

# Tertiary divergent thrust directions from partitioned transpression, Brøggerhalvøya, Spitsbergen

STEFFEN G. BERGH, HARMON D. MAHER, Jr. & ALVAR BRAATHEN

Bergh, S. G., Maher, Jr. H. D. & Braathen, A.: Tertiary divergent thrust directions from partitioned transpression, Brøggerhalvøya, Spitsbergen. *Norsk Geologisk Tidsskrift*, Vol. 80, pp. 63–82. Oslo 2000. ISSN 0029-196X.

Brøggerhalvøya, located at the northwestern terminus of Spitsbergen's Tertiary fold-thrust belt, is underlain by a basement-involved thrust stack defined by an anomalous WNW–ESE strike direction relative to the overall NNW–SSE strike further south. Three kinematically separable thrust nappes are identified: (i) a lower nappe is characterized by low-angle to bedding-parallel imbricates, (ii) a middle nappe comprises macroscopic anticlines and synclines, rotated imbricate fans and duplexes within Palaeozoic–Mesozoic cover strata, and (iii) an upper nappe consists of overthrust Caledonian basement rocks. In addition, steep N–S-striking oblique-normal faults offset the fold-thrust stack and can be traced southwards into parallelism with the Forlandsundet Graben and a major transcurrent fault, the Svartfjella–Eidembukta–Daudmannsodden Lineament. A three-phase kinematic development of the nappes and bounding thrust systems is invoked: (i) an early phase of basement-involved uplift and foreland thrusting of the lower and middle nappes at oblique thrust directions varying from NW to NNE, (ii) a mid-phase out-of-sequence thrusting of the upper nappe towards the ENE, and (iii) a late-phase truncation of the nappe stack by N–S-striking normal faults with subsidiary strike-slip components. Comparisons with other segments of the fold-thrust belt further south temporally link the early-phase thrusting in Brøggerhalvøya to a Palaeocene–early Eocene coupled transpressional event (stage 1). The mid-phase ENE-directed thrusting in Brøggerhalvøya can be temporally correlated with the main Eocene decoupled transpressional event of central Spitsbergen (stages 2 and 3), while the late-phase N–S-striking normal faults may correlate with Late Eocene–Oligocene faults bounding the Forlandsundet graben (stages 4 and 5). We explain the origin of the anomalous WNW–ESE structural trend in Brøggerhalvøya as a response to differential translation and temporal changes in thrust/shortening directions. We also advocate variable degrees of coupled and decoupled orogen-normal and orogen-parallel deformation along western Spitsbergen. The overall result is that structures ascribed to the early NW- to NNE-directed shortening events (i.e. orogen-oblique motions) predominate in Brøggerhalvøya, while ENE-directed structures ascribed to the main/late stage event (i.e. orogen-normal motions) predominate in the south. Other causes of the anomalous WNW strike in Brøggerhalvøya may be location near the termination of the Carboniferous St. Jonsfjorden Trough, and changes in orientation, thickness and/or facies types of the Carboniferous through Mesozoic strata.

Steffen G. Bergh, Department of Geology, University of Tromsø, NO-9037 Tromsø, Norway (e-mail: steffen@ibg.uit.no); Harmon D. Maher, Jr., Department of Geography and Geology, University of Nebraska at Omaha, NE 68182-0199, Omaha, USA; Alvar Braathen, Geological Survey of Norway, Box 3002 Lade, NO-7002 Trondheim, Norway

## Introduction

Svalbard's Tertiary deformation province was centred along an intracontinental, dextral, transform plate boundary (Hornsund fault zone) during Palaeogene opening of the North Atlantic (Harland 1969; Birkenmajer 1972; Lowell 1972; Kellogg 1975; Steel et al. 1985; Eldholm et al. 1987). In central Spitsbergen, the Tertiary deformation is expressed as a 100–200 km wide fold-and-thrust belt (Fig. 1). In a transect (Fig. 1c), the *western hinterland* includes predominantly basement strata (Maher et al. 1986; Welbon & Maher 1992; Dallmann et al. 1993; Braathen et al. 1995; Bergh et al. 1997), local Tertiary basins (Steel et al. 1985; Gabrielsen et al. 1992), and a major transcurrent fault zone, the Svartfjella–Eidembukta–Daudmannsodden lineament (SEDL; Maher et al. 1997). The latter is considered an on-land equivalent to the Hornsund palaeotransform (Eldholm et al. 1987). The next province is a major *basement-involved fold-thrust complex* or antiformal stack, followed eastward by a *central zone* of thin-skinned fold-thrust structures developed above a basal decollement in Permian gypsum (Bergh et al. 1997). The *eastern foreland province* consists of generally flat-lying Mesozoic strata underlain by steep basement-seated fault

zones, the Billefjorden and Lomfjorden faults, with associated inversion structures (e.g. Haremo & Andresen 1992).

In this paper we present a summary of recently compiled structural mapping and stratigraphic data of Brøggerhalvøya (Figs. 1, 2), as part of a regional synthesis undertaken by the University of Tromsø and Saga Petroleum. The aim of the project is to gain an understanding of the evolution of Spitsbergen's Tertiary fold-thrust belt by focusing on the spatial and temporal distribution of transport directions and strain patterns, and their relationship to contemporaneous plate motions.

Brøggerhalvøya, located at the northwestern terminus of Spitsbergen's Tertiary deformation zone, near Kongsfjorden and Ny Ålesund (Figs. 1, 2a), displays excellent exposures of a macroscopic basement-involved fold-thrust stack (Orvin 1940; Challinor 1967; Manby 1988; Saalmann & Brommer 1997). Similar structural patterns also exist in other parts of the basement-involved portion of the fold-thrust belt in western Spitsbergen, e.g. Wedel Jarlsberg Land (Dallmann 1988), Midterhuken (Maher et al. 1986), Nordenskiöld Land (Braathen et al. 1995), Oscar II Land (Bergh et al. 1997) and St. Jonsfjorden (Welbon & Maher 1992). However, Brøggerhalvøya has an anomalous

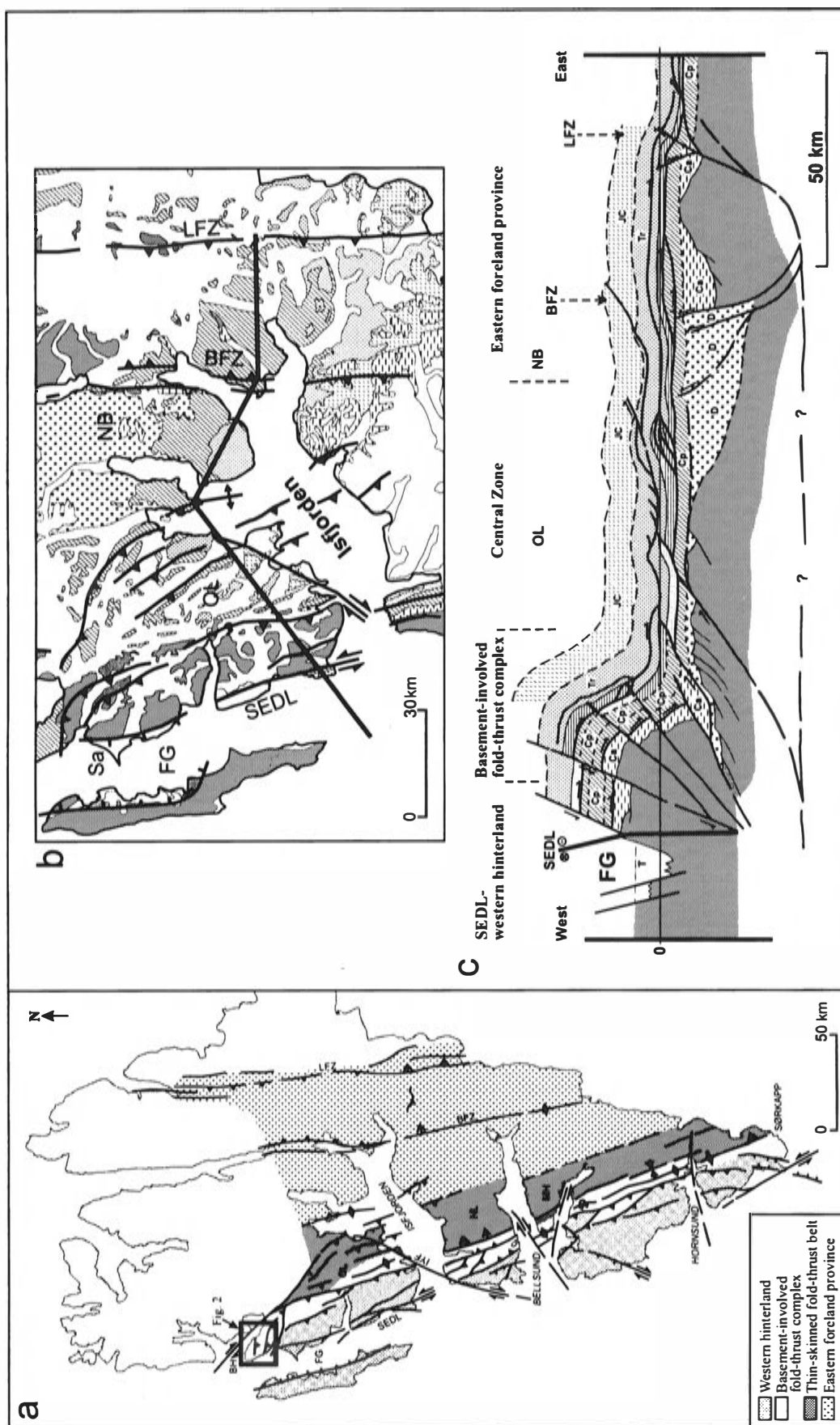


Fig. 1. (a) Simplified map of Tertiary structural domains in Spitsbergen. The box locates Brøggerhalvøya near the northwestern tip of the fold-and-thrust belt. (b) Geologic map and (c) generalized cross-section of the Isfjorden transect in central Spitsbergen. Note across-strike subdivision of tectonic zones (see Braathen et al. 1999; Bergh et al. 1998). Abbreviations: BFZ = Billefjorden fault zone, BH = Brøggerhalvøya, FG = Forlandsundet Graben, IF = Isfjorden-Ymerbukta fault zone, MH = Midterhuken, NB = Nordfjorden block, NL = Nordenskiöld Land, OL = Oscar II Land, Sa = Sarstangen, SEDL = Svartfjella-Eidembukta-Daudmannsodden lineament. Abbreviations for stratigraphic units: D = Devonian, Ca = Early-Mid Carboniferous, CP = Carboniferous-Pennian, Tr = Triassic, JC = Jurassic-Cretaceous, T = Tertiary.

WNW–ESE structural trend in comparison to the otherwise uniform NNW–SSE strike of the main fold-thrust belt (Fig. 1a). At Brøggerhalvøya, major thrust-nappes were transported to the north (Challinor 1967; Manby 1988) as opposed to a predominant ENE thrust direction to the south (Bergh et al. 1997). Understanding this anomaly is critical for the construction of viable regional models.

This paper also addresses stratigraphical/basinal facies changes within Lower-Middle Carboniferous units, which may have controlled localization and development of the Tertiary structures. The nature and timing of basement-uplift and thrust emplacements, and the degree of involvement of Tertiary sediments in the deformation are addressed by Lyberis & Manby (1993), Maher et al. (1995) and Saalman & Brommer (1997).

Divergent opinions explaining the anomalous trend and northward-directed tectonic transport in Brøggerhalvøya include; (i) dextral transpression across a restraining bend adjacent to a regional transform (Steel et al. 1985; Gabrielsen et al. 1992), (ii) bending owing to pinning of the fold-thrust termination along Kongsfjorden (Lyberis & Manby 1993) and (iii) bending against a buttress near the basement high north of Kongsfjorden (Dallmann et al. 1993). In this paper, we argue for a model involving temporally changing movement directions between and within different thrust sheets, probably as a response to deformation partitioning in a transpressive plate setting (Maher & Craddock 1988; Lepvrier 1990; Maher et al. 1995; Gray & Stamatakis 1997; Braathen et al. 1999). The model is based on consideration of the abundant structural data from the Brøggerhalvøya area in light of existing data and models for areas farther south (e.g. Lepvrier 1990; Braathen et al. 1995; Braathen & Bergh 1995; Kleinspehn & Teyssier 1992; Bergh et al. 1997). Central to our approach is fault-slip analysis to resolve multiple fault populations and the kinematic history, as a basis for regional considerations. Avoiding some of the pitfalls associated with palaeostress analysis (Twiss & Unruh 1998), we use slip-linear plots (Aleksandrowski 1985; Goldstein & Marshak 1988) to document the local strain axes, and the inferred transport directions.

## Stratigraphy and facies relationships

A formal stratigraphic scheme exists for the Caledonian basement and post-Caledonian Upper Palaeozoic-Mesozoic and Tertiary cover strata in Brøggerhalvøya (Fig. 3; Orvin 1934; Cutbill & Challinor 1965; Harland et al. 1966; Challinor 1967; Ludwig 1991). The Caledonian basement in central and eastern Brøggerhalvøya belongs to the *Nielsenfjellet Formation* of the Kongsvegen Group (Harland et al. 1966) and consists of high-grade schists, quartzites and marble-dolomites that are notably deformed. Other basement units include diamictites of presumed Vendian age. These strata are partly thrust over the sedimentary cover units to the north (Challinor 1967; see below).

