Influence of Carboniferous structures on Tertiary tectonism at St. Jonsfjorden and Bellsund, Western Svalbard

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The Tertiary fold-and-thrust belt on Spitsbergen can be divided into a western portion with basement-involved thrust stacks and an eastern thin-skinned portion within Upper Palaeozoic and Mesozoic platform cover strata. At both St. Jonsfjorden and Bellsund, Carboniferous strata structurally higher in the thrust stack are thicker and have a more complete stratigraphic succession than those in lower thrust sheets. These differences, along with observed structures, indicate that the basement-involved thrust stacks transported and telescoped a zone of Carboniferous structures responsible for a thicker Carboniferous basin to the west. This zone may be the eastern margin of the St. Jonsfjorden trough of Gjelberg & Steel. The spatial coincidence between the two sets of structures suggests that the Carboniferous basin geometry controlled the large-scale Tertiary structural architecture by localizing thrust stack development. At St. Jonsfjorden portions of Carboniferous fault surfaces were reactivated as Tertiary thrust ramps. In both areas a Middle Carboniferous angular unconformity played a role in Tertiary tectonism. Higher stratigraphic ascent of ramps into the platform cover before bending into a flat (bypasssing potential lower thrust flats often utilized elsewhere) and concentration of thrust ramps (decreasing spacing) are two mechanisms for localization of the thrust stack.

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Crystalline basement rocks exposed in western Svalbard (Fig. 1) were uplifted during Tertiary folding and thrusting (Orvin 1940; Birkenmajer 1981). During this event, older thrusts, with basement rocks involved, have been folded by movement on underlying younger thrusts during foreland propagation to form complex thrust stacks along the east margin of this basement uplift zone (Maher et al. 1986; Bergh et al. 1990; Welbon & Maher 1992). Thrust ramps in these stacks emerge from the basement and join extensive flats within platform cover of Carboniferous to Cretaceous age (Table 1). Permian carbonate–gypsum horizons of the Gipsdalen Group and/or Triassic and Jurassic shaley horizons are the most common flats. These flats continue to the northeast and form the major detachments of a zone of predominantly thin-skinned tectonics to the east (Harland & Horsfield 1974; Maher 1988; Bergh & Andresen 1990). The large-scale architecture of the Tertiary fold-and-thrust belt thus has been characterized as consisting of a thick-skinned western zone and a thin-skinned eastern zone (Maher 1988; Nøttvedt et al. 1988; Dallmann & Maher 1989). Andresen et al. (1988), Nøttvedt & Rasmussen (1988) and Haremo et al. (1990) recognized thin-skinned tectonism on the eastern side of Spitsbergen's Tertiary central basin, in the vicinity of the southern extension of the Billefjorden fault zone and possibly along the Lomfjorden fault zone and on Edgeøya. This greatly increases the known extent of thin-skinned tectonism. They also have argued for Tertiary reactivation along the Billefjorden and Lomfjorden lineaments, which would involve basement rocks, but offsets are an order of magnitude smaller than equivalent structures in the west coast zone.

Two areas, Bellsund and St. Jonsfjorden (Fig. 1), which straddle the transition between the zones of basement uplift and thin-skinned tectonism, may provide insight into controls on this large-scale architecture (uplift versus thin-skinned zones). The purpose of this paper is to describe and compare the relations between Tertiary and Carboniferous structures at these two areas, and to discuss the mechanical influence the older structures had on the younger structures, i.e. to discuss patterns of thrust localization. Other details of Tertiary tectonism in these two areas are described elsewhere (Maher et al. 1986; Welbon & Maher 1992).

