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Structural Evolution of the Tertiary West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya, NW-Spitsbergen

By Kerstin Saalmann[1] & Friedhelm Thiedig[2]

THEME 6: Eurekan Tectonics in Canada, North Greenland, spitsbergen: Fold Belts Adjacent to Extensional Ocean Basins

Summary: The Tertiary Fold-and-Thrust Belt on Brøggerhalvøya is characterized by a pile of nine thrust sheets. The lower nappes consist predominantly of Late Palaeozoic and Tertiary sediments, and the thrusts follow staircase trajectories. Additionally, they involve slices of the pre-Devonian basement. The basal sole thrust of the nappe stack climbs up-section to the NE and is inferred to crop out in Kongsfjorden. The lower nappes are overlain by four basement-dominated thrust sheets bounded by more steeply-dipping listric thrust faults. Two thrust sheets in the middle part of the nappe stack contain the syncline and anticline, respectively, of a km-scale NE-vergent fold structure. The internal deformation in the nappes is concentrated mainly adjacent to the thrust planes and is characterized by small-scale fault-related folds, duplex structures and imbricate fans.

A three-stage kinematic model is proposed: The first stage involves bedding-parallel movements leading to in-sequence foreward propagating fold-thrust evolution with ramp-flat geometries. It is followed by first out-of-sequence thrusting associated with inversion and uplift of the basement in the hinterland and formation of the km-scale fold structure causing folding and rotation of the stage-1 detachments. During the third stage the km-scale fold is eventually truncated by thrust faults in relation to the stacking of the highest basement-dominated thrust sheets by hindward propagating out-of-sequence thrusting.

The basal sole-thrust of the nappe stack coincides with the assumed position of the Kongsvegen Fault which represents a major old lineament. The curvature of the structural trend from NNW-SSE in southern segments of the West Spitsbergen Fold-and-Thrust Belt to WNW-ESE strike on Brøggerhalvøya and NE-directed thrusting is interpreted to be controlled mainly by oblique ramping on the Kongsvegen Fault. This suggests that the Tertiary deformation is partly controlled by the reactivation of pre-existing structures.

INTRODUCTION

The West Spitsbergen Fold-and-Thrust Belt is exposed for 300 km in western Spitsbergen from Sørkapp in the south to Kongsfjorden in the north (BIRKENMAJER 1981; DALLMANN et al. 1993). It is considered to have been formed due to dextral transpression (HARLAND 1969, LOWELL 1972, HARLAND & HORSFIELD 1974, KELLOGG 1975, STEEL et al. 1985) in response to the opening of the North Atlantic and Arctic Oceans and the separation of Greenland and Svalbard during the Eocene (ELDHOLM et al. 1987). Later structural studies, however, indicated that the fold belt is clearly convergent (e.g. MAHER et. al. 1986, DALLMANN & MAHER 1989, MANBY 1988, BERGH & ANDRESEN 1990, DALLMANN et al. 1993; LYBERIS & MANBY 1993a,b, BRAATHEN & BERGH 1995, BRAATHEN et al. 1995, MANBY & LYBERIS 1996, GOSEN & PIEPJOHN in press, GOSEN et al. in press, PIEPJOHN & GOSEN in press) showing compressional structures of typical foreland fold-and-thrust belts rather than en echelon folds and strike-slip faults. In this connection, the anomalous transport directions to the NNE-NE instead to the ENE on Brøggerhalvøya in the northernmost exposed part of the fold belt are of particular interest. This is considered by KELLOGG (1975) as evidence for a transpressive origin of the fold belt. In their model of a decoupled transpression, MAHER & CRADDOCK (1988) propose that the Brøggerhalvøya may represent a wedge shaped mobile zone where the deformation is still coupled in contrast to the decoupled areas further to the south.

Previous work on the structure of this area has been carried out by HOLTEDAHL (1913) and ORVIN (1934) followed by BARBAROUX (1966), CHALLINOR (1967), MANBY (1988), PIEPJOHN et al. (in press b) and THIEDIG et al. (in press). Since 1986, detailed mapping was done by students of the Hamburg and Münster universities directed by F. Thiedig.

The aim of this study is to give a brief overview on the structural geometry of the nappe stack and to present a kinematic model which also explains the anomalous transport directions in this area.

GENERAL STRATIGRAPHY

The pre-Devonian basement consists of mica schists, phyllites, marbles, and minor gneissose units of the Precambrian (HARLAND et al. 1979, LOSKE 1989, TAPPE 1989, HARLAND et al. 1993, THIEDIG et al. in press) which suffered a polyphase structural and metamorphic overprint during the Caledonian orogeny (SAALMANN 1999).

