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Thrust tectonics on Brøggerhalvøya and their relationship to the Tertiary West Spitsbergen Fold-and-Thrust Belt

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Abstract – The Tertiary fold-and-thrust belt on Brøggerhalvøya is characterized by a NE-vergent pile of nine thrust sheets. The sole thrust of the pile is located in Precambrian phyllites and climbs up-section to the northeast. Four lower thrust sheets consisting predominantly of Upper Palaeozoic sediments are overlain by two thrust sheets in the central part of the stack which contain a kilometre-scale syncline and anticline. The fold is cut by juxtaposed thrusts giving rise to the formation of three structurally higher basement-dominated thrust sheets. A multiple-stage kinematic model is proposed including (1) in-sequence foreland-propagating formation of the lower thrust sheets in response to N–S subhorizontal bedding-parallel movements, (2) a change in tectonic transport to ENE and out-of-sequence thrusting and formation of the kilometre-scale fold-structure followed by (3) truncation of the kilometre-scale fold and stacking of the highest basement-dominated thrust sheets by hind-ward-propagating out-of-sequence thrusting. The strain of the thrust sheets is predominantly compressive with the exception of the structurally highest thrust sheets, reflecting a temporal change to a more transpressive regime. Thrusting was followed by (4) N–S extension and (5) W–E extension. Comparison of the structural geometry and kinematic evolution of Brøggerhalvøya with the data reported for the fold belt further south allows us to assume a coeval evolution with the fold belt. A latest Paleocene/Early Eocene age for the main phase of thrusting is suggested for the West Spitsbergen Fold-and-Thrust Belt; the main phases therefore pre-date the separation of Svalbard and Greenland due to right-lateral movements along the Hornsund Fault Zone. The fold belt's temporal evolution followed by the formation of the Forlandsundet Graben can be linked with the plate-kinematic framework in the span between latest Paleocene and Middle Eocene times.

1. Introduction

The Tertiary 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) (Fig. 1). With the exception of the northernmost parts (Brøggerhalvøya) which show NE-directed transport, fold vergence and thrusting in the fold belt are directed to the ENE (Orvin, 1940; Harland, 1969; Harland & Horsfield, 1974; Kellogg, 1975; Birkenmajer, 1981; Dallmann *et al.* 1993), and the NNW–SSE strike of the structures runs parallel to the Hornsund Fault Zone (Sundvor *et al.* 1978) (Fig. 1). The Caledonian basement is involved in Tertiary tectonics and is predominantly exposed in the western part, whereas to the east a 'thin-skinned' tectonic style is characteristic (Bergh & Andresen, 1990; Welbon & Maher, 1992; Dallmann *et al.* 1993; Braathen & Bergh, 1995; Braathen, Bergh & Maher, 1995, 1997, 1999; Bergh, Braathen & Andresen, 1997; von Gosen & Piepjohn, in press). In the northern areas (Oscar II Land), the western basement high of the fold belt is cut by the NNW–SSE striking faults of the Forlandsundet graben, which shows a multiple stage tectonic evolution that had possibly already begun during the formation of the West Spitsbergen Fold-and-Thrust Belt (Lepvrier & Geyssant, 1985; Lepvrier, 1990; Gabrielsen *et al.* 1992; Kleinspehn & Teyssier, 1992).

Prior to the opening of the Norwegian–Greenland Sea, Svalbard was located to the north of Greenland (Harland, 1969, Talwani & Eldholm, 1977). In Early Eocene times, the opening of the North Atlantic and Arctic oceans resulted in the separation of Greenland and Svalbard by right-lateral movements (Talwani & Eldholm, 1977; Srivastava & Tapscott, 1986). The West Spitsbergen Fold-and-Thrust Belt was previously thought to have resulted from dextral transpression along the DeGeer Fracture Zone/Hornsund Fault Zone during the separation of Svalbard and Greenland in Eocene times (Harland, 1969; Lowell, 1972; Harland & Horsfield, 1974; Kellogg, 1975; Steel *et al.* 1985), and Lowell (1972) proposed a flower structure model for its geometry. The structural style of the fold belt, however, shows a predominance of convergent structures rather than en échelon folds and strike-slip faults (Maher, Craddock & Maher, 1986; Dallmann, 1988; Manby, 1988; Bergh & Andresen, 1990; Welbon & Maher, 1992;

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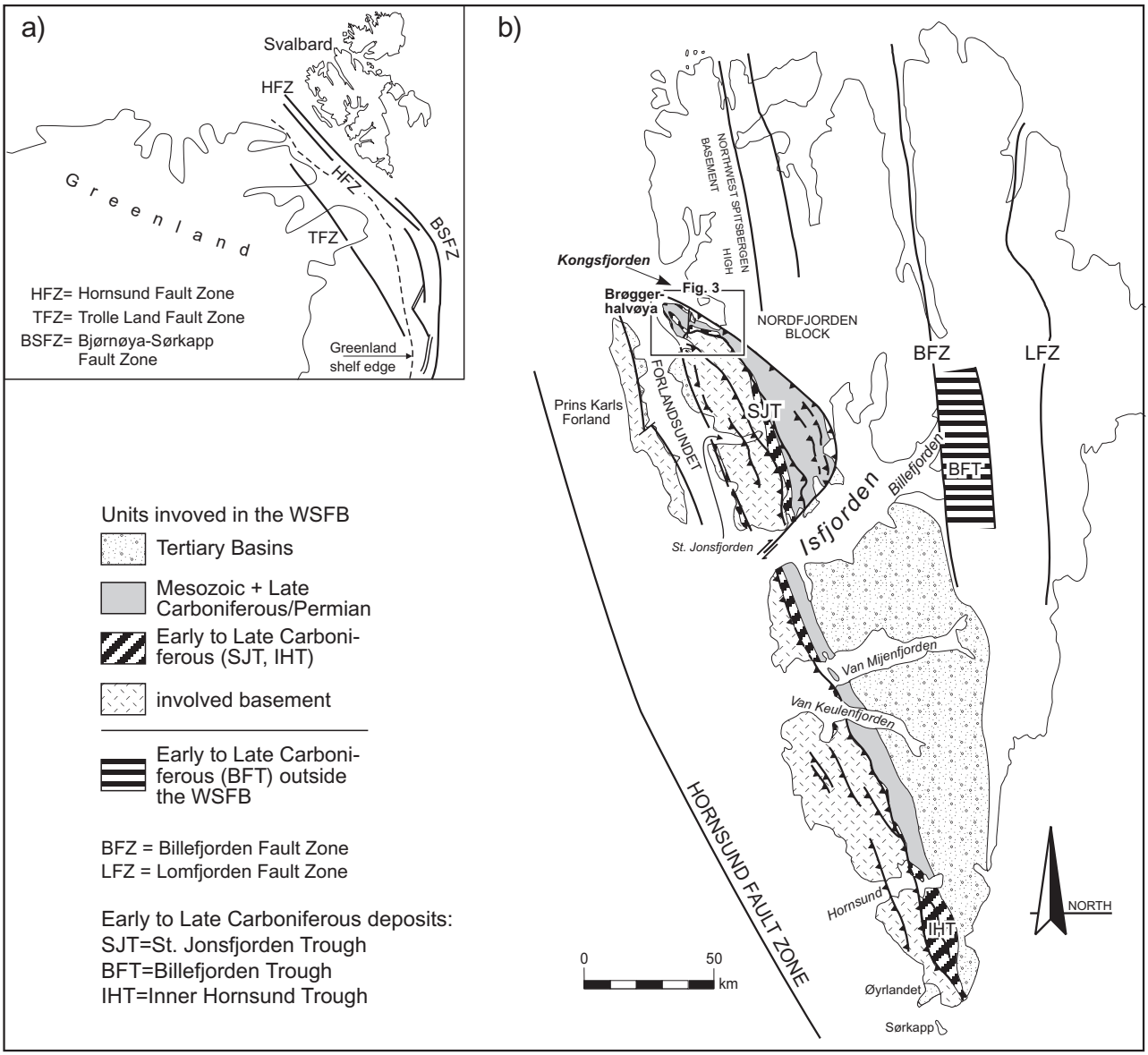


Figure 1. (a) Simplified map of the regional plate setting of Svalbard and North Greenland (modified from Eldholm, Faleide & Myhre, 1987, and Harland, 1997). (b) Location of the West Spitsbergen Fold-and-Thrust Belt (WSFB) between Sørkapp and Kongsfjorden running parallel to the western coast of Spitsbergen (after Dallmann *et al.* 1993, modified and supplemented).

Dallmann *et al.* 1993; Lyberis & Manby, 1993*a*,*b*; Braathen & Bergh, 1995; Braathen, Bergh & Maher, 1995, 1999; Manby & Lyberis, 1996; Bergh, Braathen & Andresen, 1997; von Gosen & Piepjohn, in press). Therefore, it has been proposed that the fold-and-thrust belt formation (the onset of deformation or even the main period of deformation) pre-dated the separation of Greenland and Svalbard during Late Cretaceous times (Hanisch, 1984*a*,*b*; Lyberis & Manby, 1993*a*,*b*; Manby & Lyberis, 1996, 2000) or, alternatively, that the transpressive deformation is partitioned or decoupled into two coeval parallel transcurrent and compressional belts with the latter exposed in western Spitsbergen (Faleide *et al.* 1988; Maher & Craddock, 1988; Nøttvedt, Livbjerg & Midbøe, 1988; Lepvrier, 1992; Maher *et al.* 1997).

The curvature of the fold belt in the Kongsfjorden area and the anomalous transport directions to the northeast on Brøggerhalvøya are considered by Kellogg (1975) and Harland (1969, 1997) as evidence for a transpressive origin of the fold-and-thrust belt. Other models to explain the anomalous trend imply that Brøggerhalvøya is located between two N–S-oriented, left-stepping dextral strike-slip faults causing the anomalous transport to the northeast (Lepvrier, Leparmentier & Seland, 1988; Lepvrier, 1992) or that this anomalous transport direction could be related to the formation of the Forlandsundet (Steel *et al.* 1985; Maher *et al.* 1997). In their model of a decoupled transpression, Maher & Craddock (1988) suggest that Brøggerhalvøya is located in a wedge-shaped mobile zone with a still-coupled deformation, in contrast to the decoupled areas further to the south. To summarize, all the existing models assume a status for the Kongsfjorden region involving an evolution distinct

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Stratigraphy				*Lithology*		deformation, structural role
Tertiary	Van Mijenfjorden Group	Ny-Ålesund Fm (Bayelva Mb, Leirhaugen Mb)	≥180 m	*conglomerates, sandstones, shales, coal seams*		open flexural slip folding (sandstones), tight folds (shales); shear horizons located in shales and coal seams;
		Kongsfjorden Fm (Tvillingvatnet Mb, Kolhaugen Mb)	0 - 110 m			
Triassic		Vardebukta Fm	50 m	*dark shales*		local relics; minor influence on the structural geometry
Permian	Tempelfjorden Group	Kapp Starostin Fm	90-230 m	*cherts, silicified limestones; top: glauconitic sandstones*	*stable platform deposition*	brittle fracturing, local folding of glauconitic sandstones
	Gipsdalen Group	Gipshuken Fm (Skansdalen Mb, Kloten Mb)	40 - 140 m	*carbonate breccia and laminated dolomites, marls*		laminated dolomites & marls = weak layers and detachment horizons fracturing, imbrication; local flexural slip folding
		Wordiekammen Fm (Tyrrellfjellet Mb, Mørebreen Mb)	290 m	*alternation of limestones and dolomites containing abundant cherty nodules*		imbrication, fracturing; local flexural slip folding; thinly bedded *Kiærfjellet Beds* (dolomites of the Tyrrellfjellet Member) are important detachment horizons
Carboniferous		Schetelig-fjellet Fm	8 - 120 m	*predominant limestones, dolomites, intercalated with sandstones and siltstones*	*St. Jonsfjorden Trough graben fill, syn-depositional faulting*	shales = weak layers of local importance, flexural folding; imbrication, fracturing, local flexural slip folding; local boudinage of thin sandstones/dolomite beds
		Brøgger-tinden Fm	13 - 300 m	*conglomerates, sandstones, in upper parts intercalated with limestones and dolomites*		fracturing, imbrication (local on a decametric scale)
	Billefjorden Group	Orustdalen Fm	100 - 225 m	*various sandstones and conglomerates, to the top intercalated with shales*		only of local importance
pre-Devonian (Caledonian) basement				*phyllite, mica schist, quartzite, marble, gneiss, diamictite;* *middle greenschist to high amphibolite facies*		fracturing, imbrication, in dolomite marbles local flexural slip folding

Figure 2. Stratigraphic table of the post-Caledonian cover sediments on Brøggerhalvøya (after Cutbill & Challinor, 1965; Challinor, 1967; Ludwig, 1989, 1991; Dallmann, 1999; Thiedig, Saalmann & Piepjohn, in press) and their structural role and deformation. Gp – Group, Fm – Formation, Mb – Member.

from the fold belt further south. Brøggerhalvøya is therefore a key region for the clarification of either a transpressive or compressive origin of the West Spitsbergen Fold-and-Thrust Belt.

The purpose of this paper is (1) to describe the structural style and kinematic history of thrusting on Brøggerhalvøya, including the analysis of the temporal and spatial distribution of transport directions, (2) to compare the evolution with studies reported from the areas further south (e.g. Nordenskiöld Land, Isfjorden, Midterhuken), (3) to explain the anomalous transport directions in the Kongsfjorden area, which is a critical point for understanding the evolution of the West Spitsbergen Fold-and-Thrust Belt, and (4) to try to give a time limit for the fold belt formation. The proposed model considers the involvement of the Tertiary strata and the predominance of compressive strain and aims to contribute to the explanation of the spatial and temporal evolution of the fold belt related to the plate tectonic framework.

