The structure of the Berzeliustinden area: Evidence for thrust wedge tectonics in the Tertiary fold-and-thrust belt of Spitsbergen

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The Berzeliustinden area forms part of the Tertiary fold-and-thrust belt of western Spitsbergen. The relations of a basement-involved thrust fault, décollement structures, and a fault repeating part of the stratigraphy are investigated. The deforming mechanism is thought to be 'wedging' of a basement-involved thrust block into bituminous shaly beds of the overlying strata. The thrust fault thus does not continuously cut through to the surface, but lifts the overlying strata, forming a backward directed bedding-parallel thrust fault on top of the wedge. The presence of two bituminous shale formations, both potential splitting mediums for the wedge, complicates the structures. Many structural observations from adjacent areas of the fold-and-thrust belt also fit with this model. It is suggested that thrust wedges are common tectonic elements in the belt and might also be present further east beneath the relatively undeformed Tertiary strata of central Spitsbergen.

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The Tertiary fold belt of Spitsbergen is generally considered as a segment of a major dextral transform zone formed during the opening of the Northeast Atlantic Ocean between the Barents and the Northeast Greenland Shelves in the Paleogene. Tertiary deformation in Svalbard is therefore assumed to be of transpressive origin (Harland 1969; Harland & Horsfield 1974; Lowell 1972; Birkenmajer 1972a; Kellogg 1975). However, little detailed work has been published which would yield reliable data for the interpretation of the tectonic evolution of the fold-and-thrust belt.

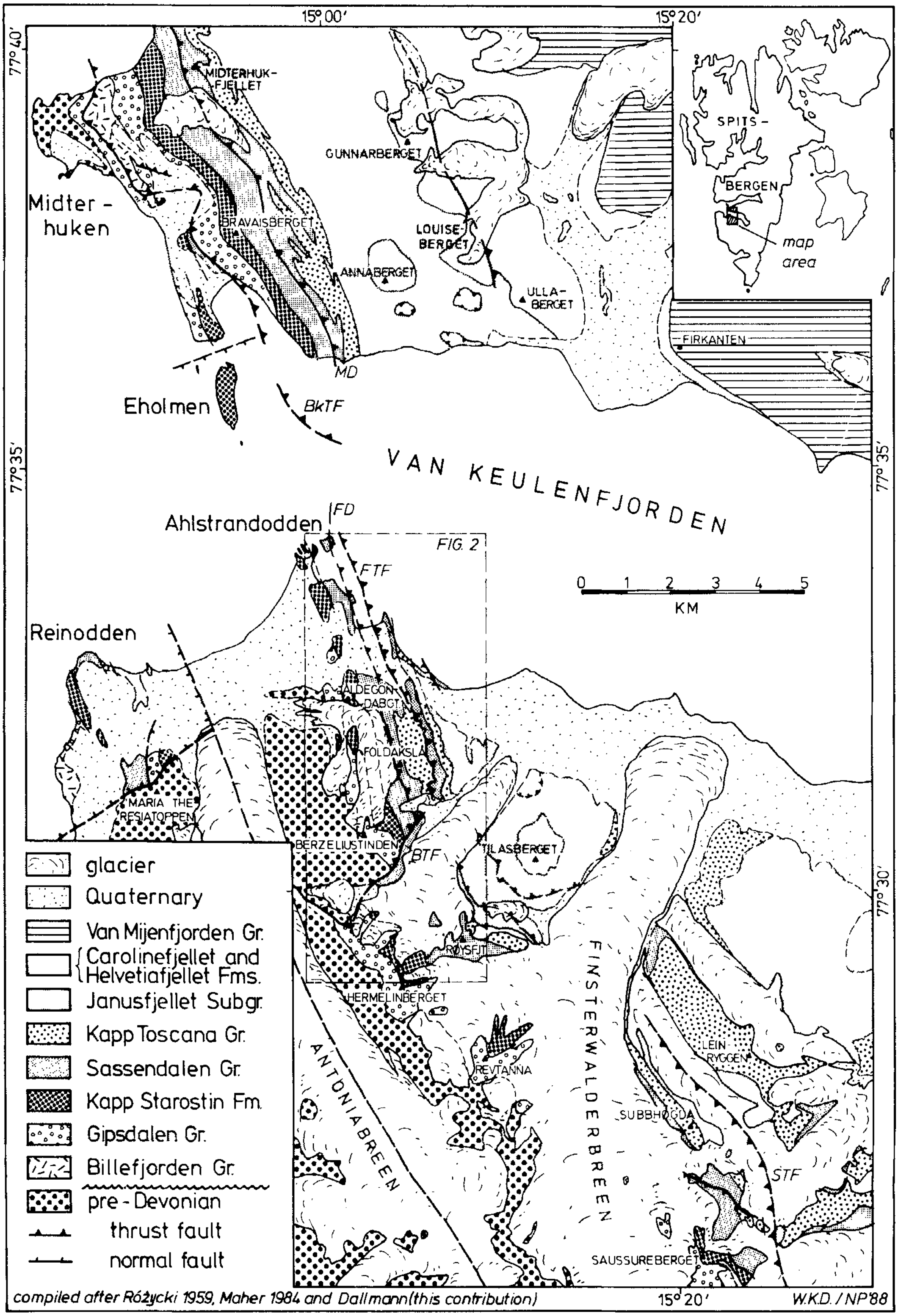
Tertiary deformation in Svalbard has also regained interest in the course of modern hydrocarbon exploration in the 1980s. Many of the results that have been gained, especially geophysical data, are still proprietary, although some of the data are now being released (Faleide et al. 1988; Nøttvedt & Rasmussen 1988; Nøttvedt et al. 1988a).

Compressive deformation is mainly accommodated by the strata underlying the Lower Cretaceous Festningen sandstone in large parts of the orogen, whereas the upper stratigraphical units do not show evidence of significant shortening. This led to the erroneous assumption that the fold-and-thrust belt is constrained to the western margin of the Tertiary Central Basin of Spitsbergen (Orvin 1940; Birkenmajer 1972a, 1981). Supported by recent field work (Andresen et al. 1988a, b; Bergh et al. 1988a, b; Haremo et al. 1988; Haremo & Andresen 1988; Nøttvedt et al. 1988b), a new understanding has evolved that eastward directed tectonic translation has affected most of Spitsbergen, in the eastern part concentrated to the major north-south trending lineaments.

With the present contribution, I want to present an analysis of a small area within the strongly deformed western part of Spitsbergen in order to investigate the operating mechanisms of displacement in the lower part of the sedimentary succession. I further want to test the applicability of the results to adjacent areas of the fold-and-thrust belt.