The post-Caledonian cover consists predominantly of Late Palaeozoic rocks. In the investigated area, the Early Carboniferous Orustdalen Formation only occurs at the southwestern coast of Brøggerhalvøya, a single outcrop is located at Kulmodden (Fig. 2). The Middle Carboniferous Brøggertinden Formation was deposited in a N-S trending major halfgraben (St. Jonsfjorden Trough, CUTBILL & CHALLINOR 1965). It is dominated by coarse clastic sediments and intercalated with

[1] J. W. Goethe-Universität Frankfurt a. M., Senckenberganlage 32-34, D-60054 Frankfurt a. M., <saalmann@em.uni-frankfurt.de>

[2] Steinkamp 5, D-22844 Norderstedt, <friedhelm.thiedig@t-online.de>

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shales and limestones (Fig. 1). Lateral facies and thickness variations (ranging from 10-300 m) were attributed to syn-depositional normal faulting (LUDWIG 1988). N-S to NW-SE oriented lineaments have affected the sedimentation patterns of the Carboniferous deposits in Svalbard (GJELBERG & STEEL 1981, STEEL & WORSLEY 1984). A reconstruction of the pre-Tertiary configuration of the Brøggerhalvøya area by means of restoration of the Tertiary thrust tectonics indicate the existence of NW-SE in addition to N-S striking lineaments (SAALMANN 1999). The northeastern basinal margin of the St. Jonsfjorden Trough is represented by a NW-SE striking fault in the Kongsfjorden (STEEL & WOPRSLEY 1984, their Fig. 10) which follows the Kongsvegen Fault of HARLAND & HORSFIELD (1974).

The Scheteligfjellet Formation (Late Carboniferous), predominantly carbonates, is also restricted to the St. Jonsfjorden Trough, though it marks the transition to the stable platform conditions of the overlying Wordiekammen, Gipshuken and Kapp Starostin formations.

Mesozoic deposits are almost absent on Brøggerhalvøya except for relics of Early Triassic dark shales (CHALLINOR 1967) which merely occur in the Ny-Ålesund area where they are overlain by Tertiary deposits. Except for small remnants on Scheteligfjellet and to the northeast of Slåttofjellet, Tertiary strata are only preserved in the basinal structure to the south of Ny-Ålesund. They include a succession of up to 300 m thick conglomerates, sandstones, shales and coal seams (ORVIN 1934, MIDBOE 1985).

STRUCTURE

The structure of Brøggerhalvøya is characterized by a NE-vergent nappe stack (BARBAROUX 1966, CHALLINOR 1967, MANBY 1988, PIEPJOHN et al. in press b; Thiedig et al. in press). BARBAROUX (1966) already distinguished five thrust sheets, seven or nine nappes were established by MANBY & LYBERIS (1996) and PIEPJOHN et al. (in press b), respectively (Fig. 2). An additional thrust sheet named Forlandsundet nappe in this paper is exposed to the south of Brøggerhalvøya west of Comfortlessbreen (Fig. 2).

In the western part of the peninsula, five sediment-dominated nappes are exposed which are separated by the N-S trending Scheteligfjellet Fault (= Schetelig Fault of ORVIN 1934) from the structurally higher basement-dominated thrust sheets in the east (Fig. 2). The Scheteligfjellet Fault is proposed to be a transfer fault (MANBY 1988, PIEPJOHN et al. in press b). Definitely, the fault shows a multiple phase activity. This is indicated by the absence of the Nielsenfjellet and Bogegga thrust sheets to the west of the Scheteligfjellet Fault (Fig. 2).

The nappe stack can be divided into three structural units:
1) The Garwoodtoppen to Kiærfjellet nappes of the lower part are exposed mainly in the western part of the peninsula and consist predominantly of post-Caledonian cover sediments. However, except for the Garwoodtoppen nappe, the involvement of slivers of the Caledonian basement indicate a thick-skinned tectonic style. The thrusts branch off a major basal

Brøggerhalvøya (St Jonsfjorden Trough)								Lithology
Tertiary	? Paleocene ?		Van Mijenfjorden Gp	Ny-Ålesund Subgroup	Brøggerbreen Fm	Bayelva mb	≥160 m	conglomerates, sandstones, shales; coal seams
						Leirhaugen mb	5 - 20 m	
					Kongsfjorden Fm	Tvillingvatnet mb	25 - 70 m	
						Kolhaugen mb	0 - 40 m	
Cretaceous Jurassic					HIATUS eroded			
Triassic	Early		Sassendalen Gp		Vardebukta Fm		50 m	dark shales
Permian	Late	Tatarian			no sedimentation			
		Kazanian Kungurian	Tempelfjorden Group		Kapp Starostin Fm		230 m	cherts, silicified limestones; top: glauconitic sandstones
	Early	Artinskian	Gipsdalen Gp	Charlesbreen Subgroup	Gipshuken Fm	Dolomit mb	30 - 140 m	laminated dolomites
						Kloten mb		carbonate breccia with laminated dolomite and limestone clasts
		Sakmarian Asselian			Wordiekammen Fm	Tyrrellfjellet mb	140 m	alternation of dolomites and limestones, partly silicified, with abundant cherty nodules
Carboniferous	Late	Gzhelian Kasimovian				Mørebreen mb	150 m	
		Moscovian			Scheteligfjellet Fm		8 - 120 m	limestones, dolomites; sandstones and siltstones
	(Middle)	Bashkirian			Brøggertinden Fm		13 - 300 m	conglomerates and sandstones; in the upper part intercalated with limestones and dolomites
	Early		Billefjorden Gp		Orustdalen Fm		100 - 225 m	sandstones, quartzarenites, litharenites, conglomerates
Devonian					HIATUS			
					pre-Devonian basement			

