Multiphase tectonic evolution of the Sørkapp–Hornsund mobile zone (Devonian, Carboniferous, Tertiary), Svalbard

WINFRIED K. DALLMANN

Dallmann, W. K.: Multiphase tectonic evolution of the Sørkapp–Hornsund mobile zone (Devonian, Carboniferous, Tertiary), Svalbard. *Norsk Geologisk Tidsskrift*, Vol. 72, pp. 49–66. Oslo 1992. ISSN 0029-196X.

The structure of the post-Caledonian strata within the West Spitsbergen Fold Belt is dominated by a Palaeogene compressive tectonic event, though earlier deformation also is documented. The Sørkapp–Hornsund area shows abundant evidence for the nature and the relative ages of these events. A multiphase tectonic history can be devised with implications for the post-Caledonian tectonic history of Svalbard.

1. Post-Caledonian basin formation (Devonian), faulting and considerable uplift at the end of the Devonian. The so-called 'Svalbardian Phase' of folding cannot be seen in the Sørkapp–Hornsund area.
2. Folding and thrusting along a NNW–SSE trending belt within the area of the former Devonian basin during the Early (or Mid-) Carboniferous, the so-called 'Adriabukta Phase'.
3. Synsedimentary faulting during the Middle Carboniferous, and the establishment of the Sørkapp–Hornsund High, which remained a land area until the earliest Triassic.
4. Compressive reactivation of the same mobile zone during the Palaeocene/Eocene with formation of a complex thrust system leading to a crustal shortening of minimum 8 km across the Hornsund area. Deformation presumably dies out towards the south, but is taken over by another fold–thrust zone offshore to the west.
5. Subsequent faulting along with the opening of the Atlantic/Arctic Oceans produced the dominating structures of the present setting.

The majority of these movements are related to a defined zone of weakness within the basement, here called the 'Sørkapp–Hornsund mobile zone'. It comprises, besides other structures, the previously defined Carboniferous 'Inner Hornsund Fault Zone' and the southern part of the 'Tertiary fold-and-thrust belt'. This mobile zone is supposed to be one of several long-lived tectonic lineaments that have controlled the tectonic development of Svalbard. The pre-existing orientations of these lineaments are thought to be responsible for apparent disagreements between regional stress fields and modes of deformation.

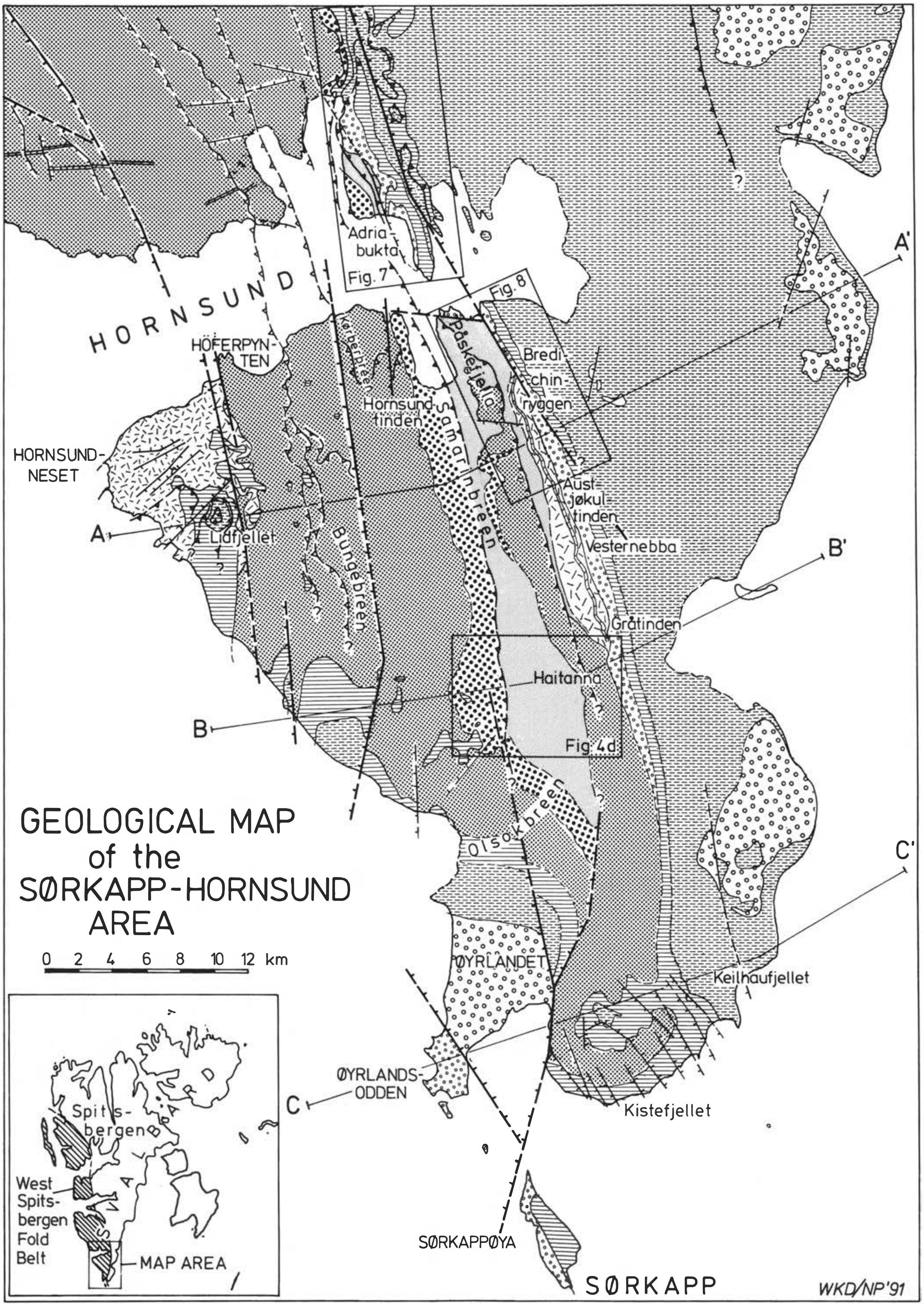
W. K. Dallmann, Norsk Polarinstitutt, P.O.B. 158, N-1330 Oslo Lufthavn, Norway.

The West Spitsbergen Fold Belt has been known since early this century (De Geer 1909, 1912, 1919; Holtedahl 1913; Hoel 1925; Orvin 1934). Frebold (1935) and Orvin (1940) have presented summaries of the fold-belt structures. It was believed that deformation was mainly of Tertiary age – as Tertiary strata locally are involved – overprinting pervasive Caledonian deformation in the pre-Devonian basement.

Since the recognition of plate tectonics, Svalbard has been considered to be part of a transform zone during the Palaeogene opening of the North Atlantic and Arctic Oceans. The Tertiary part of the fold belt (referred to as the Tertiary fold-and-thrust belt) has been ascribed to relative movements between the Barents and Greenland Shelves, and it has been considered to be a 'typical' strike-slip or transpressive orogen (Harland 1969, Harland & Horsfield 1974, Lowell 1972, Birkenmajer 1972a, b, Kellogg 1975). Recent structural investigations, however, show that the Tertiary folding and thrusting particularly must be ascribed to convergent tectonics (Maher et al. 1986; Bergh et al. 1988; Dallmann 1988; Maher 1988; Nøttvedt et al. 1988; Dallmann & Maher 1989; Bergh & Andresen 1990; Haremo et al. 1990), though there is no doubt about its setting in or close to a major transform zone.

In order to understand the fold-belt kinematics, it is essential to consider also the long history of events that took place between the Caledonian Orogeny and the Tertiary. Several deformation episodes are known from Svalbard, particularly from the Late Palaeozoic.

Extensive faulting during the Late Devonian ('Svalbardian movements') is responsible for the preservation of the Devonian graben of northern Spitsbergen and its continuation below the younger cover strata of central Spitsbergen (Orvin 1940). Beside Late Devonian faulting and graben formation, folding of Late Devonian age also has been described, by Vogt (1928), Schenck (1937) and Orvin (1940). The folding was ascribed to horizontal forces and assumed to be coeval with the Bretonian phase of the Variscan Orogeny (Orvin 1940). This age is based on an angular unconformity on Bjørnøya, where a continuous Devonian to Carboniferous stratigraphy is exposed (Vogt 1928). After the plate-tectonic revolution in geology, the Devonian movements also were ascribed to transcurrence, accommodated by major N–S trending faults running through Spitsbergen and separating ap-


HORNSUND
Adria-
bukta
Fig. 7
Fig. 8
HÖFERPYN-
TEN
Påskefjella
Bredi-
chin-
ryggen
Hornsund-
tinden
Samarinbreen
HORNSUND-
NESET
Aust-
jøkul-
tinden
Vesternebba
A
A'
Lidfjellet
Bungebreen
B'
Gråtinden
Haitanna
B
Fig 4d
Olsokbreen
GEOLOGICAL MAP
of the
SØRKAPP-HORNSUND
AREA
0 2 4 6 8 10 12 km
C'
ØYRLANDET
Keilhaufjellet
ØYRLANDS-
ODDEN
C
Kistefjellet
Spitsbergen
SVALBARD
West
Spits-
bergen
Fold
Belt
MAP AREA
SØRKAPPØYA
SØRKAPP
WKD/NP'91

proximately the Laurentian from the Baltoscandian part of the Old Red Continent (Harland 1971, 1972; Friend & Moody-Stuart 1972; Harland et al. 1974), though evidence for this model is questioned (Lamar et al. 1986).

The Carboniferous strata are characterized by abundant breaks in sedimentation, erosional unconformities and syntectonic sediment facies indicating tectonic instability (Birkenmajer 1964, 1981; Harland 1969; Gjelberg & Steel 1981; Steel & Worsley 1984). Carboniferous folding and thrusting of the 'Adriabukta Phase' has been reported by Birkenmajer (1964, 1975) from the Hornsund area on southern Spitsbergen and correlated with the Mid-Carboniferous Erzgebirge Phase of the Variscan Orogeny.

Significant thickness variations of Permian and Triassic strata (Mørk et al. 1982; Steel & Worsley 1984) indicate that block movements, though less prominent, were going on during these periods.

From this, it can be assumed that the crust underlying the Mesozoic and Tertiary strata was multiply deformed, cut be zones of weakness and laterally very differentiated, before it was affected by the Tertiary transform movement. This fact may be important for understanding the kinematics of the Tertiary fold-and-thrust belt and the apparent contradiction of transcurrence and shortening directions.

In order to document the relations of the Tertiary and older structures, it is necessary to relate all structures to definite episodes of deformation and to recognize possible reactivations. This is difficult in many parts of Svalbard, as age references often are lacking. The Sørkapp–Hornsund area on southern Spitsbergen, which is discussed in the following text, is one of few areas suited for such studies. The present work is restricted to the post-Caledonian tectonic development, though also Caledonian and older structures may have a significant influence on the problem.

The Sørkapp–Hornsund area—geological overview

A geological overview of the Sørkapp–Hornsund area is given in Fig. 1. From west to east, the area is subdivided into three main tectonic regions: (1) a basement high in the west, (2) a fold-and-thrust belt in the centre and (3) a foreland basin in the east.

Western basement high

The western basement high consists of medium-grade to slightly metamorphic rocks of Precambarian to Ordovician age folded and thrust during the Caledonian Orogeny (Smulikowski 1965; Birkenmajer 1972b, 1978a, b).