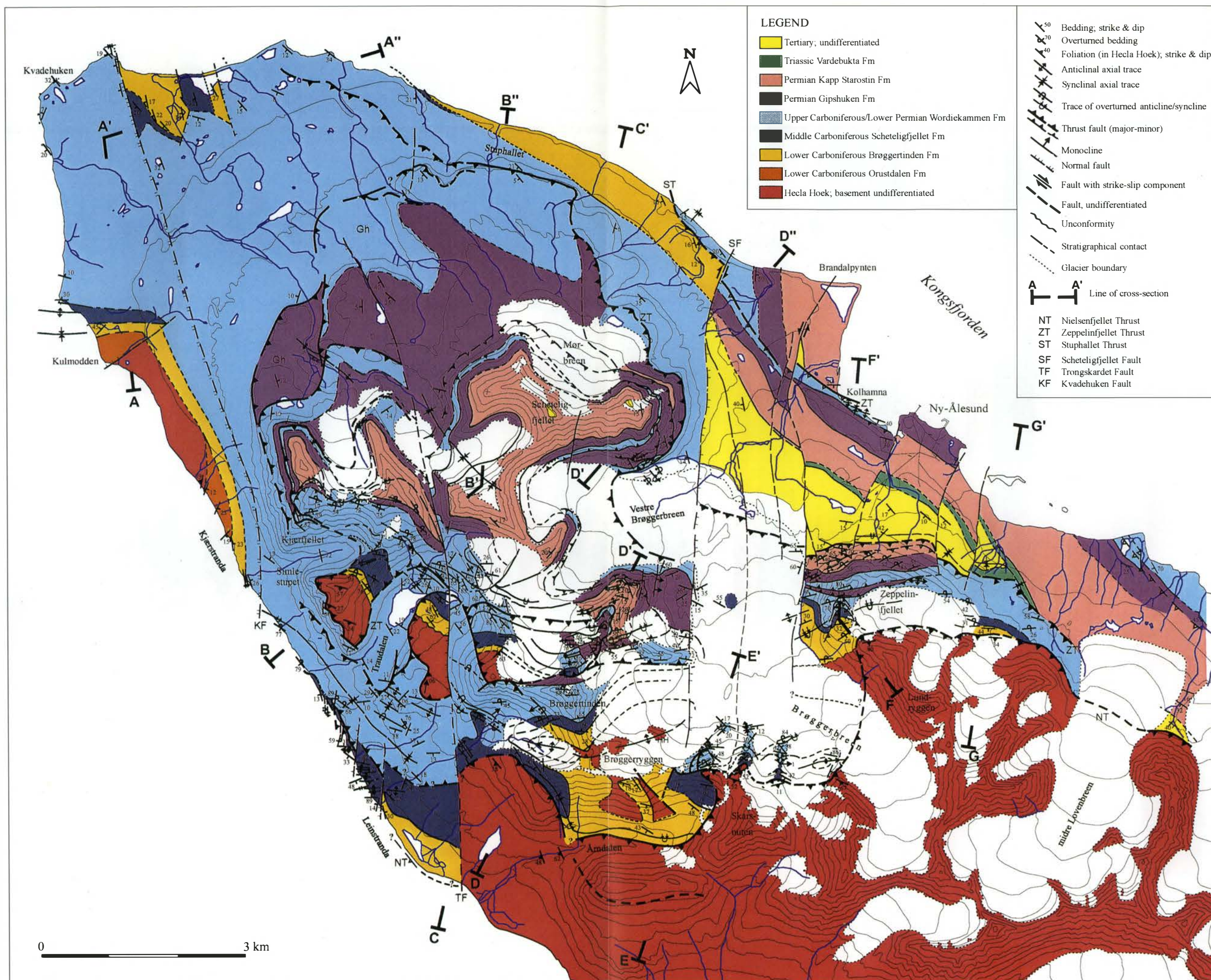
The Palaeozoic succession starts with the *Orustdalen Formation*, with pale grey terrestrial sandstones and conglomerates, and with local coal horizons. The succession crops out west of the Kvadehuken fault (Challinor 1967), where it onlaps a basement high between Kulmodden and Kjørstranda (Fig. 2), and is unconformably overlain by the mid-Carboniferous Brøggertinden Formation of the lowermost Gipsdalen Group (Cutbill & Challinor 1965). The Orustdalen Formation is absent to the east of the Kvadehuken fault, where the Brøggertinden Formation unconformably overlies the Caledonian basement in the core of a major anticline between Brøggertinden and Åmdalen (Fig. 2). The unconformity is also seen in the uppermost thrust nappe near Traudalen (Fig. 2), where the Orustdalen Formation is absent.

The *Brøggertinden Formation* is characterized by fluvial, deltaic sandstones and conglomerates and intercalated marine carbonates, characterized by a reddish, brown or orange coloration (Gjelberg & Steel 1981; Ludwig 1991). Abundant local angular unconformities exist within the formation. Notably, there is a change from terrigenous facies to marine deltaic facies and associated thickness increase towards the north and northwest, i.e. in the lowermost nappe unit, while the formation is thinner in the middle nappe (Fig. 3). Accurate thickness estimates have been reported from various localities, e.g. 13 m thickness in eastern Brøggerhalvøya (Ludwig 1991; Saalman 1995; Saalman & Brommer 1997), 100–300 m in central parts, and ca. 300 m at Kvadehuken in the northwest (Fig. 2).

The succeeding Gipsdalen and Tempelfjorden groups (Fig. 3) are composed of a nearly 1200 m thick, heterogeneous biogenic carbonate succession. The Gipsdalen Group is notably thicker in the Brøggerhalvøya area than its counterpart along the strike of the fold-thrust belt to the south (Dallmann & Mørk 1998). The first carbonate unit, the *Scheteligfjellet Formation*, marks a mid-Palaeozoic (Moscovian) transgression and shift from predominantly terrestrial facies to marine and lagoonal environments. This formation represents a mixed unit of intercalated clastics, marls and light grey, fossiliferous carbonates and dolomite breccias (Challinor 1967). The base of the formation is defined by the first occurrence of dark grey, massive to cherty limestone, locally with colonies of fusulinids and syringapora (Gobbett 1964; Ludwig 1991). Challinor (1967) also noted the presence of thick limestone breccias with erratic Hecla Hoek constituents in the west (at Kjørffjellet). The Scheteligfjellet Formation varies in thickness, from ca. 150 m at Brøggertinden to ca. 8–25 m near Ny Ålesund (Saalman & Brommer 1997), and the formation appears to be absent in the north, at Stuphallet (Fig. 2).

The Carboniferous-Permian *Wordiekammen Formation* (including the Mørebreen and Tyrellfjellet members; not differentiated on the map) averages ca. 250 m in thickness and is the most dominant exposed unit of the lower and middle thrust nappes in Brøggerhalvøya. The formation constitutes a generally well-bedded, but still heteroge-







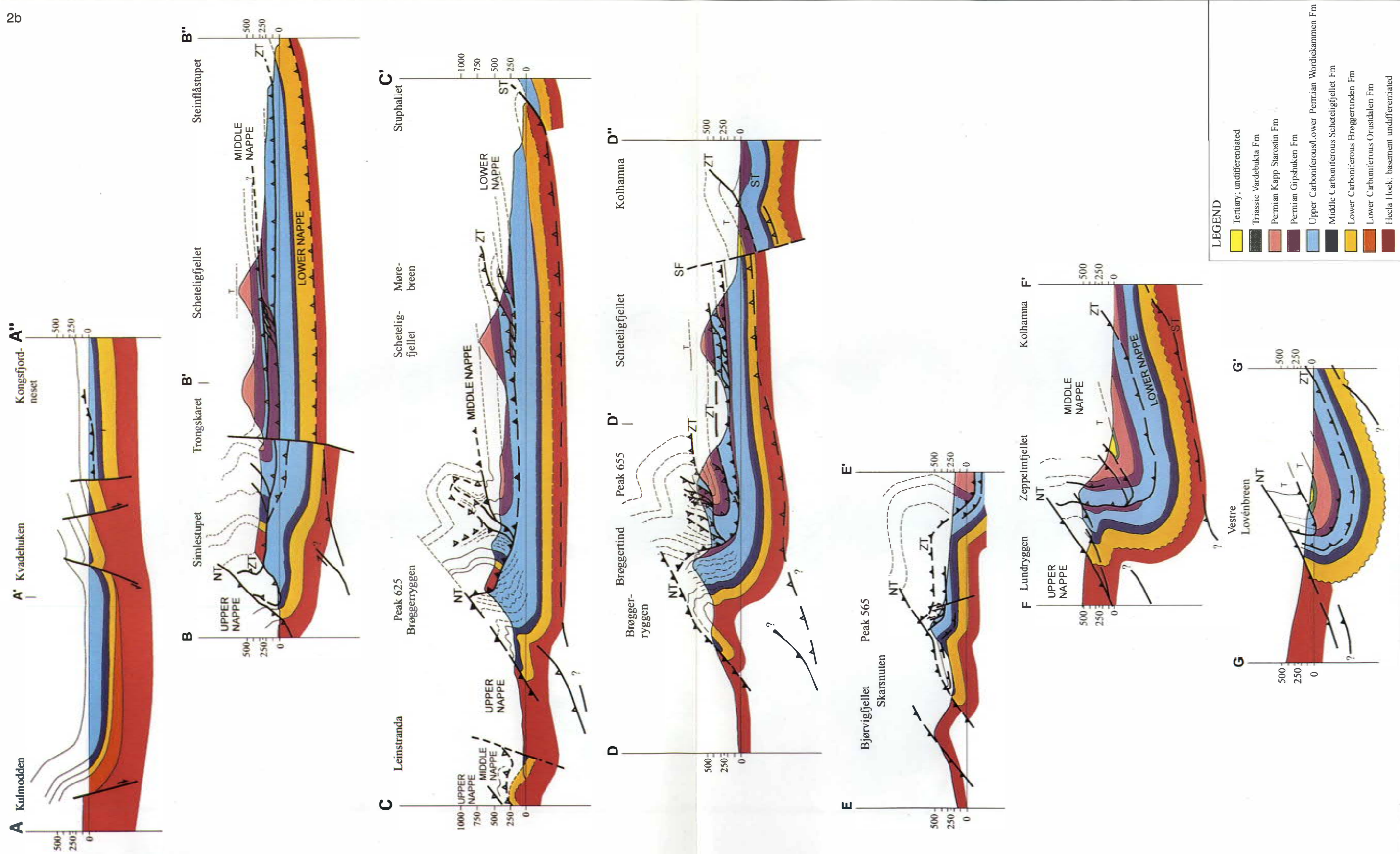


Fig. 2. (a) Geological and structural map, and (b) cross-sections of Brøggerhalvøya, with lines of cross-sections shown in (a). The map was derived by extensive re-mapping and modification of existing data (Orvin 1934; Challinor 1967; Midbøe 1985; Manby 1988).

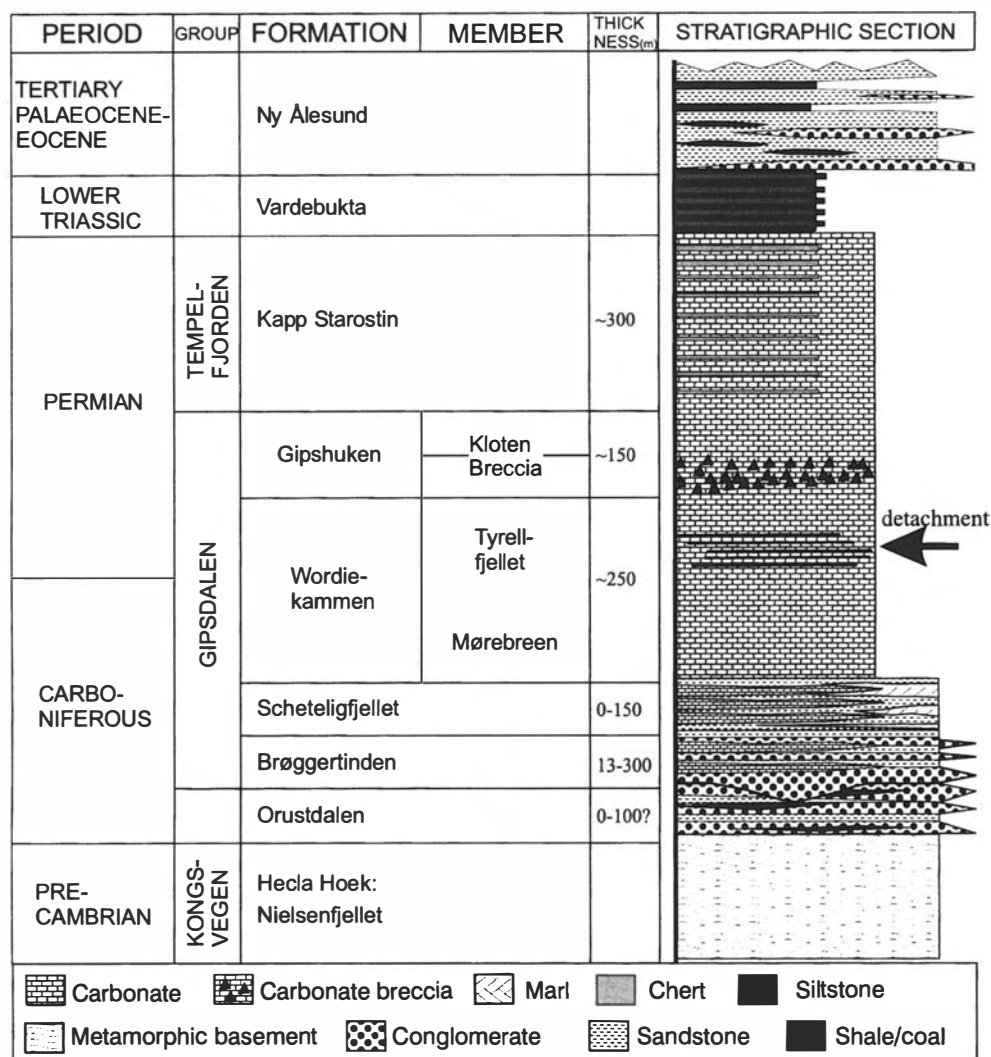


Fig. 3. Stratigraphical scheme for Brøggerhalvøya showing nomenclature and lithologies used and described in the text (modified after Cutbill & Challinor 1965 and Challinor 1967).

neous carbonate sequence (limestone-dolomite), with local cherty nodules indicative of sabkha or evaporite conditions. Distinctive marker beds include fossiliferous biosparites that contain fragments of crinoids and fusulinide foraminifera (Cutbill & Challinor 1965; Saalman & Brommer 1997). Distinctive levels of the Wordiekammen Formation are of particular structural importance; e.g. the thinly laminated and incompetent Kjærfjellet beds of the Tyrellfjellet Member (Challinor 1967) constitute a main detachment horizon (see below).

The *Gipshuken Formation* (Permian) is up to 150 m thick, and consists of a relatively uniform carbonate sequence. It is built up of a lower, laterally extensive limestone breccia (Kloten Breccia; Challinor 1967), and an upper laminated dolomite-limestone member. Distinctive gypsiferous deposits (evaporites) characterize the formation elsewhere in Spitsbergen, but are absent at Brøggerhalvøya. The Kloten Breccia (80 m thick), which forms a regional stratigraphic marker, contains angular laminated clasts up to 0.5 m in size and intercalated laminated dolomites and was likely formed as a solution-collapse breccia in a sabkha-supratidal environment (Challinor 1967; Saalman & Brommer 1997). The breccia is

valuable when trying to restore structural offsets and thrust repetitions within the nappes, e.g. near Brøggertinden, Zeppelinfjellet, Scheteligfjellet, and at Kolhamna (Fig. 2). Locally, the Gipshuken Formation is complexly folded and thickened by imbricate thrusts, or dismembered and tectonically thinned, the latter especially in the central and southern parts of Brøggerhalvøya.

