Tertiary structure of the Sørkapp-Hornsund Region, South Spitsbergen, and implications for the offshore southern extension of the fold-thrust Belt

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Bergh S. G., Grogan P.: Tertiary structure of the Sørkapp-Hornsund Region, South Spitsbergen, and implications for the offshore southern extension of the fold-thrust Belt. *Norwegian Journal of Geology,* Vol. 83, pp. 43-60. Trondheim 2003, ISSN 029-196X.

The Sørkapp-Hornsund region of southern Spitsbergen has undergone a complex Tertiary tectonic history, including contractional and transpressional uplift and transtensional subsidence and reactivation. Major Palaeozoic features such as the Sørkapp-Hornsund High and related basins, greatly influenced Tertiary structural development. The main elements of the region include, from west to east; the Hornsund Fault Zone (offshore), the Lidfjellet-Øyrlandsodden Fold Zone, the Øyrlandet Graben, the Sørkapp-Hornsund High, and the Tertiary fold-thrust belt. Offshore seismic data indicate that Tertiary structural features similar to those of the Sørkapp-Hornsund region are present below the shelf extending south to 75°50'N, including terraces, detached fold-thrust structures, and steep basement-involved extensional and strike-slip faults that delimit basement highs and basin margins. South of 75°50'N, the contractional structures diminish abruptly in frequency and are replaced by a geometry more characteristic of a passive margin and reflecting rifting phases dating back to the Late Cretaceous.

A multiple-event Tertiary tectonic history is proposed to explain the present day onshore-offshore structural pattern: *Phase A* (Paleocene – possible Early Eocene) involved WSW-ENE directed contraction and formation of the fold-thrust belt and the Lidfjellet-Øyrlandsodden Fold Zone. The Sørkapp-Hornsund High was inverted as a foreward propagating wedge along basement-involved, ENE-vergent thrusts. During *phase B* (Mid-Late Eocene?) local transtensional basins such as the Øyrlandet Graben, formed obliquely (NNE) to the Sørkapp-Hornsund High and the fold-thrust belt, in a right-stepping transfer zone between the two segments of en echelon contractional deformation zones. Paleocene-Eocene strata of the graben were tilted southwards and the basin margins reactivated by dextral strike-slip movements directed subparallel to the NNW-striking Hornsund Fault Zone, situated offshore. *Phase C* (possible Late Eocene) included reactivation of the Lidfjellet-Øyrlandsodden Fold Zone by sinistral strike-slip duplexing that also affected the fold-thrust belt and the Sørkapp-Hornsund High by means of sinistral transtension, producing NNW-striking normal faults. A south-plunging basement uplift was produced by reorientation of strata adjacent to the Sørkapp-Hornsund High, possibly due to local NW-SE contraction and/or movements along a ENE-striking transfer fault zone situated offshore and to the south of Sørkapp. *Phase D* (Late Eocene - possible Oligocene?) resulted in ENE- and WNW-striking transfer fault zones that offset and partition all the main structural elements, onshore and offshore.

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Introduction

The Sørkapp-Hornsund region is important to the understanding of the geological evolution of Svalbard (e.g. Harland 1969) and the western Barents margin (Figs. 1 and 2). The province exhibits Proterozoic to Tertiary strata that reveal a prolonged and complex tectonic development (e.g. Birkenmajer 1984, Dallmann 1992, Winsnes et al. 1993; Dallmann et al. 1993b). Devonian extension (Birkenmajer 1964) was followed by Early to Middle Carboniferous extension and local transpression forming major basins and highs (Birkenmajer 1964, Gjelberg & Steel 1981; Steel & Worsley 1984). Permo-Triassic uplift and erosion (Birkenmajer 1981) were succeeded by Tertiary contractional-transpressional and extensional tectonics (Birkenmajer 1972; Lowell 1972; Kellogg 1975; Steel et al. 1985; Dallmann 1992).

The goal of this paper is to resolve the Tertiary structural development of the region in greater detail, with emphasis on the Sørkapp-Hornsund High (Fig. 2). The study also attempts to compare and correlate Tertiary tectonic elements and kinematic deformation episodes in the Sørkapp-Hornsund area with those of the western Barents margin (Fig. 1; Skilbrei 1992; Eiken 1994; Grogan 1994; Grogan et al. 1999). This is achieved by examining both offshore seismic data, and the structural features of central Spitsbergen (e.g. Dallmann et al. 1993a; Teyssier et al. 1995; Bergh et al. 1997; Braathen et al. 1999a).

Geological and tectonic overview

The major tectonic elements of the Sørkapp-Hornsund region (Figs. 1 and 2) are well exemplified and include, from west to east: 1) the Hornsund Fault Zone, now situated offshore west of Spitsbergen, 2) the Lidfjellet-Øyrlandsodden Fold Zone, 3) the Øyrlandet Graben, 4)

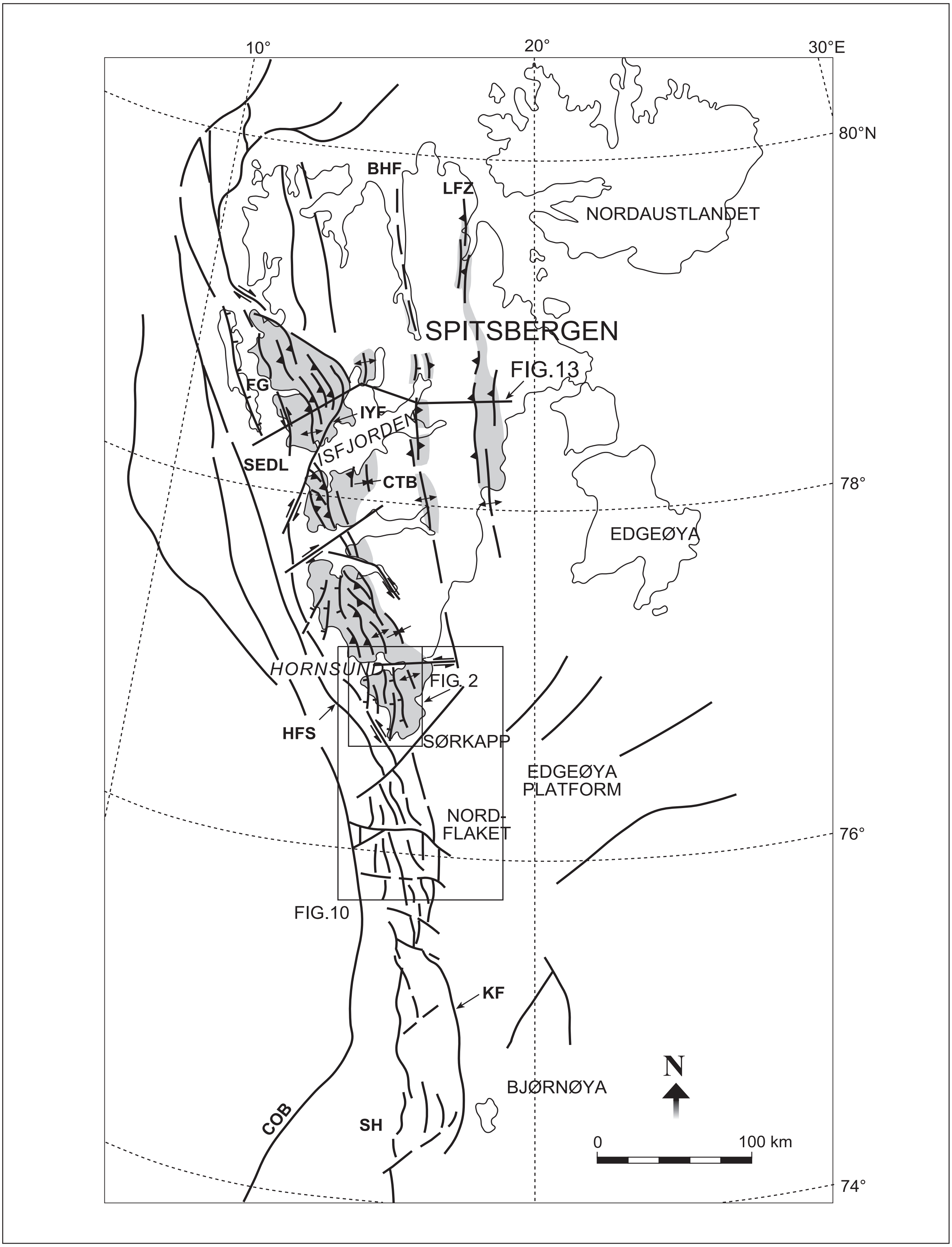


Fig. 1. Structural map of Svalbard and the northern Barents Shelf showing major Tertiary faults and fault systems. Shaded areas delineate the extent of Tertiary deformation on Spitsbergen. Abbreviations are as follows: BFZ=Billefjorden Fault Zone, COB=Continent-Ocean boundary, CTB=Central Tertiary Basin, FG=Forlandsundet Graben, HFZ=Hornsund Fault Zone, IYF=Isfjorden-Ymerbukta Fault Zone, KF=Knølegga Fault, LFZ=Lomfjorden Fault Zone, SH=Stappen High, SEDL=Svartfjella-Eidembukta-Daumannsodden Lineament.

the Sørkapp-Hornsund High and Inner Hornsund Fault, and 5) the Tertiary fold-thrust belt, including the Central Tertiary Basin (Dallmann 1992; Dallmann et al. 1993b; Winsnes et al. 1993).

The principal controlling tectonic lineaments are assumed to have been the Hornsund Fault Zone, situated offshore to the west (Fig. 1), and the Inner Hornsund Fault in the east (Fig. 2). These lineaments have probably represented deep-rooted zones of weakness since Early Carboniferous time, and which now demarcate the Sørkapp-Hornsund High, which comprises uplifted and eroded pre-Devonian basement (Fig. 2).

The geological history of the Sørkapp-Hornsund High began with deposition of Early Carboniferous sediments adjacent to an incipient basement high (Fig. 1; Birkenmajer 1964, 1975). These units were gently folded and uplifted in the Middle Carboniferous (Birkenmajer 1964; Dallmann 1992). Subsequently, Upper Carboniferous and Permian sediments of the Inner Hornsund trough were deposited to the east (e.g. Steel and Worsley 1984). Triassic strata rest unconformably on basement and Lower Carboniferous strata across the central part of the Sørkapp-Hornsund High (Fig. 2), suggesting that it comprised a land area throughout most of the Carboniferous and Permian, until the earliest Triassic. Jurassic and Cretaceous strata form a continuous sequence overlying the Triassic to the east, while Paleocene-Eocene sediments were deposited in the Central Tertiary Basin and smaller local grabens.

