BASIN INVERSION AND THIN-SKINNED DEFORMATION ASSOCIATED WITH THE TERTIARY TRANSPRESSIONAL WEST SPITSBERGEN OROGEN

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ABSTRACT

Structural observations along an east-west traverse across central Spitsbergen demonstrate that the thin-skinned deformation associated with the Tertiary (Paleocene to Eocene?) West Spitsbergen orogenic belt extends across the island. The previously recognized eastern limit of deformation corresponds to a ramp in the sole thrust as it steps up from a decollement horizon in the Permian Gipshuken Formation to a flat bedding-parallel thrust in the Triassic Botneheia Member. This compressional event also resulted in reactivation of the Billefjorden and Lomfjorden fault zones causing uplift and inversion of the middle Carboniferous Billefjorden trough. Uplift of Mesozoic strata along the Billefjorden fault zone prior to subhorizontal decollement thrusting in the upper part of the Janusfjellet Formation is interpreted to cause the previously described "hiatus" in the Late Jurassic sequence, as well as omission of part of the Late Triassic-Early Jurassic succession.

INTRODUCTION

Reconstruction of the Norwegian-Greenland Sea using ocean-floor magnetic anomalies provides evidence for a Paleogene dextral transform plate boundary along the west coast of Spitsbergen. This transform plate boundary, often referred to as the DeGeer Zone (e.g., Harland, 1969), persisted from Late Cretaceous (80 Ma or Chron 25) to early Oligocene time (36 Ma or Chron 13) when the plate vector between Greenland and Eurasia changed direction and the two plates started to separate (Fig.1) (Eldholm et al., 1987; Myhre and Eldholm, 1988; Roest and Srivastava, 1988). During the latter phase a major extensional fault zone, the Hornsund fault zone, developed offshore Spitsbergen, marking the transition from continental to oceanic crust. Due to a compressional stress component across the transform plate boundary during Paleocene to Eocene time, an east-directed fold-and-thrust belt, the West Spitsbergen orogenic belt, developed along the west coast of Spitsbergen. This orogenic belt has been considered a "typical" strike-slip or transpressive orogen based on its age of formation and proximity to the DeGeer Zone (Harland, 1969; Lowell, 1972; Harland and Horsefield, 1974; Kellogg, 1975). More recently, however, it has been demonstrated that many of the features cited as typical of a transpressive orogen, like steepening of reverse faults towards the interior of the foldbelt, en echelon folds, and strike-slip faults (Lowell, 1972), instead appear to be part of a gently south-plunging fold-and-thrust-belt that extends across Spitsbergen to Storfjorden (Andresen et al., 1992). Evidences for dextral strike-slip movement appear to be restricted to the younger Forlandsundet Basin (Lepvrier, 1990; Gabrielsen et al., 1992; Kleinspehn and Teyssier, 1992). The aim of this paper is to describe the evolution of the thin-skinned fold-and-thrust structures and their kinematic interaction with the steeply dipping, reactivated Billefjorden and Lomfjorden basement fault zones. Movement on the Billefjorden and Lomfjorden basement faults is associated with inversion of a Mid-Carboniferous basin some 100 to 150 km east of