Fig. 1: Stratigraphic table of the post-Caledonian cover sediments on Brøggerhalvøya (After CUTBILL & CHALLINOR 1965, CHALLINOR 1967, MIDBØE 1985, LUDWIG 1988, SIDOW 1988, WUTHENAU 1988, WEBER 1990, BROMMER 1994, SAALMANN 1995, DALLMANN (ed.) in press). Note that on Brøggerhalvøya the Gipshuken Formation consists of a calcareous breccia and laminated dolomites and lacks gypsiferous beds reported from other localities. Important detachments are located in the Wordiekammen and Gipshuken formations.

detachment within the phyllites of the pre-Devonian Nielsenfjellet Formation and cut up-section to the NE along staircase trajectories (Fig. 3). The flats are predominantly located in the limestones and dolomites of the Wordiekammen and Gipshuken formations. Subordinate reverse faults within the Kongsfjorden, Kvadehuken, and Kiærfjellet nappes gave rise to intense folding and imbrication. These narrow deformation zones consist of fault-related folds, pop-up structures, imbricate fans and duplex structures (Fig. 4a). Prominent outcrops occur in the Kvadehuken nappe striking parallel to the southwestern coast of Brøggerhalvøya (Leinstranda, Kiærstranda).

2) The Ny-Ålesund and Nielsenfjellet nappes in the middle part of the nappe stack differ from the other thrust sheets in containing the syncline and anticline, respectively, of a km-scale NE vergent fold structure (Fig. 3). However, due to erosion the Nielsenfjellet nappe is only preserved to the east of the Scheteligfjellet Fault (Fig. 2). The anticlinal structure can be observed to the north of Haavimbfjellet where overturned Carboniferous beds rest on basement rocks (Ludwig 1988, Saalmann & Brommer 1997, Piepjohn et al. in press b) (Fig. 3, section D-D').

The internal deformation of the nappes is remarkably weak. Merely within the Ny-Ålesund nappe, adjacent to Austre Brøggerbreen to the west of Zeppelinfjellet, a broad imbricate zone within the Late Palaeozoic strata is exposed. It is associated with the Zeppelin Thrust (Orvin 1934) which represents a subordinate reverse fault within the Ny-Ålesund nappe north of Zeppelinfjellet and Sherdahlfjellet (Fig. 2) carrying steeply-dipping Late Palaeozoic rocks on Tertiary sediments of the Ny-Ålesund basin (Orvin 1934, Midbøe 1985, Saalmann et al. 1997, Piepjohn et al. in press a). It splays into several thrust faults giving rise to intense shearing and fracturing of the rocks. To the west of the Scheteligfjellet Fault, the Ny-Ålesund nappe is preserved as a tectonic klippe (Fig. 2). At Kiærfjellet and Brøggerfjellet in the southwestern part of the peninsula, the basal thrust of the Ny-Ålesund nappe, the Ny-Ålesund Thrust, is tilted and dips to the NE (Fig. 2, Fig. 3 sections A-A', B-B'}. On the other hand, in the north, the thrust dips gently to the SW indicating that the thrust plane is curved and involved in folding (Challinor 1967, Wuthenau 1988, Piepjohn et al. in press b).

3) The basement-dominated thrust sheets in the eastern and southern part of Brøggerhalvøya are bounded by more steeply dipping reverse faults. In schistose lithologies, Tertiary thrust faults can best be identified with the help of fault-bounded slivers of Carboniferous sediments. The dolomite marbles north of Engelskbukta show imbricate fans, mesoscale folds and duplex structures which resemble thrust-related structures in the Late Palaeozoic carbonates and differ markedly from pre-Devonian (Caledonian) ductile deformation of these rocks. Therefore, they are thought to be related to the Tertiary thrust tectonics. Like in the sediment-dominated nappes, the internal deformation of the crystalline thrust sheets is weak and the strain is concentrated mainly adjacent to the thrust planes, though many subordinate faults within the thrust sheets may escape ones notice and pre-Devonian cleavage planes may have accomodated large amounts of the strain.

KINEMATIC MODEL

Orvin (1934) proposed that the folding predates the thrusting. However, the NE-plunging Ny-Ålesund Thrust (visible at Kiærfjellet, Fig. 3 section A-A') and the folding of this thrust fault (Fig. 3, section B-B') clearly indicates pre-folding thrust tectonics (Challinor 1967, Wuthenau 1988, Saalmann & Thiedig 1999, Piepjohn et al. in press b). Therefore, the Ny-Ålesund Thrust is older than the km-scale fold structure. However, the folded thrust cannot be observed directly in the field, though it can be reconstructed with the help of cross sections (Fig. 3, section B-B').