The Upper Permian *Kapp Starostin Formation* represents a distinctive, almost 300 m thick ridge-forming unit composed of silicious and fossiliferous (brachiopods, bryozoans, corals, sponges) limestones and cherts (Challinor 1967). The uppermost part of the formation contains green glauconitic horizons. This unit acted as a competent level; the strata are severely involved in the folding and thrusting only locally (e.g. northern Zeppelinfjellet and east of Brøggertinden).

The uppermost stratigraphical units of Brøggerhalvøya include a thin shale and siltstone unit, the Lower Triassic *Vardebukta Formation*, which is unconformably overlain by Tertiary sandstones and coal deposits near Ny Ålesund (Fig. 2). In addition, two Tertiary exposures are present in the peak of Scheteligfjellet and north of Kolhamna (Fig. 2). The coal-bearing Tertiary deposits near Ny Ålesund have

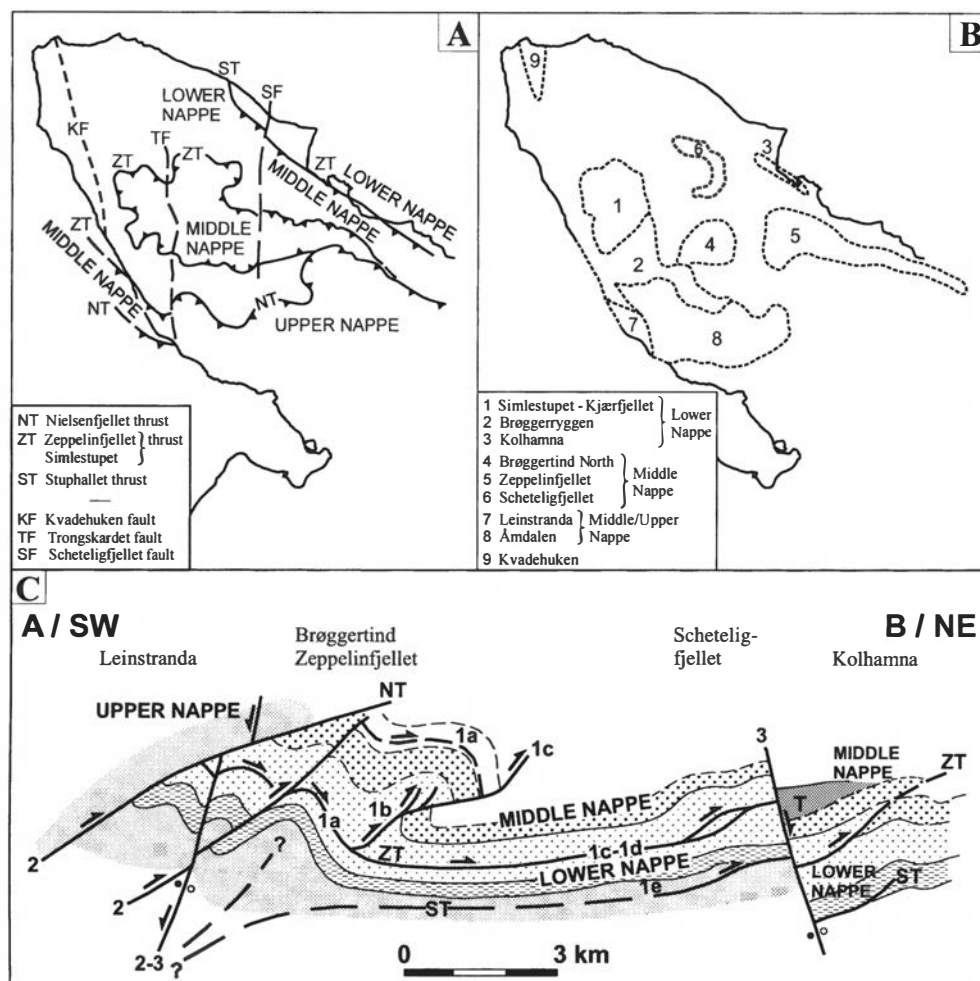


Fig. 4. A: Simplified structural subdivision of Brøggerhalvøya into a lower, middle, and upper nappe, bound by major thrusts. The most important N-S-striking faults are also included. B: Location of structural domains used for kinematic analysis, i.e. adjacent to the main nappe-bounding thrusts (see Figs. 7–9). C: Generalized cross-section of the thrust stack in Brøggerhalvøya (for legend and location [line A-B], see Fig. 10). The suggested kinematic development, indicated with numbers, is discussed in the text.

been described in detail by Orvin (1934) and Midbøe (1985), and more easterly located outcrops by Saalman (1995) and Saalman & Brommer (1997). The sequence (Ny Ålesund Formation) is made up of siliciclastic sandstones, with some shale and coal intercalations, and polymict conglomerates commonly arranged as lensoidal-shaped channel deposits, indicating alluvial-fluvial and deltaic-lagoonal depositional environments.

### Structural overview

The overall cross-section geometry (Fig. 2) of Brøggerhalvøya (Orvin 1934, Challinor 1967) displays a complex, basement-involved antiformal stack containing thrusts with offsets on the order of kilometres. These thrusts migrated through associated fault-propagation folds with notably overturned limbs, and with out-of-the-syncline thrust imbricates and flats to the foreland. The thrust stack is cut by steep, N-S-striking normal faults.

Three composite thrust nappes have been identified (Fig. 4A, C):

1. A lower nappe is characterized by E-W-trending, basement-involved folds in the south, a truncated foot-wall syncline in the east-central area, and relatively flat-

lying strata further north. Detachments that emerge to the north indicate an allochthonous status for all these units.

2. A middle nappe contains map-scale and complex, N–NW-verging anticline–syncline pairs and closely related imbricate fans and duplex structures. Its floor thrust (Zeppelinfjellet thrust) is defined as a complex flat or detachment in the upper Wordiekammen and/or lower Gipshuken Formation, which emerges along the NE limb of the major syncline (Fig. 2b; sections B and D). Notably, the Tertiary rocks in the Ny Ålesund area belong to the middle nappe, and have been ‘dropped down’ by the Scheteligfjellet fault. Small klippen of basement rocks occur on either side of Traudalen.
3. An upper nappe is composed of various basement (Hecla Hoek) rocks in the southern part of the map area (Fig. 4C).

The most prominent nappe-bounding fault is the *Zeppelinfjellet thrust* (Challinor 1967), which defines the floor thrust of the middle nappe (Figs. 2, 4C). The thrust consistently cuts up-section, locally emplacing basement strata over Gipsdalen Group rocks, e.g., at Simlestupet (Fig. 5a) and east of Traudalen. Hangingwall cut-offs of the upper Palaeozoic formations suggest displacement in excess of 2 km on the Zeppelinfjellet thrust in the hinterland section.



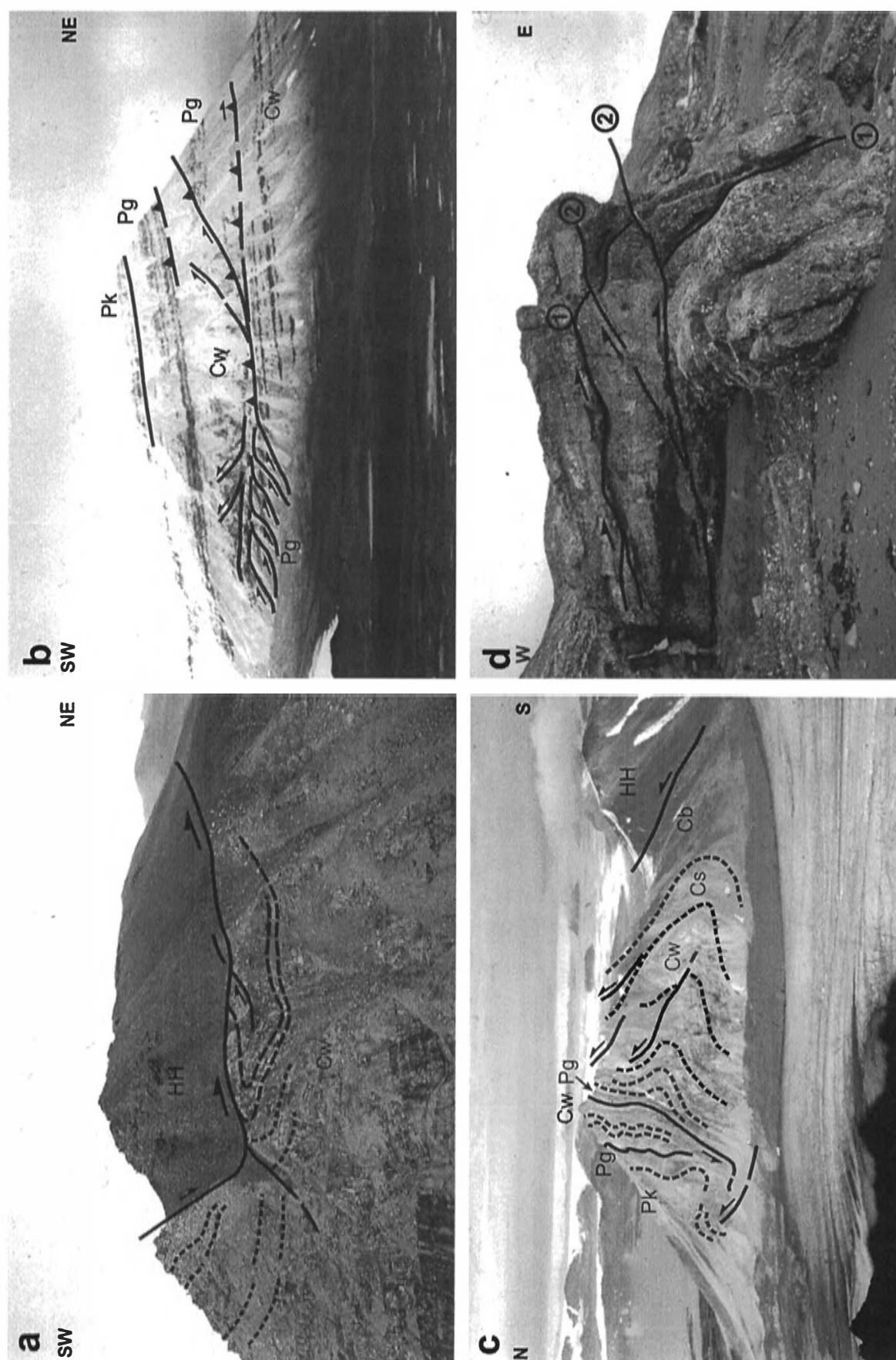


Fig. 5. (a) Klippen of Caledonian basement (Hecla Hoek - HH) rocks emplaced over the upper-Carboniferous Wordiekammen Formation (Cw) strata in the footwall to the rotated Zeppelinfjellet thrust. Note the near-recumbent syncline with back-limb cut-off below the thrust surface. The mountain side is approximately 300 m high. (b) Structural repetition of strata in Scheteligfjellet (ca. 500 m high), at the transition between the lower and middle nappes. A prominent duplex and associated backthrusts can be seen near the ramp portion of the upward propagating Zeppelinfjellet thrust in the Gipsbukken Formation. (c) Eastward view of Zeppelinfjellet (ca. 700 m high), showing the main, overturned syncline of the upper nappe, overriden by Hecla Hoek strata of the upper nappe along the Nielsenfjellet thrust. Note local imbrications and out-of-the syncline thrusts that cut a northward-tilted, older thrust (Zeppelinfjellet thrust) and the forelimb of the macrofold. (d) Mesoscale fold at Leinstranda outlining a two-stage relationship. A rotated, N-verging, earlier thrust cut by younger, out-of-sequence thrusts with ENE-directed displacement. Note person for scale. Abbreviations on the photographs in Figs. 5 and 6: HH = Hecla Hoek, Cb = Carboniferous Brøggertinden Formation, Cs = Carboniferous Scheteligfjellet Formation, Cw = Carboniferous-Permian Wordiekammen Formation, Pg = Permian Gipsbukken Formation, Pk = Permian Kapp Starostin Formation.



In the south and east, the Zeppelinfjellet thrust is clearly folded and locally dips 80° northward, e.g. at Brøggerryggen and Zeppelinfjellet (Fig. 2b, sections D and F). Further north, the Zeppelinfjellet thrust migrates into the foreland as a bedding-parallel detachment, or 'out-of-the syncline' thrust, consistently emerging along the north limb of the major syncline. Internally, the syncline region of the middle nappe is segmented by numerous imbricates and splay faults initiating along the Zeppelinfjellet thrust (detachment) and projecting out of the major syncline (Fig. 2, sections B, C and D; Fig. 4c). The detachment is exposed in Scheteligfjellet (Fig. 5b) and at Kolhamna, on either side of the Scheteligfjellet normal fault (see below; Fig. 2b, section D). The thrust exposed near Kolhamna probably corresponds with the Zeppelinfjellet thrust in Scheteligfjellet (Fig. 4A), hence it does not represent the lowest exposed thrust in Brøggerhalvøya (i.e. *Ny Ålesund thrust*) as suggested by Saalman & Brommer (1997). The link between the two thrusts is suggested by the similar stratigraphic level of the thrusting, and with an overall hangingwall syncline structure on either side of the Scheteligfjellet fault (see Fig. 2b; section D, and description below).

The structurally lowermost thrust in Brøggerhalvøya, the *Stuphallet thrust*, is exposed along the shoreline between Stuphallet and Brandalpynten (Fig. 2, section C). There, red sandstones of the Brøggertinden Formation are structurally emplaced over dolomites of the Wordiekammen Formation. This structure represents a thrust ramp initiating from a deeper stratigraphic level, e.g., in the Brøggertinden Formation or in the basement (Fig. 4C).