Regional context and previous work

The Berzeliustinden area is situated at the boundary between the mostly metamorphic Caledonian 'Hecla Hoek' complex, which forms the major part of the west coast of Spitsbergen, and the overlying cover sediments of Carboniferous to



15°00′
15°20′
77°40′
77°35′
77°30′
MIDTERHUK-FJELLET
Midter-huken
BRAVAISBERGET
GUNNARBERGET
LOUISE-BERGET
ANNABERGET
ULLA-BERGET
FIRKANTEN
MD
Eholmen
BkTF
VAN KEULENFJORDEN
Ahlstrandodden
FD
FIG. 2
FTF
0 1 2 3 4 5
KM
Reinodden
ALDEGONDABGT
FOLDAKSLA
MARIA THERESIATOPPEN
BERZELIUSTINDEN
BTF
TILASBERGET
RØYSFJT
HERMELINBERGET
REVTANNA
ANTONIABREEN
FINSTERWALDERBREEN
LEIN-RYGGEN
SUBBHØGDA
STF
SAUSSUREBERGET
SPITS-BERGEN
map area
glacier
Quaternary
Van Mijenfjorden Gr.
Carolinefjellet and Helvetiafjellet Fms.
Janusfjellet Subgr.
Kapp Toscana Gr.
Sassendalen Gr.
Kapp Starostin Fm.
Gipsdalen Gr.
Billefjorden Gr.
pre-Devonian
thrust fault
normal fault
compiled after Różycki 1959, Maher 1984 and Dallmann (this contribution)
W.K.D. / NP'88

Table 1. Stratigraphy and lithology of the post-Caledonian succession at Berzeliustinden.

+ The subdivision of the Janusfjellet *Subgroup* into Agardhfjellet and Rurikfjellet Formations (Parker 1967) is not strictly applicable to this area; the terminology of Różycki (1959) is therefore used.

++ These thickness values are taken from Różycki's (1959) section at Jurakammen (= Skiferkammen, c. 30 km SE of Berzeliustinden) because the thickness at Berzeliustinden is tectonically disturbed.

+++ This thickness value is uncertain because of the décollement tectonics within the formation. The tectonic thickness varies significantly.

AGE	STRATIGRAPHY GROUP	FORMATION MEMBER	LITHOLOGY	THICKNESS (m)	REFERENCES (VAN KEULENFJORDEN A. ADJACENT AREAS)
CRETACEOUS: ALB, APT	ADVENTDALEN GROUP	HELVETIAFJELLET FM.			BIRKENMAJER 1984, SPATZ 1983, NYSÆTHER 1966
		Glitrefjellet mb.	quartz sandstone with shale intercalations	100-120	
CRETACEOUS: B., HAUT.		Festningen mb.	quartz sandstone	~20	
CRETACEOUS: VAL., BERR.		JANUSFJELLET FM.+			BIRKENMAJER 1975, DYPVIK 1985
		Ullaberget mb.+	grey/greenish shales w. intercalated sandstone	~120++	
JURASSIC: MALM		Tirolarpasset mb.+	grey shales w. sideritic intercalations	~270++	
JURASSIC: DOGGER		Ingebrigtsen-bukta mb.+	dark argillaceous shales, bituminous	~190++	PČELINA 1970
		Brentskardhaugen bed	phosphorite conglomerate	0,5	
JURASSIC: LIAS	KAPP TOSCANA GROUP	WILHELMØYA FM.	sandstone	3	BIRKENMAJER 1972 b
TRIASSIC: RH, NO.		DE GEERDALEN FM.	sandstone w. grey shale intercalations	~130	
TRIASSIC: KA., LAD.		TSCHERMAKFJELLET FM.	grey shales	12	
TRIASSIC: ANIS.	SASSENDALEN GROUP	BRAVAISBERGET FM.	sandstone black shales	~20 (?) 200+++	BUCHAN et al. 1965, KORCINSKAJA 1971, MAHER 1987, MØRK et al. 1982
TRIASSIC: SKYTH		TVILLINGODDEN FM.	alternating sandstones and grey shales	250-300	
		VARDEBUKTA FM.	sandstone, calcareous. grey shale w. interbedded calcar. sandstone	~ 30 130-150	
PERMIAN: UP	TEMPELFJORDEN GROUP	KAPP STAROSTIN FM.	cherty lime- and dolostones, cherts	~250	CUTBILL & CHALLINOR 1965, CUTLER 1981, WINSNES 1966, NYSÆTHER 1977
PERMIAN: LOWER	GIPSDALEN GROUP	GIPSHUKEN FM.	dolostone, partly cherty	~180	
CARB		REINODDEN FM.	sandstone and conglomerate, some dolostone	~220	KLEINSPEHN et al. 1984
			WHOLE SUCCESSION:		MAHER 1984, RÓŻYCKI 1959, SUN 1980

Tertiary age, which generally dip towards the Tertiary Central Basin in the east (Fig. 1). West of this boundary, cover rocks preserved upon the down-faulted block of Reinodden (Fig. 1) and on Renardodden (W of map area) show that the post-Caledonian strata extended further west prior to the faulting event. These tensional tectonics post-date a compressional tectonic event of Paleogene age (Harland 1969; Birkenmajer 1972a). The intensity of Tertiary deformation evident from field observations decreases gradually from west to east (Orvin 1940).

Discrimination of Caledonian and Tertiary structures is difficult in the Caledonian basement. Therefore, the deformed younger strata overlying the Caledonian unconformity often have to be used to critically analyse the Tertiary movements.

The structure of the Berzeliustinden area has been described by several authors (Różycki 1959; Sun 1980; Hauser 1982). Różycki's (1959) descriptions made in 1934 were extraordinary in their time, but have to be reconsidered with our modern knowledge of fold-and-thrust belts. Sun (1980) and Hauser (1982) provided detailed structural descriptions and analyses of the Berzeliustinden area, although some of my observations diverge from theirs and lead to other genetic interpretations.

Detailed mapping and structural analysis have also been carried out in the adjacent Midterhuken area (Fig. 1) by Maher (1984) and Maher et al. (1986).

The lithologic succession summarized in Table 1 is critical for understanding the structure of the post-Caledonian strata. Detailed descriptions of the stratigraphical units of the area are provided by Różycki (1959), Sun (1980) and Maher (1984). Further references are given in Table 1.

Fig. 1. Geological map of post-Caledonian outcrops along the Tertiary Spitsbergen fold belt, from Midterhuken to south of Van Keulenfjorden. The map has been compiled from current field work and earlier maps, i.e. Różycki (1959) and Maher (1984). For time scale see Table 1.

The structure of the Berzeliustinden area

General description

The stratigraphic units represented in the Berzeliustinden area (Fig. 2) comprise parts of the Caledonian basement ('Hecla Hoek') of Precambrian age and unconformably overlying younger rocks ranging from the Upper Carboniferous to the Lower Cretaceous (Table 1). The basement rocks are mainly Proterozoic dolomites, quartzites, and greenish quartz-feldspar rocks which have been subjected to Caledonian low-grade metamorphism, whereas the younger succession is essentially unmetamorphosed, the maximum temperature being determined to 110–300°C by the conodont colour index (Hauser 1982).