St. Jonsfjorden area

Detailed mapping in the St. Jonsfjorden area has documented a northeast-directed thrust stack involving basement rocks and platform cover strata up into Triassic age units (Welbon & Maher, 1992). Three major thrusts, referred to collectively as the Vegard thrust complex, occur (Fig. 2) and are briefly described below from structurally lowest to highest. The *Lower Vegardfjella thrust* is subparallel to foliation and lithologic layering in basement rocks of the hanging wall. A footwall flat occurs within the Nordenskiöldbreen Formation in western exposures, while to the east, Tårnkanten

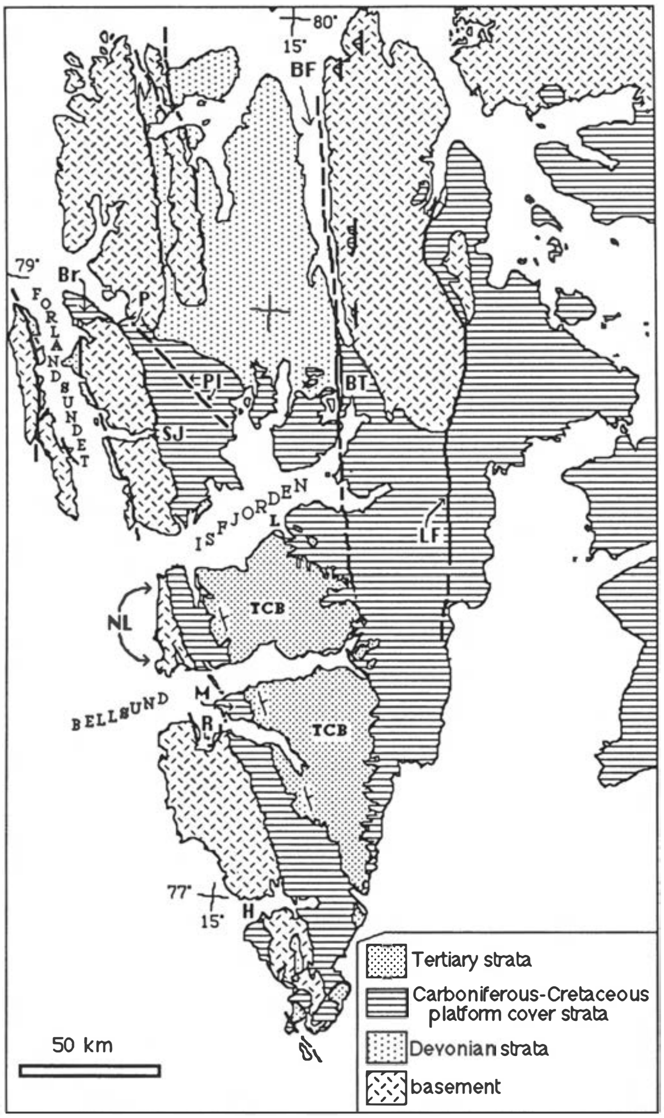

Fig. 1. Geologic map of Spitsbergen modified from Winsnes (1988). Features and localities discussed in text as follows: BF, Billefjorden fault zone; Br, Brøggerhalvøya; Bt, Billefjorden trough; H, Hornsund fjord; LF, Lomfjorden lineament; M, Midterhuken; NL, Nordenskiöld Land; P, Pretender; Pl, Pretender lineament; R, Reinodden; SJ, St. Jonsfjorden; TCB, Tertiary central basin. West coast outcrop belt of basement rocks from Brøggerhalvøya to Hornsund has a Tertiary overthrust and uplift margin on the east side.

sandstones are found in the footwall (Fig. 2). We infer the presence of a down-to-the-west Carboniferous fault in order to explain why the Lower Vegardfjella fault locally cuts down-section in the direction of transport. As the Tertiary thrust crossed the Carboniferous fault it continued at a somewhat lower stratigraphic level. A similar west-side-down Carboniferous fault is exposed in the hanging wall just above where the Lower Vegardfjella thrust continues in the subsurface to the east. Further east the thrust is thought to join a major subsurface detachment beneath an exposed fold and thrust duplex with subhorizontal enveloping surfaces (described below). The exposed thrust surface is folded, likely by underlying thrusts which also join the major, subsurface detachment to the east (Fig. 2). Significant for later considerations, the Lower Vegardfjella thrust has a common root with the Upper Vegardfjella thrust. Based on matching Nordenskiöldbreen Formation cut-offs, displacement on the Lower Vegardfjella fault is estimated at 1.5–2 km.