The structurally uppermost thrust, the *Nielsenfjellet thrust* (Fig. 5c; Saalman & Brommer 1997), cuts obliquely and down-section along the strike eastward, and decapitates the fold-thrust systems of the middle and lower nappes. Decapitation is evident between Åmdalen and Skarsnuten, and between Zeppelinfjellet and Midtre Lovenbreen (Fig. 2), where the Nielsenfjellet thrust removes the entire Palaeozoic-Mesozoic stratigraphy of the steep limb of a major syncline (Manby 1988; Lyberis & Manby 1993). Southwestern exposures in the footwall of the Nielsenfjellet thrust reveal mesoscopic, oblique-thrust faults that offset earlier, now tilted, bedding-parallel contractional detachments. These are abundant in the coastal sections near Leinstranda-Kjærstranda (Fig. 5d). The hangingwall to the Nielsenfjellet thrust (i.e. upper nappe) is composed of Hecla Hoek basement phyllites and quartzites, with a well-developed Caledonian fabric (Manby 1988) and, near Leinstranda, variously interbedded sandstones and carbonates of the Scheteligfjellet Formation.

Other prominent structures of Brøggerhalvøya include N-S-striking, steep faults that cause alternating left- and right-lateral separation of the fold-thrust structures and strata involved (Figs. 2, 6a, b). Examples are the Kvadehuken, Trongskardet (Fig. 6a) and Scheteligfjellet faults (Challinor 1967). The Scheteligfjellet fault juxtaposes Tertiary and Wordiekammen Formation strata with a

minimum stratigraphic throw of 400 m 'down-to-the east'. This fault dies out southward (Fig. 2a). The Trongskardet and Kvadehuken faults down-drop strata to the west by approximately 200 m, and have a more regional extent. They can be traced across Brøggerhalvøya and, in the south, may link up with the eastern margin of the Forlandsundet Graben (see Maher et al. 1997).

## Kinematic data

The map and cross-sections of Brøggerhalvøya's fold-thrust stack (Fig. 2) indicate substantial variation in structural style, timing, kinematic nature and tectonic (thrust) transport directions. We now describe these variations by assessing geometric, attitude and displacement features in order to establish fold and fault populations. Our proposed subdivision is based on the recognition of the three main nappe units with associated bounding thrusts, and the cross-cutting steep N-S-striking faults. Mesoscopic structural data have been gathered in close association to the major thrusts and, for convenience, have been split into nine structural domains (Fig. 4B), namely: (1) Simlestupet/ Kjærfjellet, (2) Brøggerryggen, (3) Kolhamna, (4) peak 655 north of Brøggertinden, (5) Zeppelinfjellet, (6) Scheteligfjellet, (7) Leinstranda, (8) Åmdalen and (9) Kvadehuken.

## Lower nappe strain

Lower nappe structures can be studied in three areas (see Fig. 4); (i) underneath the Zeppelinfjellet thrust in Simlestupet-Kjærfjellet (domain 1), (ii) in the valley south of Brøggerryggen (domain 2) and (iii) between Kvadehuken-Stuphallet and north of Kolhamna (domain 3). In the former areas, folds and mesoscale thrusts in the Scheteligfjellet Formation are attributed to the floor thrust of the lower nappe. Further upsection, gently dipping beds of the Wordiekammen Formation dolomites are tectonically overlain by the basement Hecla Hoek phyllites and succeeding Palaeozoic formations, emplaced along the bedding-parallel Zeppelinfjellet thrust which acted as the roof-thrust of the lower nappe (Fig. 2, section B, Fig. 5a). This thrust is weakly folded, and to the north it clearly projects underneath strata of the middle nappe, before cutting to the surface in Scheteligfjellet (Figs. 2, 5b). Abundant thrust flats and low-angle splay faults cut strata both in the footwall and hangingwall of the Zeppelinfjellet thrust. Local, tight, recumbent and ENE-verging fault-propagation folds occur in the footwall (Fig. 2, sections B and C, Fig. 5a). At Brøggerryggen, a macroscopic, basement-involved anticline is an important structure in the lower nappe (Fig. 2b, sections C and D). This anticline folds the Zeppelinfjellet thrust and shows faults truncating bedding at a low angle and with variable strike. In the north, at Stuphallet, the floor-thrust of the lower nappe is exposed as a bed-truncating imbricate zone.

From Simlestupet, poles to bedding of strata in the

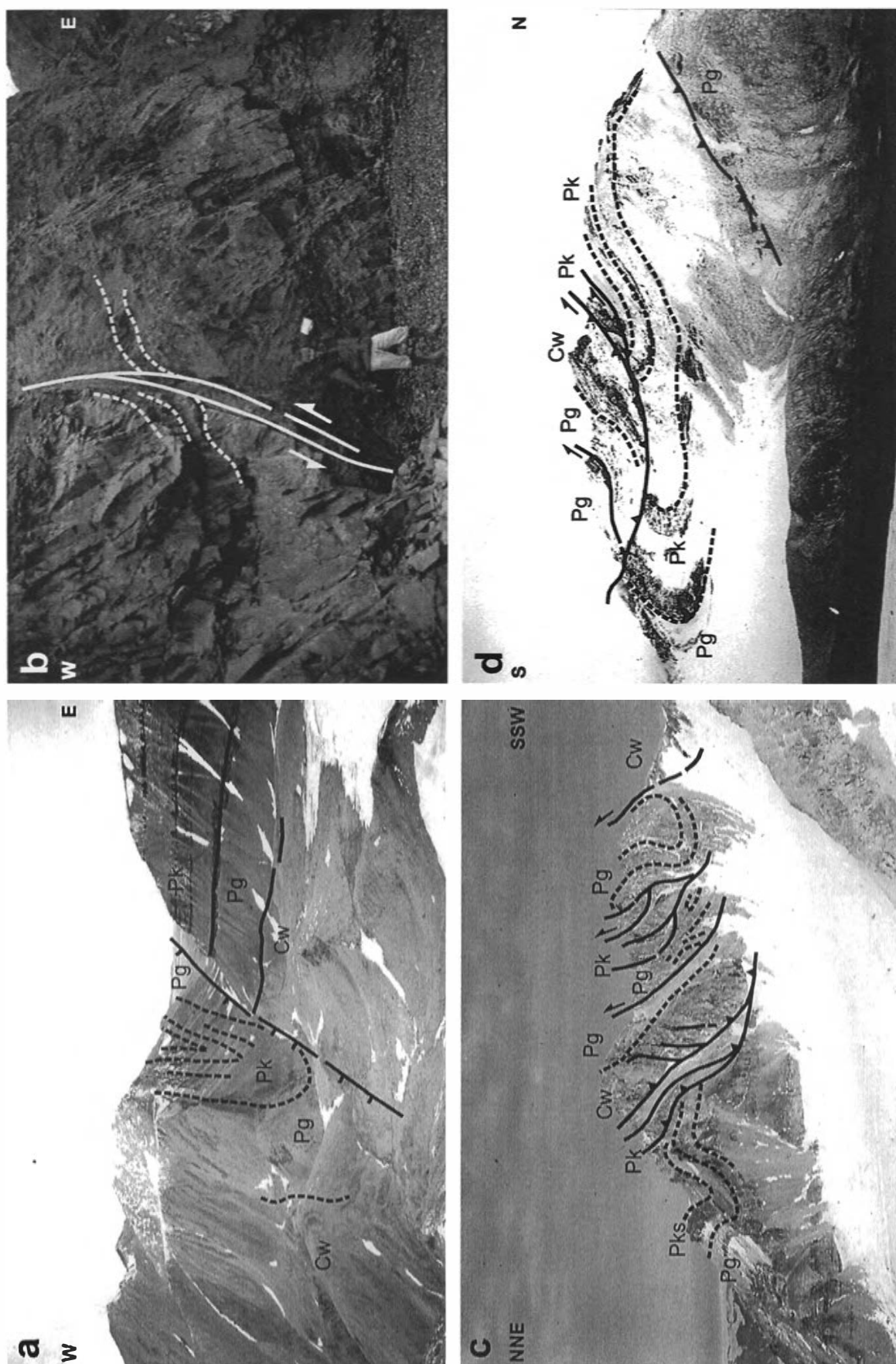


Fig. 6. (a) Northward view of the Trongskardet fault east of Kjerfjellet. Note truncation and down-throw of folded (part of overturned syncline in hangingwall of the Zeppelinfjellet thrust) strata to the west. Mountain sides are approximately 300 m high. (b) N- to NE-striking normal fault near the boundary between Hecla Hoek phyllites (right) and Brøggerinden Formation strata (left) at Kulmodden. (c) Imbricate thrust fan in peak 655 north of Brøggerinden (see Fig. 2b, section D). The fan is defined by repeated thrust sheets, or horses, of alternating Wordiekanamen, Gipshuken and Kapp Starostin formation strata. Note tight to recumbent folds and local overturned strata in the individual horses. The mountain side is approximately 500 m high. (d) Major syncline in the footwall of the imbricate stack north of Brøggerryggen (opposite, westward view of fan in 6c).



immediate footwall of the Zeppelinfjellet thrust group along a girdle indicating a gently ESE-plunging fold axis and NNE vergence (Fig. 7b). Similar NNE–SSW-striking girdles of folded bedding characterize the anticline south of Brøggerryggen. Here, an additional NNW–SSE spread of poles also produces a weak cross-fold interference pattern (Fig. 7a). Near Kolhamna, folded bedding displays a girdle indicating a subhorizontal, W-plunging fold axis (Fig. 7c).

Mesoscopic faults of the lower nappe indicate a similar strain pattern to that suggested by the macroscopic folds. At Brøggerryggen (Fig. 7a) and Simlestupet (Fig. 7b), two maxima representing faults striking NW–SE and dipping moderately SW or NE, are interpreted as conjugate thrusts. Near Kolhamna (Fig. 7c), E–W striking conjugate faults characterize the footwall of the Zeppelinfjellet thrust. Fault striae plotted as composite slip-linears (Fig. 7a–c) suggest three categories of faults: (1) NW–SE- and E–W-striking faults with dominantly dip-slip signatures, either reverse ‘top-to-the-NE or SW’ slip directions at Brøggerryggen (Fig. 7a) and Simlestupet (Fig. 7b), and ‘top-to-the-N’ reverse-slip movements at Kolhamna (Fig. 7c); (2) a secondary, reverse fault-slip population with NW or SE movement directions (Fig. 7a, b); (3) N–S-striking subvertical faults with kinematic natures implying mainly normal-slip (e.g. the Kvadehøken fault; Fig. 7d), but with oblique sinistral and dextral strike-slip components (Fig. 7a–c). In combination, the difference in terms of thrust directions within the lower nappe (shown as movement plane plots; for method, see caption in Fig. 7) seems substantial, i.e. from NW to NNE.

#### *Middle nappe strain*

A macroscopic syncline–anticline fold system and related faults characterize the middle nappe (Figs. 2, 4c). North of Brøggertinden this pattern defines an imbricate thrust fan that emerges from the core of the syncline and repeatedly cuts the Wordiekammen, Gipshuken and Kapp Starostin formation strata of the forelimb (Fig. 2, section C and D, Fig. 6c). A near-recumbent syncline is apparent in the footwall of one of the main thrust imbricates (Fig. 6d). Northward, the thrust system links with a duplex in Scheteligfjellet (Fig. 5b). At Zeppelinfjellet, on the down-dropped side of the Scheteligfjellet fault, a corresponding macroscopic fold-thrust complex is well displayed (Fig. 2b, section F) beneath the Nielsenfjellet thrust (= sole thrust of upper nappe; Fig. 5c). The steep forelimb of the syncline is cut and modified by internal imbricates and blind thrusts, as exemplified by a subvertical, bedding-parallel structural discontinuity that repeats the Wordiekammen, Gipshuken and Kapp Starostin formations (Fig. 5c). The steep strata above the fault (in the hangingwall) are imbricated and have associated ‘down-to-the-N’ verging mesofolds (Fig. 2b, section F). The fact that these southward-dipping thrust-imbricates cut and fold this discontinuity precludes it from being a late-stage normal fault (as proposed by Lyberis & Manby 1993). Rather, it

represents a rotated thrust (i.e. the Zeppelinfjellet thrust). Another important structural observation is that these imbricates override Tertiary sediments of the Ny Ålesund area (Fig. 2), thus constraining the timing of fold-thrust belt development relative to Tertiary sedimentation (see Lyberis & Manby 1993; Maher et al. 1995; Saalman & Brommer 1997).

Bedding and fault orientation data from Zeppelinfjellet and Brøggertinden (peak 655) of the middle nappe (Fig. 8a, b) show a clear deviation from the lower nappe structures. Plots of contoured poles to bedding planes concentrate along well-defined girdles indicating NNW-vergent macrofolding (Fig. 8a, b). Correspondingly, the majority of mesoscale imbricate faults strike on average WSW–ENE and dip moderately SSE and NNW, and display reverse NNW and SSE tectonic transport directions when plotted as slip-linears and M-planes. More variable movement directions are evident for splay faults of the major duplex system at Scheteligfjellet, showing ‘top-to-the-N–NNE’ shear directions (Fig. 8c). Composite slip-linear plots of striated faults from Zeppelinfjellet also include data of the steep N–S-striking faults similar to those of the lower nappe described above (Fig. 8a).

#### *Upper nappe strain*

The upper nappe consists mainly of overthrust basement rocks. The Caledonian foliation of these rocks varies in strike from E–W to NW–SE and dips moderately S to SW (Fig. 2). Mapscale structures of presumed Tertiary age are difficult to demonstrate. However, brittle to semi-ductile shear fabrics that deform the Caledonian ductile fabrics, and internal stacking and incorporation of Carboniferous rocks in macroscopic slivers further south are all assigned to the Tertiary event (Manby 1988; Lyberis & Manby 1993).