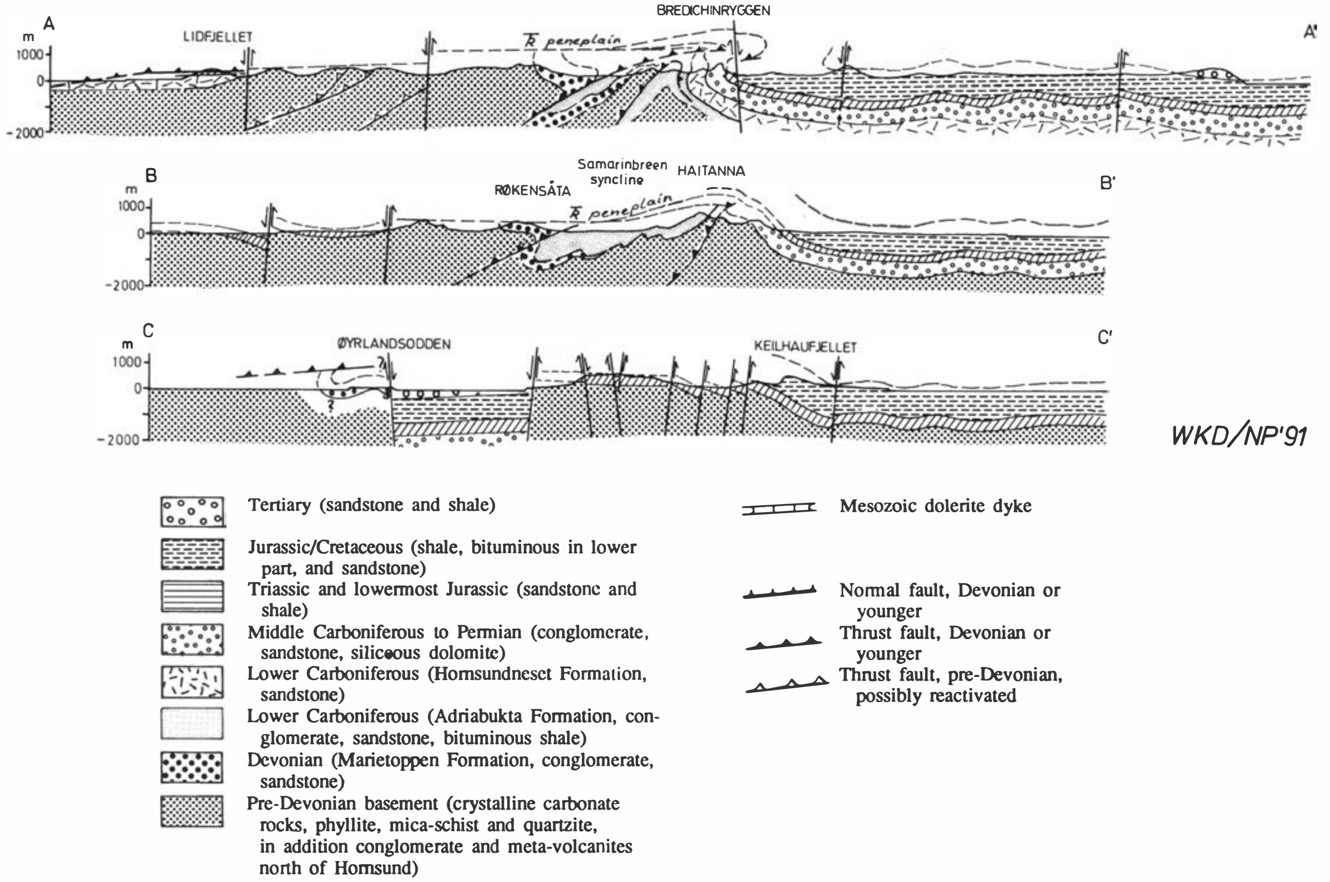


Fig. 1. Geological map and cross-sections, Sørkapp–Hornsund area, southern Spitsbergen, Svalbard. The entire land area south of Hornsund is called 'Sørkapp Land'. Generalized after Winsnes et al. (in press and Ohta & Dallmann (1991)).

South of Hornsund these are overlain by unfolded Lower Carboniferous (sandstones of the Hornsundneset Formation) and Triassic strata (several sandstone and shale formations), both with angular unconformities at their bases and between them. The unconformity between the Carboniferous and Triassic beds attains locally up to c. 10° close to the N–S trending faults (T. S. Winsnes, pers. comm. 1990). The throw exceeds 800 m at the northern part of the Körberbreen–Bungebreen Fault, as is obvious from the elevation difference of the Triassic base (Winsnes et al., in press).

To the south, at Olsokbreen, the sediment cover bends down southward. Triassic strata are overlain by Jurassic through to Tertiary strata, which at Øyrlandet proceed into a blind graben structure, the Øyrlandet Graben, with c. 3000 m downthrow to the east and southwest (Fig. 1, cross-section C).

North of Hornsund, E–W trending Mesozoic dykes can be used as a control on Tertiary deformation. They cross-cut all structures of compressive origin and are displaced only by normal faults (Birkenmajer & Morawski 1960; Birkenmajer 1986; J. Czerny and Y. Ohta pers. comm. 1990). Similar normal faults are known from all over western Spitsbergen and normally are referred to Oligocene extensional tectonics related to the opening of the Norwegian–Greenland Sea (Talwani & Eldholm 1977).

Structures related to convergent tectonics are found only in two places close to the western coast: At Lidfjellet and Sergeijevfjellet (close to Hornsundneset), northeast vergent thrust faults have emplaced Carboniferous on Triassic, and Triassic on Cretaceous strata. At Øyrlandsodden and on Sørkappøya, Permian and Triassic strata form close, partly overturned, northeast-vergent folds. These two features indicate the presence of a Paleogene (or possibly Late Cretaceous) zone of folding and thrusting immediately off the west coast of Sørkapp Land (Figs. 1, 12).

Central fold belt

The central part of Sørkapp Land is the southern continuation of the West Spitsbergen Fold Belt. It is intensely folded and thrust in the Hornsund area, but is gradually less deformed to the south. At the southern end of Sørkapp Land (Keilhaufjellet), a single monocline with a c. 2000 m down-to-east displacement forms the transition from the western basement high to the eastern foreland basin (Fig. 1, cross-sections B, C).

The strongly deformed northern part, however, shows particularly two parallel structural zones. Both of them have a similar east-northeast vergence.

The western part of the fold belt is a syncline, here called the Samarinbreen Syncline, with Devonian (Marietoppen Formation) and lowermost Carboniferous (Adriabukta Formation) clastics in its core. The unconformity surface between Caledonian basement and the respective overlying strata is dipping moderately east to overturned at the western synclinal flank, while it is intensely folded and thrust at the eastern flank (Fig. 1, cross-sections A, B).

The eastern part of the fold belt exposes Carboniferous through to Mesozoic strata (all clastics) forming a huge northeastward overturned fold where the lower limb is continuous with the flank of the eastern foreland basin (Fig. 1, cross-section A; Fig. 8). North of Hornsund, this structure is much more complicated and is discussed later on (illustrated in Figs. 7, 10).

The fold belt is cut by later faults ascribed to Oligocene extensional tectonics. A downthrow of c. 100 m can be observed at Bredichinryggen, though tectonic models discussed later infer much higher values for the area north of Hornsund.

Eastern foreland basin

Cretaceous and Tertiary sandstones and shales form the southern extension of the Central Tertiary Basin of Spitsbergen, which is considered to be the foreland basin of the Tertiary fold-and-thrust belt (Steel et al. 1981). It is deformed by a series of open syn- and antiforms with a subhorizontal enveloping surface, which possibly may be caused by subsurface reverse faults (Orheim et al. 1988) or decollement zones in the sense of Maher (1988). A few younger normal faults also cut parts of this basin, though here they are less prominent than in the areas to the west.

Svalbardian tectonic event (Late Devonian)

Svalbardian (Late Devonian) movements are supposed to have occurred after deposition of the Early to Mid-Devonian molasse sediments (Marietoppen Formation). The youngest Devonian deposits of the Hornsund area are thought to be of Emsian, possibly Eifelian age (dated by marine pelecypods; Birkenmajer 1964). The age of the unconformably overlying Adriabukta Formation is thought to be Visean (by palynomorphs; Birkenmajer & Turnau 1962), though the type area (Adriabukta) where the fossil samples were taken belongs probably only to the upper part of the formation (Meranfjellet and uppermost part of Julhøgda members) as recent mapping has shown (Fig. 8; Winsnes et al., in press).

The boundary between these two formations unfortunately is exposed only in one place, i.e. Adriabukta in Hornsund. No angular unconformity can be seen there. Birkenmajer's (1964) observation of an unconformity at this locality was later corrected by himself (pers. comm. 1990). It is, however, unavoidable to assume a regional angular unconformity at this boundary because the Devonian strata were eroded away in many places prior to the deposition of the Adriabukta Formation (Fig. 2).

Thus, the latter can be observed to unconformably overlie the Precambrian basement east of Samarinbreen and Olsokbreen. In the southern part of Påskefjella, two adjacent ridges each show one of the formations overlying the basement, i.e. the Devonian sediments have to attenuate in between (Figs. 2, 8). This may be explained by an angular unconformity of at least 8° or by faulting prior to the onset of Carboniferous sedimentation. Both alternatives are indicative of tectonic movements at the end of the Devonian period.

There is no further indication of Svalbardian tectonics in the present area. As folding observed within the Devonian strata is related to later events (see next section), it is most reasonable to assume that the angular unconformity is caused by faulting and tilting as proposed by Orvin (1940). There is no control on possible Svalbardian movements outside the area where Devonian strata are exposed.

Adriabukta tectonic event (Early or Mid-Carboniferous)

Birkenmajer (1964, 1975) inferred the 'Adriabukta Phase' on the basis of the following observations at Adriabukta (northern shore of Hornsund): (1) an angular unconformity between the Adriabukta and the overlying Hyrnefjellet Formation; (2) intensive folding of most of the Adriabukta Formation (Fig. 3); (3) thrusting of basement rocks with overlying Adriabukta Formation strata westward onto the Adriabukta Formation overlying Devonian rocks (see Fig. 7).

Recent work on kinematics related to the Tertiary tectonism indicates the possible alternative interpretations of this folding and thrusting as being of Tertiary age (see discussion of 'Tertiary fold-and-thrust belt' and 'strike-slip motion'). There is, however, no doubt about the presence of the angular unconformity. This fact by itself would not ascertain the existence of a folding event, if additional observations had not been made recently along the northeastern end of Olsokbreen, at the nunataks Lebedevfjellet, Røkensåta, Smerudknausen and Eggetoppen (Fig. 4).

The Devonian rocks of this area are tightly folded and unconformably overlain by gently dipping (c. 10°) Triassic strata (Fig. 4a). The folds have an axial trend parallel with the Samarinbreen Syncline (345°; Fig. 11a), tighten eastward and become overturned to the east (Fig. 4b). The easternmost exposure is a nunatak east of Eggetoppen, which surfaced above the glacier recently and therefore is not marked on the published topographic maps. There, probably inverted Adriabukta Formation sandstones and shales occur, dipping westward below the tightly folded Devonian strata and strongly suggesting a thrust contact (Fig. 4c).

These observations indicate that deformation within the Samarinbreen Syncline, and also the formation of the syncline itself, are of pre-Triassic, but post-Visean age. The angular unconformity at Adriabukta indicates an upper limit of Mid-Carboniferous age (Birkenmajer 1964).

Birkenmajer (1964), not having worked to the east of Samarinbreen, suggests that the bituminous sediments of the Adriabukta Formation represent a restricted sedimentary basin that existed contemporaneously with the deposition of the Lower Carboniferous fluvial deposits (Hornsundneset Formation) further west, assuming a basement high between the two depositional areas. Gjelberg & Steel (1981) reinterprete this model assuming that the Hornsundneset Formation, of mainly Namurian age (Siedlecki & Turnau 1964), overlies the Visean (to Namurian?) (Birkenmajer & Turnau 1962) Adriabukta Formation. This seems to be reasonable considering that the sandstones of the Hornsundneset Formation attain c. 1000 m thickness both to the east and to the west of the syncline where the Adriabukta Formation is preserved (Fig. 1). A sedimentary contact or angular unconformity between the two formations, however, has not been documented. The only exposed boundaries are on Bredichinryggen, and they are tectonized.

At Haitanna (Fig. 1, cross-section B), the geometrical relationship of the two angular unconformities (Adriabukta Formation and Hornsundneset Formation, respectively, over Caledonian basement) suggest that the Hornsundneset Formation also unconformably overlies the Samarinbreen Syncline. The age of the Adriabukta tectonic event would thus be further constrained to the Lower Namurian (coeval with the Sudetian Phase of the Variscan Orogeny, and not the Erzgebirge Phase as suggested by Birkenmajer, 1964). As the competent strata of the Hornsundneset Formation may have been affected less by this event, this is still speculative. Also, the similar age of the base of the Hornsundneset Formation east of Samarinbreen should be controlled.

The total extent of the area originally affected by the Adriabukta event is unknown. The trend of the deformed zone, however, is indicated by the trend of the syncline and the fold vergences. The presence of the Samarinbreen Syncline itself and of thrust fault(s) within it indicates that strain was concentrated along the Samarinbreen Syncline, though there may have been other similar zones to the east or west which are not exposed.