In the Tertiary, Svalbard's western margin was subjected to transform movements associated with the opening of the Norwegian-Greenland Sea (e.g. Talwani & Eldholm 1977; Eldholm et al. 1987). Previous models for Tertiary deformation in the Sørkapp-Hornsund region favour a sequence of events involving contraction and local transpression (Late Paleocene to Eocene) with formation of the fold-thrust belt and the Lidfjellet-Øyrlandsodden Fold Zone, followed by extension (Birkenmajer 1964, 1972; Dallmann 1992; Dallmann et al. 1993b; Winsnes et al. 1993). Importantly, models involving both transpression and transtension have been prevalent since they were first proposed by Harland (1972) and Lowell (1972). The present model of structural decoupling has prevailed until recently also for central Spitsbergen (e.g. Maher & Craddock 1988; Braathen et al. 1999a), and also presented as a possibility for the Sørkapp-Hornsund region (Dallmann 1992).

Structural Geology

Our research has focused on field observations at key localities within the main structural provinces (Fig. 2), and on lineaments bounding the Sørkapp-Hornsund High, together with seismic data from the continental shelf south of Sørkapp (Fig. 1). These localities are described in the following.

Lidfjellet-Øyrlandsodden Fold Zone (localities 1 and 2)

The Lidfjellet-Øyrlandsodden Fold Zone is a NNW-striking fold-fault zone situated southwest of the Sørkapp-Hornsund High and Øyrlandet Graben (Fig. 2). To the south it is exposed as a major fold system involving Carboniferous-Permian platform units on Sørkappøya and Øyrlandsodden (Fig. 2). To the north, contractional structures at Liddalen are proposed to be the more foreland and thin-skinned equivalent, comprising ENE-vergent thrusts that emplaced Triassic units above Jurassic-Cretaceous strata (Dallmann 1992). Remapping and the interpretation of profiles across Sørkappøya (Fig. 3) show the disposition of Carboniferous, Permian and Triassic sedimentary rocks (Winsnes et al. 1993). The Carboniferous-Permian boundary is assumed to lie just west of Sørkappøya. A distinctive coarse sandstone bed near the Base Triassic (Tlv; Fig. 3) was used as a marker horizon.

The principal structure of the island is a NE-verging macroscopic syncline with an overturned western limb and a gently SSE-plunging axis together with steep, superimposed faults (Winsnes et al. 1993). The individual fault throws are displayed by strike-parallel separation of the fold hinge and limbs, up to 25 m laterally. In map view, NE-striking faults in the north reveal sinistral strike-slip separation and have a curvilinear trace, parallel to drag-folded units on the southwestern limb of the macroscopic syncline, producing sigmoidal lenticular blocks (Fig. 3). These faults are interpreted to terminate in a more linear sinistral strike-slip fault that strikes NW and merges with the fault that truncates the eastern limb of the syncline. This interpretation is supported by sinistral drag in Carboniferous strata observed on Vardeholmen (Fig. 3). On a large scale, the composite fault system resembles a sinistral strike-slip duplex with floor and roof faults striking NW, and splay faults striking N to NE. Mesoscopic conjugate faults comprise three chronological groups relative to the macroscopic syncline; the oldest is orthogonal to the axial trace (Fig. 4b; NE to ENE), the intermediate is oblique to the axial trace (Fig. 4c; N and NE), and the youngest set is subparallel to the axial trace (Fig. 4d; N to NW).

At Øyrlandsodden, about 10 km further northwest along strike (Fig. 2), macroscopic NW-trending folds are observed that correlate with those on Sørkappøya (Winsnes et al. 1993). Here, the folds are juxtaposed by downthrown, unfolded Paleocene strata in the Øyrlandet Graben (Fig. 2). The master fault is interpreted to have a NW strike and a rectilinear trace, and to corre-

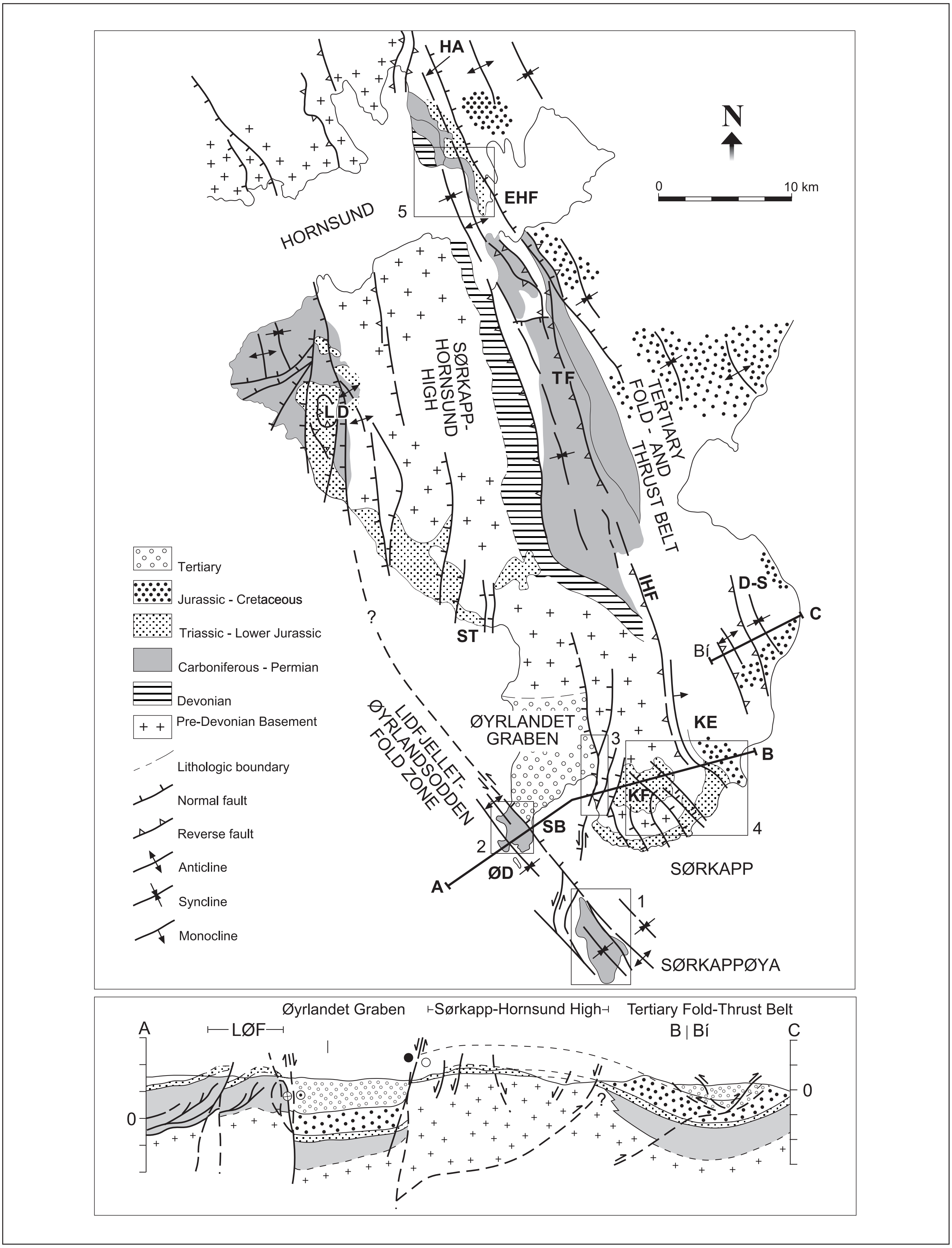


Fig. 2. Geological and structural map of the Sørkapp-Hornsund Region, with cross-section, modified after Dallmann (1992) and Winsnes et al. (1993). Annotated and framed areas denote localities described in the text. Abbreviations are: D-S=Dumskolten-Svartkuven, HA=Hyrnefjellet Anticline, EHF=Eastern Hornsund Fault, IHF=Inner Hornsund Fault, KF=Kistefjellet, KE=Keilhaufjellet, LD=Liddalen, ST=Stormbukta, SB=Sommerfeldtbukta, ØD=Øyrlandsodden.