The area is divided into two main structural units separated by the Berzeliustinden thrust fault (BTF). This fault has about 800 m east-northeastward displacement and is exposed on the southern and southeastern slope of Berzeliustinden (Fig. 3, 4a and 4c). In the lower structural unit the bedding dips moderately to the east-northeast, but is folded and overturned immediately below the BTF. Bedding in the upper structural unit (the Berzeliustinden thrust unit) forms an irregular open fold with steeply east-northeastward (normal) and westward (overturned) dipping limbs in the Upper Paleozoic and Lower Triassic strata (Fig. 3 and 4a). The BTF does not occur north of Berzeliustinden and is thought to be situated beneath the shore exposures at Ahlstrandodden.

To the east of the open fold, Middle Triassic to Jurassic strata are more intensively deformed. Two major faults can be observed at Foldaksla: a décollement zone in the black shales of the Middle Triassic Bravaisberget Formation and a thrust fault (FTF) above the Upper Triassic/Liassic Kapp Toscana Group repeating parts of the Bravaisberget Formation and Kapp Toscana Group (Fig. 4b). The strata overlying the décollement zone in the Bravaisberget Formation shales form open to tight folds, dependent on the thickness of the competent layers (Fig. 3 and 4b). The Bravaisberget Formation and Kapp Toscana Group are repeated along the whole eastern side of Foldaksla, and the fault in-between (FTF) is folded by the décollement. It thus clearly denotes that the décollement is younger than the FTF (Fig. 4b). This observation has not been made by previous authors and provides a different background for interpretations. The FTF is not present in any place structurally below the BTF.

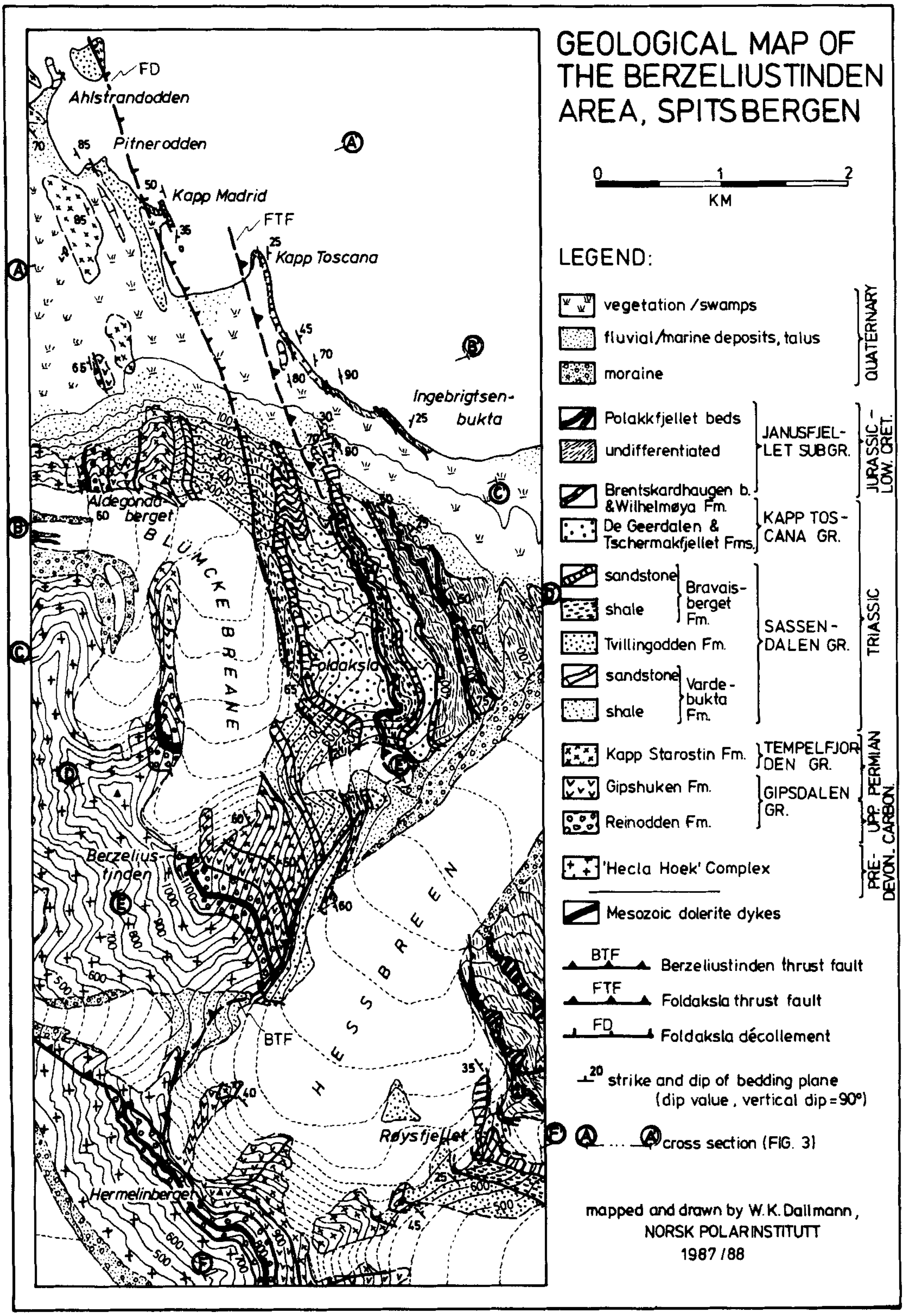
Fig. 5 presents a stereographical projection of structural elements, all measured in the post-Caledonian strata within the area of Fig. 2. The mean fold axis plunges at about 5°NNW, which is consistent with a subhorizontal mean axis which was slightly disorientated by later regional northward tilting of Southern Spitsbergen (compare map image, Winsnes 1986). Axial surface orientations are somewhat irregular, which may have a natural cause: the measured mesoscale folds are supposed to be décollement folds, which – as Fig. 3 shows – are non-cylindrical folds at regional scale. Individual mesoscale fold axes have a spread distribution. Divergent local stress fields can therefore be expected during folding (Kehle 1970). Thrust fault orientations reflect a conjugate set with an approximately W-E directed principal axis of shortening.

The Berzeliustinden thrust fault (BTF)

The BTF can easily be observed from the south on the lower slope of Berzeliustinden (Fig. 4a and 4c). In the east, it disappears beneath Quaternary talus and glacial deposits. In the west, it can be mapped in the field around the pass between Antoniabreen and Hessbreen, and then traced on air photo further down to Antoniabreen. At its southernmost outcrop, the fault plane dips at 24°NNW, but is curved and appears to have a more gentle dip (17°NNW) below the top of Berzeliustinden. As the thrust direction is supposed to be towards ENE (Fig. 5), which is agreed by all other authors (Różycki 1959; Sun 1980; Hauser 1982), it is supposed that the fault plane will approach the regional mean dip value of about 5°NNW further north and thus be situated about 200–300 m beneath the shore at Ahlstrandodden.