Block faulting through the Carboniferous

As mentioned above, tectonic instability with block faulting has been discussed by many authors (e.g. Orvin 1940; Birkenmajer 1964, 1981; Harland 1969; Gjelberg & Steel 1981; Steel & Worsley 1984). The N–S trending faults within the western basement high cross-cut the unconformably overlying Carboniferous and Triassic strata (Fig. 1), and the relative downthrow of the Carboniferous base is in many cases larger than that of the Triassic base; faults within the Carboniferous may even be overlain by undeformed Triassic strata (T. Winsnes pers. comm. 1990). Though the age of these

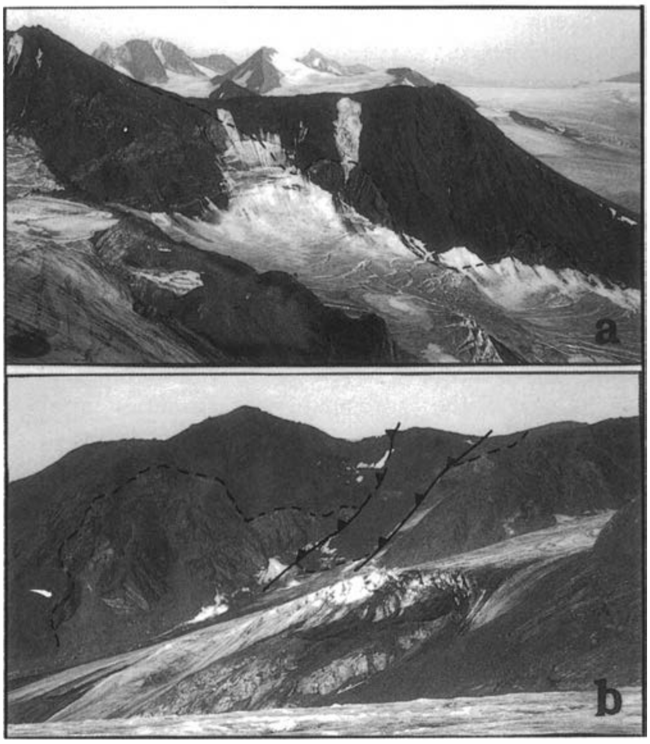


Fig. 2. Unconformities above pre-Devonian basement. (a) Folded Devonian unconformity at Tverraksla, seen from Pinsetoppen (Fig. 8), Marietoppen Formation above Proterozoic mica schists and quartzites. (b) Folded and thrust Early Carboniferous unconformity at Pinsetoppen, seen from Tverraksla (Fig. 8), Adriabukta Formation above Proterozoic mica schists and quartzites. Devonian strata is lacking.

post-sedimentary faults cannot directly be constrained closer than to post-Namurian and pre-Triassic, the implication of the general tectonic development of Svalbard (Steel & Worsley 1984) suggests mainly Middle Carboniferous ages.

Within the strata of the fold belt, none of the faults observed can be ascribed unequivocally to Carboniferous or, generally, Late Palaeozoic age. The sedimentary facies of the Carboniferous strata and their lateral distribution (Fig. 5) however, contain indications that the fold belt also has been subjected to synsedimentary faulting during the Carboniferous and, to a minor extent, the Permian:

Fig. 3. Upright tight folds in Adriabukta Formation, Adriabukta (Fig. 7).

1. At the base of the Adriabukta Formation, a conglomerate c. 450 m thick, the Haitanna member (Winsnes et al., in press; Fig. 5), is exposed at the mountain Haitanna (Figs. 1, 4d). This conglomerate is texturally and compositionally immature and clast-supported, with clasts derived from the underlying basement (Fig. 6). Finer grained, but otherwise identical conglomerates form thin layers interbedded with sandstones at higher stratigraphic levels (extending northward to Hornsund) and leave no doubt that the Haitanna member forms part of the sedimentary cycle of the Adriabukta Formation. The local appearance of this thick and very proximal delta or alluvial fan facies suggests that the assumed boundary fault of the sedimentary graben of the Adriabukta Formation (Steel & Worsley 1984) was active during sedimentation and is situated close to Haitanna, i.e. within the present fold belt.
2. The thickness of the Namurian Hornsundneset Formation varies from 0 to over 1000 m at a distance of 8000 m on Bredichinryggen (Fig. 5; Winsnes et al., in press). The stratigraphy within this formation has not been studied in detail, but no facies pattern is known that could justify the interpretation of thickness variation by differential basin subsidence. It is more appropriate to assume post-depositional faulting in Late- or post-Namurian times, which led to the erosion of the Hornsundneset Formation in many areas.
3. The Bladegga conglomerate (Figs. 5, 8), a local facies variation of the Middle Carboniferous Hyrnefjellet Formation, has been interpreted as an alluvial fan facies related to an active basin margin, the Inner Hornsund Fault Zone (Gjelberg & Steel 1981). This situation is very similar to that at Haitanna. The Hyrnefjellet Formation was rapidly deposited (Birkenmajer 1964; Siedlecka 1968) and contains mainly pebbles from the Devonian strata and the underlying basement (Birkenmajer 1984). Birkenmajer also determined the main transport direction to be towards the east-northeast, which is consistent with Gjelberg & Steel's (1981) suggestion that the Inner Hornsund Fault Zone parallels the fold belt.
4. The local cut-out of the Late Carboniferous/Lower Permian Treskelodden Formation at Bautaen (Figs. 5, 8) may indicate that minor fault activity continued even into Permian times.
5. The total lack of post-Namurian through Permian strata all over the area west of the fold belt led Steel & Worsley (1984) to the assumption that this area was a structural high, the Sørkapp–Hornsund High, a land area forming the source for most of the Middle Carboniferous graben sediments. The Inner Hornsund Fault Zone is supposed to be the boundary between the high to the west and the basin to the east. The

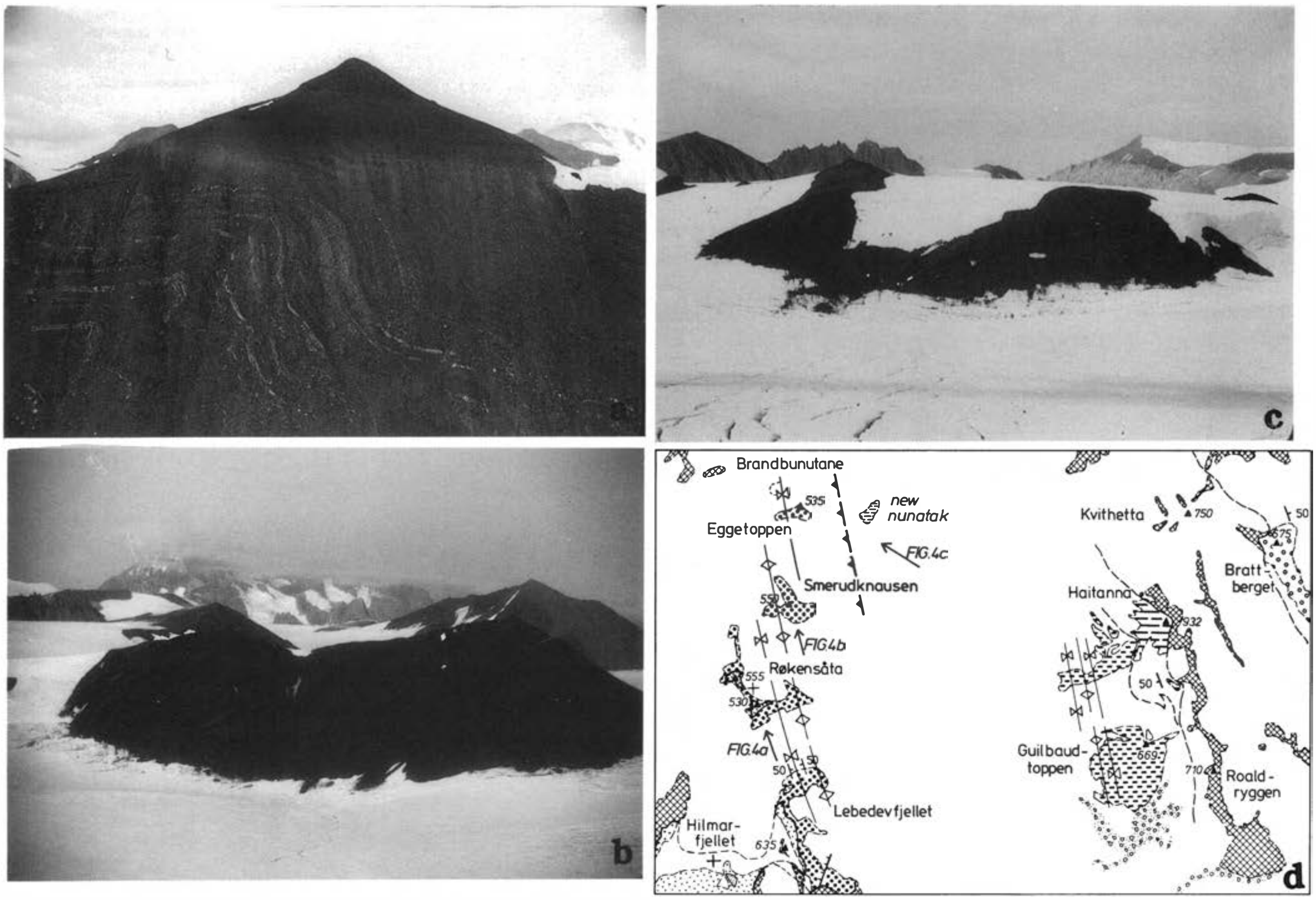


Fig. 4. Evidence for a Late Palaeozoic age of deformation in Devonian rocks. (a) Folded Devonian strata unconformably overlain by Triassic strata, Røkensåta. (b) Tight folds in Devonian strata, Eggetoppen. (c) Position of thrust, Devonian (nunatakk of Fig. 4b in background) over Lower Carboniferous (Adriabukta Formation), new nunatak east of Eggetoppen. (d) Location of photographs (a)–(c) and geological overview; for legend see Figs. 7 and 8; large slashes indicate Haitanna conglomerate member. Position indicated in Fig. 1.

Late Permian Kapp Starostin Formation shows a very thin unit (c. 6 m) of nearshore facies in parts of the fold belt (Austjøkultinden) and probably thickens eastward. Also, during the Triassic, the Inner Hornsund Fault Zone was supposedly still active, as the sedimentary development indicates a lower subsidence rate on the Sørkapp–Hornsund High than in the eastern part of the fold belt (Mørk et al. 1982).

This discussion says little about the total geographical extent of the Carboniferous fault activity, but it does indicate a certain concentration of movements along the Inner Hornsund Fault Zone and thus the present fold belt.

Tertiary fold-and-thrust belt (Palaeocene/Eocene)

Structure and kinematics of the central fold belt

The southern part of the Tertiary fold-and-thrust belt of Spitsbergen overprints the eastern part of the Samarinbreen Syncline and an adjacent zone to the east. With reference to the sedimentary record of the Central Tertiary Basin (Steel et al. 1981) and to palaeomagnetic and other offshore data (Talwani & Eldholm 1977; Myhre et al. 1982; Eldholm et al. 1984, 1987), most authors agree that deformation happened mainly during the Late Palaeocene and Eocene. Still, data from Greenland (Håkansson & Pedersen 1982) suggest that deformation may already have started during the Late Cretaceous.

In the present study area, structures are best exposed within a distance of 10 km to the north and south of Hornsund where detailed mapping has been done (Figs. 7, 8). Unfortunately, glaciers and water cover several critical areas, and the observed structures may be explained by different kinematic models (Fig. 10).