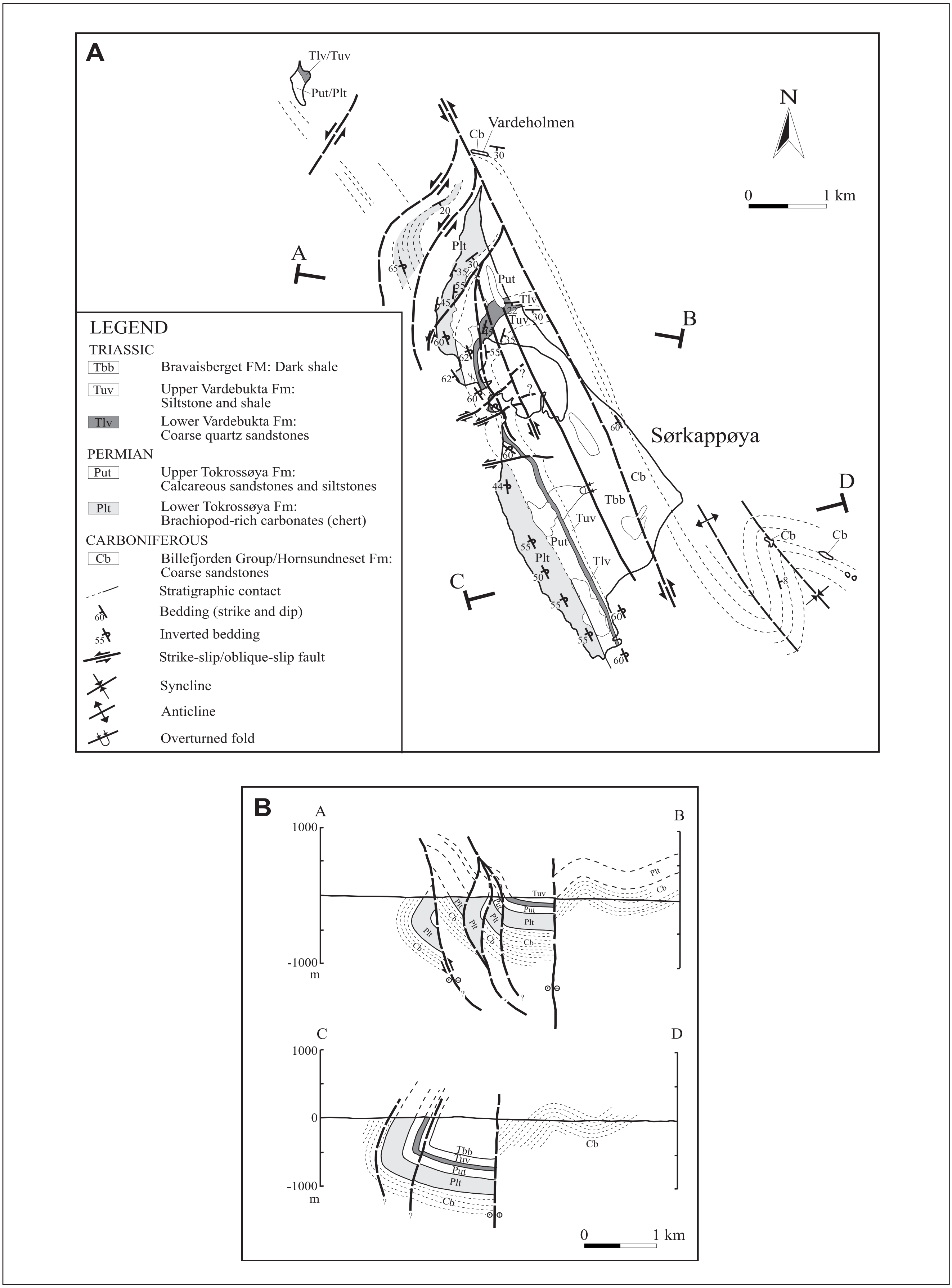


Fig. 3. Detailed geological and structural map (a) with cross-sections (b) of Sørkappøya (locality 1 of figure 2). Structures on the adjacent shallow shelf have been observed on infrared air photos and are confirmed by field data from islets and skerries (Winsnes et al. 1993).

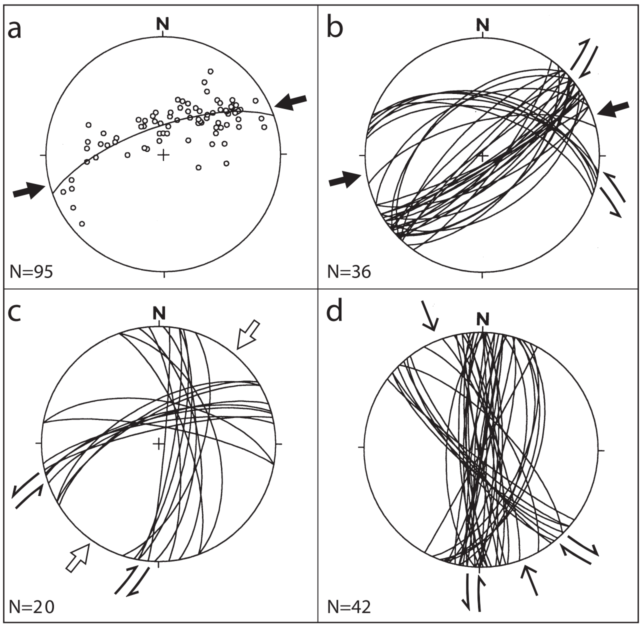


Fig. 4. Structural data from the Lidfjellet-Øyrlandsodden Fold Zone on Sørkappøya (locality 1), presented as stereographic projections, lower hemisphere, equal area Schmidt nets. (a) Poles to folded bedding and statistically estimated πs-girdle. Arrows indicate ENE-WSW shortening direction. (b) Mesoscopic conjugate strike-slip faults that are perpendicular to the main NW-trending folds and faults, plotted as great circles. Arrows indicate the same shortening direction as in 4a. (c) Mesoscopic conjugate strike-slip faults (great circles) near NW-striking major faults. Arrows indicate NNE-SSW incremental shortening direction. (d) Mesoscopic strike-slip faults (great circles) near NE-striking major faults. Arrows indicate NNW-SSE incremental shortening direction.

late with the eastern main fault on Sørkappøya (Figs. 2 and 3). Mapped mesoscale strike-slip faults at Øyrlandsodden have dominantly NE strikes, i.e. perpendicular to the macrofold system. Near the contact to the Øyrlandet Graben, the fault frequency increases and the fault strike direction changes to NW, suggesting that the faulted margin of the Øyrlandet Graben was formed coevally with the strike-slip faults. Local bed reorientation, in combination with normal and strike-slip separation of beds within the macrofold, indicate that the contact may represent a strike-slip fault.

The Øyrlandet Graben at Sommerfeldtbukta (locality 3)

The Øyrlandet Graben (Fig. 2) is one of several Tertiary half-grabens observed and described along the western coast of Spitsbergen (e.g. Steel et al. 1985; Gabrielsen et al. 1992), and on the continental margin west of Svalbard (Eiken & Austegard 1987; Eiken 1994). Strata of assumed Paleocene through Eocene age within the graben (Dallmann et al. 1993) are exposed along the eastern shore of Sommerfeldtbukta (Figs. 2 and 5), where they are in fault contact with basement rocks of the Sørkapp-Hornsund High. The exposed strata are about 100 m thick and consist of sand-, silt- and mudstones and local coal seams (Dallmann et al. 1993b). The throw along the fault is at least 2000 m down-to-the-west, based on stratigraphy and the offset of Mesozoic strata exposed further north within the graben (Dallmann 1992).

Towards the grabens eastern fault (Fig. 5), Paleocene strata strike on average E-W and exhibit gentle dip to the south. The strike changes to N-S, and steep westward dip develops due to dextral rotation. Open folds with gently south-plunging axes are found near the contact with basement lithologies in the east (Fig. 6a). Here, the contact is defined by an irregular, subvertical cataclastic fault zone, up to 100 m wide, that contains intensely tectonized breccias and vertically stacked rock layers and lenses. Fragmented siderite-bearing shales, bioturbated silt- and claystones and metapsammites observed within the fault zone are probably deformed Tertiary sediments with a subsidiary mixture of Triassic shales and basement metapsammite clasts.

East of Sommerfeldtbukta (Fig. 2) the basement rocks consist of metadolomites and psammites, and bedding strikes N to NNE and dips steeply to the west (Dallmann et al. 1993b), i.e. with the same orientation as the presumed eastern margin fault of the Øyrlandet Graben (Fig. 5). In the Kistefjellet area, Triassic shales lie unconformably on basement rocks and dip gently to the south (Fig. 2: Winsnes et al. 1993). Near the fault contact, the strike changes abruptly to NNE and the beds dip 30° to the east.

Kinematic data for the eastern faulted margin of the Øyrlandet Graben were acquired from textures within the fault rocks and small-scale faults in the adjacent basement and Triassic rocks. The similarity of geometry and orientation of these faults within the different stratigraphic units are important factors in interpreting the development of the Øyrlandet Graben, as is outlined below. Several brittle faults with dm-thick cataclasites and striations are superimposed on bedding surfaces within basement dolomites and quartzites, while bed-truncating, mm-thick faults characterize the deformation of Triassic and Tertiary strata. Two conjugate fault sets are observed in the Triassic rocks: an older set of normal faults with approximately N-S strike and moderate eastward and westward dip (Fig. 6b), and a truncating system of steep, W- to WNW-striking, conjugate strike-slip faults (Fig. 6c). Similarly oriented faults are found in Tertiary strata (Fig. 6d). In the basement strata, the dominant brittle fault sets are: (i) NNE-striking normal faults with striae that indicate down-to-the-ESE movement, (ii) N-S-striking sinistral strike-slip faults, and (iii) late normal faults striking NW and with down-to-the-SW movement (Fig. 6e, f). If the mesocopic conjugate fault sets formed as a consequence of movement along the NNE-striking fault that delimits the eastern Øyrlandet Graben margin, then

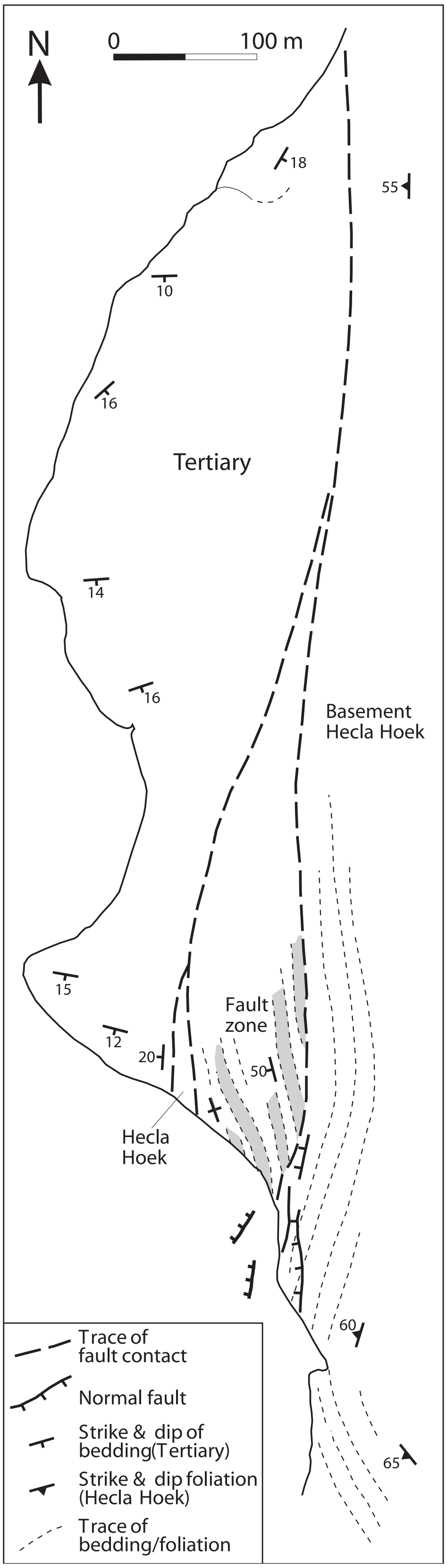


Fig. 5. Detailed structural map of the eastern margin of the Øyrlandet Graben along the eastern shore of Sommerfeldtbukta (locality 3 of figure 2).

these data suggest a kinematic development involving E-W extension (Fig. 6b) followed by WNW-ESE shortening (Fig. 6c) resulting from sinistral strike-slip motion along NNE-striking faults (Fig. 6f). A late strike-slip component along the eastern Øyrlandet fault margin is also supported by the southerly dip of strata in the graben, the cataclastic fault zone rocks and the steep orientation of the fault zone itself.