2. Stratigraphy of Brøggerhalvøya

The stratigraphic succession on Brøggerhalvøya comprises metamorphic rocks of the Caledonian basement overlain by Upper Palaeozoic sediments, local relics of

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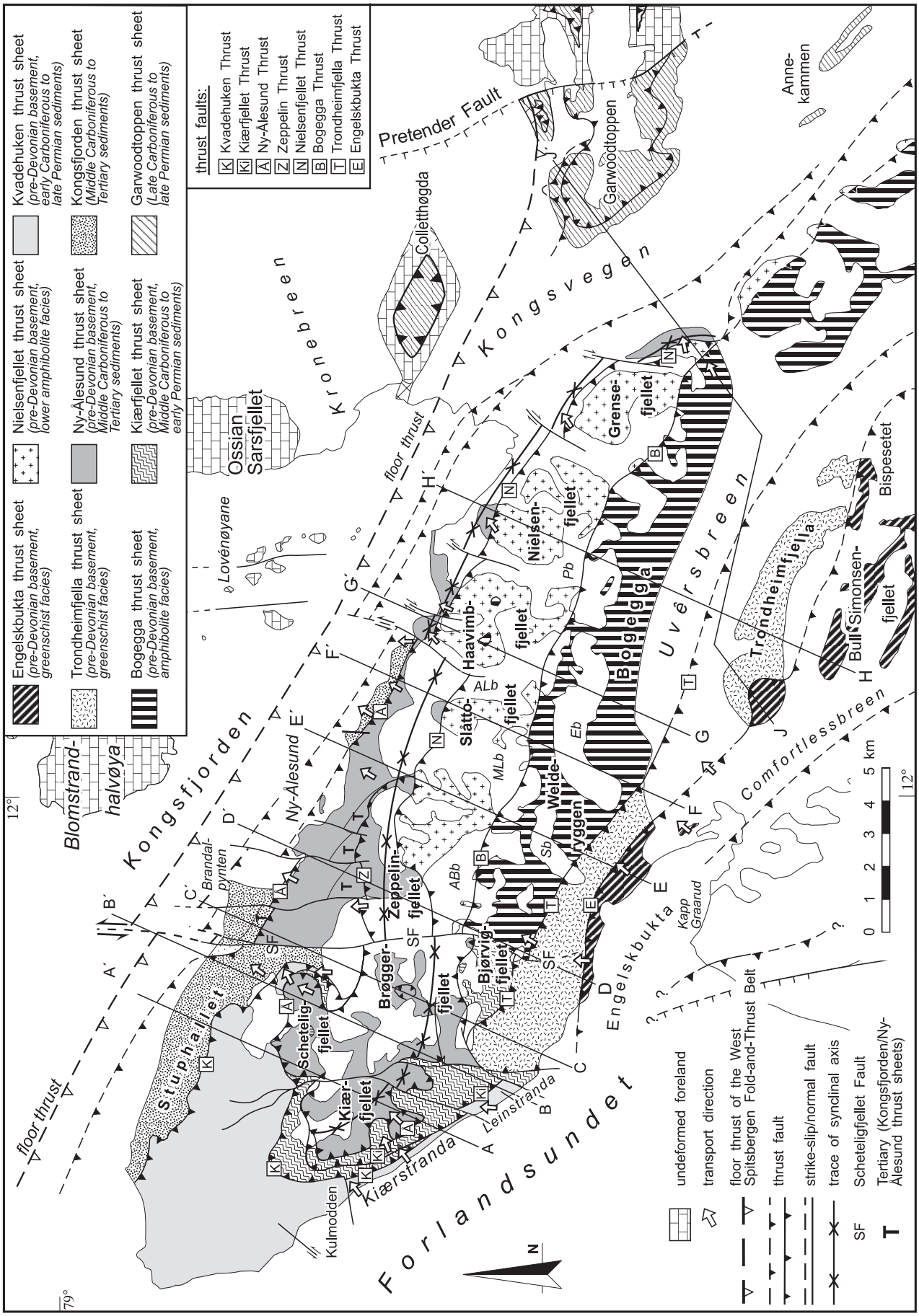


Figure 3. For legend see facing page.

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a thin succession of Triassic rocks, and Tertiary deposits (Fig. 2).

The pre-Devonian basement consists predominantly of schistose units of the Precambrian (Orvin, 1934; Challinor, 1967; Barbaroux, 1966; Harland *et al.* 1979; Harland, Hambrey & Waddams, 1993; Hjelle *et al.* 1999; Thiedig, Saalmann & Piepjohn, in press) which were affected by a polyphase tectonothermal evolution during the Caledonian orogeny with metamorphic grade ranging from greenschist to amphibolite facies (Harland, Hambrey & Waddams, 1993; Hjelle *et al.* 1999; Saalmann, 2000). These units constitute the structurally higher thrust sheets and are partly thrust onto the post-Caledonian strata.

The post-Caledonian sedimentary cover rests unconformably on the basement units. The Early Carboniferous Orustdalen Formation can only be found in the Kvadehuken thrust sheet on the southwestern coast of the peninsula. It is overlain by the Brøggertinden Formation which represents the first post-Caledonian sediments in the other thrust sheets. The Brøggertinden Formation consists mainly of coarse siliciclastic reddish sediments. The predominantly calcareous Scheteligfjellet Formation marks the transition to the stable platform conditions of the overlying Upper Carboniferous to Permian rocks. Marked lateral facies and thickness variations in both formations were attributed to syn-depositional normal faulting (Ludwig, 1989, 1991; Saalmann, 2000).

The limestones and dolomites of the Wordiekammen Formation are the first widespread post-Devonian deposits in Spitsbergen (Cutbill & Challinor, 1965; Steel & Worsley, 1984; Dallmann, 1999). On Brøggerhalvøya, the nearly 300 m thick succession can be subdivided into a lower Mørebreen and the upper Tyrrellfjellet Member (Challinor, 1967) with the latter being more thinly bedded in the lower part (Kiærfjellet Beds, Challinor, 1967). These beds are structurally important because they are the dominant detachment horizon. They are conformably overlain by the Gipshuken Formation which consists of the massive Kloten Breccia intercalated with, and overlain by, laminated dolomites and marls (Challinor, 1967; Dallmann, 1999; Hjelle *et al.* 1999).

The spiculitic cherts of the Late Permian Kapp Starostin Formation are the most competent sedimentary units. The top of this formation consists of glauconitic sandstones. They are overlain by Tertiary siliciclastic deposits which occur predominantly in the Ny-Ålesund area in addition to small remnants of Tertiary sandstones and conglomerates on the top of Scheteligfjellet (Kellogg, 1975) and to the northeast of Slåttofjellet (Saalmann, Piepjohn & Thiedig, 1997; Piepjohn *et al.* in press). To the south of Ny-Ålesund only, the Tertiary strata are underlain by thin relics of dark shales (Orvin, 1934; Challinor, 1967) which according to Challinor (1967) belong to the Early Triassic Vardebukta Formation. Thus, with the exception of these relics, Mesozoic strata are absent on Brøggerhalvøya, in contrast to areas further south.

3. Geometry and structural evolution of the thrust-stack

3.a. Structural overview

The structure of Brøggerhalvøya is characterized by a stack of NE- to NNE-vergent thrust sheets (Barbaroux, 1966; Challinor, 1967; Manby, 1988; Saalmann & Thiedig, 1997, 1998; Hjelle *et al.* 1999; Saalmann, 2000; Piepjohn, Thiedig & Manby, in press; Thiedig, Saalmann & Piepjohn, in press). Barbaroux (1966) distinguished five thrust sheets on the peninsula, while Bergh, Maher & Braathen (2000) identified three thrust nappes. Based on detailed mapping (Thiedig, Saalmann & Piepjohn, in press), nine thrust sheets can be established (Manby & Lyberis, 1996; Saalmann, 2000, Piepjohn, Thiedig & Manby, in press) (Fig. 3).

The effects of Tertiary thrusting have not been reported from areas north of Kongsfjorden (Piepjohn *et al.* 1997). Thus, the sole thrust of the stack is inferred to be located in the Kongsfjorden, with the northern and northeastern areas representing the undeformed foreland of the fold-and-thrust belt (Manby, 1988; Lyberis & Manby, 1993*a*,*b*; Manby & Lyberis, 1996; Saalmann & Thiedig, 1997, 1998; Saalmann, 2000; Piepjohn, Thiedig & Manby, in press).

The border faults of the Forlandsundet Graben can be inferred to truncate the thrusts to the west of Brøggerhalvøya (Figs 1, 3) (Orvin, 1934; Barbaroux, 1966; Manby, 1988; Dallmann *et al.* 1993; Lyberis & Manby, 1993*a*,*b*; Hjelle *et al.* 1999).

Based on the structural geometry and stratigraphic content, the pile of thrust sheets can be divided into three structural units as follows:

(1) Four sediment-dominated thrust sheets (Garwoodtoppen to Kiærfjellet thrust sheets) represent the structurally lower parts and are exposed predominantly in the west of the peninsula (Fig. 3).

(2) The Ny-Ålesund and Nielsenfjellet thrust sheets in the central part of the stack contain a NE-vergent syncline–anticline pair on a kilometric scale (Fig. 4).

(3) Three basement-dominated thrust sheets (Bogegga, Trondheimfjella and Engelskbukta thrust sheets) can be distinguished in addition to the

Figure 3. Tectonic map of Brøggerhalvøya (after Saalmann, 2000; Piepjohn, Thiedig & Manby, in press; Thiedig, Saalmann & Piepjohn, in press). Note the sigmoidal curvature of the trace of the fold axis. Directions of tectonic transport inferred from dip of thrust planes, orientation of fold axes, conjugate shear planes, cleavage planes, and fault-slip data. ABb – Austre Brøggerbreen, MLb – Midre Lovénbreen, ALb – Austre Lovénbreen, Pb – Pedersenbreen, Eb – Edithbreen, Sb – Steenbreen.

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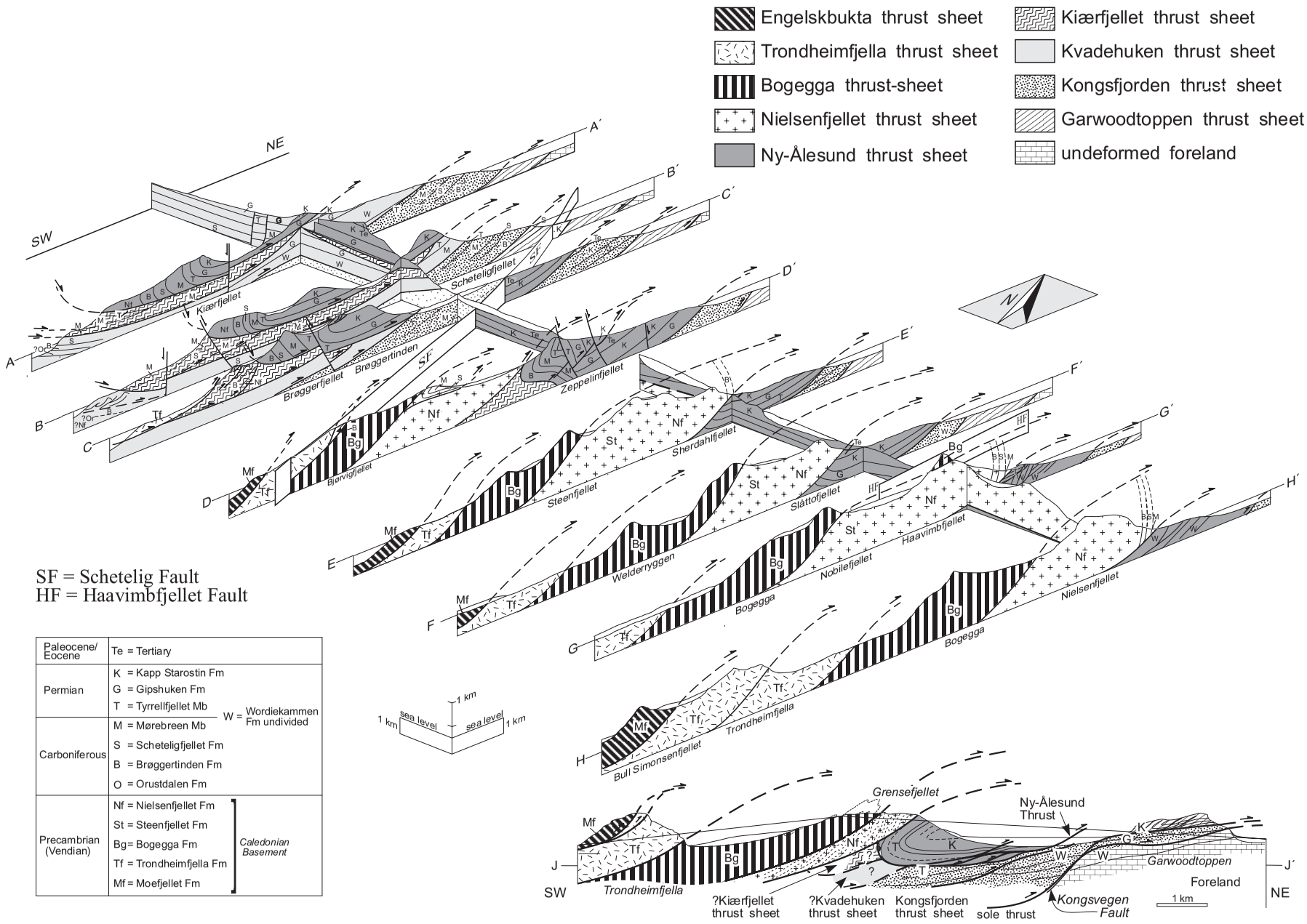


Figure 4. Fence diagram of geological cross-sections through Brøggerhalvøya illustrating its three-dimensional geometry. Section lines are marked in Figure 3.

Nielsenfjellet thrust sheet. They occur in the east and south of Brøggerhalvøya (Fig. 3).

The lower sediment-dominated thrust sheets exposed in the west of the peninsula are separated from the structurally higher basement-dominated thrust sheets to the east by the steeply dipping, N–S-trending Scheteligfjellet Fault (Fig. 3) which runs from the Kongsfjorden coastline west of Ny-Ålesund through Austre Brøggerbreen to the south of Bjørvigfjellet.

A three-stage kinematic model for the thrust tectonics is proposed. The three phases correspond to the three structural levels introduced above.

3.b. Phase 1: Formation of the sediment-dominated thrust sheets

The first phase of Tertiary tectonics resulted in the formation of the lower sediment-dominated thrust sheets. The lower thrust sheets consist predominantly of post-Caledonian cover sediments ranging in age from Early Carboniferous (only within the Kvadehuken thrust sheet) to Tertiary. In addition they involve slivers of Caledonian basement. The bedding within the lower thrust sheets dips gently to the south, except in the southern exposed part of the Kiærfjellet thrust sheet, where NE-dipping beds occur. The thrusts are characterized by gently SSE- to SSW-dipping bedding-parallel thrust faults with staircase trajectories which cut up-section to the NNE to NNW from a basal detachment located in Caledonian phyllites (Fig. 4).

The Garwoodtoppen thrust sheet is the structurally lowermost sheet. At Colletthøgda, it is thrust onto Precambrian marbles and Devonian sediments of the foreland (Tessensohn, Piepjohn & Thiedig, in press) (Fig. 3). The overlying Kongsfjorden thrust sheet is exposed along the northern shoreline of the peninsula and occurs to the west and east of the Scheteligfjellet Fault (Figs 3, 4). The Kongsfjorden thrust sheet is overlain by the Kvadehuken thrust sheet (Figs 4, 5). Exposures of the Kvadehuken thrust sheet are restricted to the west of the Scheteligfjellet Fault. This is also the case for the overlying Kiærfjellet thrust sheet that is only exposed in a small wedge on the eastern flank of Scheteligfjellet (Fig. 5) as well as in the southwestern peninsula (Fig. 3). The thrust sheets are well exposed on the eastern and northern slopes of Scheteligfjellet (Fig. 5). The thrusts run sub-parallel to the bedding planes.