Certain structures are critical and have to be related to each other by the kinematic models. These structures are:

1. The eastward-directed Braemfjellet Thrust (Fig. 9a) emplacing Precambrian basement and overturned Devonian on overturned Triassic strata.
2. The eastward-directed Kvalfangarbreen Thrust (Fig. 9b) emplacing strongly tectonized Cretaceous and

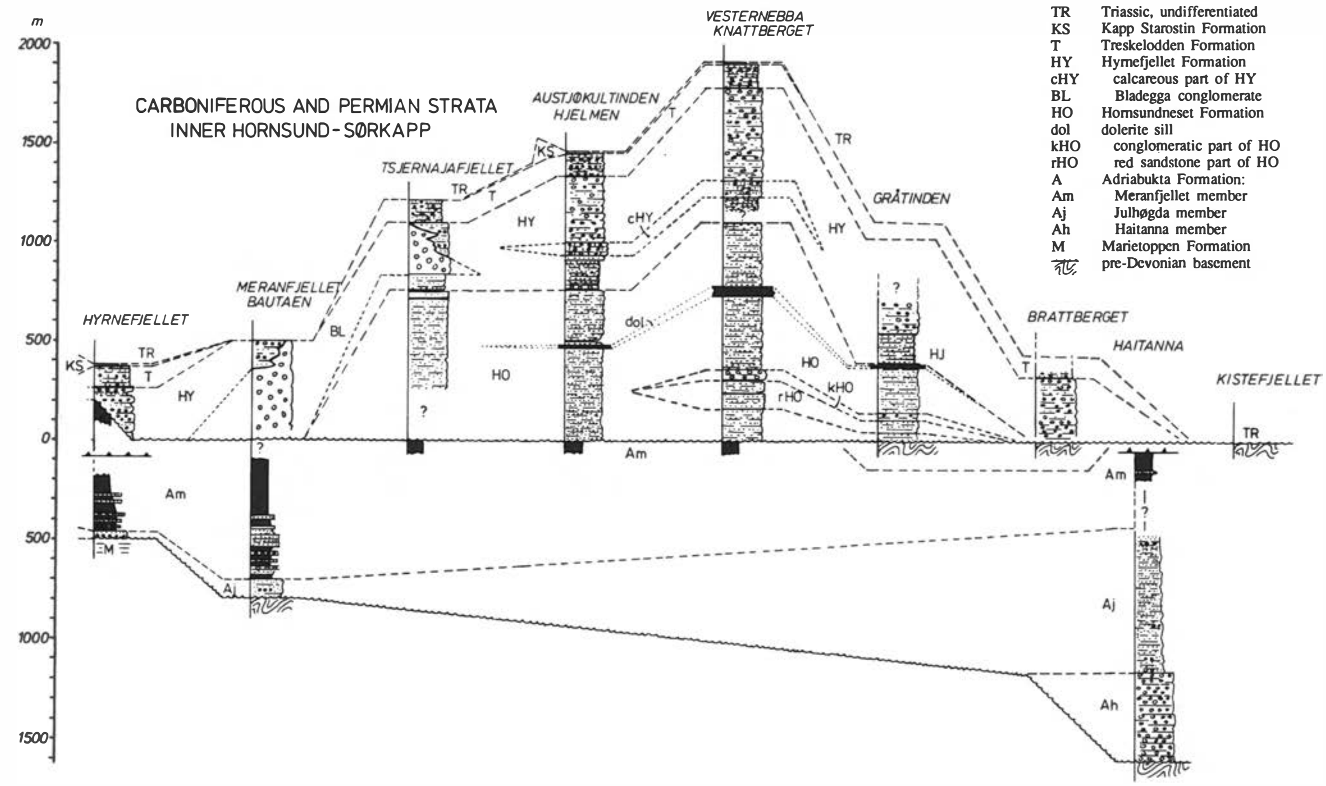


Fig. 5. Overview of Carboniferous and Permian stratigraphy along the Tertiary fold-and-thrust belt in the Sørkapp–Hornsund area. For localities see Figs. 1, 7, 8.

Fig. 6. The Haitanna conglomerate member, lower part of Adriabukta Formation: A 450 m thick, coarse, immature alluvial fan conglomerate.

Jurassic on overturned Triassic and Permian strata; this thrust is refolded.

3. The large Hyrnefjellet Antiform (Fig. 9c) and an adjacent synform that affects Late Paleozoic and Early Triassic rocks.
4. The westward-directed Mariekammen Thrust (Fig. 9d), which is rotated almost into a vertical position, emplacing basement with overlying Lower Carboniferous strata on Lower Carboniferous overlying Devonian strata. This structure may be related to the Adriabukta event (Birkenmajer 1964).
5. Westward-vergent structures, e.g. hangingwall cutoffs (Fig. 9e) in Late Palaeozoic strata.
6. The eastward-overturned Strykjernet–Isryggen Fold (Fig. 9f) within Cretaceous strata.
7. The Påskefjella thrust emplacing basement on tectonized Lower Carboniferous strata. The Påskefjella Thrust may be related to the Adriabukta event.

From this summary it is clear that most of the critical Tertiary structures are exposed north of Hornsund. The individual kinematic models are therefore developed in this area and then tested for the area south of Hornsund.

Model A (Fig. 10a). – Birkenmajer (1964, 1972a,b) presented an interpretative section of the northern shore of Hornsund as an example of multiphase ('Caledonian, Variscan, Alpine') deformation. The eastward directed Braemfjellet and Kvalfangarbreen Thrusts (new names) are ascribed to Tertiary (Alpine) deformation, while the oppositely directed Mariekammen Thrust (new name) is considered to be associated with the Adriabukta event (Variscan). The Kvalfangarbreen Thrust shows younger strata emplaced on older strata and is therefore thought to be reactivated by low-angle, normal fault displacement larger than the initial thrust displacement.

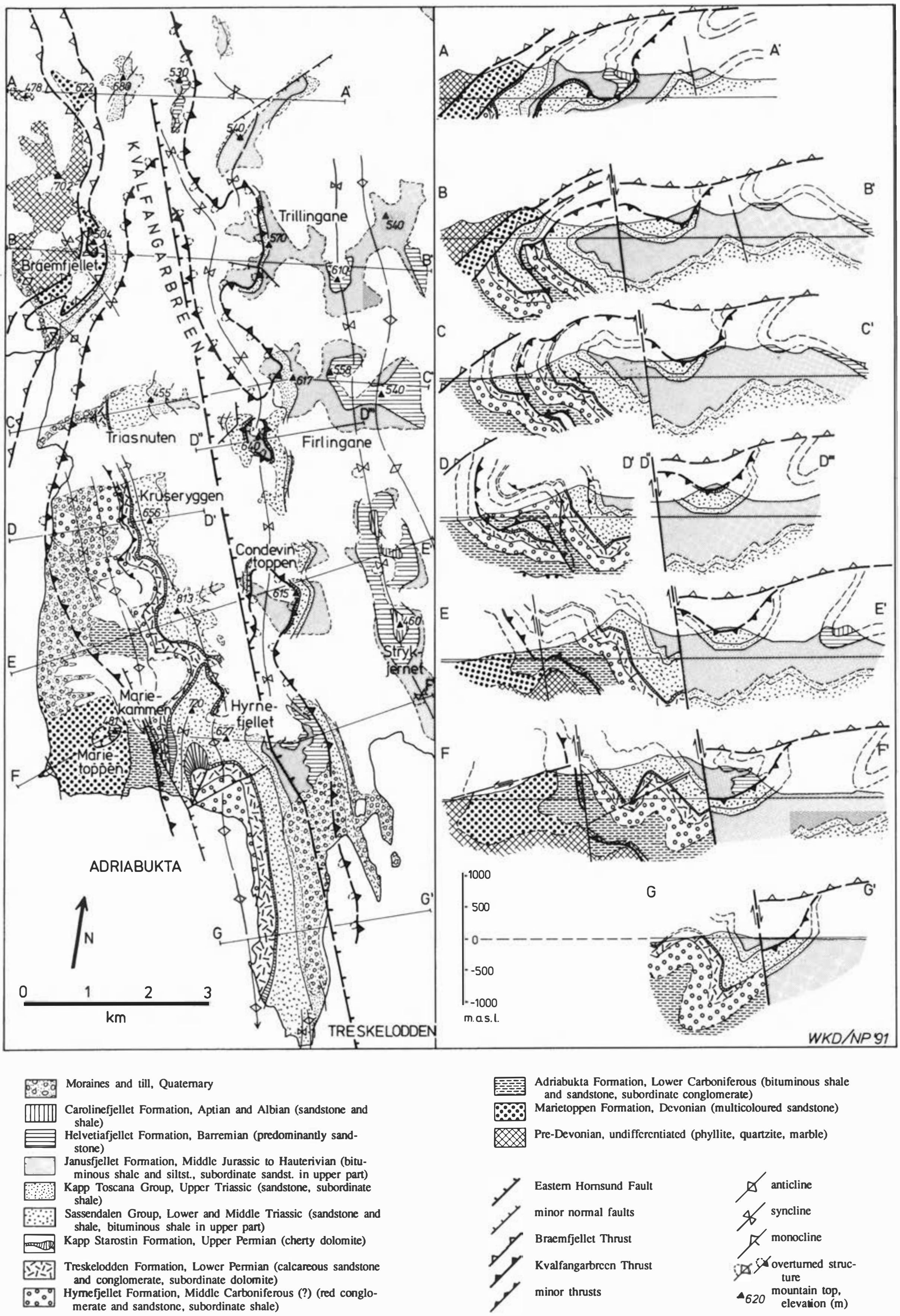


Fig. 7. Geological map and cross-sections of part of the Tertiary fold-and-thrust belt, north of Hornsund. Interpretation according to model C (compare text and Fig. 10).

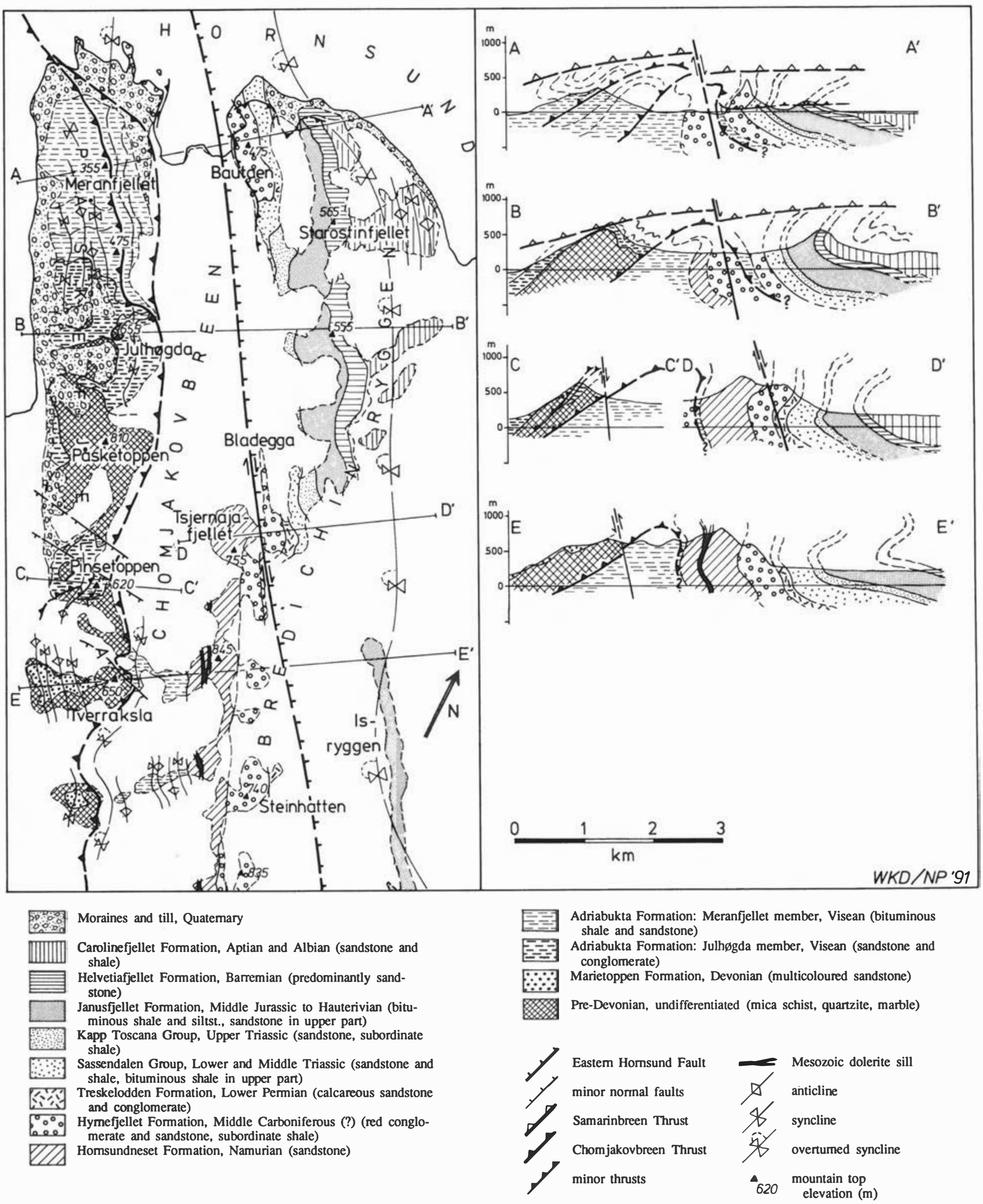


Fig. 8. Geological map and cross-sections of part of the Tertiary fold-and-thrust belt, south of Hornsund. Interpretation according to model C (compare text and Fig. 10).