At Leinstranda, Carboniferous strata of the upper nappe are deformed by mesofolds and cut by a network of complex minor faults (Fig. 2b, sections B and C). Poles to bedding from the coastal region spread along a wide girdle, indicating broad folding of the strata around a subhorizontal, SSE-plunging axis immediately below the Nielsenfjellet thrust (Fig. 9a). At Åmdalen, Carboniferous strata in the footwall adjacent to the Nielsenfjellet thrust are affected by NW-trending macrofolds (Fig. 9b). Another distinct kinematic feature at Åmdalen is that folded bedding close to the Nielsenfjellet thrust yields variable plunging fold axes, i.e. NNW-plunge above the thrust and SSE-plunge below (Castellano 1996). Composite slip-linear plots of mesofaults at Leinstranda and Åmdalen reveal two subpopulations, including low-angle thrusts with ‘top-to-the-ENE and WSW’ dip-slip to oblique-slip characteristics (Fig. 8a, b), representing fore- and backthrusts. In addition, minor conjugate sets of NNE–SSW- and ENE–WSW-striking, alternating dextral and sinistral strike-slip faults were observed (Fig. 9). When the entire fault data set is plotted as M-planes, a fairly

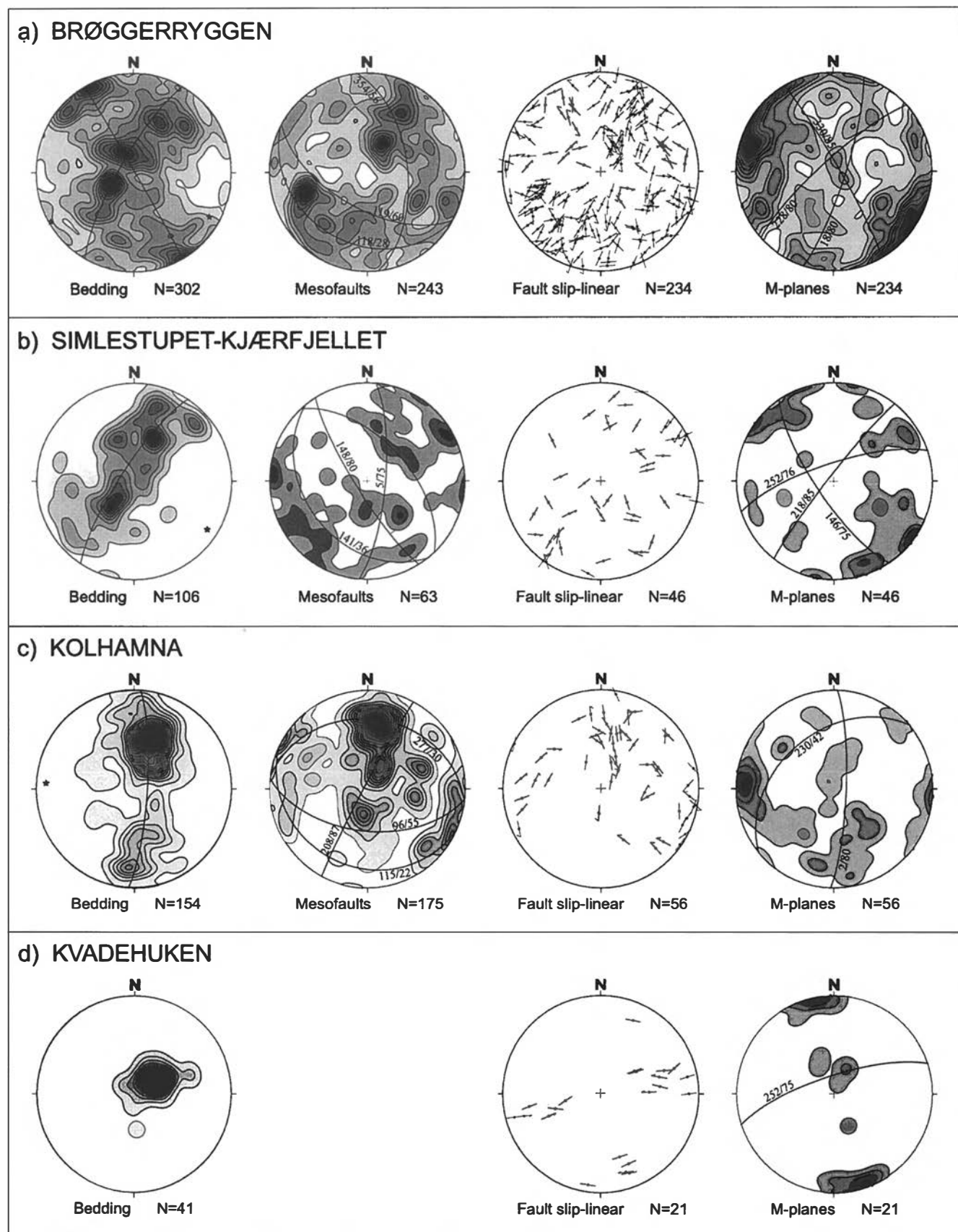


Fig. 7. Equal-area, lower hemisphere stereoplots of mesoscale structural data from domains of the lower nappe, (a) Brøggerryggen, (b) Simlestupet/Kjærfjellet, (c) Kolhamna, and (d) Kvadehukken. Stereoplots include in respective order from left to right, poles to bedding, mesofaults (undifferentiated), fault-slip linears, and movement (M) planes (showing contoured poles and average great circle orientations). The slip-linear plot method is adapted from Aleksandrowski (1985) and Goldstein & Marshak (1988). The slip-linear is defined as the pole to the fault plane decorated by a line/arrow parallel with the direction of slip of the hangingwall (movement-plane; defined by the pole to the fault and the slip striae).



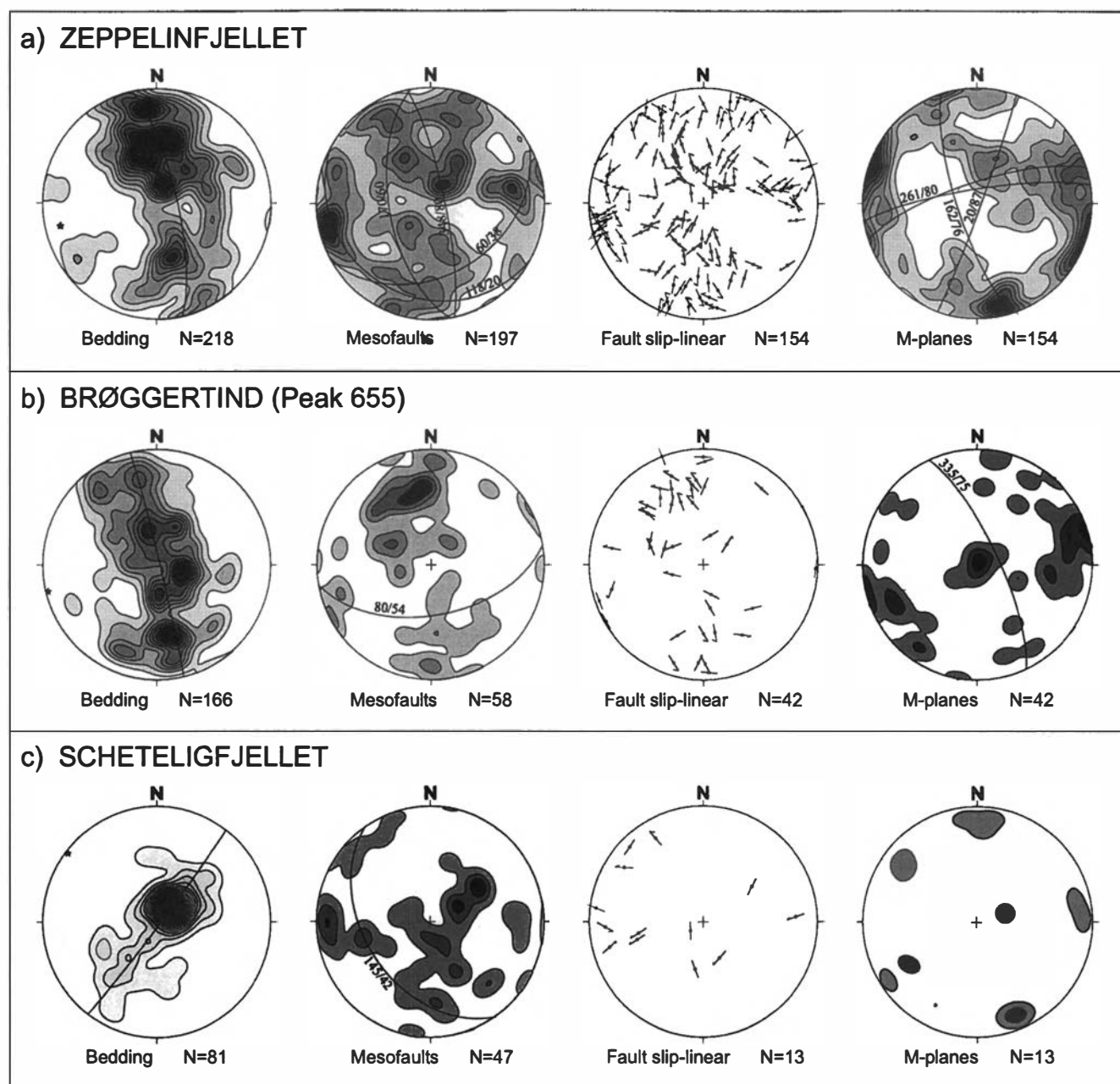


Fig. 8. Equal-area, lower hemisphere stereoplots of mesoscale structural data from domains of the middle nappe, (a) Zeppelinfjellet, (b) Brøggertinden, and (c) Scheteligfjellet. Stereoplots include in respective order from left to right, poles to bedding, mesofaults (undifferentiated), fault-slip linears, and contoured movement (M) planes.

consistent, NE to ENE tectonic transport direction can be identified.

Along strike and east of Zeppelinfjellet, the Nielsenfjellet thrust obliquely dissects the stratigraphic section of the middle and lower nappes (Fig. 2). Correspondingly, the fold-fault structural orientations and transport directions change abruptly, from NE or ENE above the Nielsenfjellet thrust (upper nappe) to NW–N in the Zeppelinfjellet thrust system (middle nappe), to N–NE tectonic transport above the Stuphallet thrust (lower nappe). Similar relations are reported from Haavimbfjellet in eastern Kongsfjord, where the Nielsenfjellet thrust dissects the entire short limb of the macroscopic, middle nappe fold structure (Manby 1988; Saalman & Brommer 1997).

## Discussion

### *Thrust kinematics and tectonic transport directions*

The gross structure of Brøggerhalvøya resembles the basement-involved fold-thrust complex of western Oscar II Land and Nordenskiöld Land further south in Spitsbergen (Fig. 1: Welbon & Maher 1992; Braathen et al. 1995; Bergh et al. 1997). This major complex includes rotated thrusts and imbricates forming an antiformal stack. The rotated thrusts are interpreted as earlier formed, leading edge ramps that were progressively modified during crustal uplift and foreland-thrust propagation. A similar kinematic model is depicted for Brøggerhalvøya's fold-thrust stack,

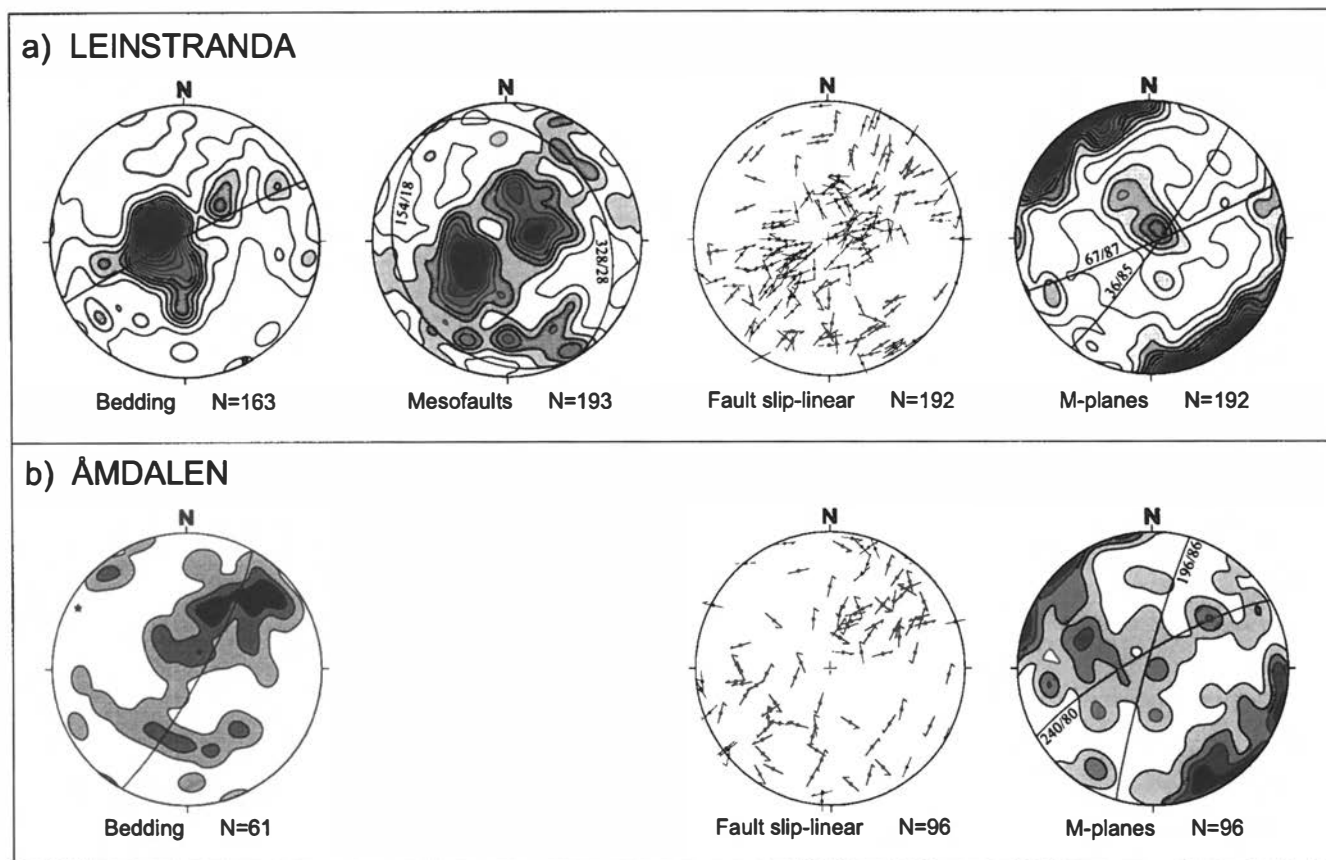


Fig. 9. Equal-area, lower hemisphere stereoplots of mesoscale structural data from domains adjacent to the upper nappe at (a) Leinstranda and (b) Åmdalen. The stereoplots show, in respective order from left to right, poles to bedding, mesofaults (undifferentiated), fault-slip linears, and contoured movement (M) planes.

where thrusts bounding the various nappes display geometries that suggest early rotation, followed by forward ('in-sequence') as well as 'out-of-sequence' thrust propagation (Fig. 4C).