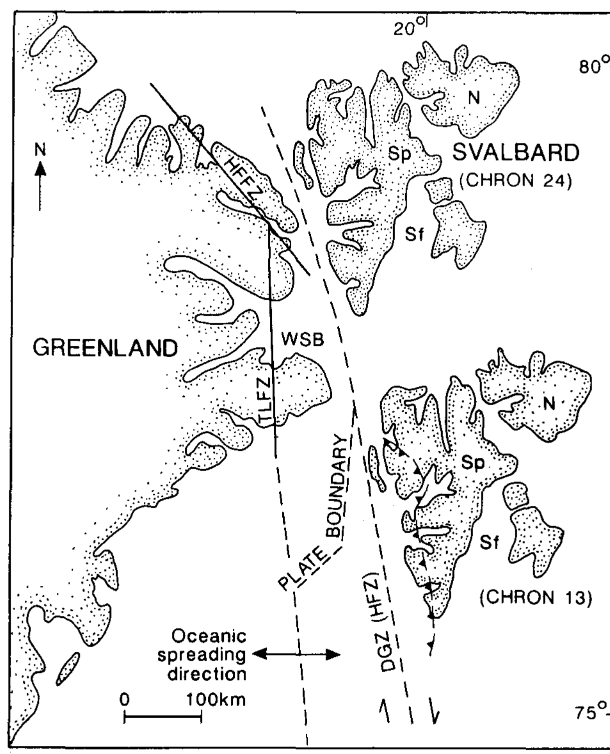

Fig.1. Early to Mid-Tertiary plate tectonic setting of Spitsbergen relative to Greenland during Chron 24 and Chron 13, based on Rowley and Lottes (1988) and Vågnes et al. (1988). DGZ = DeGeer Zone, HFZ = Hornsund Fault Zone, HFFZ = Harder Fjord Fault Zone, WSB = Wandel Sea Basin, TLFZ = Trolle Land Fault Zone, N = Nordauslandet, Sp = Spitsbergen, Sf = Storfjorden.

the inferred location of the DeGeer Zone (Haremo and Andresen, 1992).

GEOLOGIC SETTING

Depocenter and basin margins on Spitsbergen, ranging in age from late Paleozoic to present, define a northwest-southeast to north-south structural grain. This structural grain is parallel to fabric elements in the Caledonian basement and constitutes a structural inheritance during the tectonic evolution of Spitsbergen. The most prominent structural feature is the Billefjorden fault zone. Another important north-south fault zone is the Lomfjorden fault zone (Figs.2 and 3).

Five distinct depositional sequences overlie the crystalline Caledonian basement rocks in the region (Steel and Worsley, 1984; Figs.2 and 3). Devonian clastic rocks of the "Old Red Sandstone" facies, deposited in one large and several small half-grabens, comprise the lowermost sequence. The largest recognized half-graben is bordered to the east by the Billefjorden fault zone (Fig.2), which acted as a steep east-dipping reverse fault during Late Devonian crustal contraction (Lamar et al., 1986). A reversal in hanging wall/footwall relationships across the Billefjorden fault zone and possibly reactivation of several other faults during the early to mid-Carboniferous time interval resulted in a series of minor half-grabens. The best studied is the "Billefjorden trough," with its well-developed syn-rift sequence characterized by dramatic sedimentary facies changes east of the Billefjorden fault zone (e.g., Johannessen and Steel, 1992).

Late Carboniferous and Permian (postrift) carbonate and evaporite strata, with some fine-grained siliciclastic strata towards the top, make up the third depositional sequence. This shallow marine sequence is relatively uniform and covered most of Spitsbergen (Steel and Worsley, 1984).

The fourth depositional sequence, Mesozoic in age, is dominated by various coarse- and fine-grained siliciclastic sediments deposited under relatively stable shelf environments. Some authors (Harland et al., 1974; Mørk et al., 1982; Steel and Worsley, 1984; Larsen, 1987) argued for recurrent extensional movements across the Billefjorden fault zone in (1) Triassic time, to account for lateral thickness variations within the Sassendalen Group and (2) in Late Jurassic time, to account for a local hiatus within the Janusfjellet Formation. Our interpretation of these features, as will become evident below, is that most of the previously described thickness variations and the hiatus can be ascribed to Tertiary contractional deformation rather than Mesozoic extension (Haremo et al., 1990; Haremo and Andresen, 1992). Upper Cretaceous rocks are missing on Spitsbergen due to uplift and erosion, with greater uplift toward the north.
The fifth and youngest depositional sequence on central Spitsbergen is the coal-bearing Paleocene to early Eocene deposits in the Central Basin, a foreland basin to the West Spitsbergen foldbelt (Steel and Worsley, 1984; Steel et al., 1985; Helland-Hansen, 1990). Coarser grained strata, slightly younger than