Recent mapping of the nunataks to the north (Fig. 7) showed that the Kvalfangarbreen Thrust is refolded. This requires modifications of the model (Fig. 10a). A late NNW–SSE trending, subvertical fault with a down-to-west displacement through Kvalfangarbreen and eastern Hyrnefjellet, here called the 'Eastern Hornsund Fault', has to be inferred to make possible a westward-down continuation of the thrust (Fig. 10a, part II). The overturned fold below the thrust is recumbent and refolded. With the resulting constellation, geometrical problems

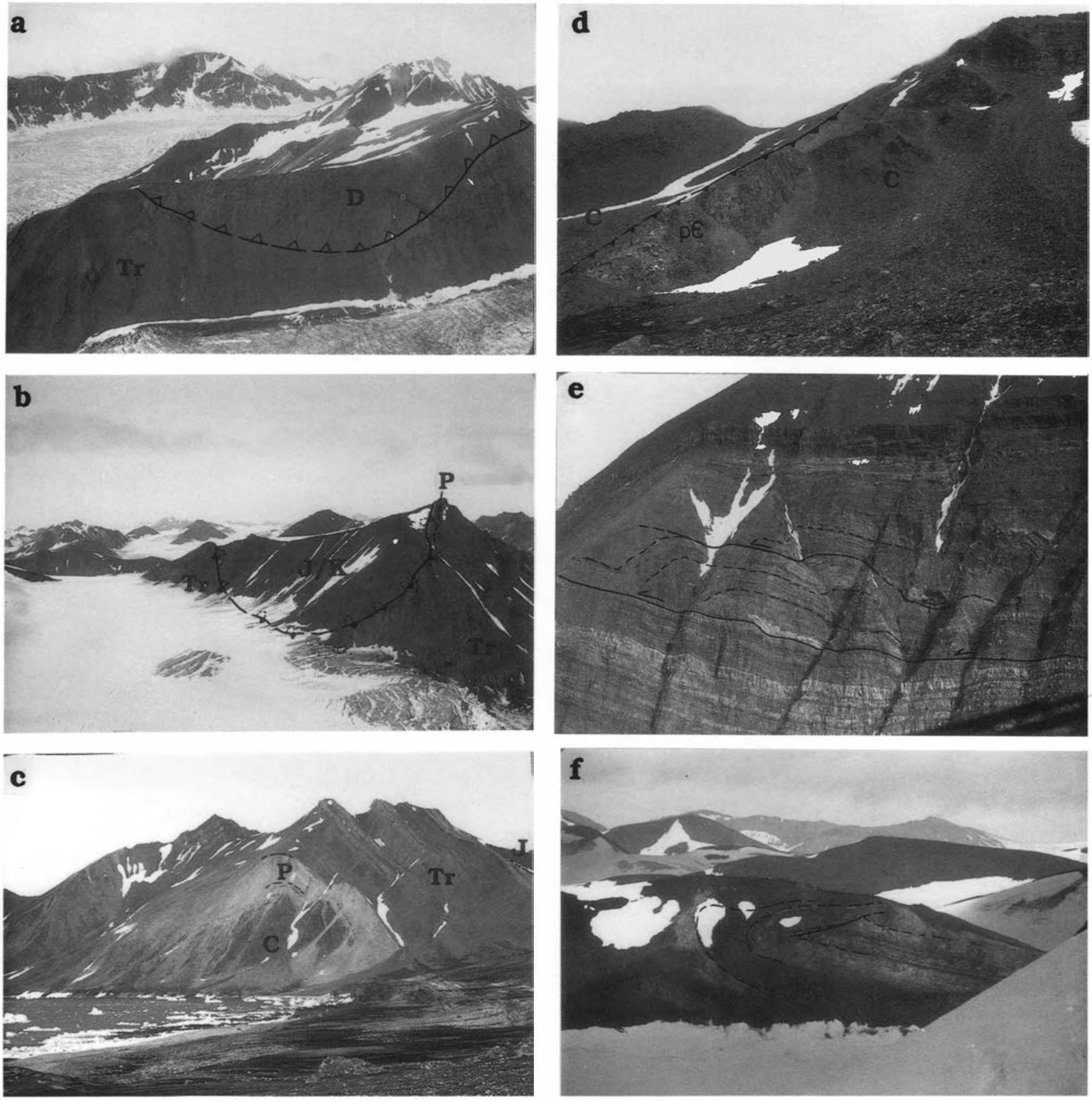


Fig. 9. Critical structures of the Tertiary fold-and-thrust belt at Hornsund. For locations see Figs. 7, 8. (a) The Braemfjellet Thrust at Braemfjellet, Devonian thrust over inverted Triassic rocks. (b) The refolded Kvalfangarbreen Thrust at Condevintoppen, Jurassic/Cretaceous thrust 'over' inverted Triassic – an inverted hangingwall cutoff? (c) The Hyrnefjellet Anticline; Carboniferous, Permian and Triassic strata. (d) The Mariekammen Thrust; a slice of crystalline basement thrust into the black shales of the Adriabukta Formation. (e) Westward directed hangingwall cutoffs, Kruseryggen. (f) The recumbent Strykjernet–Isryggen Fold at Isryggen in Cretaceous strata. D, Devonian; C, Carboniferous; P, Permian; Tr, Triassic; J, Jurassic; K, Cretaceous.

appear when projecting the Hyrnefjellet Antiform down to depth. The section cannot be balanced on the basis of observations.

Beside these geometrical problems, this model has other weak points! It requires a period of considerable horizontal extension (estimated to at least 2000 m) between periods of shortening, a deformation sequence unknown from other parts of the fold belt. It requires a down-to-west displacement of the Eastern Hornsund Fault, though the probable continuation of this fault south of Hornsund shows down-to-east displacement (Fig. 8). Also, the model does not explain other observed features which would necessitate auxiliary models (see model C).

Model B (Fig. 10b). – This model tries to explain observations by continuous eastward directed thrusting in order to avoid the intermediate extensional phase. The

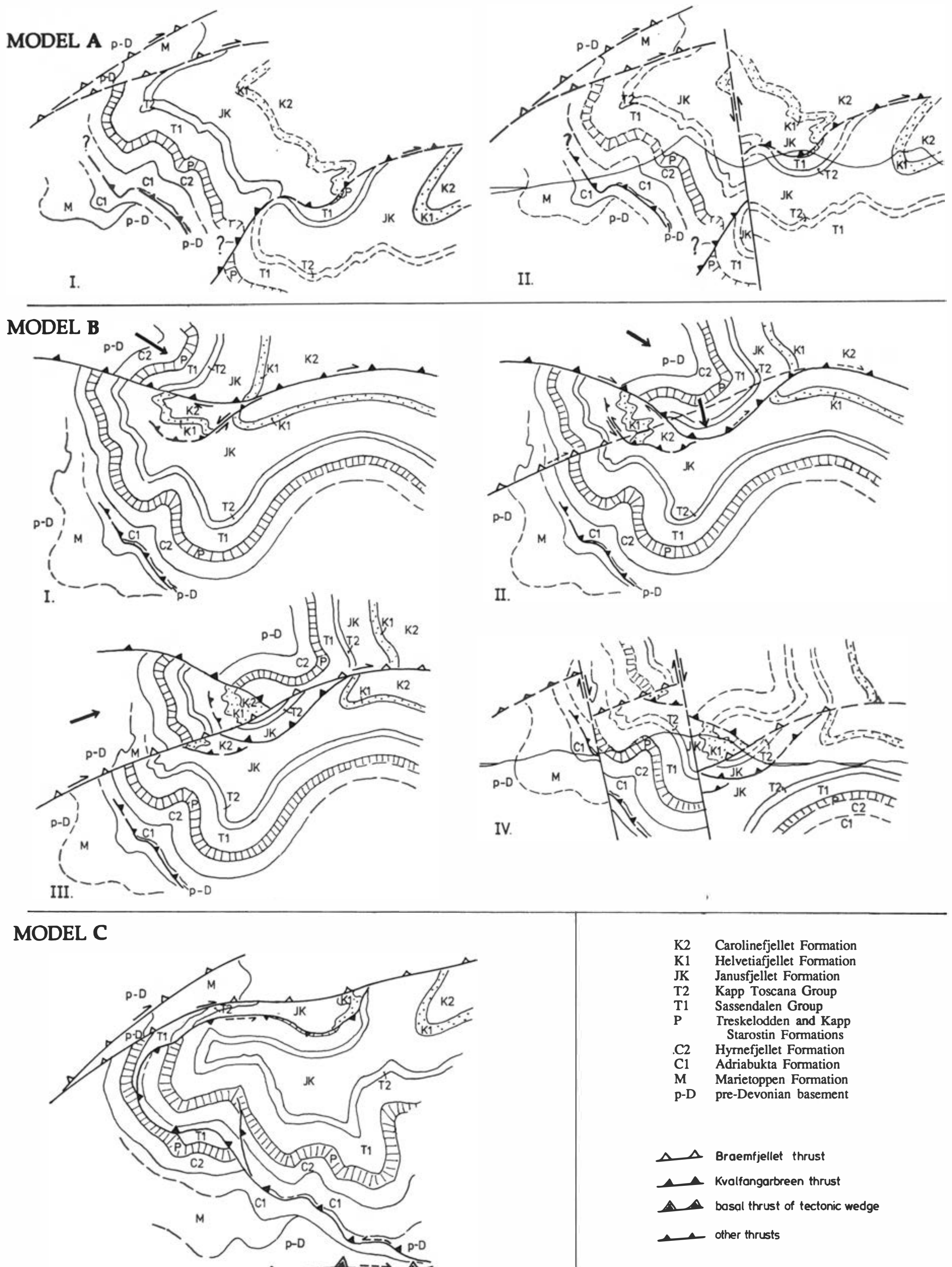


Fig. 10. Three alternative kinematic models to explain the structure of the Tertiary fold-and-thrust belt north of Hornsund. (a) Modified after Birkenmajer (1964), the Kvalfangarbreen Thrust interpreted as a thrust (left sketch) which later was reactivated as a low-angle normal fault (right sketch). The sketches show the situation at Condevintoppen (see Fig. 7). (b) Interpretation by continuous thrusting (out-of-sequence), where the incompetent bituminous shales of the Janusfjellet Formation permit that a fold core of Helvetiafjellet Formation sandstones is squeezed off. The sketches show the situation at Hyrnefjellet and four stages of the possible development. (c) Interpretation by back-thrusting and subsequent overfolding. Composite section; only the intermediate stage is shown here; the present situation is illustrated by the cross-sections in Fig. 7.

Mariekammen Thrust is here still related to earlier tectonics (Adriabukta event). The Tertiary Braemfjellet thrust developed at the flank of a rising basement antiform and causes a recumbent syncline to the east of it. Similar tectonics have been observed in other places on Svalbard (Dallmann 1988).

The low shear strength of the bituminous shales of the Jurassic/Cretaceous Janusfjellet Formation has been described from other areas of Svalbard (Dallmann 1988; Haremo et al. 1990). It may permit that the core of the synform (consisting of competent Cretaceous sandstones) is squeezed apart.

The subsequent Kvalfangarbreen Thrust cross-cuts the recumbent fold and is thus able to emplace the Cretaceous rocks of the inner remnant of the fold core on overturned Triassic and Permian strata of the upper limb of the recumbent fold.

The steep Eastern Hornsund fault also is important in this model, but the displacement is down-to-east as observed at its assumed continuation south of Hornsund (Fig. 8). Another advantage of this model is that the thrusts are in sequence, i.e. foreland-propagating, without an intermediate extensional phase. On the other hand, this model appears very contrived and requires assumptions of unobservable sections. Squeezed-off fold cores like those assumed here are not known from other places of the fold belt.