The concave shape along strike of the fault in the southern part, which makes the fault geometrically similar to a low-angle strike-slip fault (Hauser 1982), may imply that the original

Fig. 2. Geological map of the Berzeliustinden area. Location indicated on Fig. 1. Partly after Różycki (1959) and Sun (1980), with modifications and details by the author. The topography is taken from map sheet E11, 1:50,000, Norsk Polarinstitutt.


GEOLOGICAL MAP OF THE BERZELIUSTINDEN AREA, SPITSBERGEN
0 1 2
KM
LEGEND:
vegetation /swamps
fluvial/marine deposits, talus
moraine
QUATERNARY
Polakkfjellet beds
undifferentiated
JANUSFJELLET SUBGR.
Brentskardhaugen b. &Wilhelmøya Fm.
JURASSIC - LOW. CRET.
De Geerdalen & Tschermakfjellet Fms.
KAPP TOSCANA GR.
sandstone
shale
Bravaisberget Fm.
Tvillingodden Fm.
SASSENDALEN GR.
sandstone
shale
Vardebukta Fm.
TRIASSIC
Kapp Starostin Fm.
TEMPELFJORDEN GR.
Gipshuken Fm.
Reinodden Fm.
GIPSDALEN GR.
UPP. CARBON. PERMIAN
'Hecla Hoek' Complex
PRE-DEVON.
Mesozoic dolerite dykes
BTF Berzeliustinden thrust fault
FTF Foldaksla thrust fault
FD Foldaksla décollement
20 strike and dip of bedding plane (dip value, vertical dip=90°)
A ... A cross section (FIG. 3)
mapped and drawn by W.K. Dallmann, NORSK POLARINSTITUTT 1987/88
FD
Ahlstrandodden
Pitnerodden
Kapp Madrid
FTF
Kapp Toscana
Ingebrigtsenbukta
Aldegondaberget
BLÜMCKEBREANE
Foldaksla
Berzeliustinden
BTF
HESSBREEN
Røysfjellet
Hermelinberget

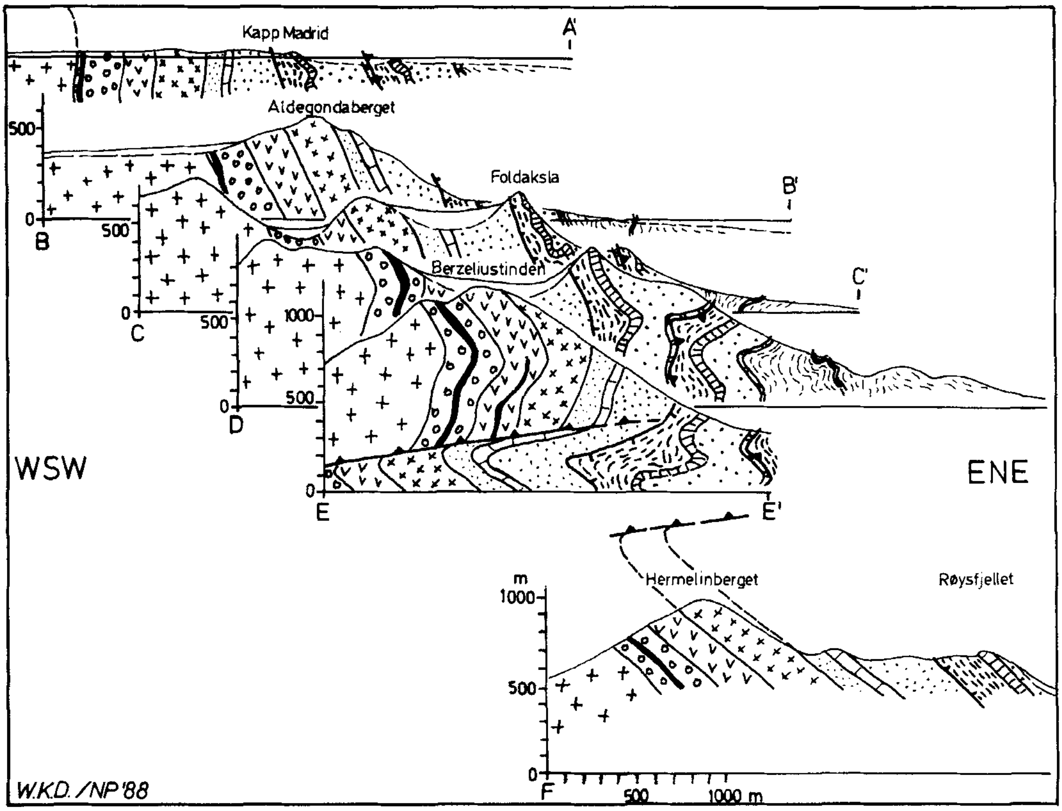


Fig. 3. Series of geological cross sections through the Berzeliustinden area. Locations indicated on Fig. 2. For legend see Fig. 2. Note that the Berzeliustinden thrust fault dips slightly northwestward – the apparent easterly dip (Fig. 4a and 4c) is a result of the oblique surface section. The structural pattern suggests that the entire mountain area is a thrust unit.

southern edge of the Berzeliustinden thrust unit was not far from this point. Alternatively, the curvature may have been caused by structural inhomogeneities at greater depth, or it may have been generated by later heterogeneous displacement along a fault, which can be suggested at greater depth (e.g. the possible northward extension of the thrust fault indicated beneath Saussureberget on Fig. 1).

The amount of displacement along the BTF has been estimated to 2 km by Hauser (1982). If, however, all structural elements are projected into a vertical plane normal to the direction of movement, the amount of displacement along the thrust can be determined to be only about 800 m in its outcrop area (Fig. 3, section E-E'). On the other hand, if the displacement accommodated by folding in both the upper and lower tectonic unit is added, the total amount of displacement is about 1.5 km.

The entire structure of the southern side of Berzeliustinden (Fig. 3 and 4a) suggests that the thrust developed within a regional, open fold, at its eastern, moderately dipping limb, as the bulk shear strength was exceeded. At the same time, antithetic minor faults developed in the most competent strata (the silica-cemented dolomites and cherts of the Permian Gipshuken and Kapp Starostin Formations). Some of these faults are rotated by later tightening of the large fold above the BTF (Fig. 4c), which obviously was a drag effect caused by movement on the thrust plane.