In general, there is little internal deformation of the thrust sheets above the flats of the major thrusts, in contrast to ramp positions where the thrusts cut up-section and subordinate thrust faults and splay faults caused intense imbrication and subordinate folding. Therefore, deformation is mainly concentrated in narrow zones adjacent to the major thrusts with duplex-structures, pop-up structures and imbricate fans

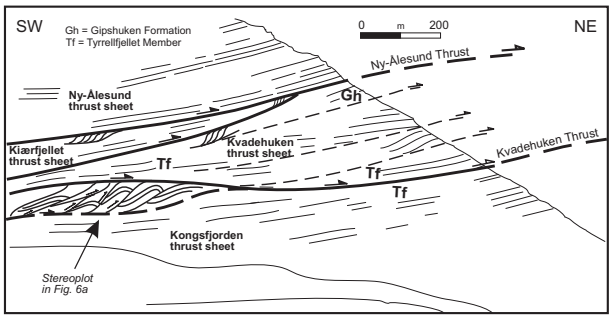


Figure 5. View towards the northwest to Scheteligfjellet showing four thrust sheets (Kongsfjorden to Ny Ålesund thrust sheets). The Ny-Ålesund thrust sheet cuts and overrides the Kiærfjellet and Kvadehuken thrust sheets with the former being preserved only as a small wedge. A duplex structure within the Kongsfjorden thrust sheet consists of S-dipping imbricates on a scale of several metres in limestones and dolomites of the Wordiekammen Formation.

accompanied by some fault-related folds. Good examples are exposed at Kiærstranda and Leinstranda on the southwestern coast of Brøggerhalvøya, where the basal thrust in this area cuts up-section from the basement to the Wordiekammen Formation. Typical structures of Tertiary thrusting are also preserved in the Kongsfjorden thrust sheet to the north of Austre Lovénbreen on the coast of Kongsfjorden, where duplex-structures, imbricates and small-scale folds within limestones of the Wordiekammen Formation demonstrate the internal deformation of the thrust sheet associated with subordinate thrusts probably cutting up-section from a basal detachment (Fig. 6).

Measurements of fault-planes, slickensides on thrust planes, thrust-related cleavage-planes and fold axes in the lower thrust sheets (Fig. 7) indicate an approximate overall N–S contraction during emplacement of the lower thrust sheets (with local variations ranging from NNW- to NNE-directed transport). At Kiærstranda, on the other hand, SW–NE shortening can be observed (Fig. 7d). However, this outcrop is located close to the Ny-Ålesund thrust sheet which contains a NE-vergent syncline that was formed during a later tectonic stage (phase 2). As can be seen from cross-sections (Fig. 4, southeastern parts of section A–A′), the underlying thrust sheets were also affected by the folding and their thrusts are tilted to the northeast. Therefore, tilting and rotation of originally N-vergent structures during later deformation could explain the apparent NE-transport directions at Kiærstanda. In contrast to the southern areas, the northern parts of Brøggerhalvøya were not affected by subsequent (phase 2) folding, so that the N–S shortening observed in these areas can be interpreted to reflect the approximate original transport direction during phase 1.

Regarding the stack of the lower thrust sheets, the sheets progressively involve greater portions of the

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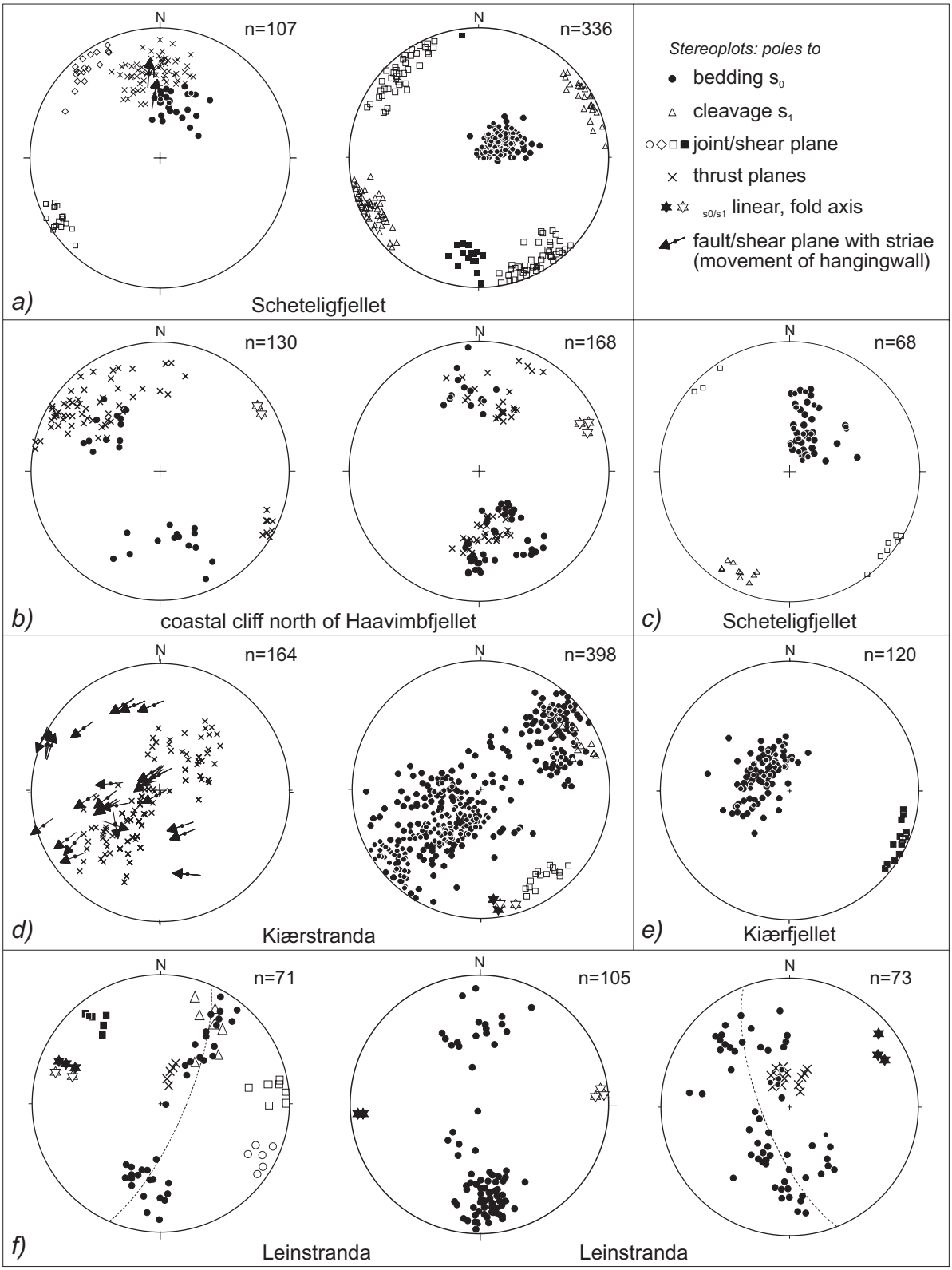


Figure 6. Phase 1 imbricate fans, duplex-structures and folds of the Kongsfjorden thrust sheet at the shoreline to the north of Haavimbfjellet within Wordiekammen carbonates representing a large-scale triangle structure above a subsurface detachment. In the southeastern parts of the outcrop, SE- to S-dipping thrust faults sub-parallel to bedding predominate. NNW- to N-dipping thrusts in the northwestern part of the+ section are interpreted to represent back-thrusts.

Caledonian basement to the south, resulting in an overall wedge-shaped geometry of the stack in cross-section. This geometry suggests a ramp-flat mode of fold-thrust generation (Boyer & Elliott, 1982) with a forward-propagating mode of thrusting (in-sequence thrusting).

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3.c. Phase 2: Kilometre-scale folding

A kilometre-scale NE-vergent syncline–anticline pair (Orvin, 1934; Challinor, 1967; Manby, 1988; Lyberis & Manby, 1993*a*; Saalmann & Brommer, 1997; Saalmann, 2000; Piepjohn, Thiedig & Manby, in press) is exposed in the Ny-Ålesund and Nielsenfjellet thrust sheets, respectively (compare sections in Fig. 4), and is a main and characteristic structure of both thrust sheets. The axial trace of the syncline can be traced from the west of Kiærfjellet striking NW–SE to Brøggerfjellet where it curves into a W–E trend and is cut and displaced to the north by the Scheteligfjellet Fault (Fig. 3). From Zeppelinfjellet it runs to the east and southeast sub-parallel to the Kongsfjorden coastline and finally curves to a NNW–SSE orientation at Grensefjellet. Thus, the overall course of the axial trend has a sigmoidal shape. The syncline is well exposed at Brøggerfjellet and Zeppelinfjellet (Figs 4, 8), as well as at Grensefjellet.

The Ny-Ålesund thrust sheet is exposed on both sides of the Scheteligfjellet Fault. In the west, it forms a tectonic klippe and constitutes the mountain tops of Brøggerfjellet, Kiærfjellet and Scheteligfjellet (Fig. 3). In these areas, the steeply dipping to overturned short limb of the syncline is preserved. East of the Scheteligfjellet Fault, the gently SW-dipping synclinal long limb is exposed to the north of Sherdahlfjellet, Haavimbfjellet and Nielsenfjellet. Eastern Grensefjellet, however, contains steeply W-dipping inverted strata of the Wordiekammen to Kapp Starostin formations which belong to the overturned short limb.

In addition to the kilometre-scale fold, the internal deformation of the thrust sheet comprises typical imbricate fans and folds in the vicinity of the ascending Ny-Ålesund Thrust, which are also associated with second order faults (Figs 8, 9).

The anticline of the kilometre-scale fold structure is exposed in the structurally higher Nielsenfjellet thrust sheet. This thrust sheet is only preserved in the eastern peninsula. It consists predominantly of Caledonian phyllites and quartzites, but on the northern slopes of Haavimbfjellet and Nielsenfjellet it also contains remnants of overturned and steeply SW-dipping Carboniferous strata (Brøggertinden to lower Wordiekammen formations) which confirm the anticlinal structure of the sheet because they rest with sedimentary contact on the metamorphic basement (Ludwig, 1991; Saalmann & Brommer, 1997; Piepjohn, Manby & Thiedig, in press). Some 100 m below, the SW-dipping carbonates already belong to the synclinal long limb of the Ny-Ålesund thrust sheet. The Nielsenfjellet Thrust cuts the short limb of the kilometre-scale fold and carries the anticline onto the syncline (Fig. 4, section G–G′).

The Nielsenfjellet thrust sheet overlies the synclinal long limb in the Ny-Ålesund area and to the north of Slåttofjellet, Haavimbfjellet and Nielsenfjellet, whereas at Grensefjellet in the east, the Nielsenfjellet Thrust truncates the overturned synclinal short limb at a higher level, indicating a more ENE-directed ascent of the thrust (Fig. 4, sections E–E′ to J–J′). This is also indicated by WSW-dipping thrust faults in the eastern parts of the peninsula and the orientation of small-scale duplex-structures in the phyllites directly above the thrust fault on Grensefjellet (Fig. 10g).

In general, the Ny-Ålesund and Nielsenfjellet thrusts strike sub-parallel to the axis of the kilometre-scale syncline and thus their dips vary between south and southwest (Fig. 10). Thrusting and folding therefore appear to have been parallel and coeval. The series of cross-sections in Figure 4 (sections B–B′ to J–J′) clearly shows that the Ny-Ålesund thrust sheet cuts and obliquely overrides the lower thrust sheets and truncates the phase 1 structures (Figs 6, 9). At the northern slope of Scheteligfjellet, the Ny-Ålesund thrust sheet truncates the Kiærfjellt thrust sheet and overlies the Kvadehuken thrust sheet (Fig. 4, section B–B′, Fig. 5). Further to the east, the Ny-Ålesund thrust sheet is thrust onto Tertiary strata (Fig. 4, section C–C′), and to the north of Slåttofjellet it overrides the Wordiekammen Formation within the Kongsfjorden thrust sheet (Fig. 4, section F–F′). This suggests that the movement was directed to the ENE.

At Kiærfjellet and Brøggerfjellet in the southwestern part of the peninsula, the Ny-Ålesund Thrust dips to the northeast (Figs 3, 4) while in the north, it gently dips to the southwest. Thus, the thrust plane is curved and folded (Fig. 4, sections A–A′ to D–D′, Fig. 6). Therefore, the Ny-Ålesund Thrust formed prior to kilometre-scale folding, probably during phase 1, while during phase 2, the previously formed Ny-Ålesund Thrust was folded. This second phase was related to increased and WSW–ENE-directed shortening (in contrast to N–S contraction during phase 1) and involved greater portions of the Caledonian basement by a thrust fault that formed in the hinterland of the older phase 1 thrust sheets. A kilometre-scale fault-propagation fold developed at the tip of this first out-of-sequence thrust (Nielsenfjellet Thrust), causing rotation and tilting as well as folding of the older (phase 1) Ny-Ålesund Thrust. Due to progressive shortening, the phase 2 Ny-Ålesund Thrust carried the syncline obliquely onto the lower thrust sheets and the overturned short limb of the fold was truncated by the Nielsenfjellet Thrust which carried the anticline onto the syncline.