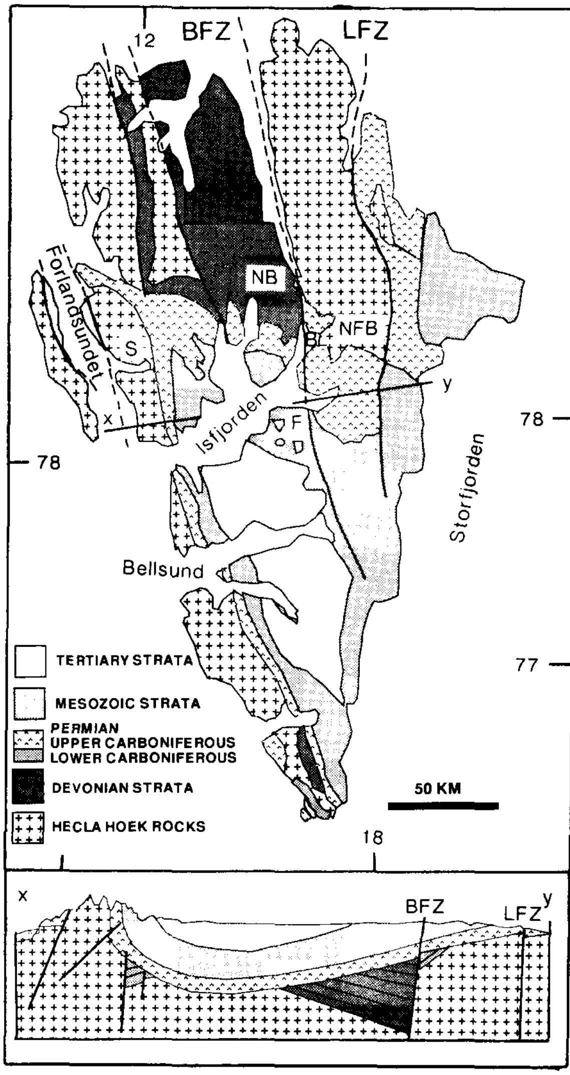

Fig.2. Simplified geologic map of Spitsbergen. BFZ = Billefjorden fault zone, LFZ = Lomfjorden fault zone, NB = Nordfjorden block, NBF = Ny Firesland Block, B = Billefjorden, F = Flowerdalen, S = St. Jonsfjorden. The profile (x-y) is schematic and not to scale, but shows the overall anatomy of the island.

the Central Basin deposits, are present in the fault-controlled Forlandsundet Basin located along the westernmost part of Spitsbergen (Kleinspehn and Teyssier, 1992).

STRUCTURAL EVOLUTION

Thin-Skinned Deformation

Structural observations in an east-west traverse across central Spitsbergen demonstrate that the contractional structures can be traced from the west coast to Storfjorden. The structural style is controlled by flats and ramps associated with development of three regionally extensive decollement horizons in:

