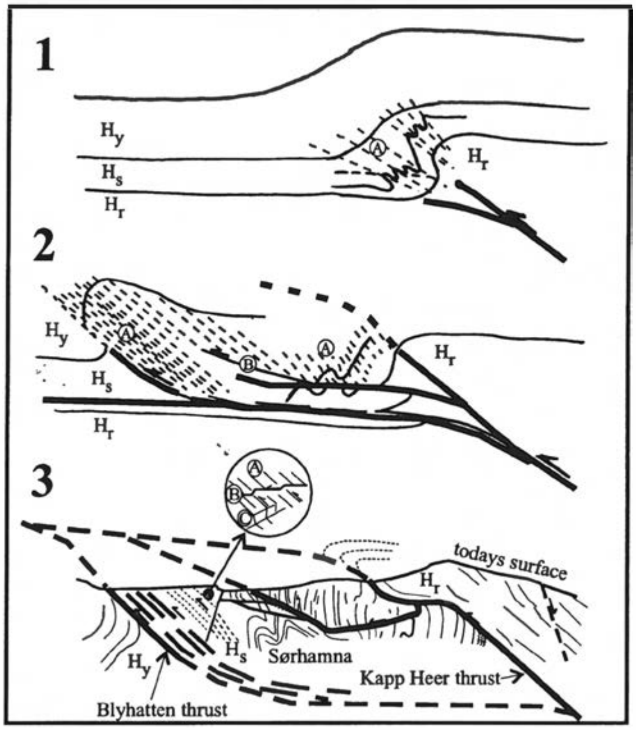


Fig. 10. Possible fault propagation model for the formation of the major basement structure. The model is discussed in the text. Cleavage and shear-bands are labelled A, B and C according to Fig. 6C and the text. Hr = Russehamna Fm.; Hs = Sørhamna Fm.; Hy = Ymerdalen Fm.

which in turn truncate or fold the main foliation (A), are consistent for many localities. However, exceptions exist. For instance, the shear bands (B) are locally deformed by folds with an axial surface parallel to cleavage A, indicating movements on this cleavage during formation of the shear-bands. Such complications are consistent with non-coaxial deformation in a shear zone.

Common mesoscopic structures in the Sørhamna Formation that may be used as sense-of-shear indicators during major thrusting/contraction are: (1) asymmetrical shear folds (Fig. 6A), (2) composite ductile fault fabrics (e.g. Lister & Snoke 1984; Simpson & Schmidt 1983; Dennis & Secor 1987, 1990), (3) outcrop-scale stacked units and foliation/bedding duplexes (Fig. 6B; e.g. Tanner 1992), (4) cleavage and faults with slip-related lineations (frictional wear, tool pit, cross fractures, growth fibre; Hancock 1985; Petit 1987). In combination, most of the observed meso-structures support deformation by non-coaxial, top-to-the-WNW shear in the unit. A similar WNW transport direction is evident in slip-linear plots (Fig. 7C) of mesoscopic thrust-faults. These kinematics are also those of the major thrusts. A pattern of synthetic (WSW-directed) and antithetic (ESE-directed) reverse faults is interpreted as representing fore- and backthrusts, respectively (Fig. 7C).

In the Sørhamna Formation, a distinct population of mesoscopic folds with down-to-the-ESE vergence (Fig. 8b), i.e. opposite to the transport direction described above, are found near the shale-sandstone contact. These structures are associated with shear-bands or faults that modify the fold-limbs and hinges. A consistent down-to-the-ESE, normal offset and thinning of sandstone beds (Fig. 8B) suggests that the deformation is extensional in character. Alternatively, the folds may be interpreted as parasitic (forelimb position) to the major hanging wall anticline of the Kapp Heer thrust. While employing the dominant cleavage A, these structures cut other outcrop scale structures, indicating that they formed after the major contraction.