3.d. Phase 3: Development of the basement-dominated thrust sheets

The formation of the structurally higher basement-dominated Bogegga to Engelskbukta thrust sheets resulted in progressive dissection of the basement by additional out-of-sequence thrusting. Tertiary thrusting juxtaposed different basement units. The thrust sheets formed by hinterland-directed propagation of

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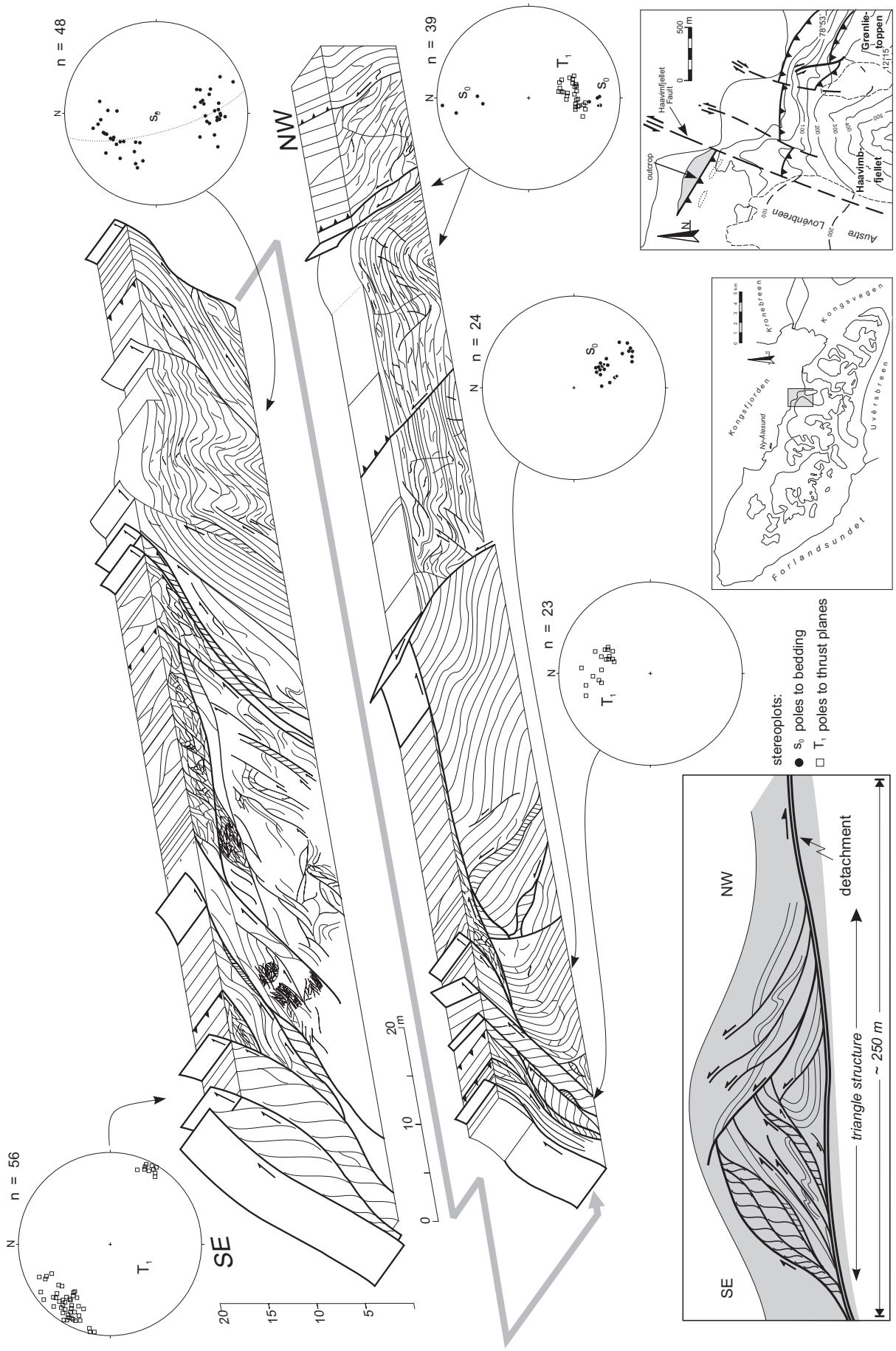


Figure 7. For legend see facing page.

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the thrusts, so that the structurally highest Engelskbukta thrust sheet represents the youngest unit on Brøggerhalvøya because it overrides the Scheteligfjellet Fault which was active during emplacement of the basement-dominated thrust sheets (see Section 4.b.3). Out-of-sequence thrusting is also indicated by the truncation of a fold within Permo-Carboniferous carbonates (part of the Nielsenfjellet thrust sheet) by a large-scale fault which carries crystalline basement-units onto the sediments and also by the fact that at southern Brøggerfjellet to the west of the Scheteligfjellet Fault, the Ny-Ålesund and Kiærfjellet thrust sheets are cut by the Trondheimfjella Thrust (Fig. 4, C–C′).

The distinction of Caledonian and Tertiary fabrics in the basement units of the West Spitsbergen Fold-and-Thrust Belt is a serious problem. Tertiary thrusting occurred at high crustal levels on Brøggerhalvøya by brittle faulting and lacks any evidence for metamorphic overprinting. This is in contrast to Caledonian fabrics which are related to elevated *P–T* conditions and show polyphase syn-deformational metamorphism. Although this might be a simplifying assumption, it is applicable for Brøggerhalvøya because of the absence of any metamorphic overprint of both the post-Caledonian sediments resting with depositional contact on basement rocks, as well as tectonically inserted slivers of Carboniferous rocks within basement thrust sheets. Likewise, brittle faulting is sparse in the basement except adjacent to major Tertiary thrust faults, indicating the absence of widespread Caledonian brittle thrusting.

Some of the Tertiary thrusts can be identified by tectonically inserted slivers of Middle Carboniferous sandstones and dolomites, such as the Trondheimfjella Thrust on northern Bjørvigfjellet which carries greenschist facies rocks onto amphibolite facies rocks of the Bogegga thrust sheet. Such slices of Carboniferous sediments have also been reported from areas in Oscar II Land further southeast (Ohta, Lepvrier & Thiedig, 2000) Typical imbrication is related to brittle thrust faulting; a good example is exposed on the northern coast of Engelskbukta within dolomite marbles of the Moefjellet Formation. The fault zone is related to the Engelskbukta Thrust, and imbricate fans, duplex-structures and some rare folds closely resemble thrust-related structures in the Upper Palaeozoic carbonates elsewhere on Brøggerhalvøya and are therefore interpreted to be related to Tertiary thrust-tectonics. They cut the Caledonian metamorphic foliation. Such structures are rare in schistose basement lithologies and can only be found in the vicinity of major Tertiary thrusts. Cataclastic horizons are also ascribed to Tertiary thrusting if they are located near major brittle thrust faults.

The Bogegga thrust sheet overlies the Nielsenfjellet thrust sheet (Figs 3, 4). The thrust sheet successively overrides greater parts of the Nielsenfjellet thrust sheet to the ENE (Fig. 3) suggesting ENE-directed movement.

Fault-slip data for the overlying Trondheimfjella thrust, although relatively sparse, also indicate ENE-directed slip, while the thrust planes predominantly dip to the southwest (Fig. 11b) suggesting a minor strike-slip component. In the western parts of the Engelskbukta thrust sheet, NNE-directed thrusting is indicated by S- to SSE-dipping imbricates with some associated N–S- to SSW–NNE-striking slickensides (Fig. 11a, western part). Thrusting was accompanied by strike-slip, however, inferred from dextral en échelon tension gashes striking sub-parallel or slightly oblique to the thrust faults, as well as some slickensides showing ENE-directed movements so that oblique-slip rather than dip-slip on these thrust faults can be expected. A few kilometres further to the east, the transport directions change to more SW–NE-oriented shortening indicated by NW-dipping (back-)thrusts and the gently SW-plunging axis of a Tertiary fold (Fig. 11a, central part). The importance of a strike-slip component during emplacement of the Engelskbukta thrust sheet is obvious in the southeastern continuation of this unit at the front of Comfortlessbreen to the south of the peninsula: dolomite marbles are cut by major NNW–SSE-oriented dextral strike-slip faults and several associated NW–SE-trending thrust faults and folds striking at an acute angle to, and curving into, the major faults. This pattern corresponds to a dextral transpressional system (Fig. 12). During SW–NE convergence the strain was partitioned into transport-perpendicularthrusting/folding and transcurrent movements on obliquely oriented planes. This is a unique pattern in this area and can only be observed in the uppermost Engelskbukta thrust sheet. Clearly transpressive patterns have not been observed at other localities on Brøggerhalvøya. This emphasizes the special status of the Engelskbukta thrust sheet.

3.e. Summary of the kinematic evolution

The Tertiary thrust tectonics on Brøggerhalvøya comprise a complex and multi-stage fold-thrust (Fig. 13).

(1) The early phase of N- to NNE-directed thrusting led to the formation of the lower sediment-dominated thrust sheets in a ramp-flat mode of fold-thrust generation and a forward-propagating mode of thrusting (in-sequence thrusting) with first the development of the Ny-Ålesund thrust sheet, followed by

Figure 7. Equal-area, lower hemisphere stereoplots of mesoscale structural data of the phase 1 Kongsfjorden and Kvadehuken thrust sheets (fault-slip data plotted by projection of the slip vector on the pole to the fault plane). (a–c) Kongsfjorden thrust sheet; (d, f) Kvadehuken thrust sheet, (e) Kiærfjellet thrust sheet.

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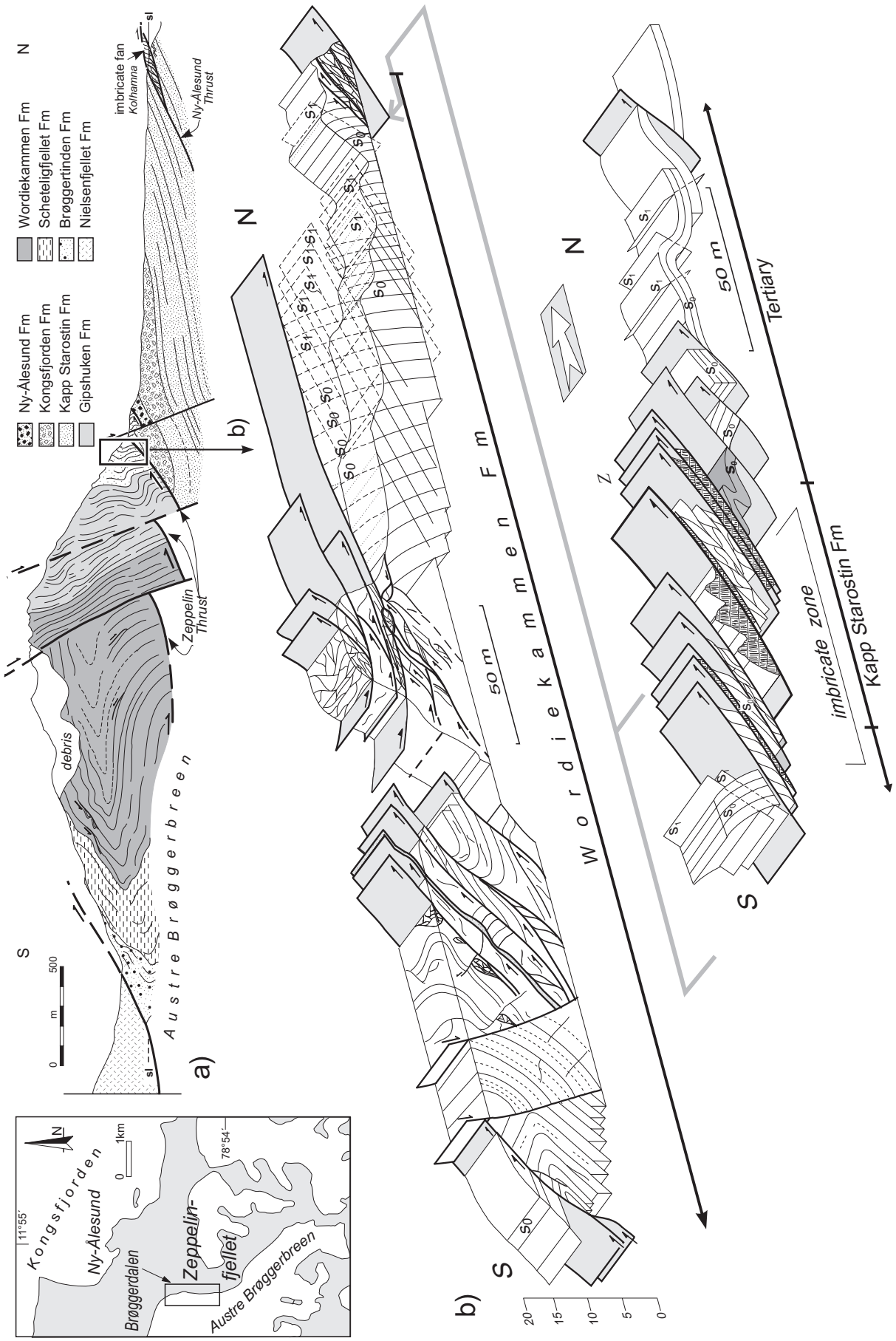


Figure 8. For legend see facing page.

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the formation of the Kiærfjellet, Kvadehuken, Kongsfjorden and Garwoodtoppen thrust sheets.

(2) The Ny-Ålesund thrust sheet overrides the lower thrust sheets and thus, the Ny-Ålesund Thrust exposed in the north cannot represent the initial phase 1 Ny-Ålesund Thrust. The tectonic transport changed from N- to ENE-directed thrusting. Due to enhanced shortening, the first out-of-sequence thrust in the hinterland of the phase 1 in-sequence structures involved greater portions of the basement and led to its inversion and uplift associated with the formation of a kilometre-scale fault-propagation fold at the tip of the thrust fault (Fig. 13). The phase 1 Ny-Ålesund Thrust was tilted, rotated and folded (Fig. 4, section A–A′ to D–D′; Fig. 13). Because of progressive shortening and unfavourably oriented phase 1 structures, a new thrust fault (phase 2 Ny-Ålesund Thrust) was developed using the dolomites of the Tyrrellfjellet Member and Gipshuken formations as slip planes. The phase 2 Ny-Ålesund thrust obliquely cut and overrode the earlier phase 1 structures (e.g. Fig. 9). Concurrently, the Nielsenfjellet Thrust truncated the overturned short limb of the fold structure and carried the anticline onto the syncline.

(3) Stacking of the structurally higher basement-dominated thrust sheets occurred by hindward-propagating additional out-of-sequence thrusts (Fig. 13). The emplacement of the structurally highest Engelskbukta thrust sheet (phase 3b), and perhaps even the formation of the Trondheimfjella thrust sheet, took place during the change from clearly compression-dominated thrusting to thrusting associated with an enhanced strike-slip component. This was accompanied by a change of convergence from WSW–ENE to SW–NE.

Thrust-tectonics was followed by extension (phases 4 and 5).

(4) Large-scale W–E-trending, fold axis-parallel normal faults with downthrow to the north, which occur for example at southern Brøggerfjellet and at Zeppelinfjellet (Fig. 3, Fig. 4, B–B′, C–C′, D–D′) could be linked with late tectonic collapse of the fold belt. Fold belt-parallel normal faults can also be observed at outcrop scale. At Grensefjellet, where the fold axis strikes NNW–SSE, normal faults show downthrow to the ENE.

(5) The subsequent extensional event is much more pronounced on Brøggerhalvøya. Several normal faults ranging from outcrop to nearly regional scale show W–E to WSW–ENE extension. These faults cut pre-existing structures (including the late tectonic phase 4 normal faults) (Fig. 3), and a reactivation of N–S-striking older faults can often be observed. This phase may be related either to the latest extensional phases of the Forlandsundet Graben or to younger extension during progressive opening of the North Atlantic.