Model C (Fig. 10c). – This model also aims to explain structures by continuous compression, but operates with back-thrusting and wedge insertion, which are known from other parts of the fold belt (Dallmann 1988; Dallmann & Maher 1989). The Mariekammen thrust is here interpreted as being of Tertiary age. It constitutes a back-thrust developed on top of a tectonic wedge which uses the bituminous shales of the Adriabukta Formation as the splitting horizon. The basal thrust of the wedge is not exposed north of Hornsund. The back-thrust ramps through Late Palaeozoic and Mesozoic strata, the Kvalfangarbreen Thrust being its upper continuation.

Subsequently, another eastward-directed thrust, the Braemfjellet Thrust, was initiated, causing the underlying recumbent fold and the inversion of the back-thrust. The structures observed along the Kvalfangarbreen Thrust at Condevintoppen, Firlingane and Trillingane thus represent an inverted hangingwall cutoff.

The Braemfjellet Thrust is out of sequence in this model, i.e. the general foreland-propagating sequence is interrupted. Out-of-sequence thrusts also are known from other parts of the fold belt, north of Isfjorden (Bergh & Andresen 1990). The Eastern Hornsund Fault through Hyrnefjellet is needed also in this model to bring parts together, and it has the same down-to-east displacement that is observed south of Hornsund, though the downthrow here is considerably higher.

This model explains also other features observed in the area. One of them is the presence of westward-directed thrust ramps with hangingwall cutoffs within the Lower Permian Treskelodden Formation (Fig. 9e). They have a back-thrust direction and may be splays of the Mariekammen thrust (which is not possible, if the latter is ascribed to the Early Carboniferous Adriabukta event). Also, the distinct structural break between Triasnuten and Braemfjellet (Fig. 7) is explained, if the Mariekammen and Kvalfangarbreen thrusts form one continuous structure.

Model C is favoured, because it uses 'traditional' fold-belt structures and explains the observed structures without auxiliary models. Map and cross-sections (Fig. 7) are therefore drawn according to this model.

It may be argued that the required back-thrust displacement of c. 3000 m is very large. A reason could be that earlier (Devonian and Carboniferous) tectonics gave rise to subsurface structures comprising competent fault blocks that prevent the basal thrust from proceeding eastward. Crustal shortening thus may be accommodated by more intensive deformation of the wedge. Experiments with gypsum models show that a high-angle contact of a thrust and a competent obstacle may result in higher back-thrust displacemens on top of the wedge (R. Gabrielsen pers. comm. 1991).

How does the area south of Hornsund (Fig. 8) fit into this model? As the overturned to recumbent Strykjernet–Isryggen Fold (Fig. 9f) is continuous across Hornsund, the related Braemfjellet Thrust also is supposed to be continuous. It is reasonable to suggest that one of the thrusts observed at Chomiakovbreen and Samarinbreen is the southern continuation of the Braemfjellet Thrust. It is quite probable that thrusts inherited from the Adriabukta event were reactivated, and that they accommodated the renewed thrust displacement, as both have the same trends and vergences. It has not been possible to discriminate Carboniferous and Tertiary deformation along these thrusts or within the complexly folded Adriabukta Formation in Påskefjella. Also, the basal thrust of the tectonic wedge assumed in the third model could continue into this area, possibly as a reactivated older thrust (as suggested in Fig. 8). It thus could be responsible for the complicated fold structures in Påskefjella.

In other words, the area south of Hornsund probably shows a lower structural level, where the base, not the roof, of the tectonic wedge is exposed.

However, Tertiary deformation diminishes southward, and in the area around Haitanna probably only a regional flexure fold is left. The latter decreases even more further south and ends up at Keilhaufjellet as a simple monocline dipping eastward down to the foreland basin (Central Tertiary Basin).

Implications of the Lidfjellet–Øyrlandsodden fold zone

It is noted above that two areas at the west coast of Sørkapp Land show compressional structures. Their trends and vergences correspond to those of the central fold belt. Their age is post-Lower Cretaceous, as shown by the strata involved.

The down-faulted Palaeocene strata on Øyrlandet probably is not deformed, though exposures are too small to document this with certainty. It does not, however, necessarily indicate that deformation is older. Seismic studies of the Tertiary strata of the Central Tertiary Basin show that deformation has taken place at lower stratigraphic levels, while the Tertiary and parts of the Cretaceous strata were uplifted and remained apparently undeformed (Faleide et al. 1988). Similar kinematics may be suggested here, though exposures are too limited to permit kinematic modelling.

The Lidfjellet–Øyrlandsodden fold zone is observed in the area where the central fold belt dies out, and it continues farther south than the latter (Fig. 12). This observation could be interpreted as an en echelon arrangement of two lineaments, or it simply may be a coincidence. The lateral extent of the Lidfjellet–Øyrlandsodden fold zone is not known, nor is it sure that deformation occurred simultaneously.

The distinct separation of these two zones of fold–thrust deformation, however, supports the view that Tertiary (and possible Upper Cretaceous) compressive deformation is controlled by a system of defined tectonic lineaments.

Shortening estimates

The following estimates are based solely on map-scale structures. Possible layer-parallel shortening is not taken into account.

Within the Lidfjellet–Øyrlandsodden fold zone, the thrust at Lidfjellet shows a minimum displacement of 1800 m, i.e. the minimum offset of the Triassic base in vergence direction (Winsnes et al., in press), but much higher values can be imagined. At Øyrlandsodden, too little is exposed to make any suggestions.

Within the central fold belt, the amount of shortening increases rapidly northward (Fig. 1). At Keilhaufjellet in the south, shortening is only 200–300 m owing to downwarping and minor folding of the Central Tertiary Basin strata. Sinuous bed estimates at Haitanna suggest approximately 700 m shortening by regional flexuring of the Triassic strata. Similar estimates indicate at least 1800 m across the southern part of Påskefjella, if one assumes that no thrusting occurred in addition to the overturned Strykjernet–Isryggen Fold. Thrusting has, however, probably occurred, as the area lies within the transition to the Hornsund area, where much higher shortening is documented.

North of Hornsund (Fig. 7), the total amount of shortening is the sum composed of the displacement along the Braemfjellet Thrust, the shortening accommodated by the underlying recumbent fold and the shortening related to the Kvalfangarbreen Thrust. The minimum thrust displacement at Braemfjellet corresponds to the thickness of the stratigraphic gap (Carboniferous through to Middle Triassic), which is c. 500 m (thicknesses according to Birkenmajer 1964, 1977). Assuming the third model (Figs. 7, 10c), a sinuous bed estimate for the smallest recumbent fold is roughly two times the minimum length of the refolded upper limb, measured at Firlingane–Triasnuten, i.e. 4500 m. The Kvalfangarbreen Thrust, interpreted as a refolded back-thrust, has a displacement of a minimum of c. 3000 m, i.e. the minimum displacement of the top of the Triassic strata at Trillingane/Braemfjellet.

The minimum amount of total shortening assuming such a back-thrusting model is thus c. 8 km across the structure north of Hornsund. Much higher values are possible, especially because the real displacement along the Braemfjellet Thrust is not known. Also, the basal thrust of the tectonic wedge may have a larger displacement than the related back-thrust, presuming that a part of the displacement is transferred eastward and accommodated by bedding-parallel slip within the central basin strata, as observed further north in the fold belt (Haremo et al. 1990). Additional shortening may have occurred by reactivation of the Caledonian thrusts west of Braemfjellet (Figs. 1, 12). A total amount of shortening of 10–12 km (or even higher) across the central fold belt at Hornsund appears reasonable.

The second model (squeezed-off fold core, Fig. 10b) requires very similar minimum amounts of shortening. The first model (thrust reactivated as a normal fault, Fig. 10a) would probably require a smaller minimum amount. No calculation is made, because sections cannot be balanced on the basis of the available data when using this model.

Tertiary extensional faulting

Normal faults with mainly a NNW–SSE trend cross-cut the central and western parts of the Sørkapp–Hornsund area. They are generally thought to relate to the development of the passive continental margin off Svalbard to the west in the Oligocene, though some may have developed during an Early to Mid-Palaeocene tensional phase (Steel & Worsley 1984). The latter is probably observed in the western part of Sørkapp Land. Upwarping of Triassic strata against the faults in the Höferpynten area (Fig. 1, section A; Winsnes et al., in press) indicates that the faults formed prior to the Late Palaeocene–Eocene convergent deformation.

As mentioned above, Tertiary reactivation of Carboniferous faults is obvious in the Höferpynten area, where the displacement of Lower Carboniferous strata is larger than that of Triassic strata in the same place. Most faults, however, lack such an indication. On the contrary, many of them clearly cross-cut compressional features, e.g. the fault bounding the Øyrlandet Graben to the southwest (Fig. 1) and all normal faults observed within the central fold belt and the Lidfjellet–Øyrlandsodden fold zone.

A major fault through the inner part of Hornsund is inferred by all three alternative kinematic models (Figs. 7, 8, 10). This fault follows the trend of the fold belt and has (according to the preferred model) a down-to-east displacement, which is highest at Condevintoppen/Firlingane (c. 1500 m?; Fig. 7), diminishing both south- and northward. At Tsjernajafjellet, south of Hornsund, it is c. 100 m (Fig. 8; observed), while it cannot be traced to the north and south of the areas covered by Fig. 7 and 8 owing to ice cover.

Evidence of strike-slip motion

It has been pointed out repeatedly that vergences within the Tertiary fold-and-thrust belt are normal to the trend of the belt and the passive continental margin. To bring this into accordance with the overall transform setting of Svalbard in the Palaeogene, kinematic models of decoupled transform and convergent motions have been developed (Maher & Craddock 1988; Nøttvedt et al. 1988). Similar relations of vergence and fold-belt trend are characteristic of the Carboniferous Adriabukta event (Fig. 11a, b).

Locally within the central fold belt of Sørkapp Land, however, there is still structural evidence for strike-slip motion. The sandstones and shales of the upper part of the Adriabukta Formation in Påskefjella (Fig. 8) and Adriabukta (Fig. 7) are more complexly folded than similar strata in other parts of the fold belt. A stereographical projection of fold axes (Fig. 11c) shows that most axes fit with a small circle of radius 45°, which indicates that the fold axes were rotated about an axis *R* oriented 230°/65°. If this axis *R* is transferred into a diagram showing poles to bedding, it is easy to explain the distribution of poles to bedding by rotation about the same axis (Fig. 11d).

In any case, this rotation must pre-date regional folding about the Tertiary north-northwest trending, subhorizontal axis (Fig. 11b). Axis *R* is therefore probably rotated out of its original position, i.e. its original plunge may have been more gentle. It is, however, oriented almost normal to both the Carboniferous and Tertiary fold axes (Fig. 11a,b). This indicates that the two motions were not combined (transpression), but occurred separately (subsequently or decoupled). Thus the axis *R* probably indicates a phase of strike-slip motion along previously formed, west-southwest dipping slip planes.