The *Upper Vegardfjella thrust* has a complicated geometry of hanging wall and footwall cut-offs, with minor flats (Fig. 2). It forms a major ramp that ascends to Triassic age units where it has a leading edge juncture with the Vegardbreen thrust. As part of the thrust stack, it is also folded. Nordenskiöldbreen Formation cut-offs indicate approximately 1.5 km of offset. The age relationship between Lower and Upper Vegardfjella thrusts is uncertain. The *Vegardbreen thrust* is the most notable in terms of extent and amount of movement. The thrust geometry is complex. Notable flats occur within the Nordenskiöldbreen and Bravaisberget Formation, and a truncated, overturned fold limb with abundant minor structures occurs in the eastern hanging wall. An overall northeast dip in the eastern portion of the study area is due to rotation above underlying thrusts as the highest exposed thrust in the stack. This implies a foreland-propagating thrust sequence. Some 2.5–3.2 km offset (in different cross-sections, Welbon & Maher 1992) restores cut-offs within the upper part of the Vardebukta Formation without unfolding handing-wall structures. Unfolding adds c. 1.4 km. The movement on the Vegardbreen thrust that is needed to restore the Tvillingodden Formation includes that contributed by the Upper Vegardfjella since the Tvillingodden cut-offs are northeast of the leading edge juncture between the two.

Northeast of where the Vegardbreen thrust re-emerges (Fig. 2a), Permian Kapp Starostin and Triassic strata are repeated many times mainly by folding and occasional thrusts. This is especially evident at Klampen where six fold pairs are exposed in the mountian side. The across-strike width of this zone with subhorizontal enveloping surfaces is c. 8 km. These structures are interpreted to have formed above a long flat within underlying Gipshuken Formation gypsum (Harland & Horsfield 1974; Maher 1988; Bergh et al. 1988; Bergh & Andresen 1990). This eastern zone is thin-skinned in character, and represents a contrast to the Vegard thrust stack where basement rocks are exposed and significant thrust ramps and associated uplift exist. Minimum line-length shortening across the entire study area is c. 13 km (Welbon & Maher 1992).

Differences in Carboniferous stratigraphy between thrust sheets exist and are described below from the top down. The hanging wall of the Vegardbreen thrust has the most complete and thickest section with about 1 km of Orustdalen through to Tårnkanten Formation strata. Below (hanging wall of the Upper Vegardfjella thrust) some 400 m of Orustdalen Formation, grey orthoquartzites occur, while the stratigraphic thickness of the overlying Vegardfjella through to Tårnkanten Formations is less than the 750 m structural width in cross-section (otherwise indeterminable owing to abundant small-scale

Table 1. Stratigraphic nomenclature of units discussed in text. Thicknesses are maximum values. Cutbill & Challinor (1965) provide the basic framework for Svalbard's Carboniferous units.

	Carboniferous formations recorded at:			
	Reinodden, Midterhuken, Bellsund (Cutler 1981; Hauser 1982)	Nordenskiöd Land (Hjelle et al. 1986)	St. Jonsfjorden (Steel & Worsely 1984)	Brøggerhalvøya (Fairchild 1982)
Eocene–Palaeocene: Van Mijenfjorden Group (3000 m thick)				
Lower Cretaceous–Jurassic: Adventdalen Group (1200 m thick)				
Upper Triassic–Jurassic: Kapp Toscana Group (510 m thick)				
Lower–Middle Triassic: Sassendalen Group (870 m thick)				
Lower Permian: Tempelfjorden Group (460 m thick)				
Permian–Middle Carboniferous Gipsdalen Group (1800 m thick)	Gipshuken Nordenskiöldbreen Reinodden	Gipshuken Nordenskiöldbreen Reinodden	Gipshuken Nordenskiöldbreen Tårnkanten Petrelskardet	Gipshuken Nordenskiöldbreen Scheteligfjellet Member Brøggertinden
Lower Carboniferous: Billefjorden Group (1250 m thick)	Orustdalen	Vegard Orustdalen	Vegard Orustdalen	Orustdalen
Devonian: Andre Land, Red Bay, and Siktefjellet Groups (8000 m thick)				
Crystalline basement				