The drag effect was distinctly greater in the Triassic sandstones and shales below the thrust fault, where the sandstone part of the Vardebukta Formation and the overlying beds were completely inverted. Displacement along the fault plane decreases gradually towards the east, as it is compensated by folding. Although the outcrops are covered by talus and moraines further east, it

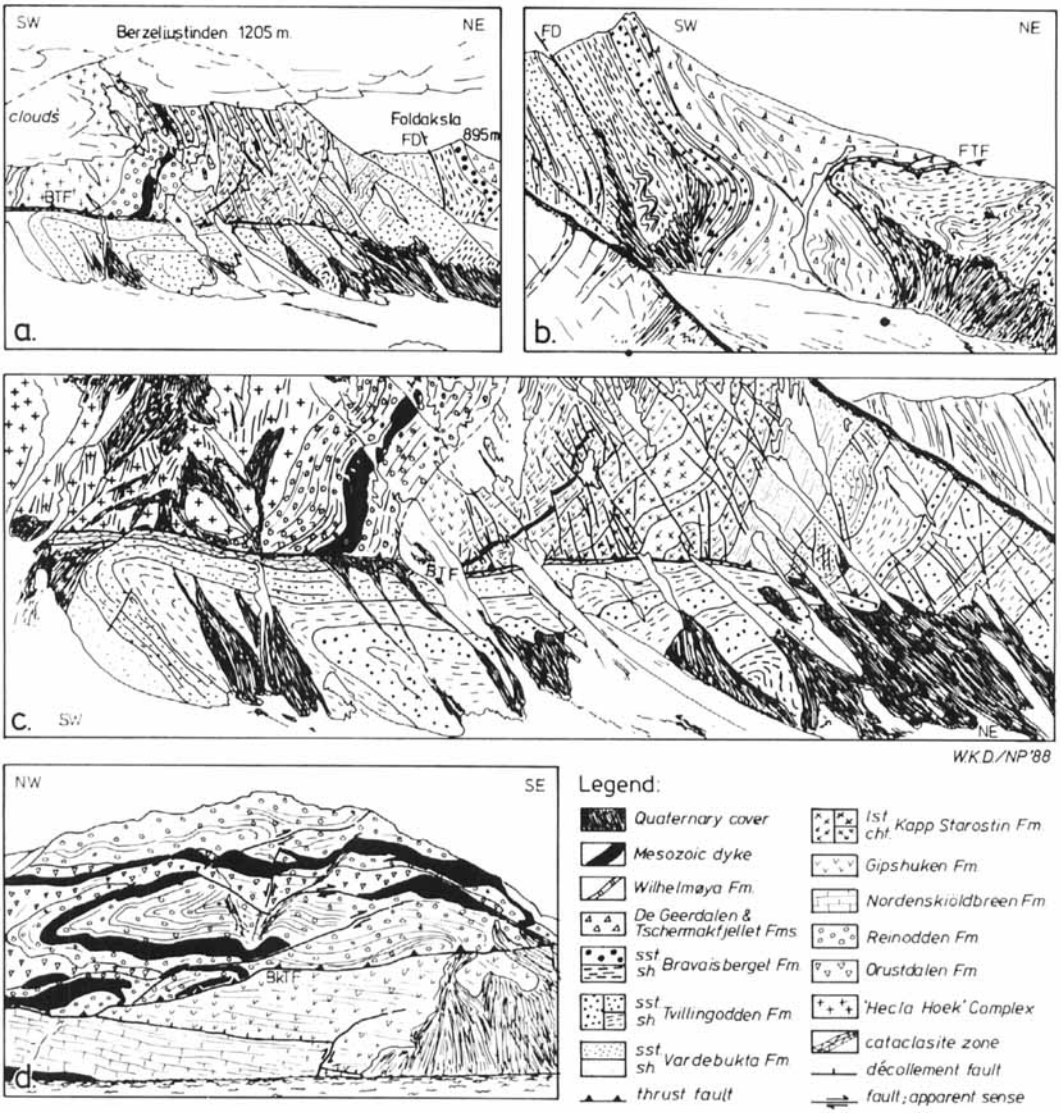


Fig. 4. Field views drawn from photographs.

a. Berzeliustiden and Foldaksla, seen from the pass between Hermelinberget and Røysfjellet in the south. Note that the apparent easterly dip of the Berzeliustinden thrust fault is due to an oblique surface section (see Fig. 3).

b. Detailed view of Foldaksla as seen from Røysfjellet, with its décollement and the stratigraphic repetition. Fold axes are about normal to the picture.

c. Detailed view of the Berzeliustinden thrust fault as seen from Røysfjellet. The most conspicuous structures are the major drag folds below the thrust fault and the set of antithetic faults which are especially well developed in the silica-cemented Permian beds (Gipshuken and Kapp Starostin Formations). Fold axes are about normal to the picture.

d. Detailed view of the Bravaisknatten thrust fault for comparison, seen from the fjord SE of Midterhuken (see Fig. 1 for location). This is a system of thrusts associated with more intense deformation of the overthrust unit – even a c. 20 m thick dolerite sill is folded isoclinally. The fold axes are subhorizontal, plunging into the picture from the right to the left (compare to Maher 1984). (The Orustdalen Fm., belonging to the Lower Carboniferous Billefjorden Group, consists mainly of sandstones and is not present in the Berzeliustinden area.)

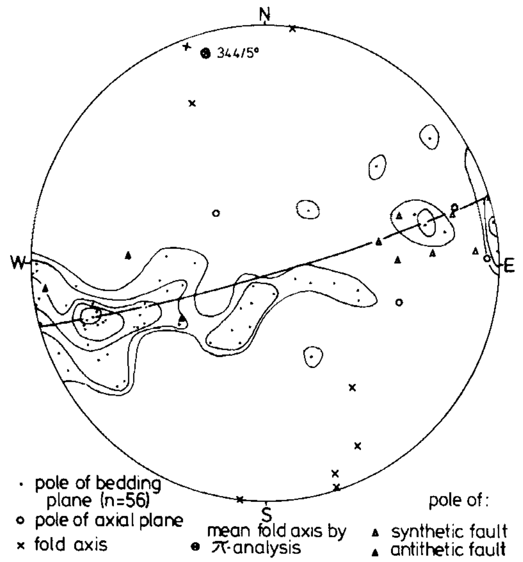


Fig. 5. Stereographical equal area projection of structural elements from the Berzeliustinden area. Contour lines indicate density of poles of bedding. All plotted elements are mesoscale structures. They show a symmetric arrangement of folds and syn- and antithetic faults indicating thrusting from WSW, and later tilting of the whole system a few degrees to the north.

can be suggested that the BTF dies out in the black shales of the Bravaisberget Formation, where displacement is totally accommodated by folding (fault-propagation folds; Suppe & Medwedeff 1984; Jamison 1987) and internal shear zones in the shales. The capacity of these shales to undergo this type of deformation is confirmed in the décollement zone described below.