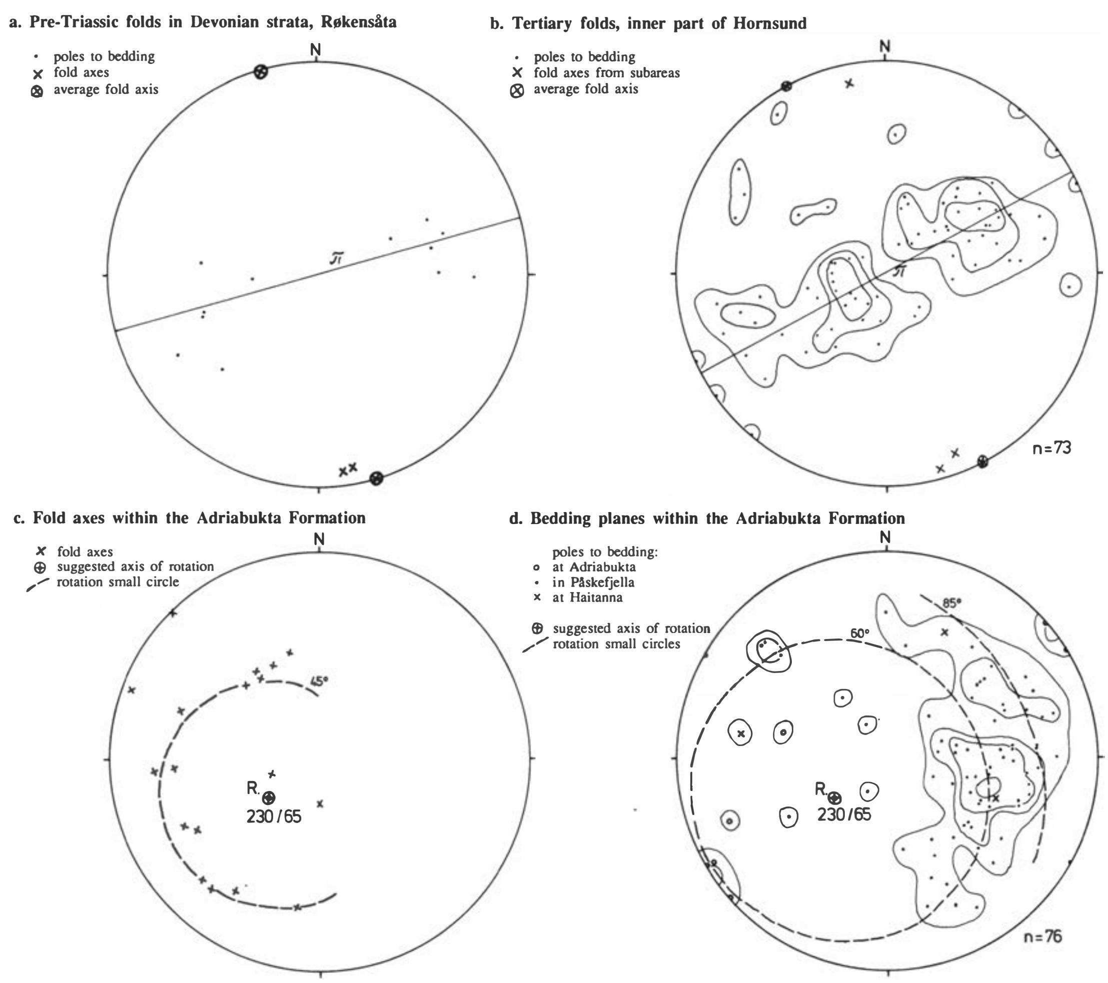


Fig. 11. Stereographic plots illustrating Early Carboniferous and Tertiary fold phases. See discussion in the text.

The rotated fold axes (Fig. 11c) do not coincide with initially formed axes of either event and indicate an even earlier phase of either strike-slip (if initially west-southwest plunge), dextral transpression (if southwest plunge) or sinistral transpression (if initially west or west-northwest plunge). It is not possible to say whether these rotations (refolding events) occurred during the Carboniferous or Tertiary folding event.

Another indication of transcurrent motion is given by the oblique arrangements of several normal faults within the lateral overlap area of the two fold zones (Sørkapp–Hornsund mobile zone and Lidfjellet–Øyrlandsodden fold zone; Fig. 12). These display a typical dextral transtension constellation. It is, however, uncertain, whether transtension is of Tertiary or Late Palaeozoic age, as the Tertiary movements simply may have reactivated the earlier established pattern of lineaments. (As mentioned above, both Late Palaeozoic and Tertiary displacement is observed along some of these faults.) Dextral transtension during the Late Palaeozoic would, however, be the opposite direction of what Harland (1971) expected.

Large-scale drag folds close to the Eastern Hornsund Fault at Tsjernajafjellet (Fig. 8) also indicate dextral strike-slip in addition to the down-to-east displacement. The folds involve Triassic strata, i.e. the oblique-slip is supposedly of Tertiary age.

Conclusions

The discussion on the post-Caledonian deformation history of the Sørkapp–Hornsund area points out that reactivation of structures has been an important process. Figure 12 shows the regional distribution of deformation related to the individual events.

The most striking structure in this context is the southern part of the West Spitsbergen Fold Belt, which obviously has been a mobile zone through the entire post-Caledonian. The eastern boundary of the Late Palaeozoic Sørkapp–Hornsund High, the Inner Hornsund Fault Zone, the Early Carboniferous Adriabukta deformation and the southern end of the Tertiary fold-and-thrust belt have all been located within this zone and have similar regional trends. Deformation accommodated within this zone has been normal faulting, thrusting and folding, i.e. both extension and shortening. Forces mainly have been tension or compression, though

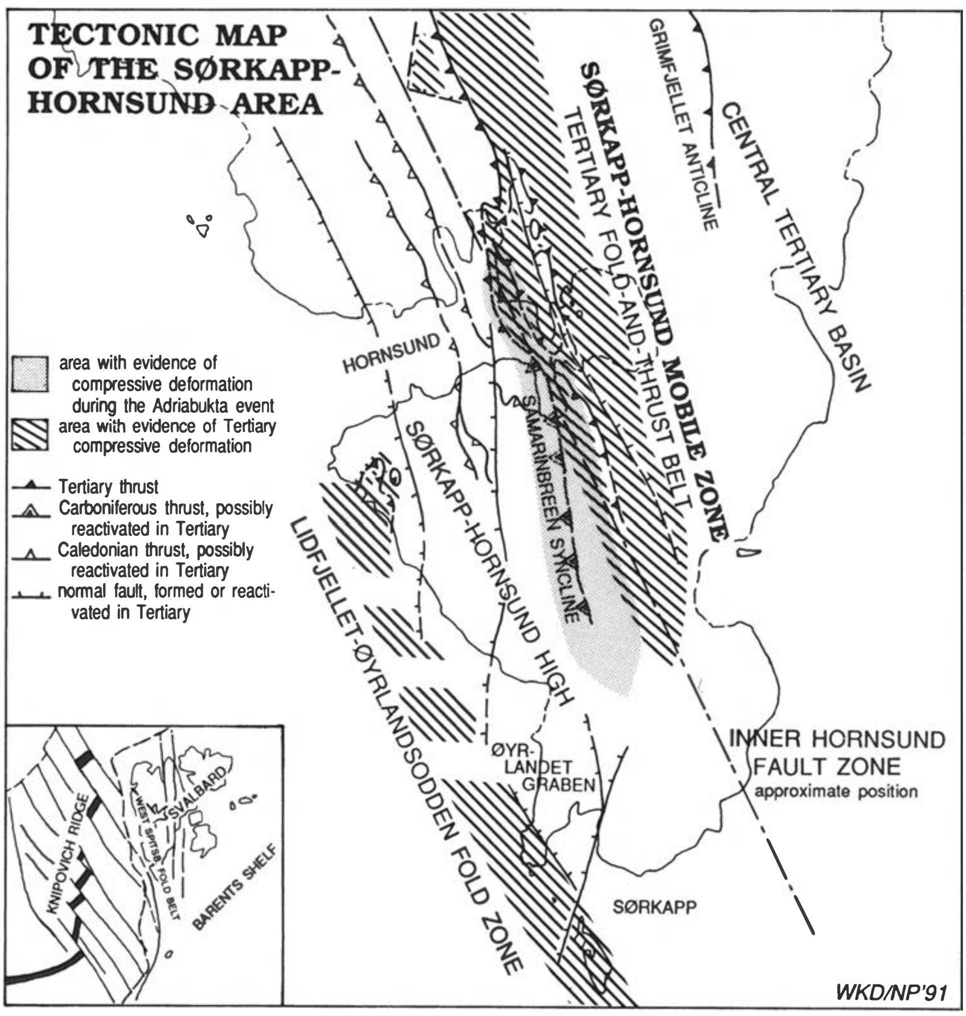


Fig. 12. Tectonic map of the Sørkapp–Hornsund area, Southern Spitsbergen, Svalbard, illustrating the distribution of deformation phases and structures. Much of the deformation of different ages is concentrated within the Sørkapp–Hornsund mobile zone. The oblique relations of fold zones and faults indicate an en echelon arrangement owing to transtension of unknown age. The insert map (simplified from Max & Ohta 1988) shows the regional plate tectonic setting.

Table 1. Post-Caledonian tectonic events within the Sørkapp–Hornsund mobile zone.

Event/structure	Age	Deformation	Local stress field
Svalbardian(?) event	Post-Emsian/pre-Visean, probably Latest Devonian	Block tilting or faulting	Extensional (transtensional?)
Adriabukta event	Post-Visean/pre-Bashkirian	East-northeast vergent, locally tight folding and thrusting	Compressional, zone(s) of transpression?
Inner Hornsund Fault Zone	Carboniferous, fading out during Permian/Early Triassic	Synsedimentary block faulting, formation of Sørkapp–Hornsund High, NNW–SSE trend	Extensional (transtensional?)
Tertiary fold-and-thrust belt	Palaeocene/Eocene	East-northeast vergent folding and thrusting, fading out to the south; >8 km shortening in Hornsund	Compressional, zone(s) of transpression?
Passive ocean margin formation	Oligocene	Normal faulting, NNW–SSE trend	Extensional (transtensional?)

there also is local evidence for periodical strike-slip (Table 1).

It is concluded that much of the deformation responding to different regional stress fields through time was channelized and accommodated within the Sørkapp–Hornsund mobile zone.

Similar zones are known from other parts of Svalbard, e.g. the Billefjorden Fault Zone (Lamar et al. 1986; Reed et al. 1987; Haremo et al. 1990), or are suggested, e.g. the Lomfjorden Fault Zone (Nøttvedt et al. 1988). Maher & Welbon (this volume) argue that the central western margin of the Tertiary fold-and-thrust belt is the reactivated basin margin of the Carboniferous St. Jonsfjorden Trough. Similar relations are observed at the northeastern margin of this trough (Bergh & Andresen 1990). Dallmann (1989) suggests multiple reactivation of the Renardodden Fault in Bellsund, which possibly is the northern continuation of the Inner Hornsund Fault Zone.

The present work thus supports a view where Svalbard is considered as a system of tectonic blocks separated by mobile zones (long-lived tectonic lineaments). The latter have accommodated most of the deformation during the individual tectonic events. A similar interpretation is given by Gabrielsen (1984) and Gabrielsen & Færseth (1988) for the western Barents Shelf, and it is not surprising that the mainland of Svalbard seems to have been affected in a similar way.

As the orientation of a mobile zone is determined before the onset of a deformation event, the sense of movement within the mobile zone does not need to reflect directly the main axis of the stress field. This fact may help to explain variations in observed compression directions in plate-tectonic transforms regimes, both during the Carboniferous and Tertiary. It also gives room for coeval compression, extension and/or strike-slip in different mobile zones, related to their configuration and orientation within the regional stress field.

Acknowledgements. – Many thanks to Professor K. Birkenmajer (Polish Academy of Sciences) and Dr Y. Ohta (Norwegian Polar Research Institute) for fruitful discussions on parts of the paper. I am grateful also to Dr H. D. Maher Jr. (University Nebraska) for collaborative field work during the initial phase of the present study.

Manuscript received March 1991

References

Bergh, S. G. & Andresen, A. 1990: Structural development of the Tertiary fold-and-thrust belt in Oscar II Land, Spitsbergen. *Polar Research 8*, 217–236.

Bergh, S. G., Andresen, A., Bergvik, A. & Hansen, A. I. 1988: Tertiary thin-skinned compressional deformation on Oscar II Land, central Spitsbergen. *In* Dallmann, W. K., Ohta, Y. & Andresen, A. (eds.): Tertiary tectonics of Svalbard. Extended abstracts from symposium held in Oslo 26 and 27 April 1988. *Norsk Polarinstitutt Rapportserie 46*, 51–54.

Birkenmajer, K. 1964: Devonian, Carboniferous and Permian formations of Hornsund, Vestspitsbergen. *Studia Geologica Polonica 11*, 47–123.

Birkenmajer, K. 1972a: Tertiary history of Spitsbergen and continental drift. *Acta Geologica Polonica 22(2)*, 193–218.

Birkenmajer, K. 1972b: Alpine fold belt of Spitsbergen. *24th International Geological Congress (Montreal), Section 3*, 282–292.

Birkenmajer, K. 1975: Caledonides of Svalbard and plate tectonics. *Geological Society of Denmark Bulletin 24*, 1–19.

Birkenmajer, K. 1977: Triassic sedimentary formations of the Hornsund area, Spitsbergen. *Studia Geologica Polonica 51*, 1–74.

Birkenmajer, K. 1978a: Cambrian succession in south Spitsbergen. *Studia Geologica Polonica 59*, 7–46.