3.f. Shortening

On Brøggerhalvøya, a balanced restoration of the stack is only feasible for the Kongsfjorden, Kvadehuken and Kiærfjellet thrust sheets because they are well exposed and show in-sequence thrusting. A restoration has been done for a section from Kiærfjellet (Simlestuppet) to Scheteligfjellet where transport directions do not vary significantly between the three thrust sheets. A line-length-balanced section of these thrust sheets shows shortening from 16.2 km to 7.9 km (= 8.3 km = 51 %) (Saalmann, 2000). This is in accordance with shortening estimates of 12 and 15 km by Manby (1988) and Piepjohn, Manby & Thiedig (in press), respectively. The displacement of the overlying Ny-Ålesund thrust sheet cannot be balanced because of out-of-sequence thrusting and ENE-directed transport (and thus an orientation out-of-plane to the two-dimensional section). An estimated minimal displacement of the Ny-Ålesund thrust sheet of approximately 5 km (without considering the kilometre-scale folding) could be added to the balanced amount. The displacement of the Nielsenfjellet thrust sheet cannot be reconstructed but must be at least equal to, and probably exceeds, the displacement of the Ny-Ålesund thrust sheet. It is obvious, however, that phase 2 (formation of the Ny-Ålesund and Nielsenfjellet thrust sheets) is the major phase of shortening on Brøggerhalvøya. The displacement of the basement-dominated thrust sheets inferred from simple minimum restoration to the horizontal suggests an amount of approximately 4 km, but real displacement would be in excess of this amount. Hence, the total amount of shortening exceeds the restored 12–15 km significantly. The 40 km shortening of the post-Caledonian strata as proposed by Lyberis & Manby (1993*b*), however, is unsubstantiated and too high.

4. Discussion

4.a. Comparison with the fold belt further south

4.a.1. Detachments

Detailed studies of the fold belt south of Brøggerhalvøya have been carried out during the past

Figure 8. (a) The N–S cross-section at Zeppelinfjellet: On the northern slopes, steeply dipping Upper Palaeozoic rocks are thrust over the Tertiary Ny-Ålesund Basin along the Zeppelin Thrust which represents a subordinate reverse fault within the Ny-Ålesund thrust sheet. South of Zeppelinfjellet, basement rocks of the Nielsenfjellet thrust sheet are carried over the Ny-Ålesund thrust sheet (location of the Zeppelin Thrust after Orvin, 1934). The fold structure is cut by post-thrusting extensional faults with downthrow to the north. (b) Shear zone within the Ny-Ålesund thrust sheet west of Zeppelinfjellet related to the Zeppelin Thrust which pinches out at the surface. The fault cuts the steeply inclined short limb and carries Upper Palaeozoic rocks over flat-lying Tertiary strata in the north. Adjacent to the thrust fault, sandstones of the Kapp Starostin Formation are intensely sheared and fractured, and exhibit imbrication of the Lower Permian limestones.

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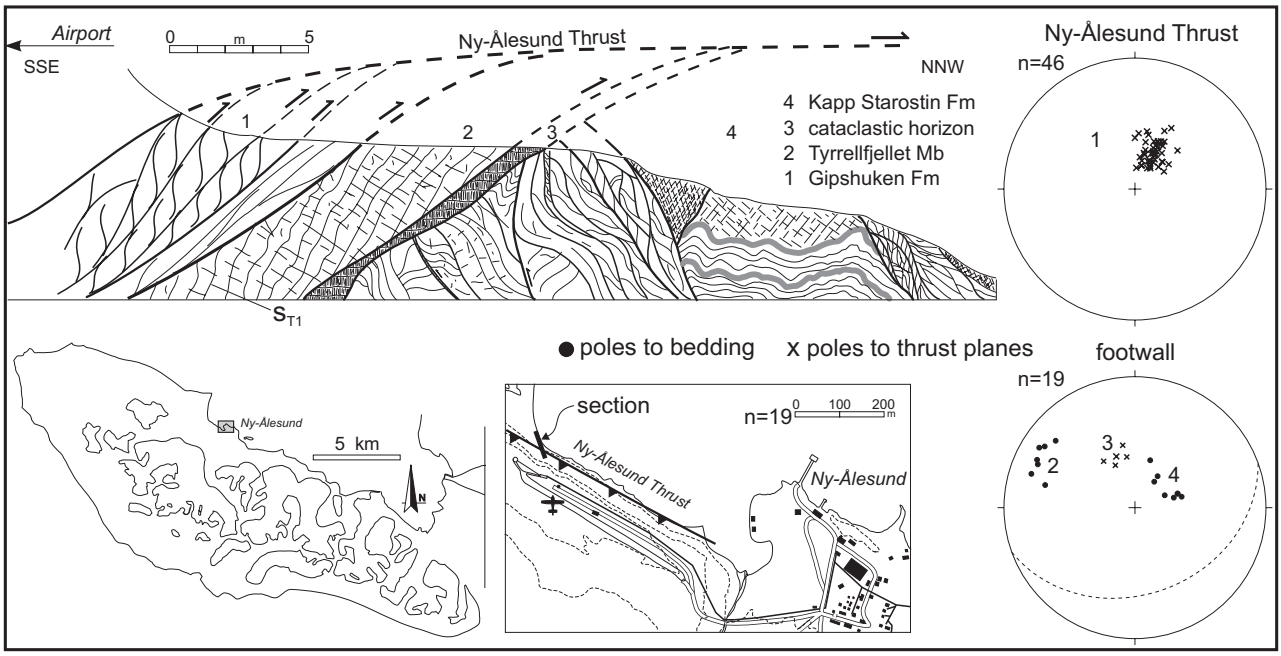


Figure 9. Phase 2 Ny-Ålesund Thrust at the coast north of the Ny-Ålesund airport (Kolhamna) where imbricated dolomites of the Early Permian Gipshuken Formation (Ny-Ålesund thrust sheet) were carried to the NNE on intensely sheared carbonates of the Wordiekammen Formation and Kapp Starostin cherts belonging to the phase 1 Kvadehuken and Kongsfjorden thrust sheets, which in contrast show vergences and shearing directed to the NNW.

20 years. An overview of Tertiary thrust tectonics in different segments of the West Spitsbergen Fold-and-Thrust Belt with comprehensive references is given by Dallmann *et al.* (1993) and Harland (1997).

On Brøggerhalvøya, the flats of the thrust faults are preferentially located in the carbonates of the Wordiekammen Formation (e.g. Fig. 5). The phase 2 Ny-Ålesund Thrust uses the thinly bedded dolomites of the Tyrrellfjellet Member and upper Gipshuken Formation as slip-planes (Fig. 13); these are therefore the most important detachment horizons. The basal detachment is located in phyllites of the Caledonian basement.

In regions further south, the Gipshuken Formation comprises gypsiferous beds which also represent important and major detachment horizons.

While Mesozoic sediments are nearly completely removed in the Kongsfjorden region, except for local thin relics of Triassic shales which have only local importance, the thickness and stratigraphic portion of Mesozoic strata increases to the south. In southern Oscar II Land (south of Brøggerhalvøya and north of Isfjorden), a Triassic sequence is preserved, and directly to the north of Isfjorden, Jurassic and Lower Cretaceous siliciclastics occur in the central to eastern parts of the fold belt (Ohta *et al.* 1992). A thick Mesozoic succession (up to 6100 m) also constitutes a large portion of the post-Caledonian column in Nordenskiöld Land (between Isfjorden and Bellsund) (Ohta *et al.* 1992). The Mesozoic sequence consists predominantly of fine-grained siliciclastics which represent incompetent and weak layers during Tertiary contraction (Braathen & Bergh, 1995) These deposits could accommodate large amounts of strain by folding and moreover include several important detachment horizons. In addition, Lower Carboniferous strata which also contain possible weak horizons are more widespread in the central and southern segments, whereas on Brøggerhalvøya, local occurrences of Lower Carboniferous sandstones and shales are restricted to one thrust sheet (Kvadehuken thrust sheet).

Thus, in contrast to the southern portions of the fold belt, the number of possible detachment horizons is markedly reduced on Brøggerhalvøya due to reduced thickness of the post-Caledonian cover.

4.a.2. Shortening

The amount of shortening varies along-strike in different segments of the fold belt. It ranges from 2–4 km in Wedel Jarlsberg Land and Bellsund (Dallmann, 1988), 8 km north of Van Keulenfjorden (von Gosen & Piepjohn, in press) to 10–14 km at Hornsund (Dallmann, 1992) and 13 km in the St. Jonsfjorden area (Welbon & Maher, 1992). Shortening of 20 km has been reported from Oscar II Land (Bergh, Braathen & Andresen, 1997) and although it exceeds the 12–15 km on Brøggerhalvøya (Manby, 1988; Saalmann, 2000; Piepjohn, Manby & Thiedig, in press), the relative shortening (in percent) of 45% is minor compared with 51–60% in the Kongsfjorden

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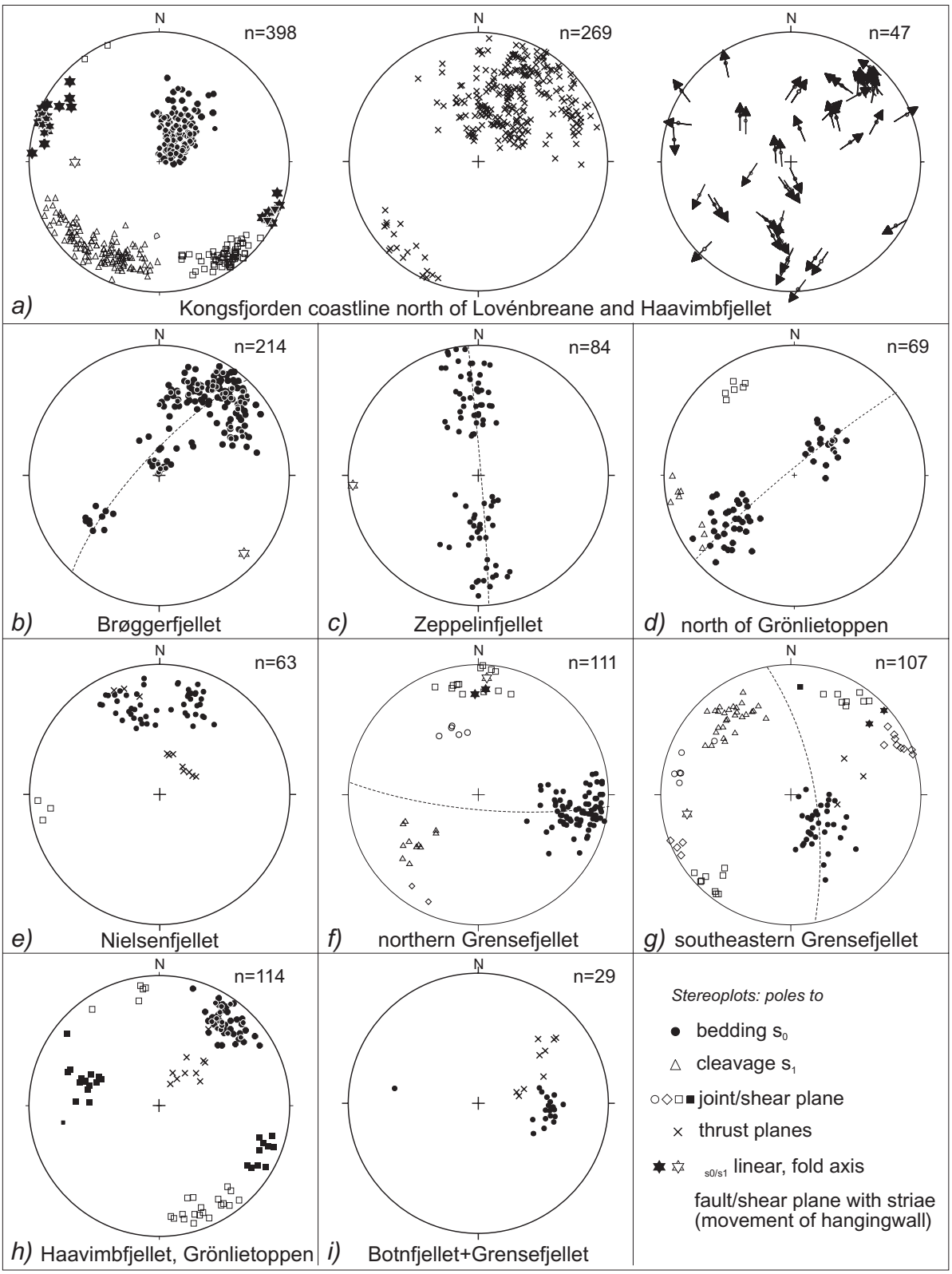


Figure 10. Equal-area, lower hemisphere stereoplots of structural and fault-slip data of phase 2 structures and the kilometre-scale anticline–syncline pair in the Ny-Ålesund and Nielsenfjellet thrust sheets. (a–d) Ny-Ålesund thrust sheet; (e–i) Nielsenfjellet thrust sheet.

area. An unsubstantiated minimum estimate of 80 km of shortening for the whole fold belt is given by Manby & Lyberis (1996), but in light of the estimates for the onshore regions, this seems to be exaggerated. Although it is difficult to simply compare the different values, especially when only a small part of the whole stack can usually be restored (in-sequence thrusting), the along-strike dimensions of the fold belt do not vary too much and thus would allow a comparison of the different regions. The main shortening occurred

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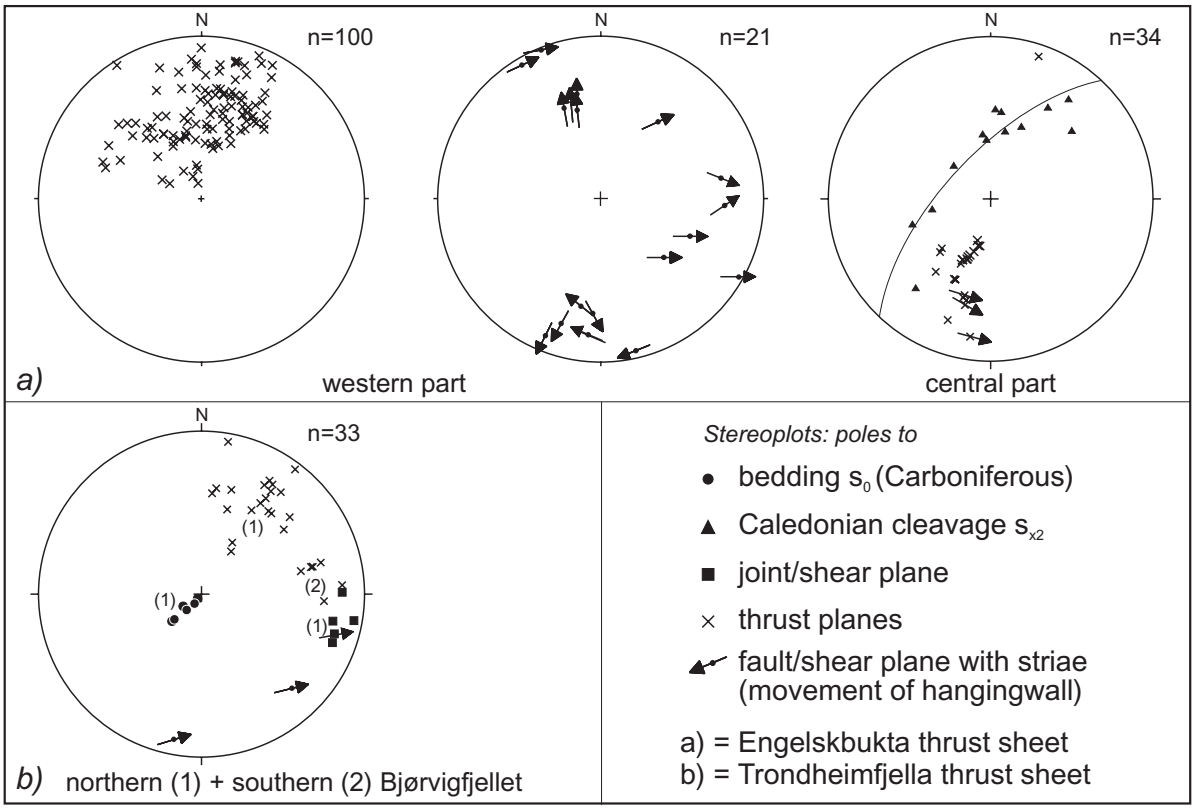


Figure 11. Equal-area, lower hemisphere stereoplots of mesoscale structural and fault-slip data of the phase 3 basement-dominated thrust sheets (a) Engelskbukta thrust sheet; (b) Trondheimfjella thrust sheet.

in the second stage during ENE-vergent folding and thrusting and the same applies to Brøggerhalvøya where phases 2 and 3 are dominant, as well in contrast to phase 1 as suggested by Bergh, Maher & Braathen (2000).