Next, we will focus on the kinematics and relative timing of the fold-thrust structures, with emphasis on changing thrust transport directions of individual fold-thrust structures and nappes. For simplicity, and as a guide for the reader through the following discussions, the main kinematic conclusions are presented here. Based on the nature and kinematics of the various fault populations, we suggest a three-stage kinematic evolution of the Brøgger-halvøya fold-thrust stack (Fig. 4C):

1. An early phase of oblique thrust directions that varied spatially and temporally from NW to NNE, with some evidence of a clockwise rotation of transport direction with time (Fig. 10). This was primarily an 'in-sequence' pattern with initial development of the fold-thrust stack, and subsequent foreland migration as bedding-parallel slip planes and as local imbricate faults in the Carboniferous-Permian strata.
2. A mid-phase of basement uplift, folding and 'out-of-sequence' thrusting toward the ENE (Fig. 10).
3. A late phase of dissection of the fold-thrust stack by N-S-striking faults of predominantly normal slip, but with

secondary strike-slip components. The latter movement may be linked to dextral motion along the SEDL.

The three major thrust nappes identified have bounding thrusts with varying kinematic characteristics (Fig. 10). The sole thrust of the lower nappe, exposed near Stuphallet in the foreland to the north, defines a bedding-parallel thrust, close to the basement-cover contact that cuts stratigraphically upsection. The sole thrust of the middle nappe, the Zeppelinfjellet thrust, served as a decollement within the Gipsdalen Group strata. In the south, it is rotated within the main fold-uplift of the middle nappe, whereas in the northeast, it proceeds as a flat along the NE limb of the main syncline. These relationships are supportive of formation of; first the Zeppelinfjellet thrusts, then the Stuphallet thrust, consistent with 'in-sequence' thrust propagation. Contrary to this, the southernmost and structurally highest thrust, the Nielsenfjellet thrust, clearly decapitates the underlying structures, thus defining a late 'out-of-sequence' thrust (Fig. 4C).

Importantly, there is a marked change in the thrust transport direction of the three nappes (Fig. 10). The transport directions estimated from the Simlestupet-Kjærfjellet and Kolhamna-Stuphallet areas of the lower nappe (domains 2, 3 and 6; Figs. 4, 7) are to the N and NNE, while those in the interior of the map (middle nappe)



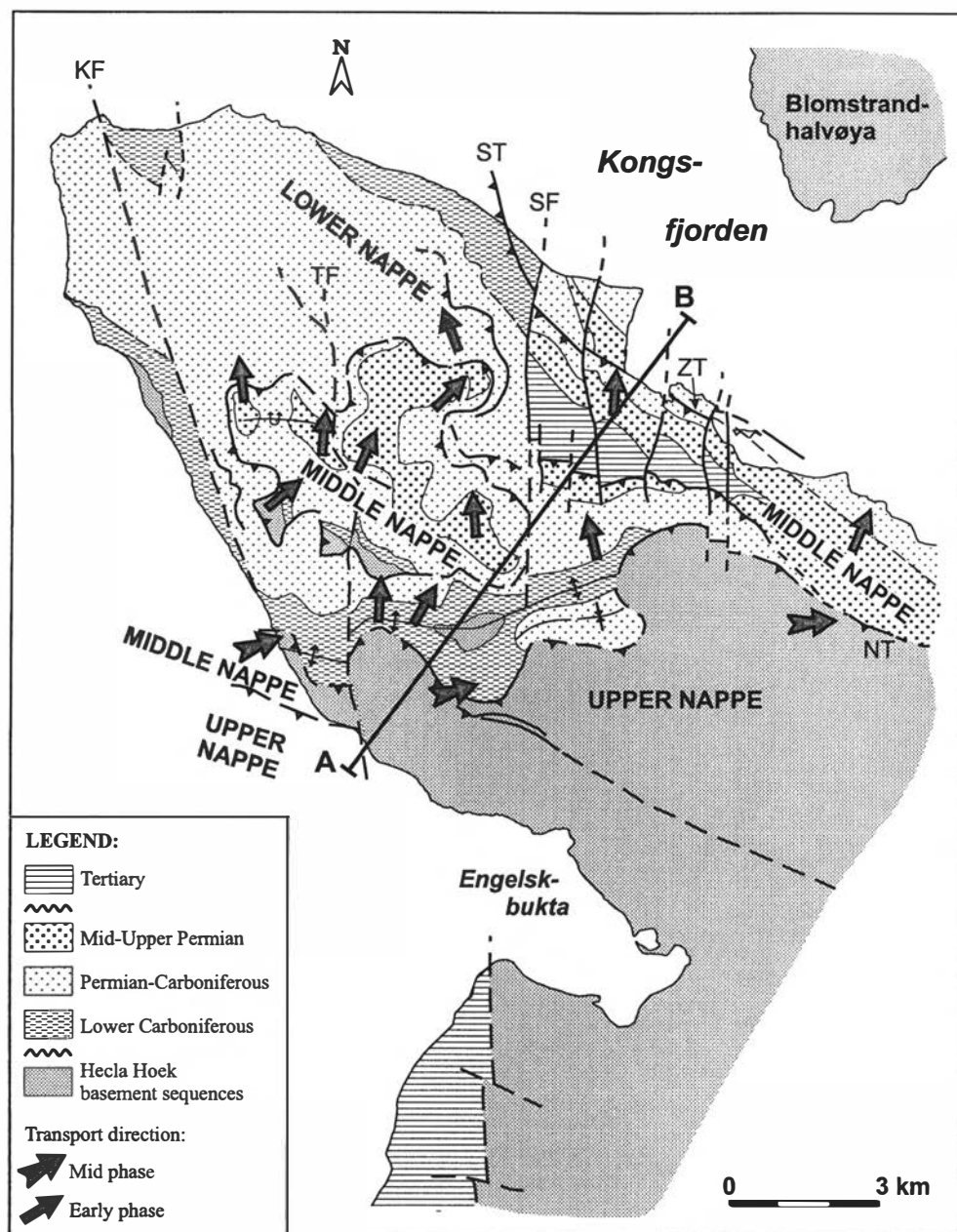


Fig. 10. Summary diagram of thrust-tectonic transport directions for the lower, middle and upper nappes of Brøggerhalvøya. See Fig. 4C for the cross-section.

are to the NNW to NW (domains 2, 4, 5 and 8; Figs. 4, 8). In contrast, the upper nappe shows uniform NE to ENE transport directions (Figs. 9, 10). Interference of the different transport directions, such as in the footwall and hangingwalls close to the nappe-bounding thrusts (Figs. 7, 8), caused variable fold-thrust attitudes, and typical cross-fold patterns with doubly plunging fold axes (see Challinor 1967).

These variations suggest that the middle nappe, which is related to the major, complex syncline, consists of transported and rotated structures associated with an earlier phase of development of the nappe (Fig. 4C). Foreland propagation then produced the Zeppelinfjellet thrust detachment and the accompanying duplex structures in Scheteligfjellet evolving from the forelimb of the syncline. In other words, within the nappe stack, there is

good evidence for an earlier N–NW-directed transport direction, which then rotated some 30° to a NE direction, and ended with a late-stage, ENE-directed ‘out-of-sequence’ movement of the upper nappe.

Early deformation in the middle nappe may be evident on a large scale in the Zeppelinfjellet area. There, the Zeppelinfjellet thrust is interpreted as decapitating both limbs of the major syncline to the south (Fig. 5c, Fig. 2, section F). This macrofold was likely further enhanced and modified during northward rotation of the Zeppelinfjellet thrust, and during subsequent overthrusting of the upper nappe.

Multiple working hypotheses can perhaps explain the wide spectra of thrust transport directions observed in Brøggerhalvøya: (a) thrust pinning and associated rotation, (b) employment of differently oriented anisotropies in

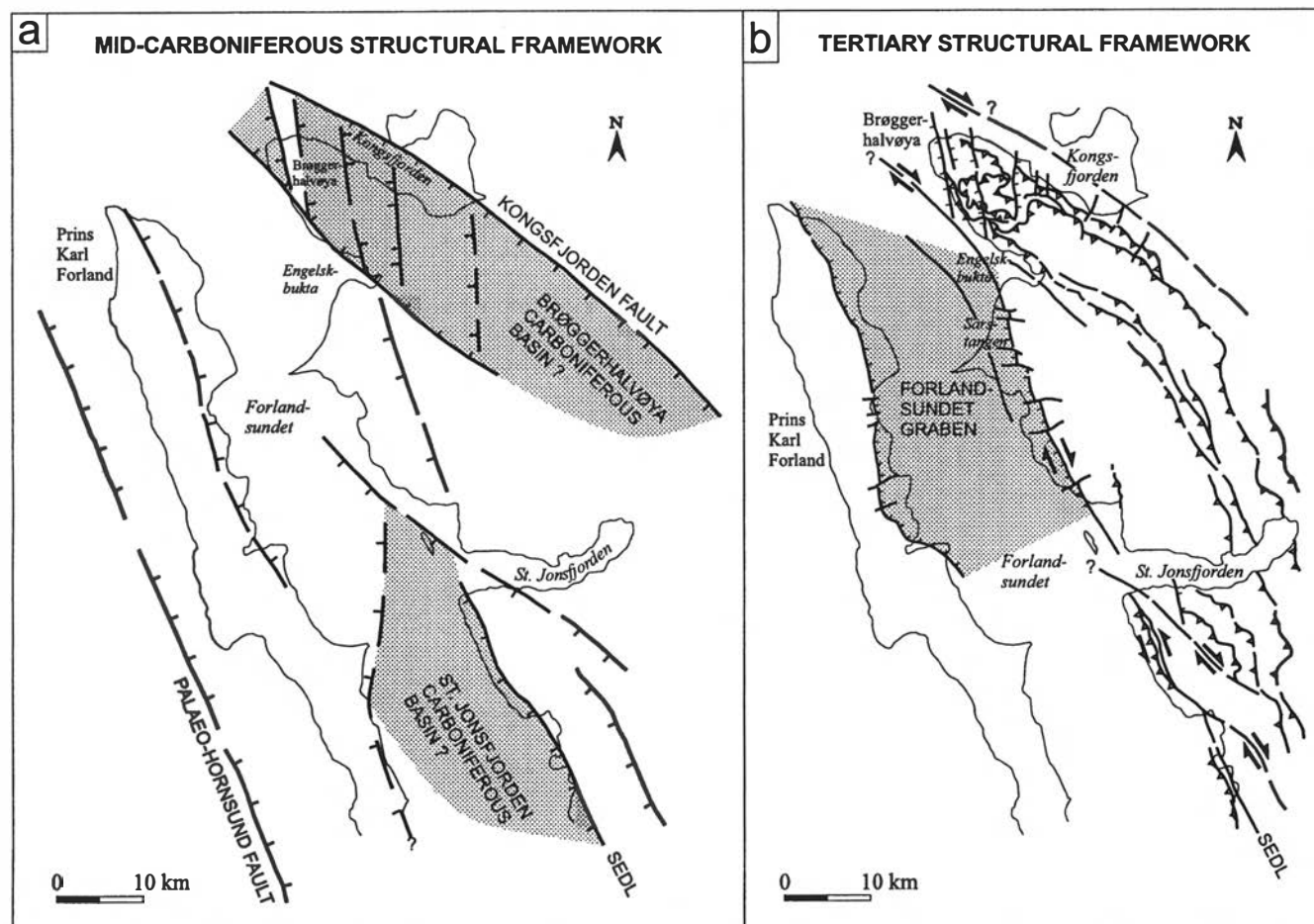


Fig. 11. (a) Tentative reconstruction of the mid-Carboniferous palaeogeography and tectonic framework based on facies variations in the Orustdalen, Brøggertinden and Scheteligfjellet formations. One or more, NNW-SSE-striking, en echelon oriented basins and/or subbasins are postulated. They are bounded to the NE by a presumed oblique fault along Kongsfjorden. Note the existence of the St. Jonsfjorden basin (Steel & Worsley 1984; Maher & Welbon 1992) to the south, and the possible precursor of the Svartfjella–Eidembukta–Daudmannsodden Lineament (SEDL). (b) Outline of the present, Tertiary structural framework in northwestern Spitsbergen. Note that the faults display variable attitudes and kinematic characters.

lateral wedges (inhomogeneous, non-planar strain), (c) response of thrust dynamics to a local and laterally changing wedge topography (Braathen et al. 1999), (d) a changing spatial pattern of decoupling (strain partitioning) or change in the degree of decoupling, and (e) changing plate motions driving the deformation. Option (a) can be ruled out because the map pattern (Figs. 2, 10) does not show the curvature in transport directions that would be produced in this case. Hypothesis (b) suffers from a lack of evidence for the presence of lateral wedges. Option (c) might be expected to produce the opposite pattern as that observed, with more oblique motions occurring later as the topography builds and contributes to the dynamics. We favour a combination of (d) and (e), since plate motions are known to have changed throughout Tertiary deformation (e.g. Talwani & Eldholm 1977; Eldholm et al. 1987) as has the local pattern of strain partitioning (Maher et al. 1997; Braathen et al. 1999).

#### *N–S fault kinematics and regional setting*

Two opinions exist concerning the nature and relative

timing of the N–S-striking, high-angle faults in Brøggerhalvøya. They are either transfer faults formed synchronously with the fold-thrust structures (Challinor 1967; Manby 1988; Lyberis & Manby 1993), or normal faults with a minor component of strike-slip, formed at a late stage of the fold-thrust belt development (Challinor 1967; Midbøe 1985). With respect to timing, our data (map pattern, Fig. 2) indicate that these faults developed after the out-of-sequence thrusting, e.g., as shown by the Trongskardet fault, which clearly truncates the Nielsenfjellet thrust in the south. Furthermore, the map view separation and fault kinematic data (Figs. 7–9) classify them as normal faults, possibly with a minor transcurrent component. Piercing points for the Trongskardet and Scheteligfjellet faults are provided by; (i) the Brøggertinden Formation cut-off line on the Zeppelinfjellet thrust, and by (ii) the major overturned syncline axis for the base Gipsbaken Formation in east Brøggertinden and Zeppelinfjellet areas. These reconstructions indicate that the faults could have either dextral and sinistral components respectively, but a normal component is required. Consequently, our data suggest the N–S-striking faults are not

thrust transfer faults, *senso stricto*, as suggested by Manby (1988) and Lyberis & Manby (1993).