The Sørkapp-Hornsund High at Kistefjellet and Keilhaufjellet (locality 4)

The Sørkapp-Hornsund High is the most critical structure of south Spitsbergen, as it was formed in the Palaeozoic (Steel & Worsley 1984) and has, to a large extent, controlled all subsequent structuring of the area. At Hornsund, the *western margin* of the high defines a transition zone west of Liddalen (Fig. 2), where Carboniferous and Permian strata pinch out against a normal fault (Liddalen fault). Further south, the high is bounded to the west by numerous younger, normal faults against Triassic strata and by the Øyrlandet Graben. The High's *eastern margin* is delineated by the Inner Hornsund Fault (Fig. 2), a presumed Carboniferous normal fault that is defined by facies changes and paleocurrent data obtained from Carboniferous strata (Gjelberg & Steel 1981; Birkenmajer 1984; Steel & Worsley 1984). At Hornsund, the boundary is superimposed by the Tertiary fold-thrust belt, and by a proposed major normal fault, the Eastern Hornsund Fault (Fig. 2; Dallmann 1992).

The southernmost onshore segment of the Sørkapp-Hornsund High is exposed at Kistefjellet and Keilhaufjellet, where basement rocks are overlain by Triassic strata (Fig. 2). The basement rocks were folded and weakly metamorphosed during the Caledonian orogeny producing tight WSW-verging folds and steep bedding with a predominantly N strike. In the western areas of Kistefjellet, where beds dip steeply to the west, and parallel to the Øyrlandet Graben margin fault, frequent brittle faults occur (as described earlier). Between Kistefjellet and Keilhaufjellet the unconformably overlying Triassic to Cretaceous sedimentary sequence is downfolded towards the south and southeast, resulting in a large-scale, dome-shaped monocline (Dallmann et al. 1993b).

Several sets of normal faults transect the monocline. The strike of observed mesoscale faults varies from WNW and NW (youngest and most common), through ENE (Fig. 7a, b). Steep N- to NE-striking normal faults with additional strike-slip components dominate the western part of Kistefjellet where they are subparallel to the Øyrlandet Graben margin and cut Triassic sandstone beds. In the central and eastern areas of Kistefjellet, several NW-striking, dextral oblique-

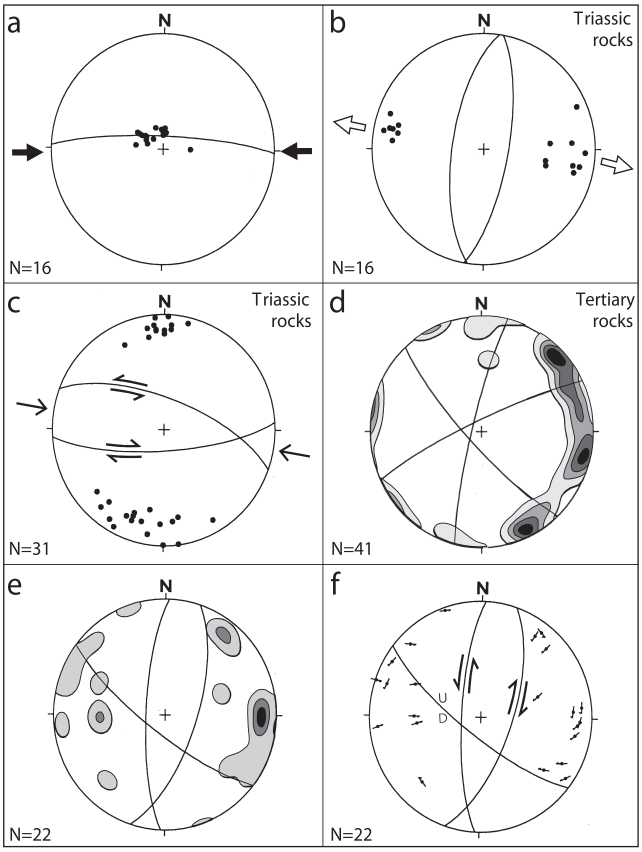


Fig. 6. Mesoscopic fault data from the eastern margin of the Øyrlandet Graben at Sommerfeldtbukta (locality 2). (a) Poles to bedding in Tertiary strata indicating southward gentle tilt of strata and broad E-W-directed folding. (b) Poles to conjugate normal faults in Triassic strata adjacent to the graben margin. Great circles represent the average orientations of the fault populations. (c) Poles to conjugate strike-slip faults in Triassic strata, with average great circle orientations and fault movements. Arrows indicate WNW-ESE incremental shortening direction. (d) Contoured poles to faults in Tertiary strata and average orientations (great circles). (e) Contoured poles to brittle faults in the pre-Devonian basement adjacent to the graben boundary, and average orientation of faults (great circles). (f) Slip-linear plot of the fault data in 6e. In this plot, the pole to the fault plane is marked with an arrow indicating the direction of motion parallel to the movement plane, which runs through the linear structure and the pole to the fault (Goldstein & Marshak 1988).

normal faults truncate the entire, monoclinally downfolded Triassic-Cretaceous sequence, including the fold-thrust belt structures further east.

The Tertiary fold-thrust belt at Inner Hornsund (locality 5)

The Tertiary fold-thrust belt at Inner Hornsund comprises several characteristic types of structure (Fig. 2). These include the Hyrnefjellet Anticline (Fig. 8), a macroscopic ENE-verging feature that folds a complete sequence from the Carboniferous to the Cretaceous, a related syncline and thrust faults further north, and the normal Eastern Hornsund Fault (Dallmann 1992; Winsnes et al. 1993) which truncates the fold-thrust belt structures. The amplitude of structures within the fold-thrust belt diminishes southwards along strike towards the eastern margin of the Sørkapp-Hornsund High near Keilhaufjellet.

The Hyrnefjellet Anticline and related syncline at Inner Hornsund (Fig. 8) verge ENE and have gently SSE-plunging axes (Fig. 9a). The eastern limb contains several mesoscopic structural elements that may be related to progressive development of the macrofold. For instance, Triassic beds are caused to repeat by thrusts with ramp-flat geometry. Geometry and orientation data from the mesoscopic thrust faults indicate formation during a late stage in the development of the macrofold. In addition, there are many late sets of N- to NW-striking normal faults and a few strike-slip faults (Fig. 9b) that cut the Hyrnefjellet Anticline. These normal and strike-slip faults are interpreted to be the result of transtensive movements that post-dated the macrofold, i.e. contemporaneous with the Eastern Hornsund Fault.

Southwards across the fjord, the Hyrnefjellet Anticline is displaced approximately 1 km laterally across Hornsund (Winsnes et al. 1993), suggesting the presence of a high-angle sinistral fault in the fjord. Carboniferous through Cretaceous strata of the the fold-thrust belt south of Hornsund become steep to overturned towards the east (Fig. 2). These units correlate structurally with the eastern limb of the Hyrnefjellet Anticline, and merge southwards with the Keilhaufjellet monocline along the eastern margin of the Sørkapp-Hornsund High. The anticline is cut by several reverse faults and dextral strike-slip faults, and is superimposed by normal faults that may be be components of the major Eastern Hornsund Fault.

In the eastern parts of the Sørkapp-Hornsund Region, at Dumskolten and Svartkuven (Fig. 2), Tertiary strata are characterized by flexural folds, monoclines and open to asymmetric anticlines and synclines. Locally, the strata are cut by low-angle thrusts and reverse imbrication structures.

The offshore shelf south of Sørkapp

Preliminary interpretations of migrated, multichannel reflection seismic data acquired by the Norwegian Petroleum Directorate in 1993 (Grogan 1994), indicate that structural features similar to those of the Sørkapp-Hornsund region can be identified below the continental shelf, at least south to 75°50'N (Fig. 10). Three seismic profiles were selected as the basis for a preliminary interpretation. The selected W-E profiles (761730, 761230 and 760730) are situated at a distance of between 30 and 50 km south of Sørkapp (Fig. 10). Interpreted line drawings of these profiles are shown in Fig. 11. The presence of Cretaceous-Tertiary strata has been verified in shallow boreholes drilled along line 760730 (Grogan et al. 1999). Seismic data coverage is limited, and regional stratigraphic and structural correlations are difficult to establish with certainty. However, we believe that data quality permits a tentative correlation between the stratigraphy and structural elements of the onshore and offshore areas.

South of Sørkapp, the profiles (Fig. 11) reveal a distinct three-fold subdivision across strike. The *eastern segment* comprises the western margin of the Edgeøya Platform (Grogan et al. 1999), where the pre-Devonian basement and overlying, dominantly Palaeozoic-Mesozoic sequence are uplifted and exhibit gently westward dipping strata. A continuous fault, the Billefjorden Fault Zone (BFZ), delimits the eastern, stable platform from the more complexely deformed subbasins and highs to the west. The *central segment* consists of folded and elongate highs and subbasins bounded by steep faults. Paleocene-Eocene sediments are preserved within the subbasins. A narrow high and related steep faults (Hornsund Fault Zone) mark the transition to the *western segment* which is characterized by a thick Pliocene-Pleistocene sedimentary wedge (Eiken 1994; Grogan et al. 1999).