The kinematic evolution of the thrust complex on Brøggerhalvøya includes the following succession of Tertiary tectonic events (Fig. 5):
1) The early phase of thrusting led to the formation of the lower sediment-dominated nappes which are characterized by gently SW-dipping bedding-parallel thrust faults with staircase trajectories suggesting a ramp-flat mode of fold-thrust generation. NW-SE-striking normal faults inherited from the Carboniferous St. Jonsfjorden Trough are supposed to represent favourite sites for ramping of the thrust faults and to cut up-section. The influence of Carboniferous structures has also been reported from other areas of the foldbelt (e.g. Maher & Welbon 1992, Dallmann 1992, Braathen et al. 1995). To the south, the nappes progressively involve greater portions of the pre-Devonian basement resulting in a wedge shaped geometry. This indicates a forward propagating mode of thrusting (in-sequence thrusting) with the development of the Ny-Ålesund nappe at first followed by the formation of the Kiærfjellet, Kvadehuken, Kongsfjorden and Garwoodtoppen nappes.

However, the Ny-Ålesund nappe in the north overrides the lower thrust sheets (Fig. 2, 3). At the northern slope of Scheteligfjellet, the Ny-Ålesund nappe truncates the Kiærfjellet nappe and overlies the Kvadehuken nappe (Fig. 3, section A-A'). Further to the east, the Ny-Ålesund nappe is thrust on limestones and dolomites of the Wordiekammen Formation within the Kongsfjorden nappe (Fig. 3, sections B-B' to E-E'). This thrust fault is exposed in carbonates of the Wordiekammen Formation at the southeastern coast of Kongsfjorden. Thrusting led to the formation of an imbricate stack (Fig. 4b) and subordinate small-scale folds.

Thus the Ny-Ålesund Thrust exposed in the N cannot represent the initial stage-1 Ny-Ålesund thrust but a new (stage-2) thrust plane that carried the syncline (Ny-Ålesund nappe) on the previously formed lower nappes:

2) The stage-1 nappes are overridden by the basement-dominated thrust sheets. The first out-of-sequence thrust in the hinterland of the earlier in-sequence structures involved greater portions of the basement and led to its inversion and uplift associated with the formation of a km-scale fault-propagation fold at the tip of the thrust fault (Fig. 5). The stage-1 structures were tilted (NE-dipping Ny-Ålesund and Kiærfjellet thrusts, Fig. 3, section A-A') and rotated, and the previously formed Ny-