We favour formation of the N–S-striking faults as *en echelon* normal faults, oriented at a high angle to a NW–SE-striking major strike-slip fault zone parallel with Kongsfjorden (see Fig. 11b), as suggested by Orvin (1940). Mechanically, such a model is also plausible because the N–S-striking faults, at least south of Ny Ålesund, die out against the basement strata, which probably served as a buttress to prevent further fault migration in that direction. Alternatively, the N–S-striking faults may represent transfer faults in a step-over zone between a Kongsfjorden fault and the Sarstangen faults further south (Fig. 11b), both with major strike-slip components. The Scheteligfjellet and Trongskardet faults project southward along strike with the east boundary of the Forlandsundet graben exposed in the Sarstangen area (e.g. Steel et al. 1985; Lepvrier 1992; Gabrielsen et al. 1992), which in turn connects with the SEDL (Figs. 1, 11b; Maher et al. 1997). Both at Sarstangen and along the SEDL there is evidence for a polyphase history with major strike-slip components. The disparities in kinematic histories and in offset magnitudes suggest that the Scheteligfjellet and Trongskardet faults do not represent a direct extension or termination of the SEDL lineament system. Instead, it is likely that the SEDL system bends, as it does several times to the south, and lies offshore western Brøggerhalvøya (Fig. 11b). In this case the N–S-striking, predominantly normal faults may represent step-over transfer structures between the dextral strike-slip zone of the 'northern' extension of the SEDL and an unexposed dextral fault in Kongsfjorden (Fig. 11b). The bends along the SEDL create distinctive, changing structural patterns along strike, as would be expected in a system with lineament parallel motion (Maher et al. 1997). This model is an elaboration of that of Orvin (1940).

#### *Carboniferous palaeogeography and tectonism*

The area represented in the present thrust stack is on the order of approximately 20 by 20 km, when the thrusts are restored with indicated transport distances in the order of kilometres for the lower and middle nappes. Over this distance, thickness changes in the Brøggertinden and Scheteligfjellet formations are at most several hundred metres. Associated thickness and facies changes described earlier are thus easily explained without resorting to Carboniferous faulting, with the exception of the relationships on either side of the Kvadehuken fault (Challinor 1967).

An important observation is the presence of an angular unconformity with the Brøggertinden Formation truncating the underlying Orustdalen Formation quartzites on the west side of the Kvadehuken fault (Fig. 2b; section A). This indicates a deformation event prior to deposition of the Gipsdalen Group. Angular unconformities from a similar stratigraphic position have been noted from the fold-thrust belt at St. Jonsfjorden (Welbon & Maher 1992),

at Nordenskiöld Land (Braathen et al. 1995), at Midterhuken (Maher et al. 1986), and in Hornsund (Dallmann 1992). Other angular unconformities higher in the section, and differences in lower Gipsdalen Group stratigraphy across the Kvadehuken fault, suggest fault activity into the Late Carboniferous and Permian. Interestingly, the thicker Brøggertinden-Scheteligfjellet section at Kvadehuken on the east side of the fault, compared with the preservation of Orustdalen Formation on the west side (Fig. 2b; section A), could be related to a reversal of fault motion with time. Such reversals within the Carboniferous are known from the Hornsund area (Steel & Worsley 1984).

In reconstructing the Carboniferous palaeogeography, it is profitable to compare the lower nappe stratigraphic sections, i.e. at (a) Kulmodden, (b) Kvadehuken, (c) Stuphallet, (d) Haavimbjelllet (Saalman & Brommer 1997) and (e) Brøggertinden. Ostensibly, these have not moved any great distance with respect to each other.

The Brøggertinden Formation is very thin west of the Kvadehuken fault, but thickens eastward and displays major changes in the marine versus terrigenous facies. These relationships suggest a west to east shift; from a high west of the Kvadehuken fault, into a fault bounded subbasin that thins eastward (Fig. 11a).

The sections in the Zeppelinfjellet and Traudalen areas in the middle nappe suggest an overall thicker basin with a more marine influence to the west. Given the tectonic transport direction, they originated from a point at least some kilometres to the south. In combination, the data are consistent with a NNW–SSE-trending subbasin bound by the Kvadehuken fault along the western margin, whereas the Kongsfjorden fault may have acted as a source and northeastern edge (Fig. 11a).

Notable facies and thickness changes also occur in the overlying Scheteligfjellet Formation carbonates, e.g. changes that might be indicative of continued, mild tectonism and in-filling in a successively more marine Upper Carboniferous-Permian basin. This basin probably deepened to the south-southeast, and received sediments from a west-northwesterly source area.

Relationships between different Carboniferous strata within the thrust stack at Brøggerhalvøya vary from those observed further south, in Oscar II Land and Nordenskiöld Land (Fig. 1). There, notable thickness and facies changes across thrusts indicate that the eastern fault margin of a westward-deepening basin (the St. Jonsfjorden Trough) was inverted during the Tertiary thrust stacking (e.g. Maher & Welbon 1992; Braathen et al. 1995). In contrast, in the Brøggerhalvøya area, it is less convincing that Carboniferous faults or facies distribution played a significant role in localizing Tertiary deformation, although the Palaeozoic basins and presumed basin-bounding faults (N–S to NW–SE strike) to some degree coincide with the Tertiary structural trends (Fig. 11). As a speculative note, and given the segmentation inherent to structural features, the absence of this pattern may indicate that the northeastern margin of the St. Jonsfjorden Trough terminates in the Brøggerhalvøya area. This in turn could



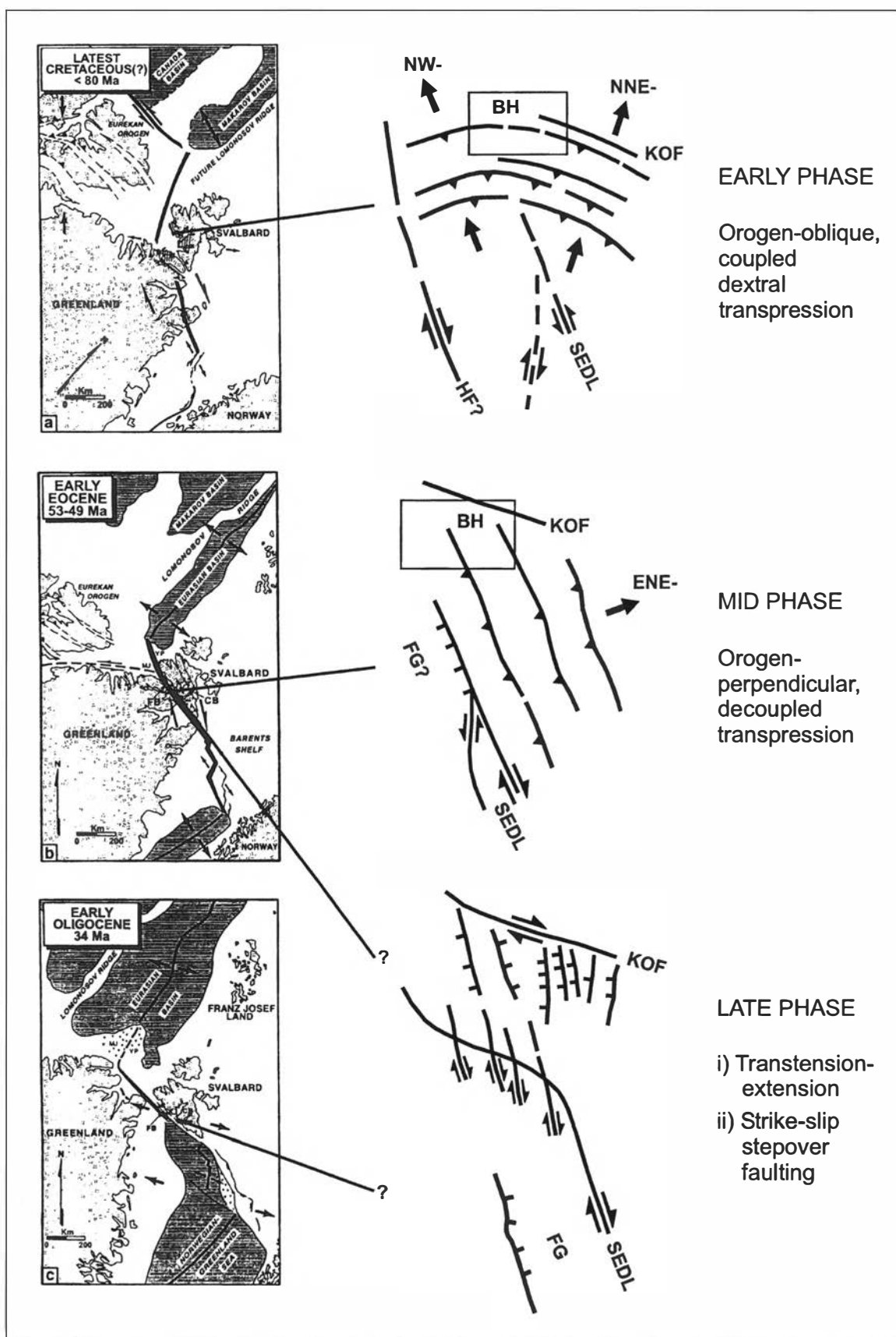


Fig. 12. Tentative tectonic model for the fold-thrust belt evolution in Brøggerhalvøya, as compared with regional tectonic models and timing of Tertiary opening phases (see Blyth & Kleinspehn 1998). The model explains the variable transport directions of the Brøggerhalvøya fold-thrust stack (BH) as being due to a temporal change in the degree of coupled versus decoupled translations. Note formation of the late phase normal faults as either en echelon faults related to dextral movements along the Kongsfjorden fault (KOF), or as strike-slip, step-over faults related to a bend in the SEDL northward. See text for further explanation. Other abbreviations: HF = Hornsund fault, FG = Forlandsundet graben, SEDL = Svartfjella-Eidembukta-Daudmannsodden lineament.

have influenced the anomalous Tertiary thrust directions and the fold-thrust belt termination. In this scenario, termination of the St. Jonsfjorden trough, with its favourably oriented basin-margin faults to the south, caused more oblique and variable Tertiary contractional structures. Pre-existing weak surfaces are known to be critical in permitting decoupling in transpressive zones, which suggests complications will develop at the termination of the controlling weak zone. On a regional scale the atypical structural orientations of the Brøggerhalvøya area could reflect more coupled transpression in the hinterland, including generally orogen-oblique thrusting. In other words, the Brøggerhalvøya area may represent the transitional area between a decoupled transpressive belt (SEDL and fold-thrust belt) to the south and a more coupled transpressive belt to the north (mainly offshore) that was inherited from the Carboniferous architecture.

### Regional implications and tectonic model

Our proposed Tertiary kinematic evolution for Brøggerhalvøya is partly compatible with tectonic models resolved for Spitsbergen's fold-thrust belt further south. For instance, in Oscar II Land, a multistage developmental history includes: early N–S oriented, orogen-oblique shortening (stage 1; latest Cretaceous–Palaeocene[?]), followed by a main phase of ENE-directed, orogen-normal contractional uplift (stages 2 and 3; Eocene), renewed 'out-of-sequence' thrusting towards the NE, and late extension (stage 5; Oligocene) (see Braathen & Bergh 1995; Bergh et al. 1997; Maher et al. 1997; Braathen et al. 1999). This history may be used as a framework for temporal and spatial kinematic correlations across- as well as along-strike in Spitsbergen (Bergh et al. 1998). In this regard, two points can be explored. *First*, despite Brøggerhalvøya's atypical WNW–ESE strike, the overall thrust development can be temporally linked with thrusts in Oscar II Land (i.e. stages 1–3) and Nordenskiöld Land (Welbon & Maher 1992; Braathen et al. 1995; Bergh et al. 1997). *Second*, Brøggerhalvøya's position at the northern strike termination of the Forlandsundet graben (Steel et al. 1985; Lepvrier 1990; Gabrielsen et al. 1992) and the SEDL transcurrent fault zone (Maher et al. 1997) has some important regional implications.

Regarding the first point, our kinematic data and transport directions in Brøggerhalvøya suggest a temporal correlation of the early-phase NW- to NNE-directed thrusting with the pre-uplift (stage 1) shortening event of Oscar II Land, and a linkage of the mid-phase ENE-thrusting with the main thrusting event of Oscar II Land (stages 2 and 3).

Regarding the second point, the late-phase N–S-striking normal faults in Brøggerhalvøya may be linked with the polyphase formation of the Forlandsundet graben. In this context, the western margin of Forlandsundet graben (Fig. 1) is defined by a set of 'down-to-the-east' normal faults that bound Eocene strata of the basin fill (Steel et al. 1985;

Gabrielsen et al. 1992). On the east side, the margin is dominated by a set of late, normal and transcurrent faults, related to the SEDL (Maher et al. 1997). Carboniferous–Permian strata enclosed by basement (Hecla Hoek) of the SEDL were first influenced by contractional uplift and rotation of strata during ENE-directed folding and thrusting (stage 2), followed by a main sinistral strike-slip overprint (stage 3), then dextral strike-slip faulting (stage 4; Maher et al. 1997), and finally late normal faulting. Accordingly, the steep SEDL fabric (stage 2) became a through-going weak surface that allowed later concentration of orogen-parallel strain, and served as a locus for decoupling of transcurrent and contractional Tertiary deformation. A favourable model for the SEDL is that it either represents a decoupled, transcurrent zone, or a deeper-seated portion of the fold-thrust belt in western Isfjorden, which developed during the main stages of fold-thrust emplacement (stages 2 and 3).

In this context (see Fig. 12), the atypical NW-directed thrusting in Brøggerhalvøya (early phase) may be a response to the presumed transcurrent movements along the SEDL (i.e. stage 3 or 4). This advocates for successive and temporal strain partitioning (decoupling) of orogen-normal and orogen-oblique/parallel deformation along the western margin of Spitsbergen (Braathen et al. 1999). Such a decoupling model may further imply that the late phase N–S-striking normal faults in Brøggerhalvøya were associated with the dextral strike-slip faulting along SEDL (i.e. stage 4), and in part, formed coeval with the Forlandsundet Graben. Alternatively, the normal faults can be correlated with the late extension event (stage 5).

Our data contribute to the debate regarding the origin of the regional bending of Spitsbergen's fold-thrust belt near its termination at Brøggerhalvøya, with its more northward-directed tectonic transport (Steel et al. 1985; Lyberis & Manby 1993). We suggest that the origin of the bent fold-thrust stack in Brøggerhalvøya is due to changing thrust/shortening directions and magnitudes along strike. For instance, the three-stage kinematic history proposed for Brøggerhalvøya (early, mid, late) is broadly consistent with that of the fold and thrust belt to the south. There, initial orogen-oblique convergent motions (stage 1) changed to orogen perpendicular convergent motions (stages 2 and 3), followed (and locally overlapping) by development of extensional features (stages 4 and 5). The difference lies in the magnitude of associated structures developed. At Brøggerhalvøya, the orogen-oblique motions predominate (stage 1), whereas in the south, the orogen-perpendicular fold-thrust structures (stages 2 and 3) are dominant. This is likely due to the unique mechanical position of Brøggerhalvøya, as the fold-thrust belt to the south bends to meet the complex hinterland zone with strike-slip lineaments such as the SEDL. This confluence may in turn have been inherited from the northern termination of the St. Jonsfjorden Trough, which localized contraction and aided the development of a decoupled system (Maher et al. 1997). In turn, both the structural bend and the Carboniferous basin geometry may have been influenced by the

difference in basement geology across Kongsfjorden (Ohta 1989), with more competent rocks to the NE.