The structural pattern of the central and eastern segments exhibits several features similar to structural elements observed on land. For example, distinct terraces (basement highs) and basins are observed between the Hornsund Fault Zone and the Edgeøya Platform. These may form offshore analogues to the Lidfjellet-Øyrlandsodden Fold Zone, the Øyrlandet Graben and/or the Central Tertiary Basin, the Sørkapp-Hornsund High, and the fold-thrust belt, respectively (Fig. 10). The interpreted top pre-Devonian basement reflection illustrates this basin and high configuration, and Palaeozoic

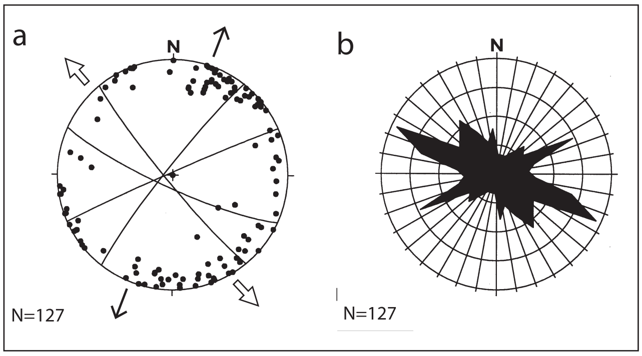


Fig. 7. Structural data from the Sørkapp-Hornsund High at Kistefjellet and Keilhaufjellet (locality 4). (a) Poles to normal and strike-slip faults, with average orientations shown as great circles. Arrows indicate the local extensional direction for the oldest fault set (open arrow) and youngest fault set (single arrows). (b) Rose diagram showing strike direction frequencies of the faults in a.

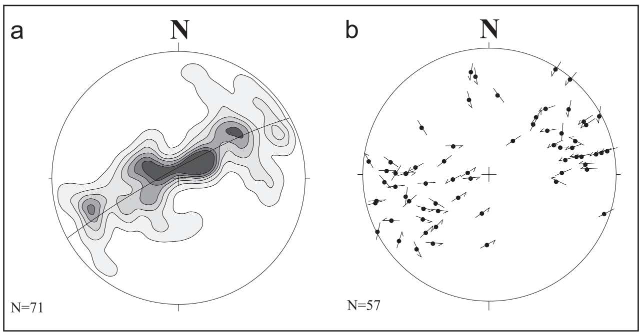


Fig. 9. Structural data from the Hyrnefjellet Anticline and adjacent area of Inner Hornsund (locality 5). (a) Contoured poles to folded bedding and statistically estimated average great circle and βaxis. (b) Mesoscopic normal faults exposed along the shore of Inner Hornsund and in the eastern limb of the Hyrnefjellet Anticline, plotted as slip-linear fault data (Goldstein & Marshak 1988).

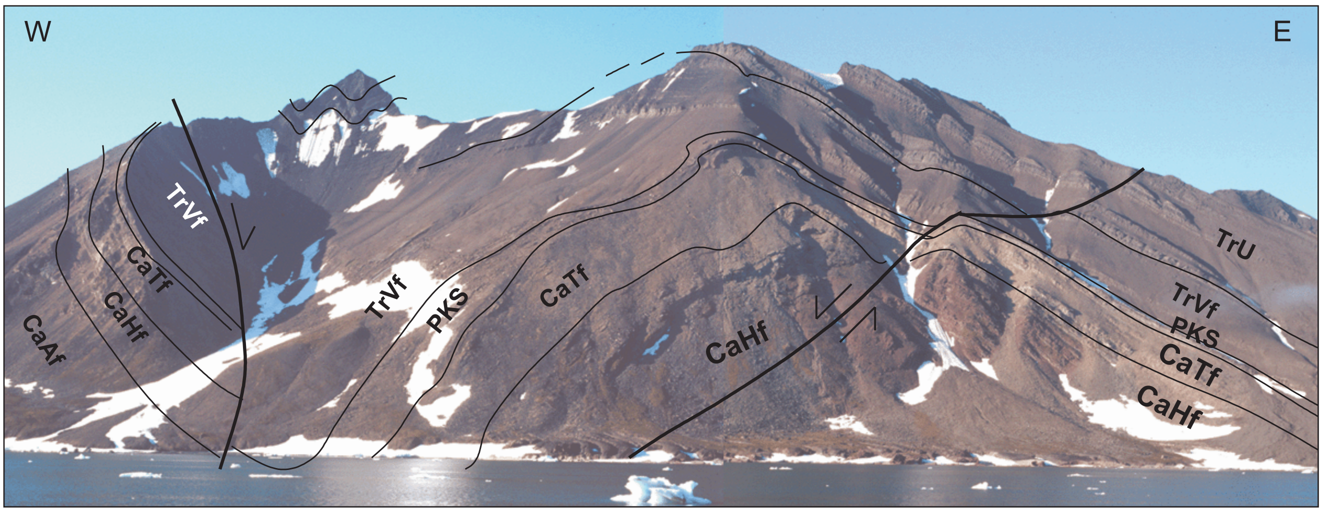


Fig. 8: The Hyrnefjellet Anticline and related syncline at Inner Hornsund (locality 5 of figure 2), viewed from the southwest. CaAf = Carboniferous Adriabukta Formation, CaHf = Carboniferous Hyrnefjellet Formation, CaTf = Carboniferous Treskelodden Formation, PKs = Permian Kapp Starostin Formation, TrVf = Triassic Vardebukta Formation, TrU = Triassic undifferentiated. Note two normal faults superimposed on the folds.

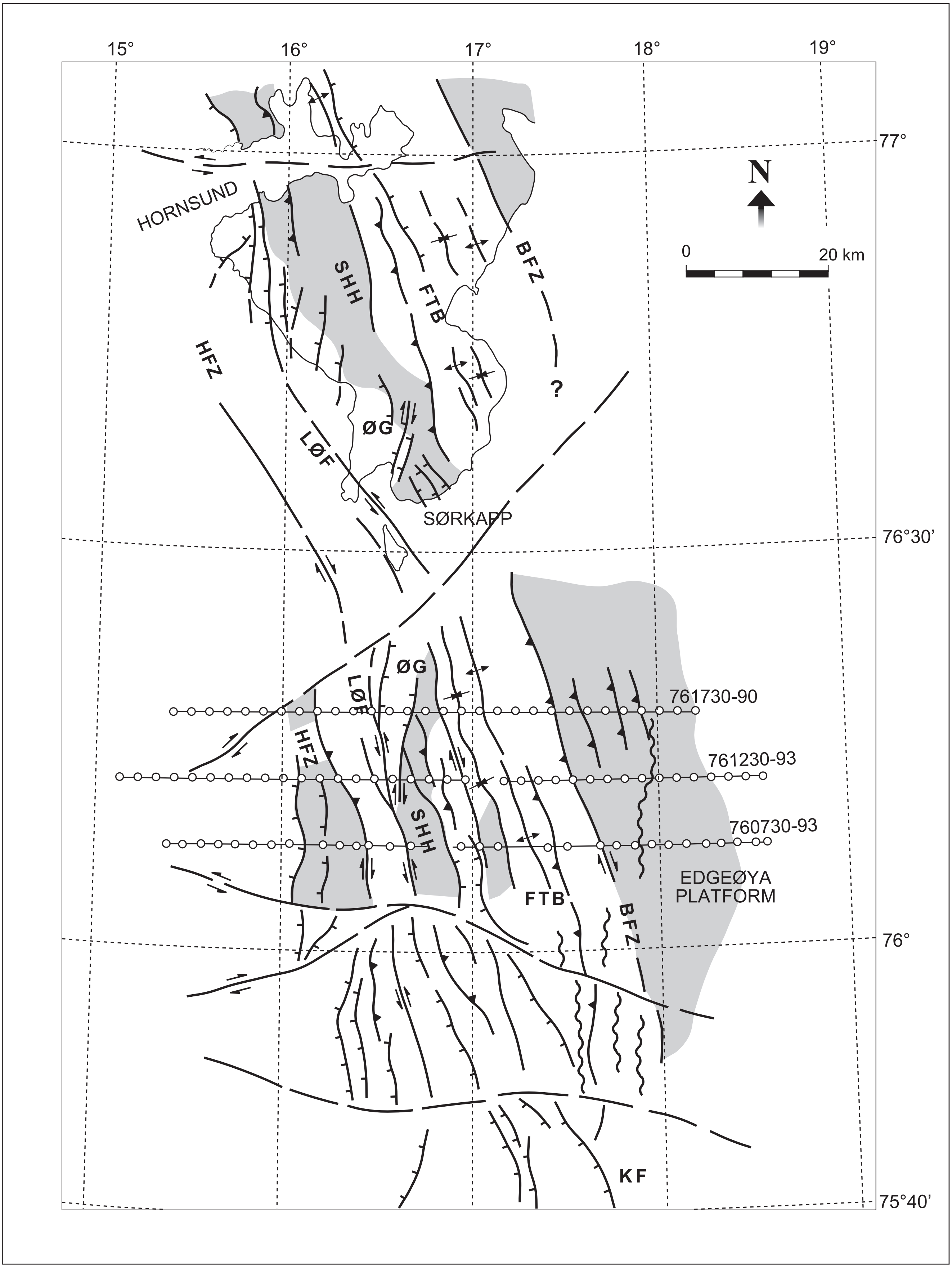


Fig. 10. Compiled structural interpretation map of the Sørkapp-Hornsund Region and the offshore Barents Shelf region (Nordflaket) south to 75°40'N. Shaded areas indicate basement highs/ridges. The map is constructed using Norwegian Petroleum Directorate's (NPD-1993) migrated and stacked reflection seismic data, and Grogan (1994).

strata exhibit conspicuous thickness variations (Fig. 11). For example, the units are thickest in the basins but absent on the highs, where Mesozoic (i.e. Triassic) units are interpreted to lie directly on basement.

A pattern of discontinuous, wavy, gently west-dipping reflections are observed in the central and eastern segments, interpreted as thin-skinned fold-thrust belt structures developed above reverse imbricate faults and possible thrust detachments. Local thickness changes are observed in the presumed Triassic through Cretaceous sequence and may be a result of early layer-parallel thrust repetitions. The thin-skinned faults are rooted to the west in several steep, basement-involved faults near the Hornsund Fault Zone (Fig. 11), and are themselves cut by steep extensional and possibly strike-slip faults that delimit the present day basement highs and basin margins. Two different fault sets can be distinguished. The first of these delimits and merges downwards into the deeper Palaeozoic basins, and thus may have been influential in the inversion of these basins. The second set consistently truncates all other structural features regardless of their position.