The Foldaksla thrust fault (FTF) and the décollement zone

The structural elements described in this section have only been observed in the tectonic unit overlying the Berzeliustinden thrust fault, i.e. they do not appear southeast of Hessbreen. However, décollement structures comparable with the one at Foldaksla have also been observed on other structural levels in other areas, e.g. on Midterhuken (Maher 1984; Maher et al. 1986) and at Saussureberget and even further south (for localities see Fig. 1).

The most striking characteristic of the FTF is the fact that it repeats parts of the stratigraphy without stratigraphical inversion. From west to east, sandstones of the Wilhelmøya Formation and then the Brentskardhaugen Bed are overlain by black shales of the Bravaisberget Formation, which here are apparently thinner and vary in structural thickness along strike. Both the Bravaisberget Formation and the Kapp Toscana Group are repeated. The stratigraphic succession continues with the Janusfjellet Formation (Fig. 3 and 4b).

While Różycki (1959) did not notice this repetition, Sun (1980) and Hauser (1982) did. They mapped, however, the fault as a straight, steeply eastward-dipping reverse fault, with the hangingwall forming an upward directed ramp on the footwall, and hence interpreted the structure as a backthrust in front of the Berzeliustinden thrust unit.

Bedding traces cannot be observed from the northern side of Hessbreen. From Røysfjellet, south of Hessbreen, however, one has a good view of the whole mountain side of Foldaksla (Fig. 4b), and it appears clearly that the FTF follows the bedding concordantly around the décollement folds. The same observation can be made from Kapp Toscana on the northern side of Foldaksla, and it is confirmed by careful mapping along the eastern mountain side.

Nevertheless, there is some evidence that the structure really is a backthrust. There is no indication along the thrust itself, but it can be assumed from regional associations. If thrusting along the FTF would have been from the west, then the thrust would be older than the BTF and would have developed independently. It would then be difficult to accept the coincidence that the FTF does not continue southward to Røysfjellet, but terminates in the same place as the BTF.

On the other hand, the local orientation of cleavage in the Bravaisberget Formation black shales at Kapp Toscana in the vicinity of the fault indicates some eastward shear (Sun 1980; Hauser 1982). It is uncertain, however, if this shear is related to the FTF or the later décollement folding.

After the cessation of thrusting along the FTF, a décollement developed in the western occurrence of the black shales of the Bravaisberget Formation. Both on the northern and southern slopes of Foldaksla, the underlying sandstones of the Tvillingodden Formation are unfolded, whereas the overlying strata form open to tight folds (Fig. 4b). The minor folds in the décollement zone, i.e. the black shales, show an acute angle upward with the thrust direction. This vergence suggests up-dip transport and thus a backthrust direction also in this case. The large folds at higher levels to the east show varying axial and axial plane orientations, probably due to the superposition of different senses of movement in the décollement zone (e.g. westward-up backthrust and eastward-down gravity displacement).

A similar décollement has been described in a higher tectonic unit on Midterhuken by Maher (1984) and Maher et al. (1986). The orientation of drag folds in the underlying Tvillingodden Formation points to a westward-up backthrust movement also here. Nevertheless, these authors preferred the interpretation of gravity-induced eastward-down movement, mainly based on the observation of fragments of a dolerite dyke, which have been displaced this way in the lowermost part of the décollement zone. It is probable also here that both movements are superimposed.

Structural evidence from the Janusfjellet Formation

Exposures in the black shales of the Janusfjellet Formation are mostly of poor quality, but the structure of the shales can be studied in some places along the shores of Van Keulenfjorden. In Ingebrigtsenbukta, a complex system of shear zones involving duplex structures at the 100 m-scale appears in the middle part of the shales, approximately at the boundary between the Ingebrigtsenbukta and Tirolarpasset Members (compare Table 1). These structures are eastward vergent and suggest some tectonic transport towards the east.

At Ullaberget and Louiseberget on the northern side of Van Keulenfjorden (Fig. 1) the uppermost beds of the Janusfjellet Formation form drag folds, well visible from the fjord, towards the overlying sandstones of the Helvetiafjellet Formation. These drag folds are westward vergent suggesting a backward directed sense of simple shear between the Helvetiafjellet Formation sandstones and the Janusfjellet Formation shales. At Louiseberget, Maher (1984) observed a backthrust within the upper levels of the Janusfjellet Formation. Even the southern trace of the Gunnarberget Fault (Fig. 1), which is not entirely understood, is a backthrust, as recent field work revealed (partly H. D. Maher pers. comm. 1988).

Southeast of the Berzeliustinden area, between Røysfjellet and Tilasberget (Fig. 1), one or two major backthrusts are situated within the Janusfjellet Formation, one of them indicated by the offset of the Polakkfjellet sandstone beds (Fig. 2) associated with west vergent asymmetrical folds. In the lower section of the Janusfjellet Formation in this area, folds with easterly vergence have also been mapped.

Although these exposures belong to other structural units, where tectonic movement along the Bravaisknatten thrust fault or Saussureberget thrust fault, respectively, might have been responsible for the deformation, these structures document that thrusting in the lower strata is compensated by shear zones within the Janusfjellet Formation shales. These shear zones have mainly a synthetic sense of shear in the lower part of the formation, and an antithetic sense of shear in the upper levels.

Discussion of the structural development

Mechanisms of deformation

A satisfactory mechanical model for the Berzeliustinden thrust unit must be expected to explain the properties derived from the above observations, which are summarized below:

1. The lower boundary of the unit is a basement-involved thrust fault, which has developed from a moderately dipping limb of an antiform, and which apparently does not cut through to the surface.
2. The upper boundary of the unit has been developed by two faults, which have been active one at a time. They show mainly an antithetic sense of movement (backthrusting), although at least one of them, a décollement, suggests a superimposed opposite sense of movement (gravity?).
3. Backthrusting happened within black shale formations (Bravaisberget and Janusfjellet Formations), which have a distinctly lower shear strength than the adjacent formations.
4. Thin competent layers (sandstones of Bravaisberget Formation and Kapp Toscana Group) situated between tectonically active black shale zones are deformed by décollement tectonics.
5. The thick, competent formations (Helvetiafjellet Formation, etc.) overlying the black