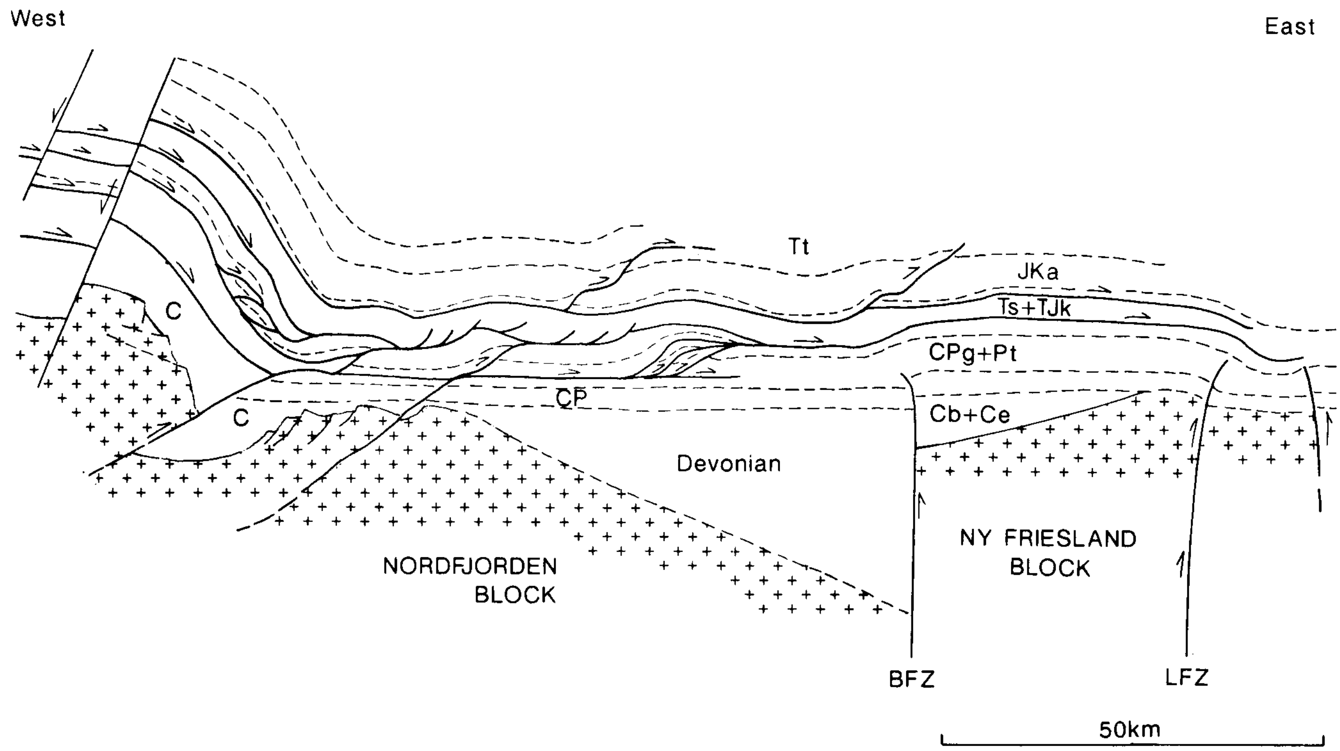

Fig.3. Diagrammatic east-west cross section across Spitsbergen showing the main structural features discussed in the text. HH=Hecla Hoek rocks, C=Carboniferous (undiff.), CP=Carboniferous/Permian (undiff.), Cb=Billefjorden Gn, Ce=Ebbadalen Gr, Cpg=Gipsdalen Gr, Pt=Tempelfjorden Gr, Ts=Sassendalen Gr (Triassic), TJk=Kapp Toscana Gr, JKa=Adventdalen Gr, Tt=Tertiary (undiff.), BFZ=Billefjorden fault zone, LFZ=Lomfjorden fault zone.

(1) the evaporites of the Permian Gipshuken Formation, (2) the Triassic Botneheia Member of the Barentsøya Formation, and (3) the Jurassic/ Cretaceous Janusfjellet Formation (Fig.3). The latter two formations are shale-dominated and rich in organic matter (Mørk and Bjorøy, 1984). Transformation of the organic matter into high-pressure fluids during deposition of the Tertiary foreland basin (Central Basin) and tectonic advance of the thrust sheets may explain the position of these decollement zones.

It can be demonstrated that the sole thrust in Permian strata steps down into Carboniferous units and even Caledonian basement rocks in the westernmost areas. In addition, Welbon and Maher (1992) have argued that some of the reverse faults in this area are controlled by extensional faults associated with the early to mid-Carboniferous St. Jonsfjorden trough (Cutbill and Challinor, 1965). The previously marked "thrust front" of the West Spitsbergen foldbelt north of Isfjorden (Harland and Horsefield, 1974) represents a ramp in the sole thrust as it steps up from a decollement zone in the Permian Gipshuken Formation to a new flat in the Triassic Botneheia Member. This latter thrust can be followed as a bedding-parallel thrust eastward to Storfjorden. Its bedding-parallel nature makes it often difficult to identify as a significant thrust, but minor splay faults, often associated with well-developed duplex structures, can be found in places where the Botneheia Member is exposed. Similar small-scale structures frequently are encountered in the lower part of the Janusfjellet Formation where it is exposed, supporting the presence of a decollement horizon at this stratigraphical level as far east as Storfjorden (Haremo and Andresen, 1992; Andresen et al., 1992).

Tertiary Basin Inversion

In the mid-Carboniferous, at least two and possibly more half-grabens developed on Spitsbergen, linked to the Billefjorden, Pretender(?), and Lomfjorden faults, respectively. The thickness of the syn-rift deposits in the Billefjorden trough, east of the Billefjorden fault zone, indicates a stratigraphic throw of a minimum of 600 m on the Billefjorden fault zone during this extensional event. Occurrence of mid-Carboniferous deposits east of the Lomfjorden fault zone suggests that this fault represented a subparallel, comparable extensional fault. Another half-graben, St. Jonsfjorden trough, existed along the west coast of Spitsbergen (Cutbill and Challinor, 1965; Welbon and Maher, 1992).