Birkenmajer, K. 1978b: Ordovician succession in south Spitsbergen. *Studia Geologica Polonica 59*, 47–82.

Birkenmajer, K. 1981: The geology of Svalbard, the western part of the Barents Sea, and the continental margin of Scandinavia. *In* Nairin, A. E. M., Churkin, M. & Stehli, F. G. (eds.): *The Ocean Basins and Margins, 5, The Arctic Ocean*, 265–329. Plenum Press, New York.

Birkenmajer, K. 1984: Mid-Carboniferous red beds at Hornsund, south Spitsbergen: their sedimentary environment and source area. *Studia Geologica Polonica 80*, 7–23.

Birkenmajer, K. 1986: Tertiary tectonic deformation of Lower Cretaceous dolerite dykes in a Precambrian terrane, south-west Spitsbergen. *Studia Geologica Polonica 89*, 31–44.

Birkenmajer, K. & Morawski, T. 1960: Dolerite intrusions of Wedel Jarlsberg Land, Vestspitsbergen. *Studia Geologica Polonica 4*, 103–123.

Birkenmajer, K. & Turnau, E. 1962: Lower Carboniferous age of the so-called Wijde Bay Series in Hornsund, Vestspitsbergen. *Norsk Polarinstitutt Årbok 1961*, 41–61.

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. 1989: The nature of the Precambrian–Tertiary boundary at Renardodden, Bellsund, Svalbard. Research Note. *Polar Research 7*, 139–145.

Dallmann, W. K. & Maher, H. D. 1989: The Supanberget area – basement imbrication and detached foreland thrusting in the Tertiary fold-and-thrust belt, Svalbard. *Polar Research 7*, 95–108.

De Geer, G. 1909: Some leading lines of dislocation in Spitsbergen. *Geologiska Föreningens i Stockholm Förhandlingar 31.*

De Geer, W. 1912: The coal region of central Spitsbergen. *Ymer*, Stockholm.

De Geer, W. 1919: On the physiographical evolution of Spitsbergen. *Geografiska Annaler 1*, Stockholm.

Eldholm, O., Sundvor, E., Myhre, A. M. & Faleide, J. I. 1984: Cenozoic evolution of the continental margin off Norway and western Svalbard. *In* Spencer, A. M. et al. (eds.): *Petroleum Geology of the North European Margin*, 3–19. Norwegian Petroleum Society, Graham & Trotman, London.

Eldholm, O., Faleide, J. I. & Myhre, A. M. 1987: Continent–ocean transition at the western Barents Sea/Svalbard continental margin. *Geology 15*, 1118–1122.

Faleide, J. I., Gudlaugsson, S. T., Eiken, O. & Hanken, N.-M. 1988: Seismic structure of Spitsbergen: implications for Tertiary deformation. *In* Dallmann, W. K., Ohta, Y. & Andresen, A. (eds.): Tertiary tectonics of Svalbard. Extended abstracts from symposium held in Oslo 26 and 27 April 1988. *Norsk Polarinstitutt Rapportserie 46*, 47–50.

Frebold, H. 1935: *Geologie von Spitzbergen, der Bäreninsel, des König Karl- und Franz-Joseph-Landes*, 1–195. Verlag von Gebrüder Bornträger, Berlin.

Friend, P. F. & Moody-Stuart, M. 1972: Sedimentation in the Wood Bay Formation (Devonian) of Spitsbergen: Regional analysis of a late orogenic basin. *Norsk Polarinstitutt Skrifter 157*, 1–77.

Gabrielsen, R. H. 1984: Long-lived fault zones and their influence on the tectonic development of the southwestern Barents Sea. *Journal Geological Society of London 141*, 651–662.

Gabrielsen, R. H. & Færseth, R. B. 1988: Cretaceous and Tertiary reactivation of master fault zones of the Barents Sea. *In* Dallmann, W. K., Ohta, Y. & Andresen, A. (eds.): Tertiary tectonics of Svalbard. Extended abstracts from symposium held in Oslo 26 and 27 April 1988. *Norsk Polarinstitutt Rapportserie 46*, 93–97.

Gjelberg, J. & Steel, R. J. 1981: An outline of Lower-Middle Carboniferous sedimentation on Svalbard: effects of climatic, tectonic and sea level changes in rift basin sequences. *In* Kerr, J. W. & Fergusson, A. J.: Geology of the North Atlantic Borderlands. *Canadian Society of Petroleum Geologists Memoir 7*, 543–561.

Haremo, P., Andresen, A., Dypvik, H., Nagy, J., Elverhøi, A., Eikeland, T. A. & Johansen, H. 1990: Structural development along the Billefjorden Fault Zone in the area between Kjellstrømdalen and Adventdalen/Sassendalen, Central Spitsbergen. *Polar Research 8*, 195–216.

Harland, B. W. 1969: Contribution of Spitsbergen to understanding of the tectonic evolution of the North Atlantic region. *In* Kay, M. (ed.): North Atlantic – Geology and Continental Drift. *American Association of Petroleum Geologists Memoir 12*, 817–851.

Harland, W. B. 1971: Tectonic transpression in Caledonian Spitsbergen. *Geological Magazine 108*, 27–42.

Harland, W. B. 1972: Early Paleozoic faults as margins of Arctic plates in Svalbard. *In*: *Proceedings 24th International Geological Congress, Montreal 3*, 230–237.

Harland, W. B. & Horsfield, W. T. 1974: West Spitsbergen orogen. *In* Spencer, A. M. (ed.): Mesozoic-Cenozoic Orogenic Belts: Data for Orogenic Studies. *Geological Society of London Special Publication 4*, 747–755.

Harland, W. B., Cutbill, J. L., Friend, P. F., Gobbett, D. J., Holliday, D. W., Maton, P. I., Parker, J. R. & Wallis, R. H. 1974: The Billefjorden Fault Zone, Spitsbergen—the long history of a major tectonic lineament. *Norsk Polarinstitutt Skrifter 161*, 1–72.

Hoel, A. 1925: The coal deposits and coal mining of Svalbard (Spitsbergen and Bear Island). *Resultater norske statsunderstøttede Spitsbergenekspedisjoner 6.*

Holtedahl, O. 1913: Zur Kenntnis der Karbonablagerungen des westlichen Spitsbergens. II: Allgemeine stratigraphische und tektonische Beobachtungen. *Videnskapsselskapets Skrifter Matematisk-Naturvitenskapelig Klasse, 1912*, Kristiania, *23.*

Håkansson, E. & Pedersen, S. S. 1982: Late Paleozoic to Tertiary tectonic evolution of the continental margin in North Greenland. *In* Embry, A. F. & Balkwill, H. R. (eds.): Arctic Geology and Geophysics. *Memoir Canadian Society of Petroleum Geologists 8*, 331–348.

Kellogg, H. E. 1975: Tertiary stratigraphy and tectonism in Svalbard and continental drift. *American Association of Petroleum Geologists Bulletin 59(3)*, 465–485.

Lamar, D. L., Reed, W. E. & Douglass, D. N. 1986: Billefjorden fault zone, Spitsbergen: is it part of a major Late Devonian transform? *Geological Society of America Bulletin 97*, 1083–1088.

Lowell, J. D. 1972: Spitsbergen Tertiary orogenic belt and the Spitsbergen Fracture Zone. *Geological Society of America Bulletin 83*, 3091–3102.

Maher, H. D. 1988: Photointerpretation of Tertiary structures in platform cover strata of interior Oscar II Land, Spitsbergen. *Polar Research 6*, 155–172.

Maher, H. D. & Craddock, C. 1988: Decoupling as an alternate model for transpression during the initial opening of the Norwegian Greenland Sea. Research Note. *Polar Research 6*, 137–140.

Maher, H. D. & Welbon, A. 1992: Influence of a Carboniferous basin margin on Tertiary tectonism at St. Jonsfjorden and Bellsund, Western Svalbard. *Norsk Geologisk Tidsskrift*, this volume.

Maher, H. D., Craddock, H. D. & Maher, K. A. 1986: Kinematics of Tertiary structures in Upper Paleozoic and Mesozoic strata on Midterhuken, West Spitsbergen. *Geological Society of America Bulletin 97*, 1411–1421.

Max, M. D. & Ohta, Y. 1988: Did major fractures in continental crust control orientation of the Knipovich–Lena Trough segment of the plate margin? *Polar Research 6*, 85–93.

Myhre, A. M., Eldholm, O. & Sundvor, E. 1982: The margin between Senja and Spitsbergen fracture zones: implications for plate tectonics. *Tectonophysics 89*, 33–50.

Mørk, A., Knarud, R. & Worsley, D. 1982: Depositional and diagenetic environments of the Triassic and Lower Jurassic succession of Svalbard. *Canadian Society of Petroleum Geologists Memoir 8*, 371–391.

Nøttvedt, A., Livbjerg, F. & Midbøe, P. S. 1988: Tertiary deformation on Svalbard – various models and recent advances. *In* Dallmann, W. K., Ohta, Y. & Andresen, A. (eds.): Tertiary tectonics of Svalbard. Extended abstracts from symposium held in Oslo 26 and 27 April 1988. *Norsk Polarinstitutt Rapportserie 46*, 79–84.

Ohta, Y. & Dallmann, W. K. (eds.) 1991: Geological map of Svalbard 1:100 000, sheet B12G Torellbreen. Preliminary edition. *Norsk Polarinstitutt.*

Orheim, A., Aronsen, H. A., Jensen, L. N., Skarpnes, O. & Larsen, B. T. 1988: Seismic mapping of Grimfjellet and Isfjorden, Svalbard; tectonic implications. *In* Dallmann, W. K., Ohta, Y. & Andresen, A. (eds.): Tertiary tectonics of Svalbard. Extended abstracts from symposium held in Oslo 26 and 27 April 1988. *Norsk Polarinstitutt Rapportserie 46*, 63–66.

Orvin, A. 1934: Geology of the Kings Bay region, Spitsbergen. *Skrifter om Svalbard og Ishavet 57*, 1–196.

Orvin, A. 1940: Outline of the geological history of Spitsbergen. *Skrifter om Svalbard og Ishavet 78* (reprint 1969; 1–57).

Reed, W. E., Douglass, D. N. & Lamar, D. L. 1987: Devonian Old Red Sandstone sedimentation and tectonic history of Billefjorden fault zone, Spitsbergen. *Geologie en Mijnbouw 66*, 191–199.

Schenck, E. 1937: Kristallin und Devon im nördlichen Spitsbergen. *Geologische Rundschau 28*, 112–124.

Siedlecka, A. 1968: Lithology and sedimentary environment of the Hyrnefjellet Beds and the Treskelodden Beds (Late Paleozoic) at Treskelen, Hornsund, Vestspitsbergen. *Studia Geologica Polonica 21*, 53–96.

Siedlecki, S. & Turnau, E. 1964: Palynological investigations of the Culm in the area southwest of Hornsund, Vestspitsbergen. *Studia Geologica Polonica 11*, 125–138.

Smulikowski, W. 1965: Petrology and some structural data of the lowest metamorphic formations of the Hecla Hoek succession in Hornsund, Vestspitsbergen. *Studia Geologica Polonica 18*, 1–107.

Steel, R. J., Dalland, A., Kalgraff, K. & Larsen, V. 1981: The central Tertiary basin of Spitsbergen – sedimentary development of a sheared margin basin. *In* Kerr, J. W. & Fergusson, A. J. (eds.): Geology of the North Atlantic Borderlands. *Canadian Society of Petroleum Geologists Memoir 7*, 647–664.

Steel, R. J. & Worsley, D. 1984: Svalbard's post-Caledonian strata – an atlas of sedimentational patterns and palaeogeographic evolution. *In* Spencer, A. M. et al. (eds.): *Petroleum Geology of the North European Margin*, 109–135. Norwegian Petroleum Society, Graham & Trotman.

Talwani, M. & Eldholm, O. 1977: Evolution of the Norwegian–Greenland Sea. *Geological Society of America Bulletin 88*, 969–999.

Vogt, Th. 1928: Den norske fjellkjedes revolusjons-historie. *Norsk Geologisk Tidsskrift 10*, 97–115.

Winsnes, T. S., Birkenmajer, K., Dallmann, W. K., Hjelle, A. & Salvigsen, O., in press: Geological map Svalbard 1:100.000, sheet C13G Sørkapp. *Norsk Polarinstitutt Temakart no. 17.*