folding and thrusting). Farther down in the stack (Upper Vegardfjella thrust footwall), the Orustdalen Formation is absent and c. 500 m of red siltstones, massive quartzites and subsidiary conglomerates of the Petrelskardet through to Tårnkanten Formation strata rest unconformably on the basement rocks. A west-side-down fault exposed within this thrust sheet cuts out some 200 m of the strata (Fig. 2a). Since this fault does not cut through the upper part of the Tårnkanten Formation it is assumed to be Carboniferous in age. These are likely related to Carboniferous faulting. Farther down in the thrust stack, in the footwall of the Lower Vegardbreen thrust, only c. 100 m of white quartz arenites stratigraphically intervene between Hecla Hoek basement rocks and fossiliferous limestones of the Nordenskiöldbreen Formation. Thus, notable thickness and stratigraphic changes exist across the Lower and Upper Vegardfjella thrusts. Low-angle unconformites at the base of the Nordenskiöldbreen Formation and within the underlying formations have been observed at four different localities within the St. Jonsfjorden study area.

With the northeast directed thrusting, higher thrust sheets originated from a position further to the southwest (Welbon & Maher 1992). Comparison of the Carboniferous rocks in the various thrust sheets clearly indicates a basin that was deeper to the west. The Carboniferous west-side-down faults are likely partly responsible for this geometry. Restoring continuity of the Nordenskiöldbreen Formation (removing the effect of Tertiary thrusting) results in west-side-down offsets of the unconformity contact with basement rocks. This is due to the varying thickness of Carboniferous strata in the thrust sheets. If significant thrust flats existed between cut-off points, then the above differences in stratigraphic thickness could be produced even if the pre-thrust geometry was that of a continuous wedge of sediments. However, the requisite flats do not exist along the Upper and Lower Vegardfjella thrusts. Therefore, cross-section reconstructions (Welbon & Maher 1992) indicate that these Tertiary thrusts directly reactivated (overprinted) Carboniferous faults which had pre-thrust throws (west-side-down) of c. 400 and 200 m, respectively. These faults probably formed a major step near the eastern margin of the westward-deepening basin, likely, the Carboniferous St. Jonsfjorden trough of Gjelberg & Steel (1981). Recent field work indicates that at Eidembukta to the southwest Carboniferous quartzites and crinoidal carbonates with strong similarities to the Tårnkanten Formation rest unconformably on Hecla Hoek rocks. Underlying units are absent. Thus, the St. Jonsfjorden trough appears to have its maximum thickness in between inner St. Jonsfjorden and Eidembukta.

Bellsund area

Similar relations between Carboniferous stratigraphy and Tertiary structures exist on Midterhuken, in Bellsund, some 110 km along strike to the southeast of St. Jonsfjorden. The northeast-dipping (rotated) and directed