The Late Permian to Tertiary tectonic history of central Spitsbergen is controversial. Very limited tectonic activity seems to have taken place along the

Billefjorden and Lomfjorden fault zones from Late Permian to Tertiary time. Harland et al. (1974), following Parker (1966), however, have argued for uplift of the Ny Friesland block relative to the Nordfjorden block (Fig.3) during the Late Jurassic to Early Cretaceous to explain a marked hiatus in the Jurassic succession south of Isfjorden. Indeed, a reinvestigation of this area has confirmed that part of the section is missing (Haremo et al., 1993). However, we interpret this to be due to basin inversion and tectonic stripping associated with the West Spitsbergen orogeny.

Inversion Structures Along the Billefjorden Fault Zone

Due to a regionally southward tilt of the post-Caledonian strata around Isfjorden, successively older strata affected by the Billefjorden fault zone can be studied by tracing the Billefjorden fault zone northward. At Gipshuken, just north of Isfjorden, several steeply east-dipping reverse faults and a west-facing monocline offset the mid-Carboniferous syn-rift sequence (Ringset and Andresen, 1988). These fault-and fold-structures can be traced southward to Flowerdalen, where the Permian Kapp Starostin and Triassic Sassendalen Groups are clearly cut by a steep reverse fault (Flowerdalen fault, Parker, 1966).

Uplift of the Ny Friesland block relative to the Nordfjorden block (Fig.3) in this area is between 300 m and 400 m, diminishing southward. Overlying Mesozoic strata are forced into a west-facing monocline that has been partly decapitated by a decollement horizon in the Janusfjellet Formation (Fig.4). The missing part of the Kapp Toscana Group and lower part of the Janusfjellet Formation is due to this decollement zone, which cuts down-section in the direction of tectonic transport (eastward) as it propagates across the monocline. It thereby juxtaposes younger rocks of the hanging wall against older rocks of the footwall. Development of a duplex structure in the Kapp Toscana Group west of the Billefjorden fault zone (Haremo et al., 1990) suggests that uplift of the Ny Friesland block along the Billefjorden fault zone took place before movement on the structurally lower decollement zone in the Botneheia Member had ceased. The Tertiary structural evolution of the Billefjorden fault zone as we envision it is summarized in Fig.4.