4.a.3. Geometry and kinematic evolution

Despite these minor differences, kilometre-scale anticline–syncline pairs are characteristic structures for the whole fold belt, and remnants of a syncline can be found from Kongsfjorden to Sørkapp (Orvin, 1934; Birkenmajer, 1981; Hjelle *et al.* 1986; Dallmann *et al.* 1990; Maher & Welbon, 1992; Ohta *et al.* 1992; Dallmann *et al.* 1993; Harland, 1997; von Gosen & Piepjohn, in press). As on Brøggerghalvøya, the deformation elsewhere is dominated by orthogonal contraction (Maher, Craddock & Maher, 1986; Dallmann, 1988; Manby, 1988; Bergh & Andresen, 1990; Welbon & Maher, 1992; Dallmann *et al.* 1993; Lyberis & Manby, 1993*a*,*b*; Braathen & Bergh, 1995; Braathen, Bergh & Maher, 1995, 1999; Manby & Lyberis, 1996; Bergh, Braathen & Andresen, 1997; von Gosen & Piepjohn, in press). The kinematic evolution of thrust tectonics on Brøggerhalvøya, even in detail, fits remarkably well with the kinematic history reported from other regions in the West Spitsbergen Fold-and-Thrust Belt (e.g. Nordenskiöld Land: Braathen & Bergh, 1995; Braathen, Bergh & Maher, 1995; southern Oscar II Land: Bergh, Braathen & Andresen, 1997; and Hornsund: Dallmann, 1992): Each segment of the fold belt is characterized by basement inversion coeval with the formation of the kilometre-scale fold post-dating a first phase of in-sequence thrusting. Recent models propose a multiple-stage thrust evolution of in-sequence thrusting, folding and basement involvement and include the following steps (Braathen & Bergh, 1995; Bergh, Braathen & Andresen, 1997; Maher *et al.* 1997; Braathen, Bergh & Maher, 1999):

(1) SSW–NNE contraction and thin skinned in-sequence thrusting;

(2) major WSW–ENE contraction giving rise to folding and involvement of Caledonian basement units, the first out-of-sequence thrusting;

(3) continued ENE-vergence, thrusting occurs along steeper faults and predominantly in the basement units in the west;

(4) orogen-oblique transport and movements along the Svartfjella–Eidembukta–Daudmannsodden Lineament (Maher *et al.* 1997);

(5) down-to-the-W and -WSW normal faulting.

A change from approximately N–S-oriented shortening axes to ENE-directed compression was also recognized by Kleinspehn, Pershing & Teyssier (1989) and Teyssier, Kleinspehn & Pershing (1995). It is important to note that in contrast to the Kongsfjorden region, the Caledonian basement was involved during the second ENE-vergent phase for the first time

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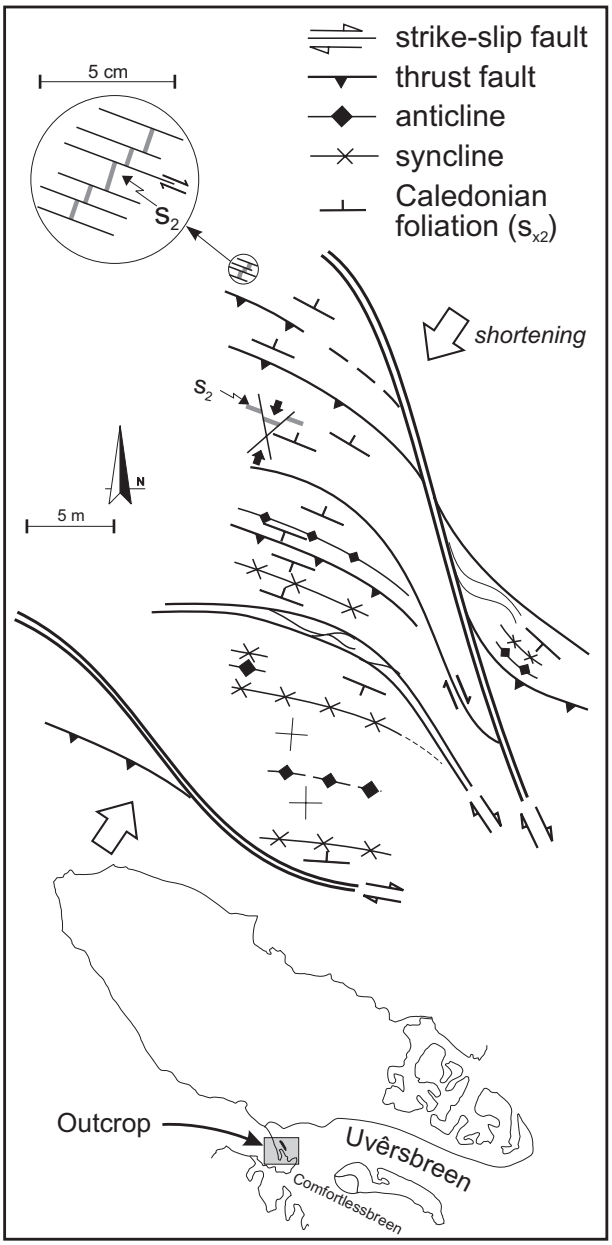


Figure 12. Outcrop of dolomite marbles within the Engelskbukta thrust sheet at Comfortlessbreen. The structural pattern displays a partitioning of the strain in dextral transcurrent movements and contractional thrusts and folds during SW–NE convergence.

(Dallmann, 1988; Braathen & Bergh, 1995; Bergh, Braathen & Andresen, 1997; von Gosen & Piepjohn, in press; Piepjohn & von Gosen, in press).

As on Brøggerhalvøya, the main ENE-vergent phase elsewhere was followed by continued out-of-sequence thrusting associated with more transcurrent movements obliquely oriented to the fold belt during the terminal stages. In southern Oscar II Land, strike-slip faulting particularly occurred along the Svartfjella–Eidembukta–Daudmannsodden Lineament, whose possible continuation to the north may be localized near the eastern border fault of Forlandsundet. A change to more NE-directed transports during these phases has also been reported (Braathen, Bergh & Maher, 1999) and this could coincide with the latest phase 3b emplacement of the Engelskbukta thrust sheet. We assume that the emplacement of the thrust sheets in the basement further south can be correlated with phases 3 and 3b on Brøggerhalvøya, and there may also be overlying and younger thrust sheets preserved in southern Oscar II Land. These facts suggest that Tertiary thrust tectonics on Brøggerhalvøya are coeval with the deformation of the fold-and-thrust belt further south, and even single phases or stages can be correlated, so that the Kongsfjorden area was not an isolated area with a different spatial or temporal structural history.

4.b. Curvature of the fold belt

If Brøggerhalvøya is contemporaneous with the rest of the fold belt, it precludes all models for the curvature and anomalous transport directions in the Kongsfjorden area which assume temporal (Lepvrier, Leparmentier & Seland, 1988; Lepvrier, 1992) or kinematic differences and/or a unique mechanical position (predominant transcurrent movements, location between strike-slip faults or in a restraining bend, mechanical coupling) (Harland, 1969; Kellogg, 1975; Steel *et al.* 1985; Lepvrier, Leparmentier & Seland, 1988; Maher & Craddock, 1988; Lepvrier, 1992; Maher *et al.* 1997; Bergh, Maher & Braathen, 2000). The curvature of the fold belt cannot be attributed to along-strike variability of shortening as suggested, for example, by Bergh, Maher & Braathen (2000) because this would imply the lowest displacements at the margins, that is, at Kongsfjorden, but this is definitely not the case (see Section 4.a). Major transcurrent faults sub-parallel or at an acute angle to the thrust faults cannot be observed in the Kongsfjorden area. We suggest that pre-existing faults as well as subsurface obstacles and topography have played a major role in influencing thrusting in the Kongsfjorden area.

4.b.1. The Kongsvegen Fault

The sole thrust of the whole stack is located in Kongsfjorden and its position and NW–SE strike correspond to the Late Cretaceous/Tertiary Kongsvegen (normal) Fault (Harland & Horsfield, 1974) which bordered the uplifted Nordfjorden Block to the north and east of Brøggerhalvøya (Fig. 14a). Regional uplift of Spitsbergen began in Early Cretaceous times and was most intense in the northern parts of Spitsbergen (Orvin, 1940; Mørk & Bjorøy, 1984; Steel & Worsley, 1984). A possible explanation for the uplift is that it could be linked to widespread Cretaceous igneous activity in the Arctic (Maher, 2001). Uplift resulted in erosion of Carboniferous to Jurassic deposits on the Nordfjorden Block (Orvin, 1940; Cutbill & Challinor,

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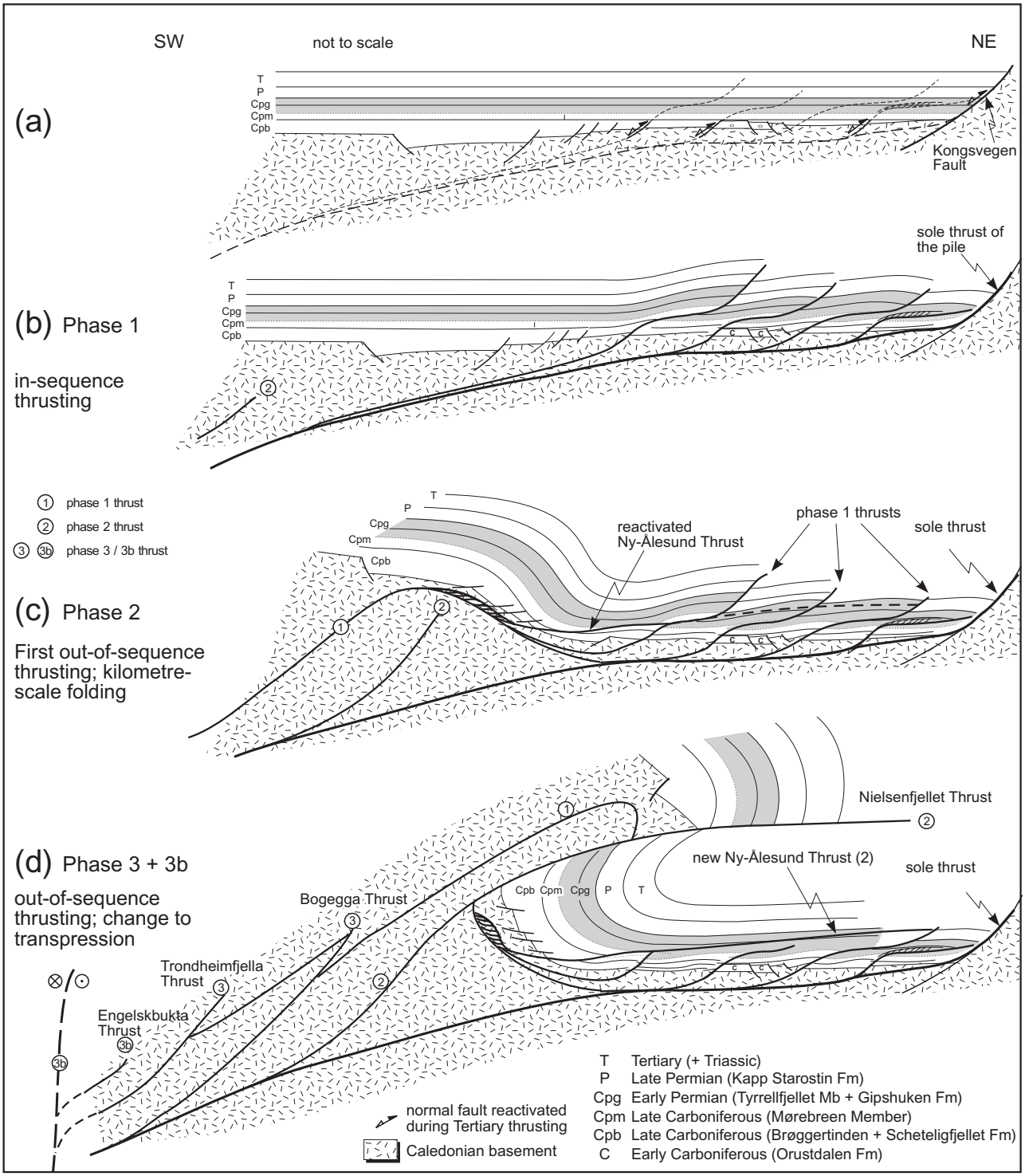


Figure 13. Simplified schematic three-phase model for the Tertiary thrust tectonics on Brøggerhalvøya (not to scale). (a) Initial pre-Tertiary configuration; (b) Phase 1: formation of the lower thrust sheets with ramp-flat geometries (probably by in-sequence thrusting); (c) Phase 2: first out-of-sequence thrusting and formation of the kilometre-scale fold-structure, folding of the phase 1 Ny-Ålesund Thrust; (d) Phase 3: truncation of the fold and transport of the anticline onto the syncline; formation of the basement-dominated thrust sheets due to development of new hindward-propagating out-of-sequence thrusts. Shift to more transpressive strain during the terminal phase 3b, that is, emplacement of the Engelskbukta thrust sheet, and perhaps the Trondheimfjella thrust sheet.