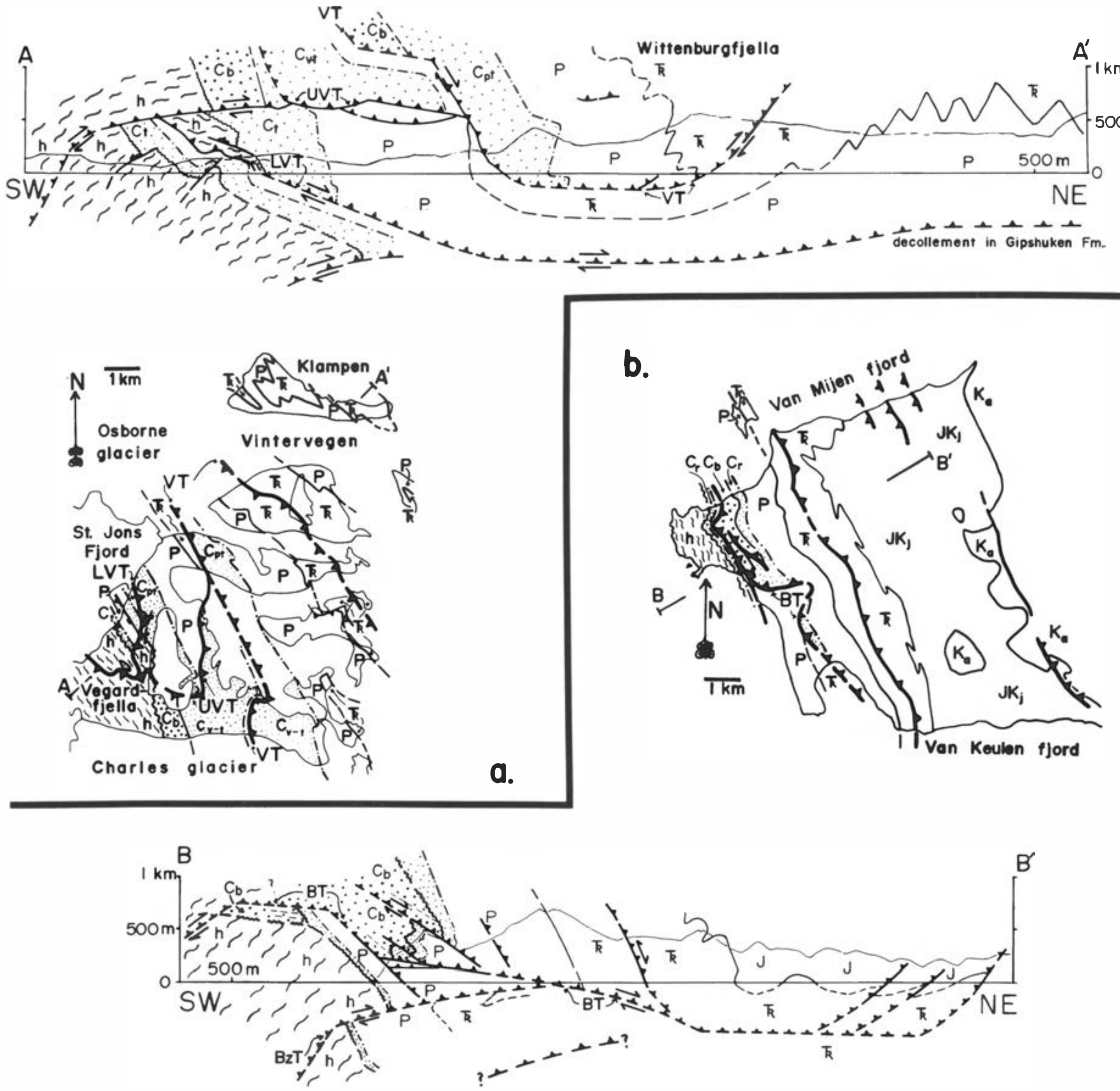

Fig. 2. (a) Simplified map and cross-section of St. Jonsfjorden study area modified from Welbon & Maher (in press). VT, Vegardbreen thrust; UVT, Upper Vegardfjella thrust; LVT, Lower Vegardfjella thrust. (b) Simplified map and cross-section of Midterhuken area modified from Maher et al. (1986) and Maher (1988). BT, Bravaisnkatten thrust; BzT, Berzeliustinden thrust (extrapolated into subsurface from the south). For both: h, 'Hecla Hoek' metamorphic basement; Cb, Orustdalen Formation strata in Billefjorden Group; Cv, Vegardfjella Formation; Cp, Petrelskardet Formation; Ct, Tårnkanten Formation; Cr, Reinodden Formation (see Table 1). The dash-dot line is the base of the Nordenskiöldbreen Formation, a useful marker horizon.