Brittle normal faults are observed in the basement carbonates at nearby locations (Fig. 9c). East of Sørhamna (Figs. 3, 4A), a steeply easterly-dipping normal fault truncates and downdrops the major unit-bounding Kapp Heer thrust at least 50 m to the east, as displayed in Fig. 8A. This 5-m-thick fault zone displays foliated cataclastites containing fractured lenses of dolomite and shale/sandstone. Shear-sense indicators, such as duplexes, stacked units, local intrafolial folds and slip-lines on small faults, suggest down-to-the-ESE movement in the zone. The consistent truncating nature and the normal, down-to-the-ESE fault transport, indicate these structures formed during Carboniferous extension (see discussion below).

Other normal faults can be traced from the basement into Carboniferous and Permian rocks. The best examples are displayed at Hornvika (Fig. 3), where two N-S striking faults, dipping steeply east and west, respectively, bound a

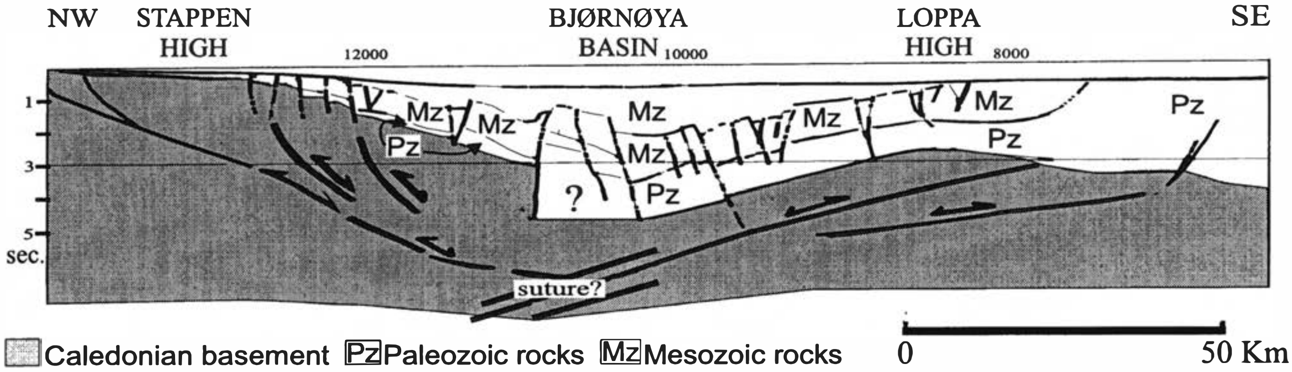


Fig. 11. Schematic NW-SE cross-section, from the Stappen High, across the northern part of the Bjørnøya Basin, to the Loppa High (modified from Gabrielsen et al. 1990). The location of the cross-section line is indicated in Fig. 1B. Note that deeper parts of the section are poorly constrained. Basement structures and the location of the suture zone are inferred. See text for further explanation.

graben that is filled with upper Gipsdalen Group carbonates (Worsley et al., submitted), with an unfaulted upper Permian drape. Further north, several NW-SE-striking, steeply NE and SW-dipping faults, some penetrating Permian strata, truncate and displace the Kapp Heer and Blyhatten thrusts (Fig. 3). These may represent tear or late-phase Caledonian faults that were later reactivated during Permian extensional faulting.

Discussion

The contractional structures within the basement units of Bjørnøya support an overall WNW-directed thrust mode of deformation, resulting in the oldest unit in the highest position. In detail, there is a polyphase history, much of which can be explained by thrust propagation within a deforming zone (Fig. 10). For example, bedding and early bed-truncating thrusts are successively rotated to westward dips when approaching the major formation-bounding Kapp Heer thrust from the west. Westward, these mesoscopic thrusts truncate the oldest intrastratal folds of the Sørhamna Formation (Figs. 4B, 6A). In addition, fold- and shear-related cleavages and shear-bands show a complex pattern of overprinting relationships (Figs. 6C, 10). These observations, together with the subvertical to overturned bedding in the footwall synclines (reverse drag), and the macroscopic hanging wall anticline, suggest that much of the strain can be ascribed to thrust propagation (Mitra 1990; Al Saffar 1993) through an overturned nappe limb (Fig. 10). In this case, the hanging wall anticline probably formed as a fault-propagation fold above a thrust (-zone) in the Sørhamna shales. During progressive deformation, this fold likely was fractured and partly incorporated in the growing thrust zone, thereby becoming part of a thrust stack or duplex structure (Boyer & Elliot 1982; McClay 1992).