1965; Mørk, Knarud & Worsley, 1982; Steel & Worsley, 1984; Dallmann, 1999) and also caused the marked reduction of the sedimentary cover on Brøggerhalvøya prior to the formation of the Tertiary basin. Uplift of the Nordfjorden Block continued during Early Tertiary times, whereas on Brøggerhalvøya, the Ny-Ålesund Basin accumulated a thick succession of Paleocene conglomerates, sandstones and shales.

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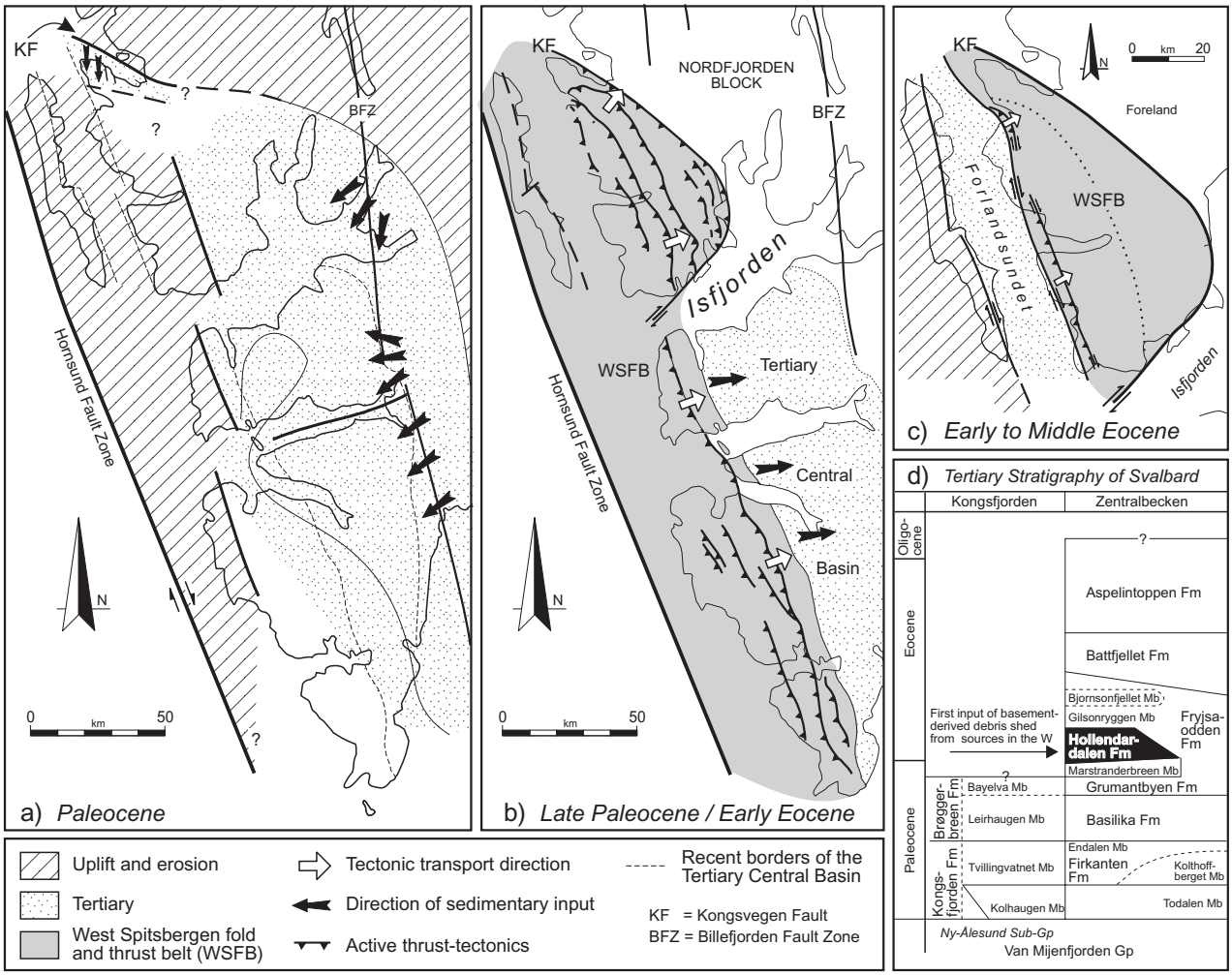


Figure 14. (a) Deposition of the Tertiary siliciclastics in Middle Paleocene times (modified after Steel & Worsley, 1984; Müller & Spielhagen, 1990). Basement-derived debris was shed from northerly directions into the Ny-Ålesund basin which was bounded to the northeast by the Kongsvegen Fault with minimum down-to-the-SW displacement of 1000 m. (b) Main phase 2 + early phase 3 of Tertiary thrusting and first input of basement-derived debris from the west into the central Tertiary basin. (c) Emplacement of the highest thrust sheets (phase 3b) during dextral transpression followed by the formation of the Forlandsundet Graben. (d) Stratigraphic table of the Tertiary sediments in Svalbard (after Dallmann, 1999). Note the first input of basement clasts into the Early Eocene Hollendardalen Formation implying a latest Paleocene/earliest Eocene age for the main phases of Tertiary thrusting.

The Ny-Ålesund Tertiary Basin is not a foreland basin. The Tertiary beds rest without exception on flat-lying Upper Permian cherts and sandstones (Kapp Starostin Formation) and there is no angular unconformity between the Upper Palaeozoic and Tertiary strata. Moreover, the detritus shed into the basin consists solely of basement-derived clasts (from the Nordfjorden Block) and of cherts derived from the underlying Kapp Starostin Formation, as well as pebble-size detritus composed of Tertiary sandstone reworked from earlier depositional cycles of the basin. In the Tertiary strata, clasts derived from older rock units on Brøggerhalvøya like Carboniferous sandstones and carbonates or local phyllites and schists cannot be found. A foreland basin would contain a greater variety of clasts and at least would show an evolution to increasing amounts of local debris with time, but this is not the case here. The sediments were shed from the north (Orvin, 1934; Atkinson, 1963; P. Midbøe, unpub. Ph.D. thesis, Univ. Bergen, 1985) and not from a fold belt in the SSW. Sections of boreholes sketched by Orvin (1934) and Midbøe (P. Midbøe, unpub. Ph.D. thesis, Univ. Bergen, 1985) show that conglomerates in the lower parts of the succession preferentially occur in the north in approach to the Kongsfjorden Fault. Therefore, it is unlikely that the basin formed in the foreland of a developing and rising fold-and-thrust belt, but rather formed prior to thrust-tectonics in an extensional (or transtensional) regime.

It is important to note that the basement to the north of Kongsfjorden was already exposed during the development of the Tertiary Ny-Ålesund basin in response to stronger uplift since Late Cretaceous times. This is indicated by the predominance of basement-derived clasts shed from the north (Orvin, 1934;

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Atkinson, 1963). There is a distinct contrast in the amount of erosion between Brøggerhalvøya (erosion of Mesozoic strata except for local thin relics of Lower Triassic shales) and the adjacent northern areas (exposure of Devonian and basement units during Tertiary times). Taking the thickness of Brøggerhalvøya for scale (Permo-Carboniferous + 50 m Triassic + Tertiary), the minimum difference in thickness of eroded beds between the adjacent Nordfjorden Block (already on Blomstrandhalvøya) and Brøggerhalvøya (being equivalent to the difference in uplift of both areas) is about 1000 m without taking into account possible Mesozoic beds. This suggests that a ~NW–SE-striking normal fault located in the Kongsfjorden area (= Kongsvegen Fault) (Fig. 14a) with downthrow to the southwest on the order of at least 1000 m separated the Tertiary basin from the basement to the north.

4.b.2. Model for the curvature of the fold belt

The second phase of ENE-directed thrusting was associated with increased shortening. The emplacement of the phase 2 and 3 thrust sheets, however, was inhibited by the uplifted basement of the Nordfjorden Block, resulting in a brake on the displacement as well as inverse reactivation of the Kongsvegen Fault as a lateral ramp during Tertiary thrusting. The ramp locked, and oblique slip on the ramp caused a rotation of the movement direction to the northeast. In addition, passive bending of the structures, resulting from pinning on the uplifted basement block probably also accounts for the fold-belt curvature. This is suggested by the sigmoidally curved trend of the fold axis on Brøggerhalvøya (Fig. 3) and by the frequency of SSW–NNE-oriented tear faults in the eastern parts of Brøggerhalvøya where the curvature from NNW to WNW is strongest. These tear faults are oriented perpendicular to the thrust faults and are interpreted to accommodate the varying transports within the Nielsenfjellet and Ny-Ålesund thrust sheets caused by varying impediment of their displacement. The Scheteligfjellet Fault is also thought to be a transfer fault (Manby, 1988; Piepjohn, Thiedig & Manby, in press), but it has a more complex evolution (see Section 4.b.3). To the east of Brøggerhalvøya, at Colletthøgda and Garwoodtoppen, ENE-directed thrust movement was not inhibited to such an extent, and thus Upper Palaeozoic strata could be thrust onto foreland rocks along the Garwoodtoppen Thrust.

The curvature and anomalous transport on Brøggerhalvøya could thus be simply explained by the pre-existing basement topography and the orientation of older structures.

4.b.3. The Scheteligfjellet Fault

The sediment-dominated lower thrust sheets in the western part of the peninsula 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. 3). To the south of Bjørvigfjellet, the fault dies out and is overlain by the structurally highest Engelskbukta thrust sheet (Fig. 3). The Engelskbukta thrust sheet shows no evidence for faulting along the projected continuation of the lineament. A finite displacement of 700–800 m downthrow to the east combined with sinistral strike-slip can be reconstructed for the Scheteligfjellet Fault, which has a multi-stage history of movement (Saalmann, 2000). It is striking that the fault is located in the area where the axis of the kilometre-scale fold curves into a W–E trend (Fig. 3) which is assumed to be caused by buttressing on the Nordfjorden Block. This suggests that the fault formed in response to locking of the displacement during progressive shortening (phase 2) and that it accommodates different amounts of displacement in the eastern and western parts of the Nielsenfjellet thrust-sheet as well as the overlying basement-dominated thrust-sheets. It is impossible to reconstruct the kinematics of the different movements along the fault. It is unlikely that the fault was very active prior to formation of the kilometre-scale fold because it would have influenced folding. Moreover, the sigmoidal bend of the fold-axis was not caused by drag during movements along the Scheteligfjellet Fault because the trace of the fold-axis does not curve into the fault. Instead, a previously bent axis was subsequently cut and displaced by the fault. The first activation of the Scheteligfjellet Fault as a transfer fault is therefore probably related to the movement of the Nielsenfjellet thrust sheet. In the southern part of Brøggerhalvøya, to the west of the Scheteligfjellet Fault, the Trondheimfjella thrust sheet is thrust onto the Ny-Ålesund thrust sheet (Fig. 3, Fig. 4, section C–C′). Thus, the Nielsenfjellet thrust sheet (anticline), and probably also the Bogegga thrust sheet, were removed in the western parts of the peninsula prior to the displacement of the Trondheimfjella thrust sheet. The emplacement of the basement-dominated thrust sheets is therefore believed to have been accompanied and partly controlled by continuous activity of the Scheteligfjellet Fault. Movements along the Scheteligfjellet Fault with a downthrow to the east and uplift of the western part during a short extensional or transpressive episode, respectively, would have caused exhumation of the kilometre-scale fold in the west followed by extensive erosion of its anticlinal part (Nielsenfjellet thrust sheet). However, detritus resulting from this erosion cannot be found today. The distribution of the Bogegga thrust sheet cannot be reconstructed with certainty. Its displacement may have been inhibited and localized to the east due to stronger uplift of the western part. Alternatively, the thrust sheet was also eroded prior to the displacement of the Trondheimfjella thrust sheet. Hence, multi-stage movements along the Scheteligfjellet Fault

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coeval with thrusting likely have influenced the architecture of the thrust-stack on Brøggerhalvøya. Movements along the Scheteligfjellet Fault ceased prior to the displacement of the structurally highest and youngest Engelskbukta thrust sheet which overlies the fault (Fig. 3).

4.c. Implications for the temporal evolution and age of the West Spitsbergen Fold-and-Thrust Belt

4.c.1. Compression or transpression?

In the Kongsfjorden area, the strain is characterized by contraction rather than transpression, but a shift to transpression occurred during the emplacement of the structurally highest thrust-sheet on Brøggerhalvøya (phase 3b) and likewise during the deformation of the westernmost areas of the fold belt in Oscar II Land. The predominance of contraction, however, does not fit very well with the assumption that development of the fold belt was contemporaneous with dextral transpression as result of the separation of Svalbard and Greenland. Models assuming Late Cretaceous rather than Tertiary thrust tectonics in Svalbard and Greenland (Hanisch, 1984*a*,*b*; Lyberis & Manby, 1993*a*,*b*; Manby & Lyberis, 1996, 2000) can be ruled out because of the involvement of Tertiary units in folding and thrusting (Lepvrier, 1994; Maher *et al.* 1995; Saalmann, Piepjohn & Thiedig, 1997; Saalmann, 2000; Piepjohn *et al.* in press).