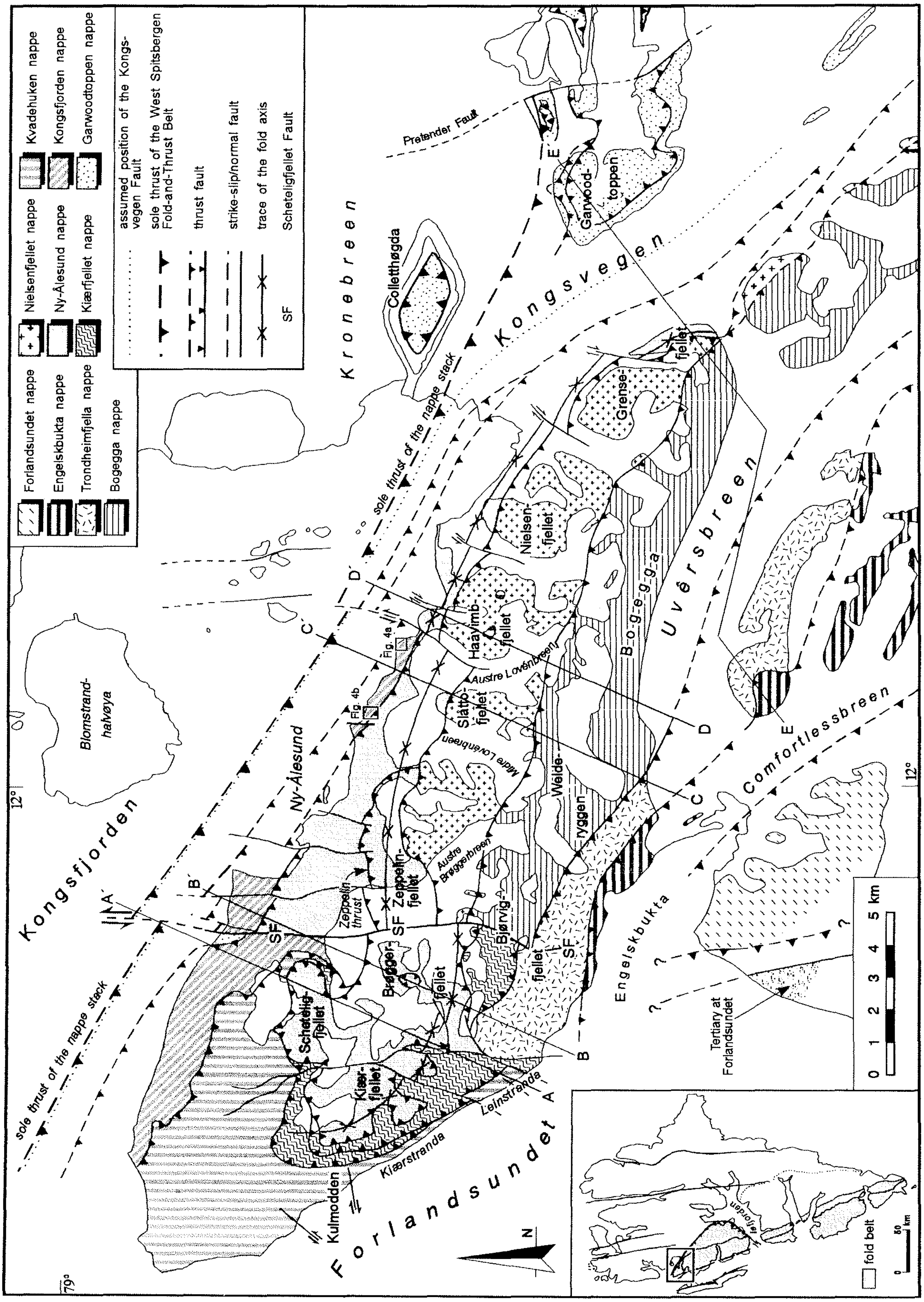


Fig. 2: Tectonic map of the nappe stack on Brøggerhalvøya (compiled from SIDOW 1988, WUTHENAU 1988, LOSKE 1989, TAPPE 1989, WEBER 1990, BROMMER 1994, SAALMANN 1995, PIEPJOHN et al. in press b, THIEDIG et al. in press, TESSENSOHN et al. in press, modified and supplemented).