On a more speculative note, the mechanically weak Sørhamna Formation may have acted as a detachment level beneath the gently folded, fairly thick and competent Ymerdalen Formation dolomites. When this unit is restored to a post-Caledonian-pre-Upper Devonian position by rotating the basement-cover contact to horizontal (uD-C in Fig. 4C), bed orientations in basement to the west dip moderately eastwards. This easterly dip of strata may indicate the occurrence of another (or more) thrust ramp at depth west of Bjørnøya.

Timing of deformation and regional implications

Major thrusting occurred between Middle Ordovician and early Devonian times, given involvement of rocks of Middle Ordovician age (Upper Ymerdalen Formation), and the truncation of these structures by basal cover rocks of late Devonian age. This timing of deformation does not correspond to that proposed by Birkenmajer (1981) and Harland & Wright (1979). Their conclusion that the Ymerdalen Formation is flat lying and undeformed, indicating deformation in the Late Precambrian, contradicts the descriptions by Holtedahl (1920) and Horn & Orvin (1928), and is inconsistent with two observations. First, when the basement-cover contact is restored to a horizontal position, then Ymerdalen Formation strata in the western part dip 15–25° eastward. Second, Ymerdalen carbonates are locally involved in the thrusting. These rocks did not escape a contractional imprint, although they represent a relatively thick competent unit that suffered less deformation. In summary, the deformation on Bjørnøya is Caledonian in age.

On Spitsbergen, the main phases of Caledonian thrusting occurred in Middle-Late Cambrian (north-central Spitsbergen) and Early-Middle Ordovician times (west-central Spitsbergen), followed by a widely distributed, but less significant, Middle Silurian event (e.g. Ohta et al. 1989; Ohta 1992) with a general northeastward shortening direction (Bjørnerud et al. 1991). In the East Greenland Caledonides, which was located next to Bjørnøya and Spitsbergen until the Tertiary opening of the northern North Atlantic Ocean (e.g. Talwani & Eldholm 1977; Muller & Spielhagen 1990), west-directed contraction, post-dating deposition of Middle Silurian carbonates (main phase ~410 Ma; Haller 1985; Hurst et al. 1985) dominated. This latest Silurian event is apparently the most reasonable timing for the contraction seen on Bjørnøya.

The shortening direction on Bjørnøya (to the WNW) compared with Spitsbergen (to the ENE) and NE Greenland (to the west) may reflect different structural positions or terranes in the Caledonian mountain belt, or may be due to along-strike changes. Such along-strike changes are well exemplified in southern Spitsbergen, where the dominant east to northeast-directed thrust-pattern changes within a few kilometres to a WSW vergence at the south tip of the island (e.g. Dallmann et al. 1993).

Post-Caledonian extension on Bjørnøya is evident as various down-to-the-west and east normal fault systems (Fig. 9B) (Horn & Orvin 1928; Lepvrier et al. 1989). Locally this faulting was clearly syn-depositional with Gipsdalen Group sediments (e.g. Worsley et al., submitted), and penecontemporaneous with the formation of the macroscopic monocline. The truncation of the monocline by the unconformity below the Tempelfjorden Group indicates formation of the flexure in Carboniferous to mid-Permian times, probably as a roll-over structure in the hanging wall of a major extensional, basin-bounding and eastwards-dipping fault to the west of Bjørnøya (Worsley et al., submitted). A subordinate population of normal faults that strike E-W is suggested as the last episode of faulting, since they involve the Permian section (Worsley et al., submitted). It is unknown if these late faults affect Triassic units. Similar episodes of major crustal extension in the Carboniferous, which lasted into Permian times, are invoked for other locales in the Barents Sea (e.g. Faleide et al. 1984; Gabrielsen 1984; Gabrielsen et al. 1990), for instance, on the Loppa High (Gudlaugsson et al., submitted) and on Spitsbergen (Cutbill & Challinor 1965;

Steel & Worsley 1984; Johannessen & Steel 1992; Maher & Welbon 1992; Dallmann 1992; Braathen et al. 1995).