A popular and attractive model implies a total partitioning or decoupling of the deformation into an internal transcurrent belt located on the modern shelf areas and an external onshore exposed belt showing the orthogonal component (Maher & Craddock, 1988; Nøttvedt *et al.* 1988; Leprvier, 1992; Teyssier, Kleinspehn & Pershing, 1995; Maher *et al.* 1997; Braathen, Bergh & Maher, 1999). However, the existence of an offshore strike-slip belt has yet to be proved. It has been suggested that the structural pattern and evolution observed in the fold belt is linked with increasing decoupling of the deformation with time, associated with the localization of strike-slip movements on major faults (like the Svartfjella–Eidembukta–Daudmannsodden Lineament: Braathen, Bergh & Maher, 1999). On Brøggerhalvøya, strain partitioning can be observed only in the latest stages of fold belt formation, and a change in the tectonic evolution is also indicated by the marked break between the emplacement of the Bogegga and Trondheimfjellet thrust sheets, probably associated with a short time-gap, when the Nielsenfjellet and Bogegga thrust sheets were eroded prior to the formation of the Trondheimfjella thrust sheet (see Section 4.b.3). It is also apparent that major strike-slip faults in the fold belt further south (like Svartfjella–Eidembukta–Daudmannsodden Lineament) only occur in the western portions of the fold belt. Although we can link transpression to the final stages of thrusting on Brøggerhalvøya, it does not necessarily follow that the Svartfjella–Eidembukta–Daudmannsodden Lineament further south was only active during the late phases. On the other hand, this lineament cut basement units and involved slices of Carboniferous strata (Maher *et al.* 1997), and thus was active during the latest stages of the evolution when the basement was involved, considering the kinematic history outlined above. This points to a temporal shift of the orientation of the regional stress field and of the overall strain regime rather than a change in the mechanical behaviour (decoupling) during thrusting. Moreover, a continual predominating strike-slip regime throughout the whole thrusting episode would imply additional major strike-slip faulting in the central or eastern zones of the fold belt, at least at some major structural boundaries. Evidence for such deformation has not been reported. A model of complete decoupling with the strike-slip component being restricted to the shear zone off-shore, seems to be highly speculative, in particular because it is hard to prove. Palaeo-stress analysis of fault populations within the Central Tertiary Basin (Kleinspehn, Pershing & Teyssier, 1989; Teyssier, Kleinspehn & Pershing, 1995) showing a prolate stress ellipsoid during WSW–ENE compression would allow the recognition of transpression (Teyssier, Kleinspehn & Pershing, 1995), but this does not necessarily prove or even demand transpression and therefore cannot be regarded as evidence for complete partitioning. It has been suggested that the early NNE-directed phase oblique and counterclockwise to the regional strike of the fold belt indicates a less decoupled stage which was followed by increased and finally complete decoupling during WSW–ENE shortening (Maher *et al.* 1997; Braathen, Bergh & Maher, 1999). The overall architecture and strike of the fold belt was formed during the main, ENE-directed phase of folding and thrusting, which does not necessarily imply a change in the mechanical behaviour, but could also simply reflect a rotation of the regional stress field caused by other factors. Moreover, one has to consider that phase 2 was characterized not only by a change in tectonic transport but also by a marked increase of shortening and strain; we wonder if this could be explained easily only with decoupling. Major strike-slip faults in the structurally lower levels of the fold belt which would link and record the transition to increasing decoupling between phase 1 and 2 have not been reported.

Another important point has been made by Manby & Lyberis (1996). They note that the width of the fold belt, about 150 km, exceeds the width of typical strike-slip belts. Although their shortening estimates of 80 km are speculative and we do not agree with many of their conclusions, this objection cannot be simply denied, although a zone of decoupled deformation on the order of 80–100 km has been described in the San Andreas Fault zone (Mount & Suppe, 1987).

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We do not rule out a minor component of dextral transpression with or without some degree of decoupling/partitioning during the different phases of the fold belt evolution, but considering the age relations outlined below, we suggest that the structural evolution and pattern reflect mainly a temporal change from compression-dominated tectonics to strike-slip-dominated strain during the terminal stages (phase 3b) and that this evolution can be linked with changes in the plate-tectonic framework.

4.c.2. Age of the fold belt and plate tectonics

Determining the age of the Tertiary strata involved in folding and thrusting is essential for unravelling the plate-tectonic configuration leading to the formation of the fold belt. However, dating of the Tertiary strata is extremely difficult due to the absence of index fossils. A 58 ± 2 Ma depositional age of the uppermost preserved beds of the Ny-Ålesund Tertiary has been suggested on the basis of fission-track data (Blythe & Kleinspehn, 1998), but this could also reflect their uplift during thrusting. A shift of the sediment source for the Central Tertiary Basin from northeast to west took place in latest Paleocene (Steel *et al.* 1985; Müller & Spielhagen, 1990) or Early Eocene times (55 Ma, indicated by fission-track analysis: Blythe & Kleinspehn, 1998) reflecting the uplift of the West Spitsbergen Fold-and-Thrust Belt in the west (Steel *et al.* 1985; Müller & Spielhagen, 1990). It is particularly important to note that, for the first time during the deposition of the Early Eocene Hollendardalen Formation, the sedimentary input was shed from the west into the Central Basin and contained basement-derived components (Steel *et al.* 1985; Müller & Spielhagen, 1990) (Fig. 14b,d), because in this region, the main phase (ENE-vergent folding, basement-dominated thrust sheets) at first involved portions of the basement (see Section 4.a.2) (Braathen & Bergh, 1995; Braathen, Bergh & Maher, 1995; Bergh, Braathen & Andresen, 1997; von Gosen *et al.* in press; Piepjohn & von Gosen, in press). This suggests that the main phases of the fold belt evolution (corresponding to phases 1 + 2 and early phase 3 on Brøggerhalvøya) already occurred prior to 55 Ma and thus about Late Paleocene to Early Eocene times (between 60–55 Ma) (Figs 14b, 15). The opening of the Greenland–Norwegian Sea beginning at Chron 25 (latest Paleocene) (Talwani & Eldholm, 1977; Eldholm, Myhre & Faleide, 1984; Jackson, 1985; Srivastava, 1985; Roest & Srivastava, 1989) was coeval with a change in spreading-direction in the Labrador Sea from ENE to NNE (Roest & Srivastava, 1989). Since Chron 24 (Early Eocene), contemporaneous spreading in the Labrador and Greenland–Norwegian seas as well as in the Eurasian Basin and North Atlantic led to the separation of Svalbard and Greenland by means of dextral displacement along the DeGeer Fracture Zone/Hornsund Fault Zone (Harland, 1969; Harland & Horsfield, 1974; Talwani & Eldholm, 1977; Eldholm, Myhre & Faleide, 1984; Srivastava, 1985; Roest & Srivastava, 1989). The tectonic development at this plate boundary can be subdivided into an earlier compression-dominated phase occurring from Chron 25 (~59 Ma) to 24 (~55–56 Ma) followed by strike-slip dominated transpression between Chron 24 and 21 (~50 Ma) (Müller & Spielhagen, 1990). This fits very well with the compression-dominated deformation of the fold belt during the early and main phases, which therefore can be related to the time-span between Chron 25 and 24. It also corresponds well with the shift to transpression during the latest stages which can be linked with the beginning of the separation of Svalbard and Greenland shortly after Chron 24. This separation was accompanied by dextral transpression (Müller & Spielhagen, 1990), and the deformation was controlled by a major wrench fault (DeGeer Fracture Zone/Hornsund Fault Zone) as the principal displacement zone and thus was transferred and restricted to the westernmost areas and probably to the shelf regions. This explains the restriction of strike-slip faults to the younger structures in the westernmost areas observed in the fold belt and also the observed continued sedimentation as well as deformation in the Central Tertiary foreland basin. Therefore, the later phases (3b on Brøggerhalvøya and younger basement thrust sheet in Oscar II Land, respectively) occurred in late Early Eocene to early Middle Eocene times (until anomaly 21, 50 Ma) (Fig. 15).

The cause of the change from SSW-NNE-directed shortening during phase 1 to ENE-vergence during phase 2 is still unknown. Note that phase 1 is not a major long-term event, but led to only minor shortening; there is little knowledge about the detailed plate motions in the Arctic, especially short-lived events. On the other hand, a degree of partitioning or decoupling might play a certain role because 'compression-dominated' does not exclude a minor transcurrent component during contraction.

The formation of the Forlandsundet Graben was not contemporaneous with stacking of the thrust sheets on Brøggerhalvøya but post-dates the displacement of the structurally highest and youngest Engelskbukta thrust sheet in this area. A Middle Eocene age proposed for the graben formation including transpressional and transtensional phases (Steel & Worsley, 1984; Steel *et al.* 1985; Lepvrier, 1990; Gabrielsen *et al.* 1992) fits well with the strike-slip-dominated transpression and subsequent transtension/extension in Middle Eocene to Oligocene times (Fig. 15).

5. Conclusions

The Tertiary West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya is characterized by a NE-vergent

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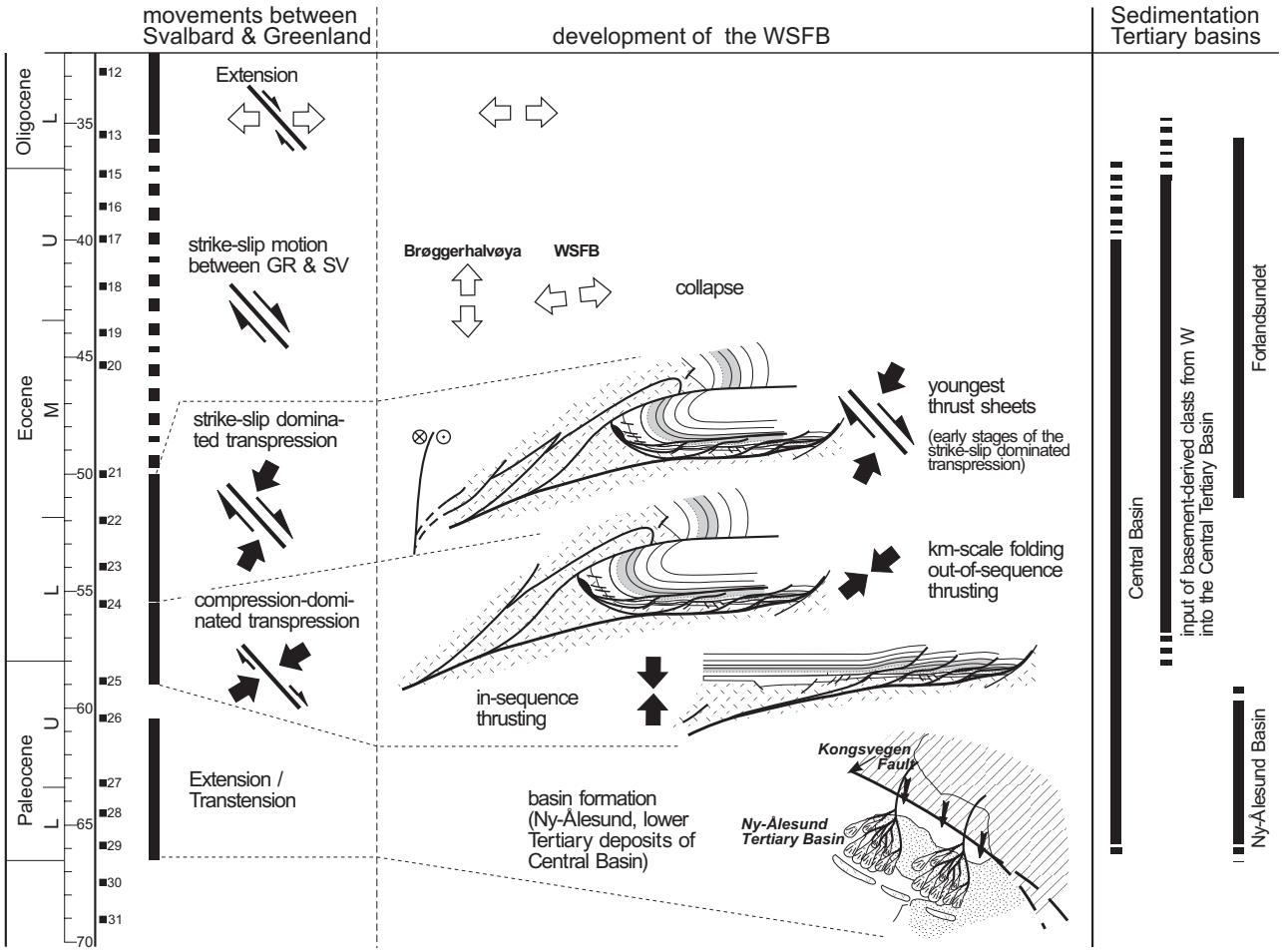


Figure 15. Timing of the structural evolution of the West Spitsbergen Fold-and-Thrust Belt (WSFB) in relation to plate-kinematics (relative movements of Svalbard and Greenland).

pile of nine thrust sheets. The tectonic style is 'thick-skinned'. The sole thrust is located in Precambrian rocks and climbs up-section to the northeast. It is inferred to be located in Kongsfjorden.

Three structural levels can be distinguished comprising (1) four lower thrust sheets consisting predominantly of Upper Palaeozoic sediments, (2) two thrust sheets in the central part of the stack which contain a kilometre-scale syncline and anticline, and (3) three basement-dominated thrust sheets which represent the structurally highest parts.

The internal deformation in the thrust sheets is weak above the flats whereas imbricate fans, duplex-structures and small-scale fault-related folds can be found mainly adjacent to the ascending thrust faults (ramp positions).

A multi-stage kinematic evolution of five phases is proposed:

(1) Subhorizontal, N- to NNE-directed, bedding-parallel movements in the lower thrust sheets resulted in in-sequence foreland-propagating fold-thrust evolution with ramp-flat geometries.

(2) A change in tectonic transport to the ENE and first out-of-sequence thrusting led to inversion and uplift of the basement in the hinterland associated with the formation of the kilometre-scale fold-structures causing folding and bending of the phase 1 detachments. The phase 1 Ny-Ålesund thrust sheet obliquely cut and overrode the lower thrust sheets.

(3) The truncation of the kilometre-scale fold by a thrust fault was followed by stacking of the basement-dominated thrust sheets by SW-propagating and ENE-directed out-of-sequence thrusting. The deformation during phase 1 to early phase 3 was clearly compression-dominated. The displacement of the highest basement thrust sheet during phase 3b, however, includes transcurrent movements and marks the shift to transpressional strain.

(4) W–E-striking normal faults with downthrow to the north reflect the collapse of the fold belt.

(5) The last phase is characterized by E–W to WSW–ENE extension along N–S- to NW–SE-striking faults cutting the older structures.

Comparison of the structural geometry and especially

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the kinematic evolution of Brøggerhalvøya with the data reported for the more southerly fold belt implies their coeval evolution.

The curvature of the fold belt in the Kongsfjorden region and associated NE-directed transport directions were caused by oblique ramping on the Kongsvegen Fault (a pre-existing normal fault with a downthrow to the southwest) which resulted in the deflection of the ENE-directed transport to the northeast. In addition, pinning and buttressing on the uplifted basement of the Nordfjorden Block is thought to have influenced the observed pattern on Brøggerhalvøya. This is indicated by the sigmoidal bend of the fold axis as well as by several tear faults including the Scheteligfjellet Fault.

A latest Paleocene/Early Eocene age for the main phase of thrusting (phases 1–3) is suggested for the West Spitsbergen Fold-and-Thrust Belt. It can be linked with the plate-kinematic framework which includes compression-dominated transpression between Chron 25 and Chron 24 (latest Paleocene to Early Eocene). This is supported by the first occurrence of basement-derived clasts in Tertiary strata of earliest Eocene age. The increasing importance of transcurrent movements during the emplacement of the highest and youngest thrust sheet (phase 3b) and coeval strike-slip fault zones in the western areas of the fold belt reflect the transition to strike-slip-dominated transpression after Chron 24 which also controlled the evolution of the Forlandsundet Graben.

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