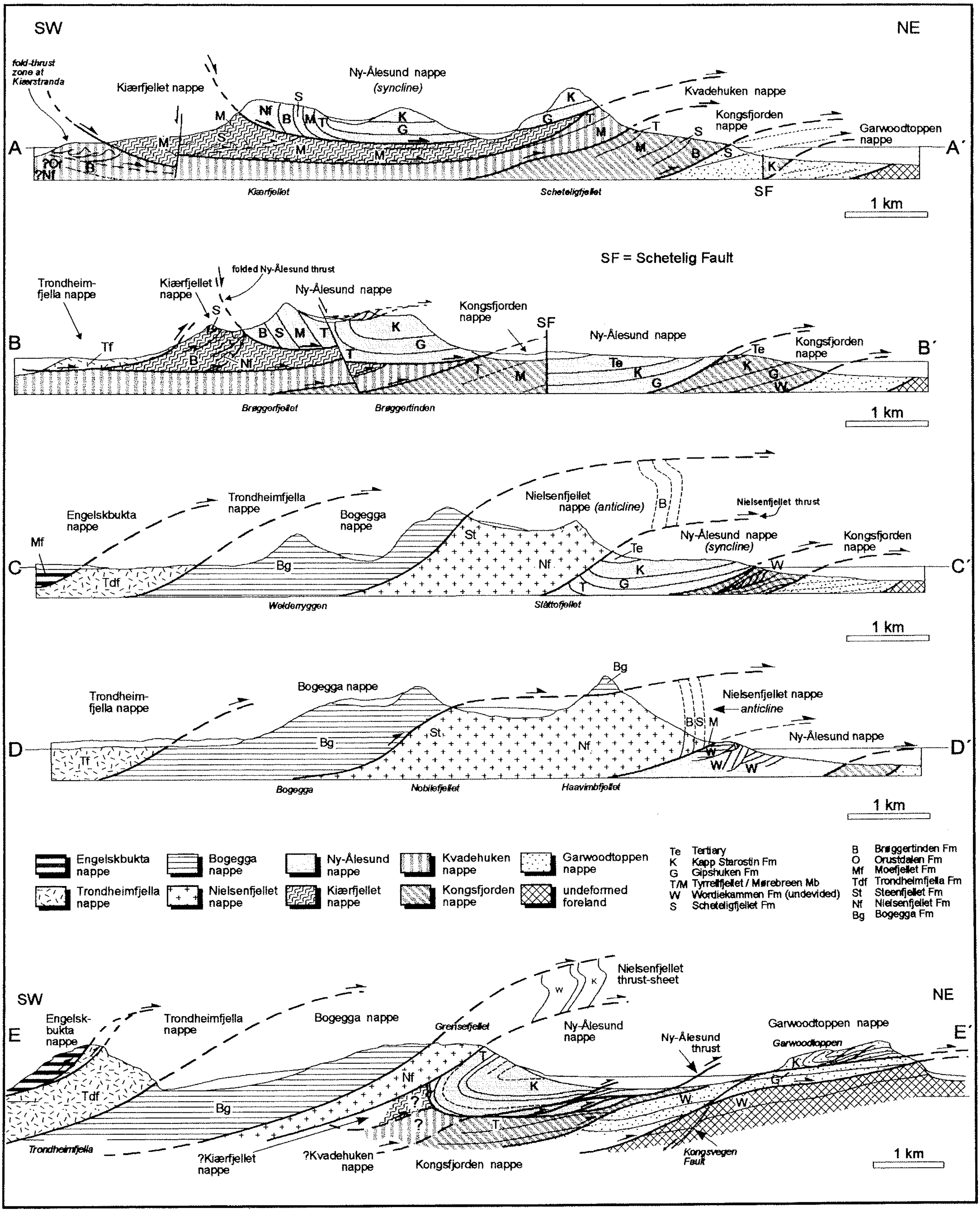
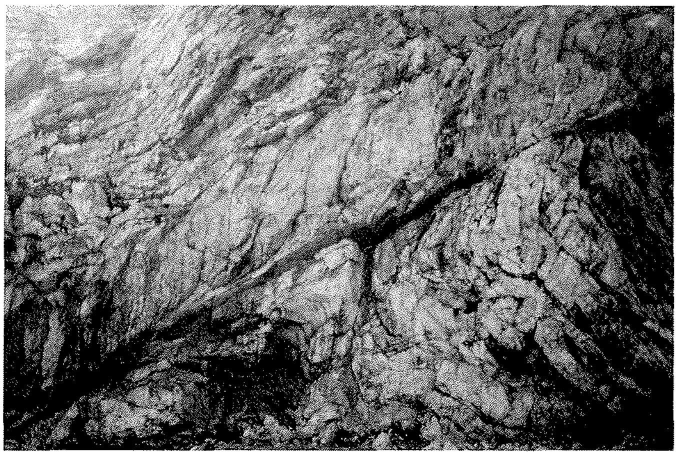
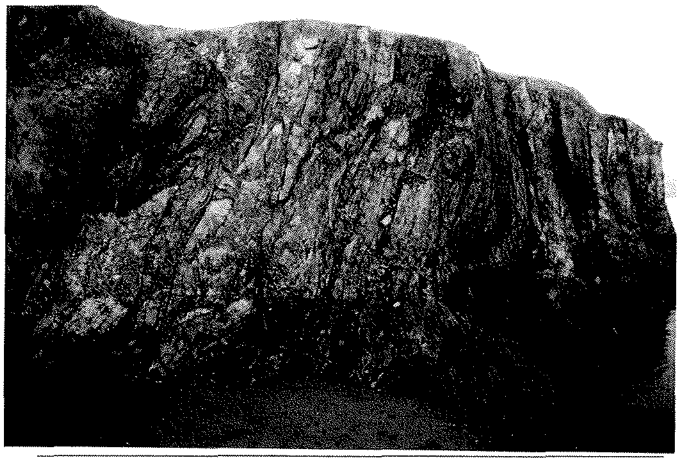


Fig. 3: Geological cross sections through Brøggerhalvøya (for locations see Fig. 2).



a) SE NW



b) SSW NNE

Fig. 4: (a) Duplex structure in limestones of the Wordiekammen Formation within the Kongsfjorden nappe at the southern coast of Kongsfjorden to the north of Haavimbfjellet (for location see Fig. 2).
(b) Characteristic structures adjacent to the stage-2 Ny-Ålesund Thrust at the southern coast of Kongsfjorden to the north of Midre Lovénbreen (for location see Fig. 2). Carbonates of the Wordiekammen Formation are stacked into an imbricate fan due to the movement of the Ny-Ålesund nappe on the Kongsfjorden nappe.

Ålesund Thrust was folded. The tilting of the stage-1 Ny-Ålesund Thrust gave rise to renewed movements until due to progressive shortening, a new thrust fault was developed using the dolomites of the Tyrrellfjellet Member and Gipshuken formations as slip planes. This new stage-2 Ny-Ålesund thrust obliquely cut the earlier structures and the syncline overrode the earlier stage-1 nappes. Concurrently, the Nielsenfjellet thrust truncated the overturned short limb of the fold structure and carried the anticline onto the syncline. The first activation of the Scheteligfjellet Fault as a tear fault is related to the movement of the Nielsenfjellet nappe for the Scheteligfjellet Fault as well as several SSW-NNE striking faults in the eastern part of the peninsula (Fig. 2) accomodated variable displacements within the thrust sheet.

3) The structurally higher basement-dominated thrust sheets were formed by hindward propagation of additional out-of-sequence thrusts. This was accompanied and partly controled by continuous activity of the Scheteligfjellet Fault. In the southern part of Brøggerhalvøya, to the west of the Scheteligfjellet Fault, the Trondheimfjella nappe is thrust on the Ny-Ålesund nappe (Fig. 2, 3, section B-B'). Thus, the Nielsenfjellet and Bogegga nappes are absent due to erosion prior to the displacement of the Trondheimfjella nappe. Movements along the Scheteligfjellet Fault ceased before the displacement of the structural highest and youngest Engelskbukta nappe which overlays the fault (Fig. 2).