The structural features encountered on land cannot precisely be correlated along strike to the south, but appear to display a significant dextral offset, that may be due to late movement along an oblique ENE striking lateral ramp or transfer fault (Fig. 10). South of 75°50'N the margin exhibits a faulted basin geometry that for the most part reflects phases of extension related to rifting events since the Cretaceous (Grogan 1994; Grogan et al. 1999). This part of the margin is also further divided into provinces separated by W- to WNW-trending lineaments that appear to exhibit a marked sinistral offset of the pre-existing contractional structures (Grogan 1994). The eastern margin of these provinces and associated subbasins are bounded by the NNW-striking Knølegga Fault (Figs. 1 and 10), which also forms the western boundary of the Stappen High (Gabrielsen et al 1990; Grogan et al. 1999).

Regional structure and kinematic interpretation

Our field and seismic data presented above provide new information as a basis for a revised kinematic interpretation of the regional Tertiary structures in the Sørkapp-Hornsund area and on the continental shelf south of Sørkapp. The following regional observations are critical to the detailed determination of a coherent kinematic model:

1. The *Lidfjellet-Øyrlandsodden Fold Zone* comprises macroscopic NNW-trending folds superimposed by ENE-, N- to NE-, and NNW-striking steep faults. Mesoscopic fault data indicate formation during shortening followed by dextral and sinistral transtensions (Fig. 4), respectively. The youngest, dominantly sinistral, faults define a macroscopic strike-slip duplex geometry.

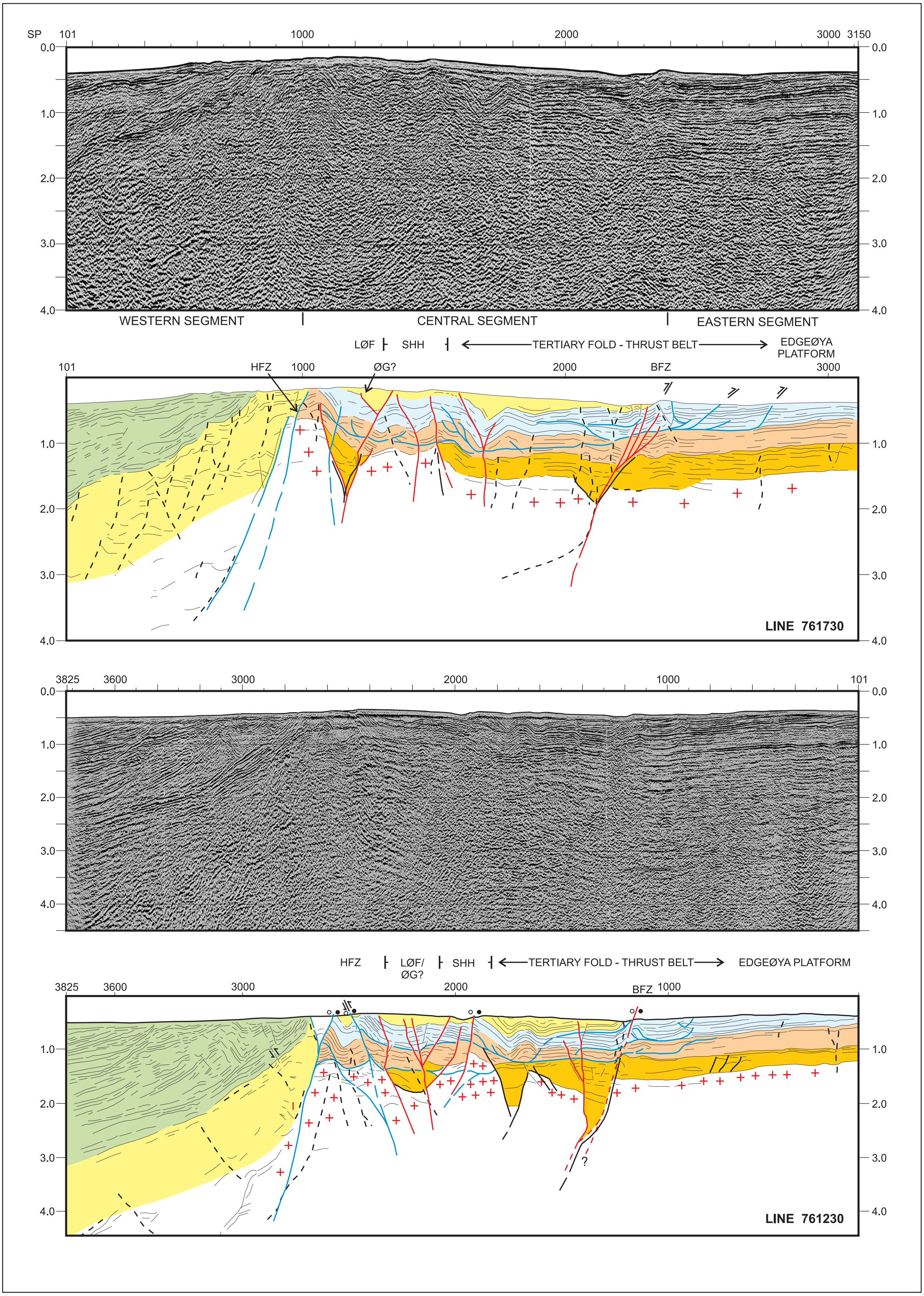
2. The *Øyrlandet Graben* is bounded to the west by a possible NNW-striking strike-slip fault, and to the east by a NNE-striking normal fault. The graben axis is dextrally oblique to the Lidfjellet-Øyrlandsodden Fold Zone, Sørkapp-Hornsund High, and the fold-thrust belt. Paleocene and younger strata within the graben are tilted gently to the south. Both the basement, Triassic and Tertiary strata adjacent to the eastern bounding fault are cut by mesoscopic N to NNE-striking normal faults, and additionally superimposed by N-S-striking normal faults and NW-striking sinistral strike-slip faults, suggesting a faulting episode involving E-W extension followed by sinistral transtension.

3. The *Sørkapp-Hornsund High* at Kistefjellet-Keilhaufjellet is a south-plunging basement structure truncated by the Øyrlandet Graben and related NNE-striking normal faults in the west. The central and eastern parts of the high are cut by younger, rectilinear, NNE- and NW-striking normal and strike-slip faults. To the east, a major south/southeast-dipping monocline is present in overlying Triassic-Cretaceous strata and projects into the fold-thrust belt. This monocline, together with the fold-thrust belt structures to the east, displays a notable sinistral bend southwards in map view, from N to NW strike (Fig. 2).

4. The *Tertiary fold-thrust belt* at Sørkapp is exemplified by the regional, south/southeast-dipping monocline at Keilhaufjellet and the broad, NNW-trending open folds and thin-skinned thrusts further east. Along strike northwards to Hornsund, the monocline is replaced by major, ENE-verging basement-involved folds (e.g. Hyrnefjellet Anticline) and thrusts, and superimposed by normal faults (Eastern Hornsund Fault).

5. Seismic data to the south of Sørkapp indicate continuation of the main tectonic features observed on land, e.g. basement highs correlative to the Sørkapp-Hornsund High, and deep Carboniferous basins bounding the High. In addition, convincing thin-skinned fold-thrust structures and detachments are observed in Triassic through Cretaceous and Tertiary strata, that are rooted against the basement-involved Hornsund Fault Zone to the west. Paleocene-Eocene strata are preserved locally in depressions bounded by fold-thrust belt structures. Younger, steep extensional and strike-slip faults cut all other structures and delimit the basement highs and Palaeozoic basin margins, in particular.

6. The Tertiary features of Spitsbergen and those on the shelf south of Sørkapp are transected by NE- and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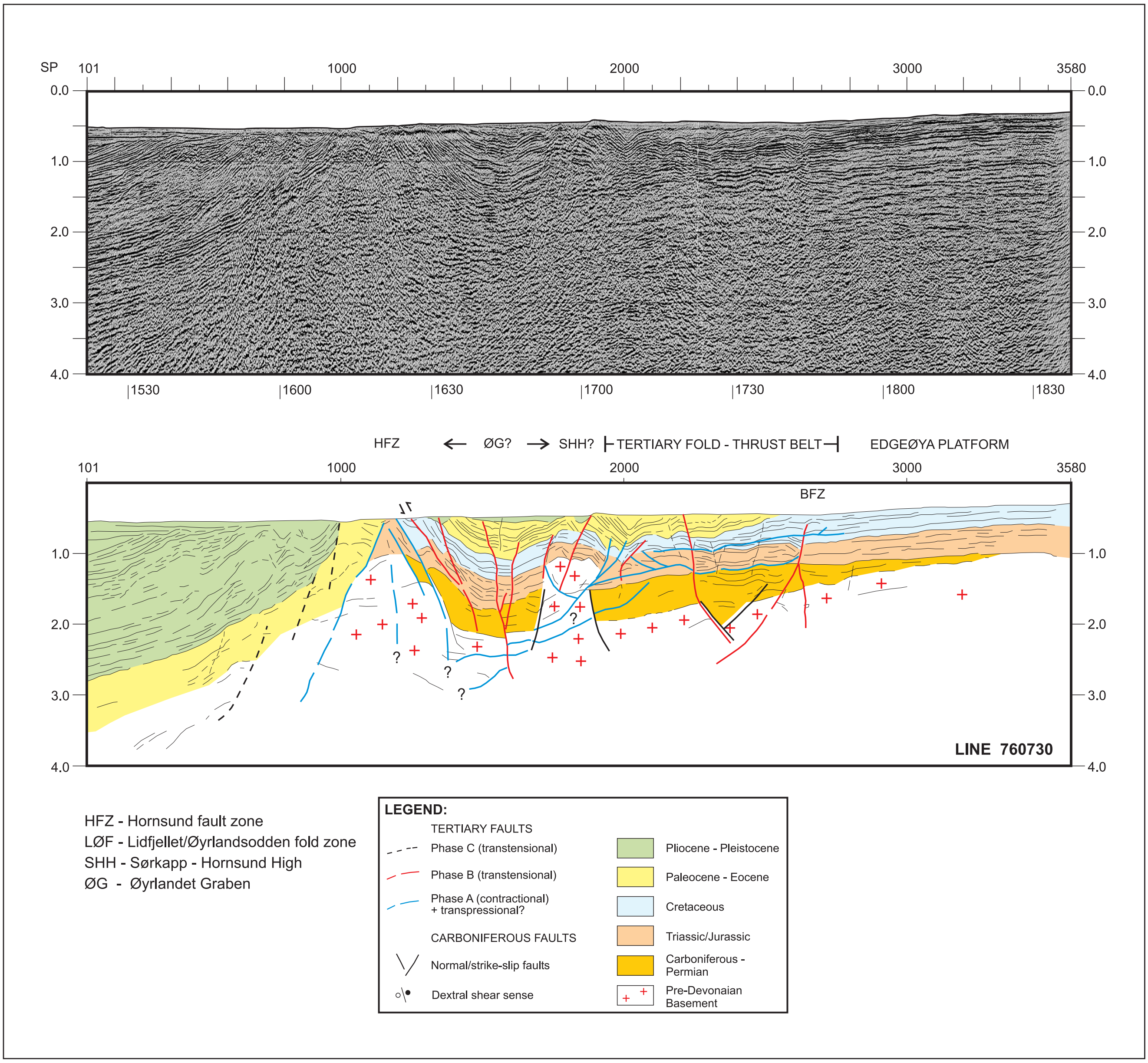