In our experience, there are broad regional similarities in kinematic histories but specific local differences along the 300 km length of the Tertiary deformation province of Spitsbergen. This would be expected from an orogen driven by changing regional plate motions, and by evolving local patterns of decoupling, bends along fault zones with orogen-parallel motions, and by evolving topography and associated wedge dynamics (Braathen et al. 1999). Overall, the main fold-thrust development at Brøggerhalvøya likely correlates with stages 1 through 3 of Oscar II land (Bergh et al. 1997), but with a prolonged development of stage 1 owing to its unique position. It is known that, with time, thrust systems can propagate along strike; hence, the mid-stage, out-of-sequence thrusting at Brøggerhalvøya may represent the propagation of the decoupled fold-thrust system developing in the south (stages 2–3), into the transition area of the pre-existing and highly oblique fold-thrust structures at Brøggerhalvøya. Stage 4 out-of-sequence, orogen-oblique thrusting of Oscar II Land appears to be absent in Brøggerhalvøya, whereas stage 5 structures are probably present as the late N–S-striking normal faults.

## Conclusions

The data presented and discussed in this paper lead to the following conclusions:

1. The kinematic history of Brøggerhalvøya is broadly consistent with that to the south, but the structural development is distinctive because it represents the termination of the fold-thrust belt, and the importance of the first phase was greater than it was to the south.
2. A three-phase kinematic history is characterized by (i) northward thrusting (early), (ii) changing to ENE-directed thrusting (mid) and (iii) then followed by dissection by N–S-striking normal faults (late).
3. Thrust transport directions at Brøggerhalvøya vary by almost an entire quadrant. This can be explained in tectonic models for the area, e.g. by evolving local and regional kinematics in a variably decoupled wedge.
4. The late-phase normal faults can be associated with dextral strike-slip movements along the SEDL fault system.
5. Dissimilar to the basement-involved fold-thrust stack to the south, there is no evidence to suggest that inversion of Carboniferous faults and basin margins played a significant role at Brøggerhalvøya.
6. This lack of inversion could be due to either misalignment of Carboniferous features (Kvadehuken fault oriented subparallel to the transport direction), or a northern termination of the St. Jonsfjorden Trough.
7. Basement structures and the termination of the St. Jonsfjorden Trough probably exerted control on the

north termination of the decoupled fold-thrust belt in this area.

**Acknowledgements.** – We acknowledge with gratitude financial support from Saga Petroleum ASA (FoU project K-TF-96-043) and the University of Tromsø. Additional funding was provided by the Geological Survey of Norway (NGU) and the University of Nebraska. The Norwegian Polar Institute is thanked for logistical support. Geir Elvebakk helped with understanding the stratigraphy and sedimentology in the field. Students Silje Berg, Pål Caspersen and Frode Karlsen provided important assistance in the field. R. Bøe, J. Hesthammer and J. A. Korstgård are thanked for their constructive reviews.

Manuscript received April 1999

## References

- Aleksandrowski, P. 1985: Graphical determination of principal stress direction for slickenside lineation populations: An attempt to modify Arthaud's method. *Journal of Structural Geology* 8, 73–82.
- Bergh, S. G., Braathen, A. & Andresen, A. 1997: Interaction of basement-involved and thin-skinned tectonism in the Tertiary fold-thrust belt of Central Spitsbergen, Svalbard. *American Association of Petroleum Geologist Bulletin* 81, 637–661.
- Bergh, S. G., Maher Jr., H. D. & Braathen, A. 1998: Along strike segmentation of Svalbard's Tertiary fold-thrust belt. *Abstract, International Conference on Arctic Margins (ICAM III)*, Celle, Germany, p 31.
- Birkenmajer, K. 1972: Tertiary history of Spitsbergen and continental drift. *Acta Geologica Polonica* 22, 193–218.
- Blyth, A. K. & Kleinspehn, K. 1998: Tectonically versus climatically driven Cenozoic exhumation of the Eurasian plate margin, Svalbard: Fission track analyses. *Tectonics* 17, 621–639.
- Braathen, A. & Bergh, S. G. 1995: Kinematics of Tertiary deformation in the basement-involved fold-thrust complex, Western Nordenskiöld Land, Svalbard; tectonic implications based on fault-slip data analysis. *Tectonophysics* 249, 1–29.
- Braathen, A., Bergh, S. G. & Maher, H. D. 1995: Structural outline of a Tertiary basement-uplift/inversion structure in western Spitsbergen, Svalbard; kinematics and controlling factors. *Tectonics* 14, 95–119.
- Braathen, A., Bergh, S. G. & Maher Jr., H. D. 1999: Application of a critical wedge taper model to the Tertiary, transpressional fold-thrust belt on Spitsbergen, Svalbard. *Geological Society America Bulletin* 111, 1468–1485.
- Castellano, T. A. R. 1996: *Kinematic Development of the Tertiary Fold-thrust Belt of Brøggerhalvøya, Spitsbergen, Norway, from Slip-linear Plots*. Unpublished Bachelor thesis, University of Nebraska, USA, 56 pp.
- Challinor, A. 1967: The structure of Brøggerhalvøya, Spitsbergen. *Geological Magazine* 104, 322–336.
- Cutbill, J. L. & Challinor, A. 1965: Revision of the stratigraphical scheme for the Carboniferous and Permian Rocks of Spitsbergen and Bjørnøya. *Geological Magazine* 102, 418–439.
- Dallmann, W. K. 1988: The structure of the Berzeliustinden area: Evidence for thrust wedge tectonics in the Tertiary fold-and-thrust belt of Spitsbergen. *Polar Research* 6, 141–154.
- Dallmann, W. K. 1992: Multiple tectonic evolution of the Sørkapp–Hornsund mobile zone (Devonian, Carboniferous, Tertiary), Svalbard. *Norsk Geologisk Tidsskrift* 72, 49–66.
- Dallmann, W. K., Andresen, A., Bergh, S. G., Maher Jr., H. D. & Ohta, Y. 1993: Tertiary fold- and-thrust belt of Spitsbergen, Svalbard. *Norsk Polarinstitutt Meddelelse* 128, 46 pp.
- Dallmann, W. K. & Mørk, A. 1998: *Lithostratigraphic Lexicon of Svalbard. Review and Recommendations for Nomenclature Use. Upper Palaeozoic to Tertiary*, in press.
- Eldholm, O., Faleide, J. I. & Myhre, A. 1987: Continent-ocean transition at the western Barents Sea/Svalbard continental margin. *Geology* 15, 1118–1122.
- Gabrielsen, R. H., Kløvjan, O. S., Haugsbø, H., Midtøe, P., Nøttvedt, A., Rasmussen, E. & Skott, P. H. 1992: The structural outline of Forlandsundet Graben, Prins Karls Forland, Svalbard. *Norsk Geologisk Tidsskrift* 72, 105–120.
- Gjelberg, J. & Steel, R. 1981: An outline of Lower Middle Carboniferous sedimentation on Svalbard: Effect of tectonic, climatic and sea level changes in rift basin sequences. In Kerr, J. W. M., Fergusson, A. J. & Machan, L. C. (eds.): *Geology of the North Atlantic Borderlands. Canadian Society Petroleum Geologist Memoir* 7.



- Gobbett, D. J. 1964: Carboniferous and Permian brachiopods of Svalbard. *Norsk Polarinstitutt Skrifter* 127.
- Goldstein, A. & Marshak, S. 1988: Analysis of fracture array geometry. In Marshak, S. & Mitra, G. (eds.): *Basic Methods of Structural Geology*, 249–268. Prentice-Hall, Englewood Cliffs, NJ.
- Gray, M. B. & Stamatakis, J. 1997: New model for evolution of fold and thrust belt curvature based on integrated structural and paleomagnetic results from the Pennsylvanian salient. *Geology* 25, 1067–1070.
- Haremo, P. & Andresen, A. 1992: Tertiary decollement thrusting and inversion structures along Billefjorden and Lomfjorden fault zones, East Central Spitsbergen. In Larsen, R. M., Brekke, H., Larsen, B. T. & Talleraas, E. (eds.): *Structural and Tectonic Modelling and its Application to Petroleum Geology*, 481–491. Norwegian Petroleum Society Special Publication 1.
- Harland, W. B., Wallis, R. H. & Gayer, R. A. 1966: A revision of the Lower Hecla Hoek succession in central North Spitsbergen and correlation elsewhere. *Geological Magazine* 103, 70–97.
- Harland, W. B. 1969: Contribution of Spitsbergen to understanding of tectonic evolution of North Atlantic region. In McKay, [initials?] (ed.): *North Atlantic – Geology and Continental Drift*, 817–851. American Association Petroleum Geologists Memoir 12.
- Kellogg, H. E. 1975: Tertiary stratigraphy and tectonism in Svalbard and continental drift: *American Association of Petroleum Geologists Bulletin* 59, 465–485.
- Kleinspehn, K. & Teyssier, C. 1992: Tectonics of the Paleogene Forlandsundet Basin, Spitsbergen: a preliminary report. *Norsk Geologisk Tidsskrift* 72, 93–104.
- Lepvrier, C. 1990: Early Tertiary paleostress history and tectonic development of the Forlandsundet Basin, Svalbard, Norway. *Norsk Polarinstitutt Meddelelser* 102, 16 pp.
- Lepvrier, C. 1992: Early Tertiary palaeostress distribution on Spitsbergen: implications for the tectonic development of the western fold-and-thrust belt. *Norsk Geologisk Tidsskrift* 72, 129–135.
- Lowell, J. D. 1972: Spitsbergen Tertiary orogenic belt and the Spitsbergen fracture zone. *Geological Society of America Bulletin* 83, 3091–3102.
- Ludwig, P. 1991: The marine transgression in the Middle Carboniferous of Brøggerhalvøya (Svalbard). *Polar Research* 9, 65–76.
- Lyberis, N. & Manby, G. M. 1993: The West Spitsbergen Fold Belt; the result of Late Cretaceous–Paleocene Greenland–Svalbard convergence? *Geological Journal* 28, 125–136.
- Maher Jr., H. D. & Craddock, C. 1988: Decoupling as an alternate model for transpression during the initial opening of the Norwegian–Greenland Sea. *Polar Research* 6, 137–140.
- Maher Jr., H. D. & Welbon, A. 1992: Influence of a Carboniferous basin margin on Tertiary tectonism at St. Jonsfjorden and Bellsund, Western Svalbard. *Norsk Geologisk Tidsskrift* 72, 67–75.
- Maher Jr., H. D., Craddock, C. & Maher, K. 1986: Kinematics of Tertiary structures in upper Paleozoic and Mesozoic strata on Midterhuken, west Spitsbergen. *Geological Society of America Bulletin* 97, 1411–1421.
- Maher Jr., H. D., Braathen, A., Bergh, S. G., Dallmann, W. K. & Harland, W. B. 1995: Tertiary or Cretaceous age for Spitsbergen's fold-thrust belt on the Barents Shelf? *Tectonics* 14, 1321–1326.
- Maher Jr., H. D., Bergh, S. G., Braathen, A. & Ohta, Y. 1997: Svartfjella, Eidembukta and Daudmannsodden lineament: Tertiary orogen-parallel motion in the crystalline hinterland of Spitsbergen's fold-thrust belt. *Tectonics* 16, 88–106.
- Manby, G. M. 1988: Tertiary folding and thrusting in NW Svalbard. *Norsk Polarinstitutt Report* 46, 17–20.
- Midbøe, P. S. 1985: Kongsfjordfeltet (Paleocen) Spitsbergen. Sedimentologisk og tektonisk utvikling. Unpublished thesis, University of Bergen, 226 pp.
- Ohta, Y. 1989: Caledonian terranes in Svalbard. *Geological Society of America Special Paper* 230, 1–15.
- Orvin, A. K. 1983: Geology of the Kings bay region, Spitsbergen. *Skrifter om Svalbard og Ishavet* 57.
- Orvin, A. K. 1940: Outline of the geological history of Spitsbergen. *Skrifter om Svalbard og Ishavet* 78, 1–57.
- Saalmann, K. 1995: *Litologie und Tektonik der nordöstlichen Brøggerhalbinsel, NW-Spitzbergen*. Unpubl. Dipl.-Arb thesis, Geol.-Paleon. Inst. Westf. Wilh.-University of Munster, 139 pp.
- Saalmann, K. & Brommer, A. 1997: Stratigraphy and structural evolution of eastern Brøggerhalvøya, NW Spitsbergen. *Munster Forsch. Geol. Palaont., Heft* 82, 147–164.
- Steel, R. J. & Worsley, D. 1984: Svalbard's post-Caledonian strata – an atlas of sedimentational patterns and paleogeographic evolution. In Spencer, A. M. et al. (eds.): *Petroleum Geology of the North European Margin*, 109–135. Norwegian Petroleum Society.
- Steel, R. J., Gjeldberg, J., Helland-Hansen, W., Kleinspehn, K., Nøttvedt, A. & Larsen, M. R. 1985: The Tertiary strike-slip basins and orogenic belt of Spitsbergen. In Biddle, K. T. & Cristie-Blick, N., (eds.): *Strike-slip Deformation, Basin Formation, and Sedimentation. Society of Economic Palaeontologists and Mineralogists Special Publication* 37, 339–359.
- Talwani, M. & Eldholm, O. 1977: Evolution of the Norwegian–Greenland Sea. *Geological Society of America Bulletin* 88, 969–999.
- Teyssier, C., Kleinspehn, K. & Pershing, J. 1995: Analysis of fault populations in western Spitsbergen: Implications for deformation partitioning along transform margins. *Geological Society of America Bulletin* 107, 68–82.
- Twiss, R. J. & Unruh, J. R. 1998: Analysis of fault slip inversions: Do they constrain stress or strain rate? *Journal of Geophysical Research* 103, 12205–12222.
- Welbon, A. I. & Maher Jr., H. D. 1992: Tertiary tectonism and basin inversion of the St. Jonsfjorden region, Svalbard. *Journal of Structural Geology* 14, 41–55.