In all, meso-scale structures like the orientation of thrust planes, fold axes, extension fractures and slickenside striae indicate thrust directions and fold vergences to the NNE - NE with no remarkable difference between the nappes. Varying transport directions within an individual nappe to the NW, N, and ENE can be ascribed to curving of thrust planes and ramping on basement obstacles or pre-Tertiary faults.

Nevertheless, the displacement of the stage-2 Nielsenfjellet and Ny-Ålesund nappes appears to be initially directed more to the ENE as can be inferred from the fact that the Ny-Ålesund nappe obliquely decapitates the stage-1 nappes and to the east progressively overrides lower nappes. Moreover, the Nielsenfjellet thrust truncates the overturned synclinal short limb in a higher level at Grensefjellet than at Slåttofjellet further to the northwest (Fig. 2, 3, compare sections C-C' and E-E').

DISCUSSION

The 3-stage model fits well with the kinematic evolution reported from other regions in the West Spitsbergen Fold-and-Thrust Belt (e.g. Nordenskiøld Land, Braathen & Bergh 1995, Braathen et al. 1995, southern Oscar II Land, Bergh et al. 1997, and Hornsund, Dallmann 1992). Therefore, it seems certain that the thrust tectonics on Brøggerhalvøya are coeval with the formation of the fold belt further south. This conclusion is at odds with the presumption that the main deformation on Brøggerhalvøya is related to an earlier NNE-directed transpressional episode predating the main deformation in other areas (Lepvrier 1992). If deformation is coeval, the problem has to be solved why on Brøggerhalvøya, thrusting is directed to the NE instead of ENE.

Concepts for Brøggerhalvøya being located in a contractional relay zone between two left-stepping strike-slip faults (Lepvrier 1992) or as being related to the development of the Forlandsundet Graben (Lepvrier et al. 1988, Steel et al. 1985) imply a major strike-slip fault in the east which could not be proved until now. Moreover, the nappe stacking on Brøggerhalvøya predated at least the final stages of the formation of the Forlandsundet Graben (the graben border faults cut the highest Engelskbukta nappe). Instead, the deformation on Brøggerhalvøya is clearly contractional, and major strike-slip faults cannot be observed.

Compared with other regions of the West Spitsbergen Fold-and Thrust Belt, the thickness of the post-Caledonian cover sediments is markedly decreased: Mesozoic strata which contain