Fig. 11. Migrated and stacked seismic lines 761730, 761230 and 760730 (NPD-1993) with interpretations, illustrating the main structural features, faulting events and interpreted correlation of onshore and offshore structural provinces. See figure 10 for location of the lines.

WNW-trending lineaments. These are most probably late transfer fault zones that exhibit both dextral and sinistral offsets.

7. The western margin of the offshore continental shelf is underlain by a thick Pliocene-Pleistocene sedimentary wedge.

Kinematic model

Consistent cross-cutting relationships and kinematic characters observed among the various structures observed on land and offshore seismic data support a coherent model for the tectonic history of the Sørkapp-Hornsund region and offshore areas during the Tertiary. We propose the following kinematic history:

Phase A: An initial WSW-ENE directed contraction (Fig. 12a) that generated both the Tertiary fold-thrust belt, and the macrofolds of the Lidfjellet-Øyrlandsodden Fold Zone as components of a possible right-stepping or *en echelon* pattern of faults striking NNW subparallel to the offshore Hornsund Fault Zone. This event may have enhanced inversion and uplift of the Sørkapp-Hornsund High as part of an eastward propagating wedge bounded by basement-involved thrusts. These thrusts may have their roots either offshore to the west (Hornsund Fault Zone) and/or along Palaeozoic basin margins (such as the Inner Hornsund Fault and faults at Liddalen). Movements along favoured

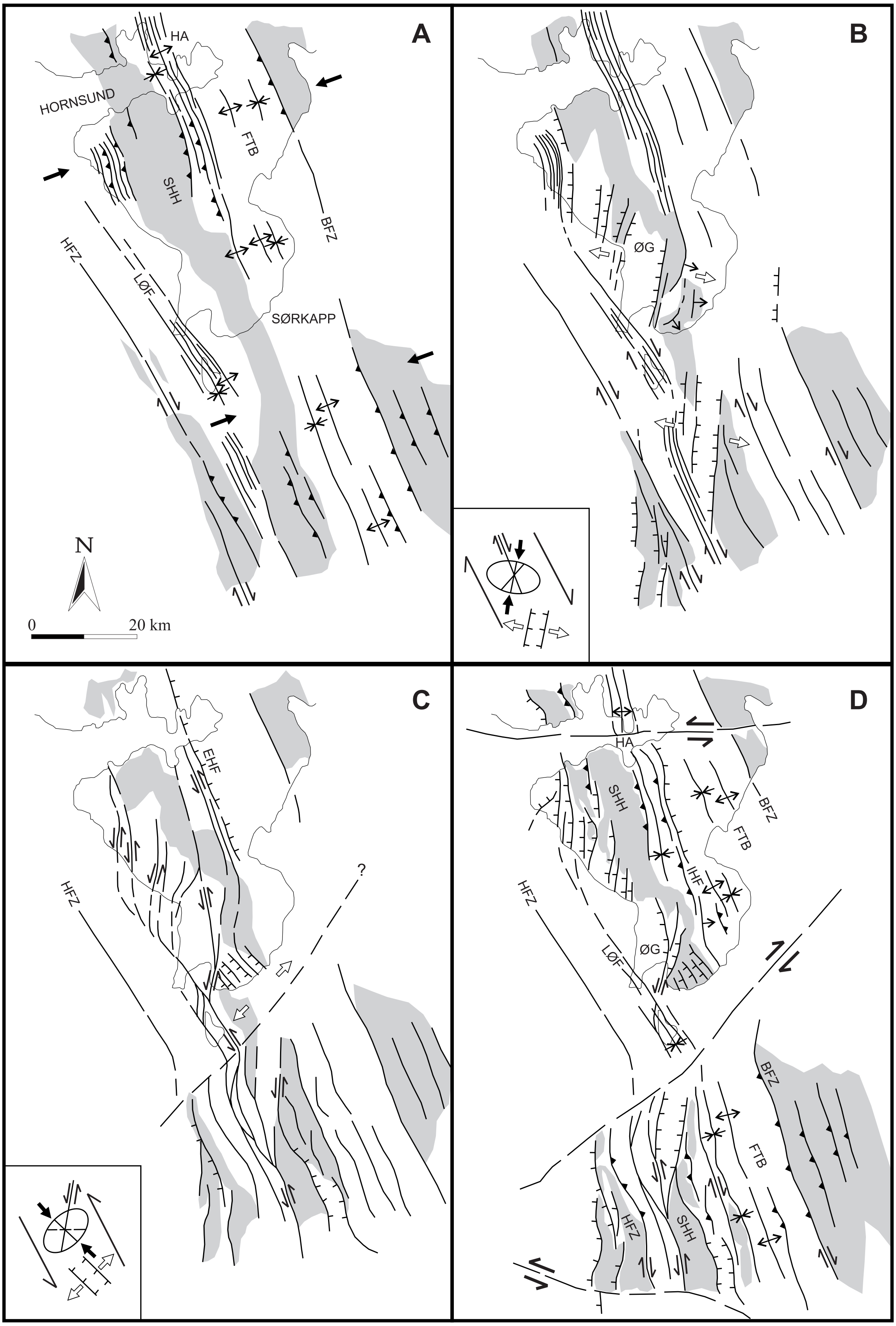

Fig. 12. Tertiary kinematic model for the Sørkapp-Hornsund Region and adjacent shelf to the south. Regional scale strain ellipses, with observed conjugate strike-slip faults and normal faults, and inferred contractional (black arrows) and extensional (open arrows) directions, are drawn for phases B and C. Abbreviations are as in figure 2.

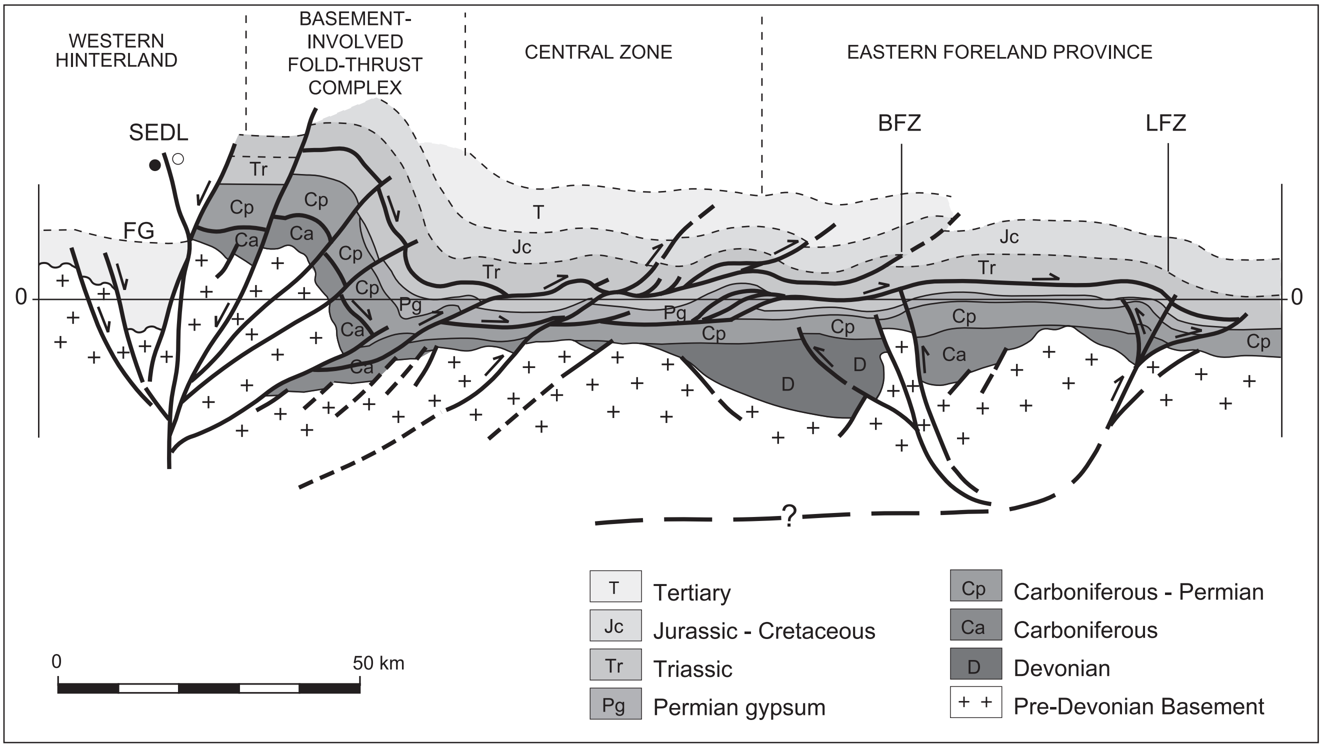

Fig. 13: Generalized west-east cross-section of the Isfjorden transect in central Spitsbergen showing the main Tertiary structural provinces as defined by Bergh et al (1997). See figure 1 for location of the section.

zones of weakness in the pre-Devonian basement may also have facilitated the uplift. The previously established Sørkapp-Hornsund High may have constituted an obstacle to the further eastward transport of fold and thrust units, such that deeper-lying, possibly blind thrusts in the basement or Devonian rocks were reactivated. Thickening occurred to the east until foreland propagation cut beneath and through the High and emerged on its eastern flank (Fig. 2; cross-section).