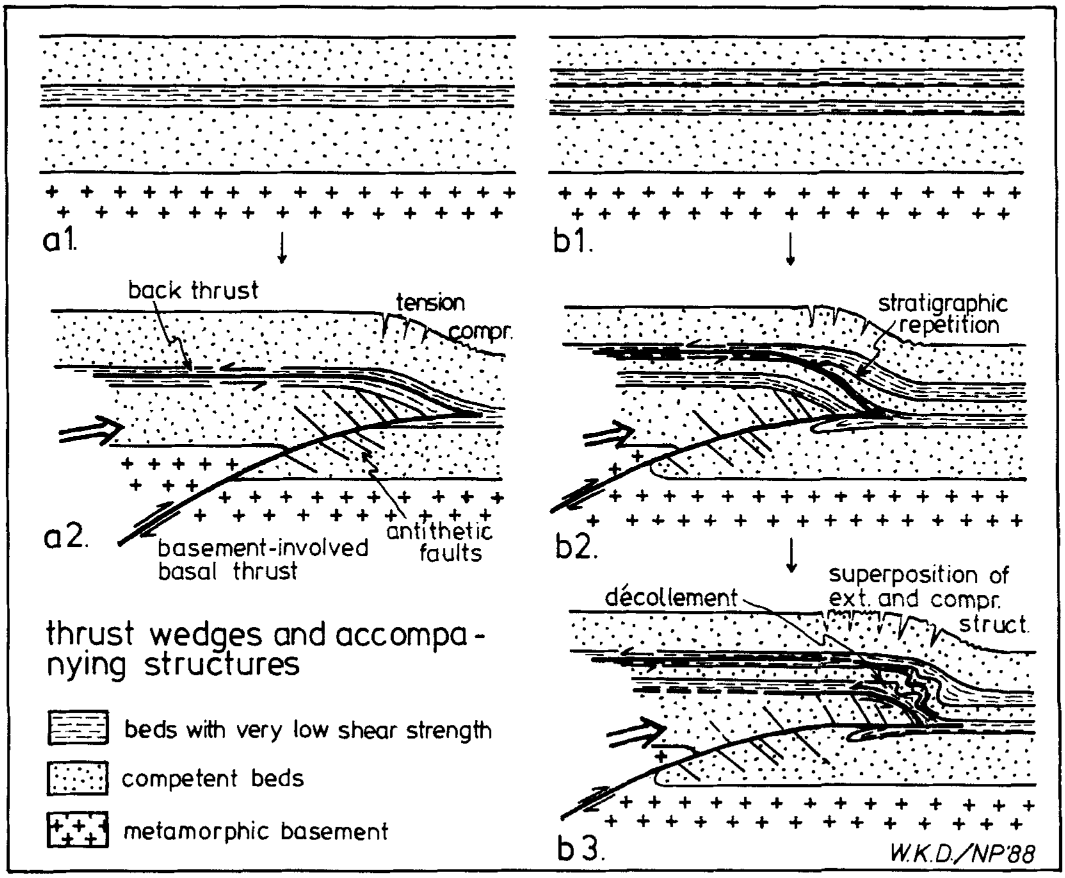


Fig. 6. Sketch illustrating the model of thrust wedge propagation and the resulting structures.
a1. Initial situation for the simple case.
a2. A basement-involved thrust turns parallel to bedding in a bituminous shale layer because of the low competence of this sediment. The overlying competent strata are lifted, and a backthrust forms between the thrust wedge and its cover.
b1. Initial situation for the more complicated case applicable to the Berzeliustinden area with two bituminous shale layers.
b2. During thrust wedge propagation the backthrust may repeat the more competent parts of the stratigraphy by ramping from the lower to the upper incompetent layer.
b3. During further propagation, the two shale beds may alternatingly accommodate the backthrust on top of the wedge giving rise to décollement surfaces.

shales which accommodate the backthrusts are only weakly deformed by open folds and superimposed minor extensional and compressional faults.

Modern review papers on marginal fold-and-thrust belts (e.g. Boyer & Elliott 1982) commonly show thrust units either with a basal thrust fault ascending to the surface, or roofed by another synthetic thrust fault. Backthrusts occur commonly in connection with synthetic thrusts to form pop-up structures (Elliott 1981; Butler 1982), likely as conjugate sets of thrust faults.

The most striking differences in the present case are that there has not been observed a synthetic thrust which cuts the strata overlying the Janusfjellet Formation black shales. Backthrusts in the Berzeliustinden area are mostly subparallel with bedding, but may dissect more competent beds interlayered with black shales (the Bravaisberget Formation sandstones and Kapp Toscana Group, which are repeated above the FTF). These properties require a mechanical model where the stresses causing the shortening observed in the lower strata are mainly transmitted to the hinterland side (west) of the thrust unit in the upper strata.

Such a mechanism requires formations within the cover sequence that have low shear strengths. Two primary situations meeting these requirements are shown schematically in Fig. 6a1 and 6b1, consisting of a metamorphic basement, a lower competent sedimentary layer, one or two incompetent layers, and an upper competent layer, the strength of which has to be significantly higher than that of the incompetent one.

A thrust fault generated within the basement will first cause uplift and flexure of the cover rocks, and then prograde into the cover sequence (e.g. Rodgers & Rizer 1981). When the edge of the lower competent layer is thrust into the incompetent layer, the thrust will tend to turn parallel to bedding within the latter instead of prograding into the upper competent layer, provided that the angle between the fault and the bedding is low enough (Fig. 6a2). As the critical angle depends on the differential shear strength of the layers, this behaviour is favoured in cover sequences containing layers with a very low shear strength, such as bituminous shales or evaporites. As the thrust progrades, the upper competent layer is lifted up. The thrust unit thus only consists of the basement and the lower part of the cover, forming a wedge splitting up the strata in front. Above the thrust unit, a décollement zone with an opposite shear direction (backthrust) develops within the incompetent layer. As the dip of this décollement zone may be moderate or steep in front of the wedge, gravity-induced structures may easily develop here complicating the structure of the décollement zone, possibly showing evidence of 'thrusting' into both directions. Minor extensional and compressional faulting may develop in the upper competent layer associated with uplift and flexure (Fig. 6a2). Further propagation of the thrust unit will cause dislocation of these flexures and thus lead to superposition of extensional and compressional structures.

If the stratigraphic succession contains more than one layer with a very low shear strength (Fig. 6b1), the process may start as described above. If, however, the competent layer in between is thin enough in relation to its shear strength, it may be dissected by the backthrust as soon as its dip in front of the wedge is steepening. In this way, the strata between the two shear zones can be repeated (Fig. 6b2). Gravity-induced structures may develop in front of the edge of the thrust unit, where a thin competent layer is situated between two incompetent units acting as décollement zones (Fig. 6b3).

Observations made in the Berzeliustinden area can be explained by this model, without interpreting thrust structures dissecting units where none have been observed (Fig. 7). The inferred sequence of events is as follows:

1. Uplift of a basement antiform in the west is followed by rupture and eastward thrusting along the Berzeliustinden thrust fault (B). Initially, the thrust may have continued into the Bravaisberget Formation black shale (B_1). Note that there are no continuous gypsum layers in the Gipshuken Formation in the Berzeliustinden area which could act as gliding horizons at a lower stratigraphical level.