The significance of Caledonian basement structures on later tectonism of the Barents Shelf is thoroughly debated (e.g. Ziegler 1988; Dore 1991; Gudlaugsson et al., submitted). Gudlaugsson et al. (submitted) argue that later extensional faulting was controlled by the Caledonian structural grain, since major normal faults tend to parallel the Caledonian trends. In this respect, reactivation of Caledonian thrusts on Bjørnøya as normal faults in the Palaeozoic is an important observation. These normal faults show a down-to-the-ESE throw of the basement and cover units, consistent with a reversal of the WNW thrust direction evident in the basement rocks of the island. This relationship is well established above, and is expressed by the similarity in orientation of mesoscopic Caledonian thrusts and Palaeozoic normal faults (Figs. 7C, 9B). Structural control by the basement grain on Carboniferous extension is not unique to Bjørnøya; it is documented from other onshore parts of the Barents Shelf as well (in Spitsbergen; Braathen et al. 1995).

A strong basement control on later extension may apply to the western Barents Shelf. An important pre-Devonian boundary/suture has been located north of Bjørnøya by Gudlaugsson et al. (1987), Skilbrei et al. (1990) and Skilbrei (1991), with aeromag and deep seismic data. In this work, the N-S trending Stappen High (Fig. 1B), with Bjørnøya as its highest point, is bound to the southeast and east by a fault zone that defines the western margin of the Bjørnøya Basin (Gabrielsen et al. 1990), which is approximately 4 km deep to the southeast and successively more shallow northward. The Hornsund/Knølegga Fault Complex bounds the high to the west, with appreciable Cenozoic deformation obscuring older relations. North of Bjørnøya, basement can be traced at 2–3-km depth as a high that splits into two domains separated by a distinct reflection signature at 5–10 seconds depth in deep seismic profiles (Skilbrei 1991; Skilbrei et al. 1993; Eiken 1994). From this location Gudlaugsson et al. (1987, submitted) present seismic sections that show contractional structures that affect the entire crust (located in Fig. 1A). Because of the significant extent of this deformation, they suggest it represents a moderately west-dipping suture zone related to closure of the Iapetus Ocean in Caledonian time.

If such a suture exists, then the present Bjørnøya and the Stappen High could form the western margin of westerly-directed Caledonian thrusts, whereas the Loppa High, located east of the Bjørnøya Basin (Fig. 1B), may form a domain of east-directed thrusting (Fig. 11). The possible intersection of opposite verging structures east of Bjørnøya may reflect the location of the regional westward-dipping suture(?) mentioned above, although, at the present, its location in the area is uncertain. If the two domains of the Loppa and Stappen Highs were reactivated as normal faults, then, the intermediate Bjørnøya Basin reflects subsidence along the Caledonian domain-bounding axis. This subsidence may have started in Palaeozoic time, perhaps reflecting a delayed collapse of the Caledonian thrust welt (Gudlaugsson et al., submitted), which developed further into a deep basin during a long-lasting Mesozoic extensional event (Fig. 11).

Conclusions

1. Map and outcrop scale structures indicate that a WNW-directed thrust event affected all three formations within the basement of Bjørnøya.
2. This thrust event must be between Middle Ordovician and late Devonian in age, and is therefore Caledonian, as argued by Holtedahl (1920).
3. A major thrust zone may exist within the Sørhamna metapelites of Bjørnøya's basement rocks.
4. Some of the Caledonian contractional structures were reactivated as normal faults in the Carboniferous.
5. On a more speculative note, this pattern of reactivation may have been responsible for parts of the Bjørnøya basin and its northeastward continuation, which may have initiated from Carboniferous collapse of a bivergent Caledonian welt.
6. Previous conclusions that the pre-Caledonian rocks on Bjørnøya remained unaffected by Caledonian deformation is not in accordance with our observations.

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