Phase B: The Øyrlandet Graben formed as part of a regional network of N- to NNE-striking normal faults, possibly in an oblique step-over zone between the two *en echelon* segments of the fold-thrust belt (Fig. 12b). A favourable mechanism for graben formation is by means of decoupled dextral strike-slip movements between the offshore Hornsund Fault Zone (Fig. 1) and the onshore Lidfjellet-Øyrlandsodden Fold Zone (Fig. 2), creating oblique NNE-striking fault-bounded basins in the transition zones between them (Fig. 12b). The main fabric of the fold-thrust belt and Sørkapp-Hornsund High underwent dextral refolding, perhaps also with local oblique offset towards the presumed regional NNW-striking strike-slip fault(s) of the region (Fig. 12b). Coevally, the overlying Triassic and younger strata were flexured and tilted towards the southeast, creating a SE-dipping monocline.

Phase C: Contemporanous with, or subsequent to, flexuring/tilting of the cover strata the Lidfjellet-Øyrlandsodden Fold Zone and the margins of the Sørkapp-Hornsund High (Fig. 12c) were subjected to sinistral transtension and strike-slip duplexing. In addition, the older normal and dextral strike-slip faults, together with segments of the fold-thrust belt were reactivated by sinistral movements and cut locally by younger, NNW- to NW-striking normal faults (e.g. Eastern Hornsund Fault).

Phase D: The main structures of the Sørkapp-Hornsund region, including the offshore, were laterally offset and segmented along ENE- and WNW-striking faults, possibly lateral ramps or transfer fault zones. The local flexuring and reorientation of strata of the Sørkapp-Hornsund High at Kistefjellet-Keilhaufjellet may be the result of such transfer faulting offshore to the south (Fig. 12d).

Discussion

Our proposed kinematic model may be evaluated and compared with those published for the evolution of southern and central Spitsbergen, respectively. Firstly, previous workers in southern Spitsbergen have favoured contraction and local decoupling and transpression followed by extension (Birkenmajer 1964, 1972; Dallmann 1992; Dallmann et al. 1993b; Winsnes et al. 1993). In general terms, our data from the study from Sørkapp-Hornsund fit into the model of Dallmann

(1992), but provide additional details regarding the spatial and temporal development of both onshore and offshore, Tertiary structures.

Secondly, models involving both transpression and transtension have been proposed since Harland (1972) and Lowell (1972) for central Spitsbergen, and a model of structural decoupling has been prevalent until recently (e.g. Maher & Craddock 1988; Faleide et al. 1988; Braathen et al. 1999a). Furthermore, the decoupling model has been verified and evaluated by new structural data and interpretations from central Spitsbergen (e.g. Braathen et al. 1995; Braathen & Bergh 1995; Maher et al. 1995, 1997; Teyssier et al. 1995; Bergh et al. 1997, 1998; Braathen et al. 1999a,b; Bergh et al. 2000), and a sequence of multiple Tertiary events is proposed. These events include: Paleocene transpression (stage 1), Late Paleocene/Eocene contraction (stage 2) and dextral transpression (stage 3), Late Eocene sinistral transtension and oblique transfer faulting (stage 4) and Oligocene-Miocene late/post-orogenic extension (stage 5). Our proposed *phase A* at Sørkapp-Hornsund may be correlated with the Late Paleocene-Eocene contraction (stage 2), *phase B* with the dextral transpression (stage 3), and *phases C* and *D* with the Late Eocene sinistral transtension and transfer faulting, respectively, of stage 4.

This chronological link between the Sørkapp-Hornsund region and central Spitsbergen can also be verified by the similarity between structural elements. In central Spitsbergen, Tertiary deformation is expressed as a composite, 100-200 km wide zone (Fig. 13) comprising: (i) a western hinterland of combined contractional and strike-slip structures, (ii) a central basement-involved fold-thrust complex, (iii) a thin-skinned fold-thrust belt, and (iv) an eastern foreland province (Braathen et al. 1999a). Importantly, and by comparison with southern Spitsbergen, the western hinterland (Fig. 3) comprises a major basement uplift thrust complex and an adjoining steep contractional-transcurrent fault zone to the west, the Svartfjella-Eidembukta-Daudmannsodden Lineament (SEDL; Figs. 1 and 13, Maher et al. 1997), and the Forlandsundet Graben, a presumed transtensional basin (Steel et al. 1985; Gabrielsen et al. 1992).

We propose a spatial correlation of the Lidfjellet-Øyrlandsodden Fold Zone at Sørkapp with the SEDL, and between the Øyrlandet Graben and the Forlandsundet Graben (Fig. 1) for the following reasons: Firstly, the SEDL is up to 3 km wide and contains Carboniferous-Permian strata deformed by large-scale folds which are themselves superimposed by steep dextral and sinistral strike-slip faults (Maher et al. 1997). Secondly, a west-side down component on the SEDL is consistent with coeval formation of the adjacent Forlandsundet graben as a local transtensive feature (Braathen et al. 1999a).

The age of deposition of the Øyrlandet Graben sediments and their relation to the Central Tertiary Basin (Fig. 1) can be further evaluated. An earlier model is that the Øyrlandet Graben was a product of passive margin development in the Oligocene, and thus reflected a purely post-orogenic extensional phase (Eiken & Austegard 1987). However, a pre-Oligocene development of the Øyrlandet Graben, most probably at a late stage of the main contractional event (i.e. synorogenic) is proposed here because the Graben both contains Paleocene through Eocene strata (Dallmann et al. 1993b) and is bounded by younger normal faults *(phase B)* and sinistral strike-slip faults *(phase C)*. In addition, these relationships imply that Paleocene sedimentation within the Graben began adjacent to the uplifted fold-thrust belt and continued under the development of a strike-slip graben and local, syntectonic subsidence, and possibly as a result of decoupled deformation. This model is supported by the observation that the various Tertiary structures (compressional, strike-slip and extensional) seem to overlap spatially and chronologically in different rocks on each side of the fault margin. If the Øyrlandet Graben evolved as an oblique, strike-slip basin situated between the Sørkapp-Hornsund High and the Lidfjellet-Øyrlandsodden Fold Zone, it may provide an onshore analogue and tectonic link to the offshore Hornsund Fault Zone and associated adjacent Tertiary grabens (Fig. 11: Eiken & Austegard 1987), and to the Central Tertiary Basin further north and east (Fig. 1).

Furthermore, lateral partitioning and alternating dextral and sinistral offset patterns, i.e. stage 4 structures, are well documented on Spitsbergen (Figs. 1 and 10). In this respect, the right-stepping transfer zone offshore south of Sørkapp may be a structural analogue to the Isfjorden-Ymerbukta fault zone in central Spitsbergen (Fig. 1: Braathen et al. 1999b), which is interpreted as a dextral thrust ramp that post-dates the main fold-thrust belt structures.

The regional correlation of structures at Sørkapp-Hornsund with other areas of Spitsbergen, and the documented dextral and sinistral strike-slip reactivation of structures in the region, have wider implications in that they emphasize those prerequisites and key processes occurring under decoupled or partitioned deformation along transform plate margins (Maher & Craddock 1988; Braathen et al. 1999a). One such requirement for reactivated strike-slip motion in a contractional system is the presence of steeply dipping zones of weakness where strike-slip motion can be localized. Examples of such motion from the Sørkapp-Hornsund region include uplift of the Sørkapp-Hornsund High, particularly in the west, which may have been facilitated by favourably oriented steep bedding and shear zones in the pre-Devonian basement, pre-existing (Carboniferous) block and basin boundaries, and the steep limbs of macrofolds. All these requirements are satisfied in the Sørkapp-Hornsund Region and are also inferred from the seismic data offshore (Fig. 11: line 761230). For example, on the shelf, the significance of Carboniferous basin margins as the locations for facilitating Tertiary deformation is supported by the geographic coincidence of Carboniferous and Tertiary basins. This relationship is also documented in central Spitsbergen, where Tertiary reverse faults are developed along Palaeozoic normal faults bounding Carboniferous half-graben basins, e.g. St. Jonsfjorden and Nordenskioldland (Maher & Welbon 1992; Welbon & Maher 1992, Braathen et al. 1995). Other examples are found along the Billefjorden and Lomfjorden Faults in northeastern Spitsbergen (Andresen et al. 1994; Haremo & Andresen 1992; Bergh et al. 1994).

Finally, a regional characteristic of the Tertiary deformation pattern offshore south of Sørkapp is that the zones dominated by contractional structures (i.e. the fold-thrust belt and Sørkapp-Hornsund High) are broad, i.e. tens of kilometres, whereas the strike-slip fault zones bounding the transpressional (Lidfjellet-Øyrlandsodden Fold Zone) and transtensional structures or grabens (e.g. Øyrlandet Graben) on Spitsbergen are narrow (i.e. less than 5 kilometres). One explanation for this is that the compressive component resulted in deformation within broad, pre-existing basement ridges or crustal basins, such as the Sørkapp-Hornsund High and adjacent Palaeozoic basins, whereas the extensional and strike-slip components were restricted to the ridge and basin margins.

The results from this study support the model of regional scale decoupling for the Tertiary deformation on Svalbard and the adjacent Barents Shelf. In the light of a decoupling deformation model, similar processes may have influenced uplift and lateral segmentation of the Edgeøya Platform along the Knølegga Fault, and also at the margins of the Stappen High further south (Fig. 1).

Acknowledgements. - Field work for this project was made possible through participation (S.Bergh) on the Norwegian Petroleum Directorate's expedition to the Sørkapp-Hornsund area in 1995. Geologists from Statoil, Norsk Hydro, Saga Petroleum, the Universities of Bergen and Oslo are thanked for their participation in the field and for many fruitful discussions. We thank the Norwegian Petroleum Directorate for permission to publish seismic data from the Nordflaket area. Winfried Dallmann, Harmon Maher and Erik Lundin are thanked for their constructive reviews.

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