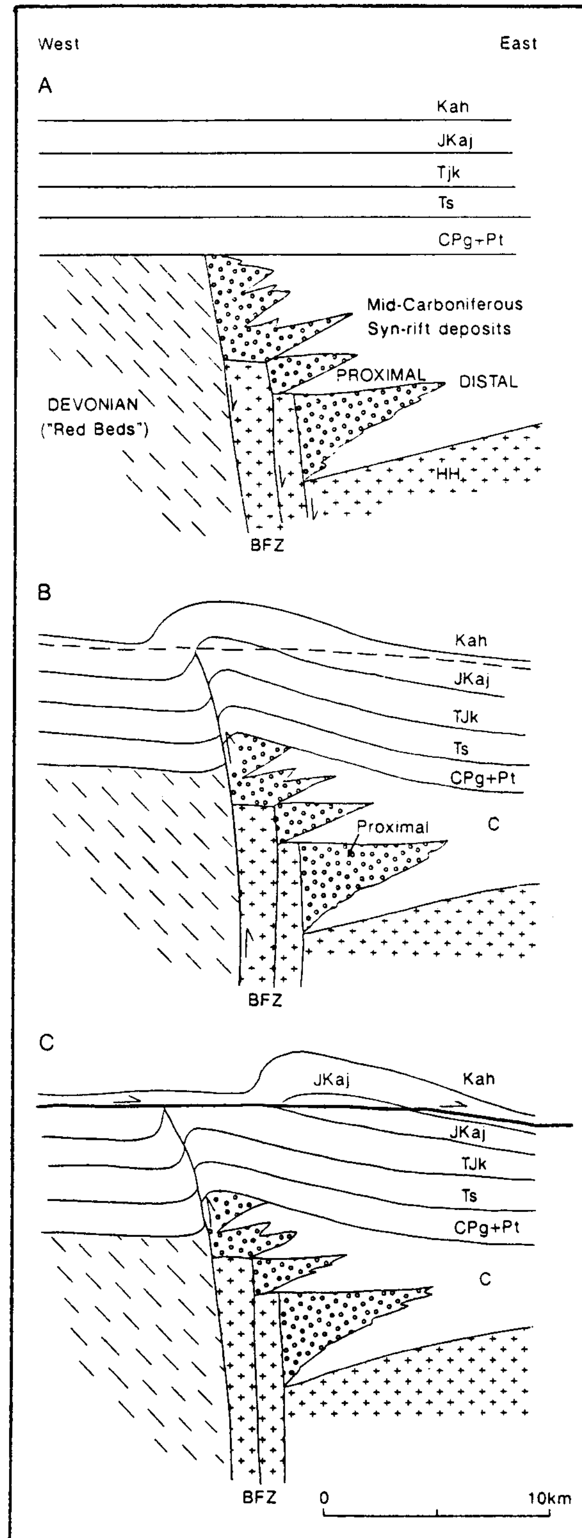

Fig.4. Structural model for the early Tertiary evolution of the positive inversion structures associated with the Billefjorden fault zone. Notice how the decollement surface in the Triassic to Jurassic Janusfjellet Fm (JKaj) decapitates the inversion structure, thus creating a reduced thickness in both the Kapp Toscana Gr. (TJk) and the Janusfjellet Fm. Kah = Helvetiafjellet Fm. of the Adventdalen Gr. See Fig.3 for explanation of symbols.

Inversion Structures Along the Lomfjorden Fault Zone

The southern segment of the Lomfjorden fault zone is characterized by a highly asymmetric east-facing anticline (Eistraryggen anticline). Units on the subhorizontal western limb are uplifted 500 m relative to the same subhorizontal beds east of the anticline (Andresen et al., 1992). The anticline can be traced northward to Sassendalen, where the lower stratigraphical levels are offset by a steep west-dipping reverse fault, which emplaces Caledonian metamorphic rocks of the hanging wall (Ny Friesland block) against upper Paleozoic rocks of the footwall (Andresen et al., 1992). Stratigraphic separation across the Lomfjorden fault in this area is approximately 700 m.

Contractional structures associated with the decollement horizon in the Botneheia Member are folded around the hinge of the Eistraryggen anticline. This suggests that movement on the Lomfjorden fault zone postdates movement on the decollement zone in the Botneheia Member and thus links the contractional movement on the Lomfjorden fault zone to the West Spitsbergen orogeny. Contractional structures also are found in the Janusfjellet Formation, but their age with respect to contractional movement along the Lomfjorden fault is uncertain.

CONCLUSIONS

The field relationships reported above demonstrate that the thin-skinned deformation associated with the West Spitsbergen orogenic belt extends across central Spitsbergen into the Storfjorden area. This is almost 100 km farther away from the transform fault linking the North Atlantic and Arctic Oceans than previously envisioned. Based on the interference between the thin-skinned contractional structures and the Billefjorden and Lomfjorden fault zones, the age of movement along these two basement-rooted fault zones seems well constrained and linked to the Paleocene to early Miocene West Spitsbergen orogeny. The reverse movement on the Billefjorden fault zone led to inversion of the mid-Carboniferous Billefjorden trough. Approximately 300 m of Tertiary uplift compared with 600 m subsidence classify the basin inversion as mild. Interaction of the thin-skinned decollement horizons with the uplifted strata above the inverted basin led to local tectonic thinning and even omission of part of the Triassic and Jurassic successions along the Billefjorden fault zone. Reactivation of the Billefjorden and Lomfjorden fault zones and their link in time with the West Spitsbergen orogeny suggest that they may be linked to the transform plate boundary (DeGeer Zone) through a decollement horizon at depth, possibly at the crustal brittle-ductile transition (ca. 15 km) as proposed by Andresen et al., 1992.

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