2. The backthrust on top of the wedge (F) dissects the Bravaisberget Formation sandstone and the Kapp Toscana Group and thus forms a ramp from the lower (Bravaisberget) to the upper (Janusfjellet) black shale formation.

3. Later on, a décollement zone developed in the Bravaisberget Formation shale (D), folding the repeated sequence between the shale formations. This might partly be controlled by backthrusting, and partly by gravity. The interaction of both mechanisms would be able to produce both eastward and westward vergent structures.

4. The regional folding of the whole area, which initially gave rise to the basement antiform, might have continued during or after this main stage of thrusting. That would at least explain the very low angle of the BTF, and the very steep orientation of the backthrusts, which suggest later eastward rotation. This regional folding resulted in a geometrical configuration, which prevented further propagation of the thrust wedge.

5. Continued thrusting along the BTF was now accommodated by fault-propagation folds in the strata in front of the former wedge. In the Janusfjellet black shales, thin-skinned deformation could proceed due to the low shear strength, forming eastward directed thrust systems in the prolongation of the BTF (I), and a backthrust at the boundary to the overlying Helvetiafjellet sandstones (U).

In and around the BTF, a total of about 1.5 km displacement can be observed. This amount has to be compensated by deformation in the overlying sedimentary cover. The total amount of backthrusting cannot be calculated from the collected data, but the projection of data into vertical

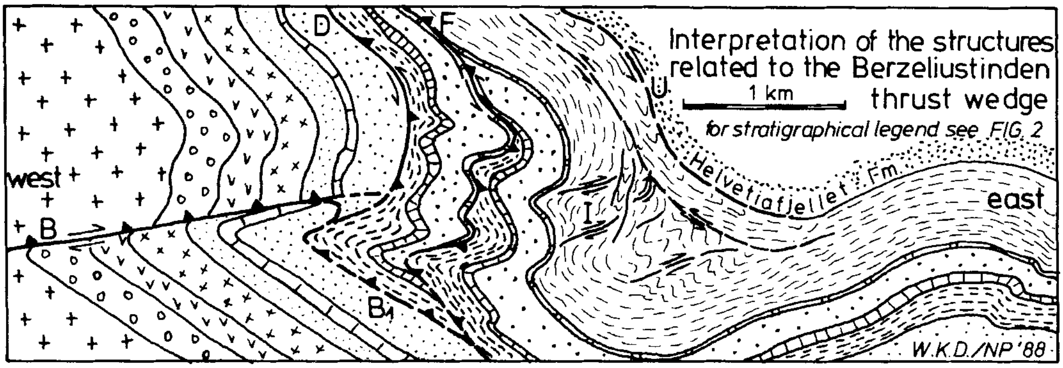


Fig. 7. The Berzeliustinden area interpreted in terms of the thrust wedge model. B: Berzeliustinden thrust fault (base of wedge); B_1: initial continuation of B, inactive during later stages of movement; F: Foldaksla thrust fault, a backthrust repeating the Triassic Bravaisberget Formation and Kapp Toscana Group that was inactive during later stages of movement; D: Foldaksla décollement, active after cessation of movement on F; I: Ingebrigtsenbukta thrust system (drawn schematically), accommodating deformation in the Janusfjellet Formation (black shales and siltstones) during late stages, when the basal thrust (B) stopped in the Lower Triassic, and the Middle and Upper Triassic strata were folded; U: possible backthrust at the base of the Helvetiafjellet Formation as observed in another tectonic unit at Ullaberget and Louiseberget (for location see Fig. 1).

cross sections (Fig. 3) indicates that the FTF has undergone at least 1 km of displacement. As there is evidence of backthrusting also in other zones, not much of the displacement was transmitted eastward. Wedging is proposed as the main deformation mechanism in the Berzeliustinden area.

Regional synthesis

The Berzeliustinden thrust unit is one of several basement-involved thrust units along the boundary between the Caledonian basement and the post-Caledonian platform strata from Midterhuken southward to Hornsund (Różycki 1959; Dallmann 1988). The northernmost unit is exposed above the eastwardly inclined Bravaisknatten thrust fault (BkTF) on Midterhuken (Fig. 1 and 4d; Maher 1984; Maher et al. 1986), which extends northward from Midterhuken into Nordenskiöld Land.

The Berzeliustinden thrust unit appears on Midterhuken beneath the BkTF and extends southward to the Berzeliustinden area. Beneath it, the Saussureberget thrust unit is exposed from there southward to Saussureberget (Fig. 1). The structurally lowermost thrust fault has different characteristics, as it can be traced over a greater distance of c. 40 km from Passhatten (S of Saussureberget) down to the Hornsund area. Along its length, the Caledonian basement rocks (or locally overlying Permo-Carboniferous rocks) are thrust onto Triassic strata, which locally are inverted close to the thrust fault (Różycki 1959; Birkenmajer 1964).

The Midterhuken, Berzeliustinden and Saussureberget thrust units all have in common that their basal thrusts apparently do not cut through to the surface, that the Bravaisberget shales act as a décollement zone, and that the Janusfjellet shales are deformed by considerable tectonic shear. It is suggested that all three units may form similar tectonic wedges, whose north-south extensions (lateral overlap), however, are not known.

As mentioned above, southern Spitsbergen is tilted to the north-northwest at an average angle of 1°. Continuously lower structural levels of the Tertiary fold-and-thrust belt are therefore exposed to the south. Altogether c. 1 km difference of structural depth is exposed from nortn of Bellsund to Hornsund. The changing properties of the individual thrust faults must therefore be regarded as a function of depth (Dallmann 1988).

A striking trend is that the basal thrusts of the individual tectonic units dip at increasingly lower angles from south to north, i.e. structurally upward. The northernmost one, the BkTF, is even tilted towards the east. This may infer a prograde rotation of the faults, each one being rotated during emplacement of the underlying tectonic wedge. Chronologically, that would mean that thrusts are increasingly younger from top to bottom (N to S), the oldest thrust fault (BkTF) being rotated most of all. This is consistent with the fact that deformation seems to be more ductile in the BkTF than it is in the BTF. The relatively competent strata of the Orustdalen and Reinodden Formations (sandstones, conglomerates, and some dolostones) and even a dolerite sill are folded isoclinally in connection with the BkTF (Fig. 4d; Maher 1984), whereas the same lithologies started to be fractured at much lower strain (Fig. 4c) at Berzeliustinden.

A system of NNW-SSE trending syn- and antiforms to the east of the thrust units (Różycki 1959) may be the response (fault-propagation folding) to similar wedges at lower structural levels, which do not reach the present level of erosion. The existence of such wedges underlying the western part of the Central Basin of Spitsbergen seems to be confirmed by seismic sections (Faleide et al. 1988; Nøttvedt & Rasmussen 1988). These tectonic wedges are believed to be the cause of the westward increasing uplift of the western flank of the Central Basin.

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