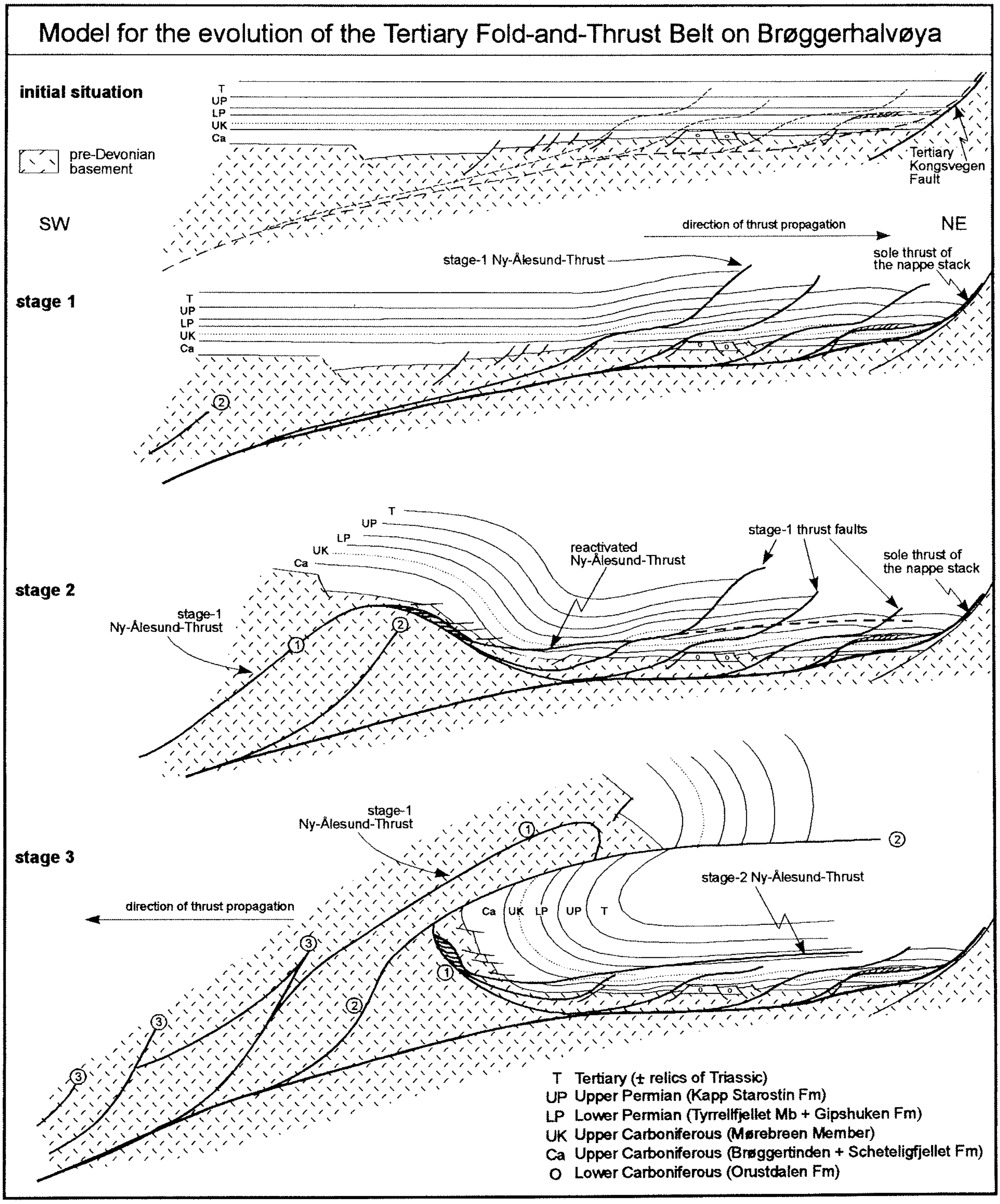


Fig. 5: Simplified model for the Tertiary thrust tectonics on Brøggerhalvøya (without scale). A three-stage structural evolution is inferred: Stage 1. Formation of the lowest nappes by bedding-parallel detachments with stair-case trajectories. The thrusts propagate in-sequence to the foreland. Stage 2. First out-of-sequence thrusting and progressive involvement of the basement leads to the formation of a km-scale fold and tilting of the stage-1 detachments and renewed movements on the stage-1 Ny-Ålesund Thrust. Stage 3. A new stage-2 Ny-Ålesund Thrust carries the Ny-Ålesund nappe on the lower stage-1 nappes. Note that the stage-2 Ny-Ålesund Thrust solely uses the Early Permian carbonates as important detachment horizons. The overturned short limb of the fold is eventually truncated by an out-of-sequence thrust carrying the anticline on the syncline followed by the formation of the highest basement nappes by hindward propagating out-of-sequence thrusting.

important detachment horizons and can accomodate large amounts of strain and shortening (DALLMANN 1988, HAREMO et al. 1990, BERGH & ANDRESEN 1990, DALLMANN et al. 1993, BRAATHEN et al. 1995, BERGH et al. 1997), are absent on Brøggerhalvøya. Curving of thrust belts is often attributed to along-strike thickness variations (e.g. GRAY & STAMATAKOS 1997, FERRILL & GROSHONG 1993). However, though certainly also playing an important part, this cannot account solely for the anomalous transport directions on Brøggerhalvøya.

The sole thrust of the nappe stack coincides with the assumed position of the NW-SE striking Kongsvegen Fault (see above). Ramping on the SW-dipping Kongsvegen Fault during WSW-ENE compression is supposed to have caused a rotation of the strain axes resulting in NE-directed thrusting with sinistral oblique slip. At Colletthøgda and Garwoodtoppen to the east of Brøggerhalvøya, the deformation can partly be accomodated by transfer in bedding-parallel detachments within Late Palaeozoic carbonates (TESSENSOHN et al. in press). To the north of Kongsfjorden, comparable deformation transfer was inhibited due to stronger uplift of the northern block and lack of a thick post-Devonian cover. Therefore, to a certain extent, passive bending of the structures resulting from pinning on the uplifted basement block may also account for the fold-belt curvature. This is indicated by the sigmoidal trace of the fold axis on Brøggerhalvøya (Fig. 2).

CONCLUSIONS

1) The Tertiary deformation on Brøggerhalvøya is characterized by a pile of nine thrust sheets. Major strike-slip faults or an en echelon-geometry of folds and thrusts which would indicate a transpressional origin of the foldbelt seem to be absent though subordinate and local transpressive movements can also be observed. However, the overall tectonic style is infered to be compression-dominated.
2) Thrusting is directed to the NE-NNE, varying transport directions within individual nappes are attributed to local basement topography and pre-existing faults.
3) The anomalous transport directions in the Kongsfjorden area may be explained mainly with active ramping on the NW-SE striking Kongsvegen Fault during WSW-ENE compression rather than by strike-slip or transpression.
4) Pre-existing Carboniferous NW-SE striking faults are supposed to have affected the development of the stage-1 lower thrust sheets in ramp-flat mode as well as the overall NE-vergence during the main stage-2 folding and thrusting (Kongsvegen Fault).

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