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

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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 (BIRKENMAIER 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, BERGHI & ANDRESEN 1990, DALLMANN et al. 1993; LYBERIS & MANBY 1993a,b, BRAATEN & BERGHI 1995, BRAATEN et al. 1995, MANBY & LYBERIS 1996, GOSSEN & PIEJOHN in press, GOSSEN et al. in press, PIEJOHN & GOSSEN 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), PIEJOHN 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 Kulumoddon (Fig. 2). The Middle Carboniferous Brøggertinden Formation was deposited in a N-S trending major halfgraben (St. Jonsfjorden Trough, CUTFIELD & CHALLINOR 1965). It is dominated by coarse clastic sediments and intercalated with
shales and limestones (Fig. 1). Lateral facies and thickness variations (ranging from 10-300 m) were attributed to syndepositional normal faulting (Ludwig 1988). N-S to NW-SE oriented lineaments have affected the sedimentation patterns of the Carboniferous deposits in Svalbard (Giebberg & 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 basinial margin of the St. Jonsfjorden Trough is represented by a NW-SE striking fault in the Kongsfjorden (Steel & Worsley 1984, their Fig. 10) which follows the Kongsevgen 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, Gipsuhken 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 Slattofjellet, Tertiary strata are only preserved in the basinial 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, Midbøe 1985).

The structure of Brøggerhalvøya is characterized by a NE-vergent nappe stack (Barbaroux 1966, Challinor 1967, Manby 1988, Piëpjohn et al. in press b; Thiédet et al. in press). Barbaroux (1966) already distinguished five thrust sheets, seven or nine nappes were established by Manby & Lyberis (1996) and Piëpjohn 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, Piëpjohn 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 Kierfjellet 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

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The internal deformation of the nappes is remarkably weak. Merely within the Ny-Ålesund nappe, adjacent to Austre Breggerbreen 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 (Ludwig 1988, Saalmann & Brommer 1997, Piepjohn et al. in press b) (Fig. 3, section D-D').

KINEMATIC MODEL

Orvin (1934) proposed that the folding predates the thrusting. However, the NE-plunging Ny-Ålesund Thrust (visible at Kjærrefjellet, 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 Kjærrefjellet, Kvadehukken, 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 Sherdahlfjellet, the Ny-Ålesund nappe truncates the Kjærrefjellet nappe and overlies the Kvadehukken 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 Kjærrefjellet thrusts, Fig. 3, section A-A') and rotated, and the previously formed Ny-
Fig. 3: Geological cross sections through Brøggerhalvøya (for locations see Fig. 2).
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 Haavimbjellet (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 Ny-Ålesund 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 Trondheimfjellja 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 Trondheimfjellja nappe. Movements along the Scheteligfjellet Fault ceased before the displacement of the structural highest and youngest Engelskbuksnappes on 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 Slattofjellet 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. Nordenskiöld 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 Engelskbuksnappes). 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 staircase 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 accommodate large amounts of strain and shortening (Dallmann 1988, Haremo et al. 1990, Bergh & Andreassen 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 accommodated 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 of 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 inferred 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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