Bravaisknatten thrust (Fig. 2b) has some 250+ m of Orustdalen Formation (Billefjorden Group; Hjelle et al. 1986) strata in the hanging wall which are absent in the footwall. Instead, as at St. Jonsfjorden, only some tens of metres of sandstones and conglomerates (Reinodden Formation, Table 1) intervene between basement rocks and limestones of the Nordenskiöldbreen Formation in the footwall. The Reinodden Formation in the hanging wall is 80 m thick. With the exception of what is probably a fairly short flap along the top of the Nordenskiöldbreen Formation, the Bravaisknatten thrust is a complicated ramp that ascends to join a flat within the Triassic shales of the Sassendalen Group. Kapp Starostin Formation strata are offset about 1.2 km (Maher et al. 1986). Basement uplift and tilting that produced a northeast dip of the Bravaisknatten fault on Midterhuken is likely related to a younger underlying basement-involved thrust (Fig. 2b), possibly a continuation of the Berzeliustinden thrust to the south (Hauser 1982; Dallmann 1988). The two may join and continue as a subsurface flat in Triassic strata (Fig. 2b).

An angular unconformity between Orustdalen and Reinodden Formation strata also is exposed on Midterhuken (Fig. 3). When the unconformity is restored to horizontal underlying strata, dip c. 25–30° SW. The angular unconformity and the differences in hanging wall versus footwall stratigraphy both suggest a greater thickness of Carboniferous strate to the west. The c. 1 km of

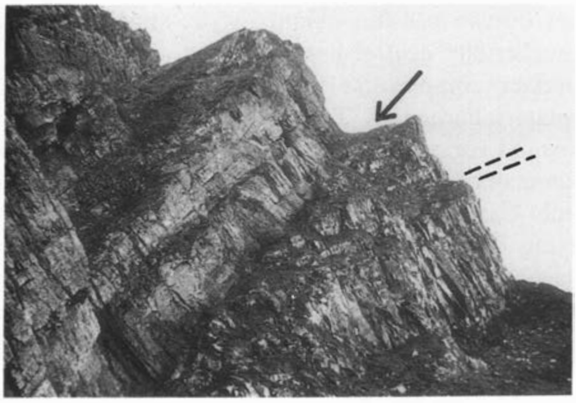

Fig. 3. Photograph of angular unconformity (arrow) on Midterhuken between orthoquartzites of the Orustdalen Formation within the Billefjorden Group and overlying pebbly dolomitic sandstones of the Reinodden Formation within the Gipsdalen Group. Dashed lines indicate trace of bedding in lower beds. Outcrop is on Midterhuken's north shore and view is to the southeast. Circa 50 m of relief is shown in the photo.

Billefjorden strata exposed on Nordenskiöld Land in northern Bellsund area (Cutbill & Challinor 1965), along strike from and somewhat to the west of Midterhuken, likely represents the thicker part of a basin. An eastern edge of the basin, the unconformity, and the absence of Billefjorden Group strata in the lower thrust sheet at Midterhuken could all be explained by erosional truncation of Billefjorden Group strata rotated above a northeast dipping listric normal fault (Fig. 4). Such a fault could be synthetic to the west-bounding Billefjorden half-graben fault of Johannessen & Steel (this volume). This would also be consistent with Reinodden Formation palaeocurrent data and facies relations, which suggest a western source area (Cutler 1981).

South of Midterhuken, on the southern shores of Bellsund, some 600+ m of steeply dipping strata of the Billefjorden Group occur in a Tertiary graben at Reinodden (Fig. 1), but are totally absent just 5 km northeast at Berzeliustinden (Hauser 1982; Dallmann et al. 1990). The Billefjorden–Gipsdalen Group contact at Reinodden is not directly visible owing to insufficient outcrop. If a Middle Carboniferous angular unconformity also exists here, limited structural data (Fig. 5) indicates that the pre-unconformity dip of Billefjorden strata is to the northeast, opposed to that on Midterhuken. With either a northeast dip or subhorizontal position of bedding, a west-side-down Carboniferous fault in between Reinodden and Berzeliustinden would explain the absence of Billefjorden strata at Berzeliustinden. Significantly, within basement rocks of westernmost Nordenskiöld Land, slivers of Billefjorden Group strata may be bounded by southwest dipping normal faults. These are of uncertain age (Hjelle 1988), but could have a carboniferous

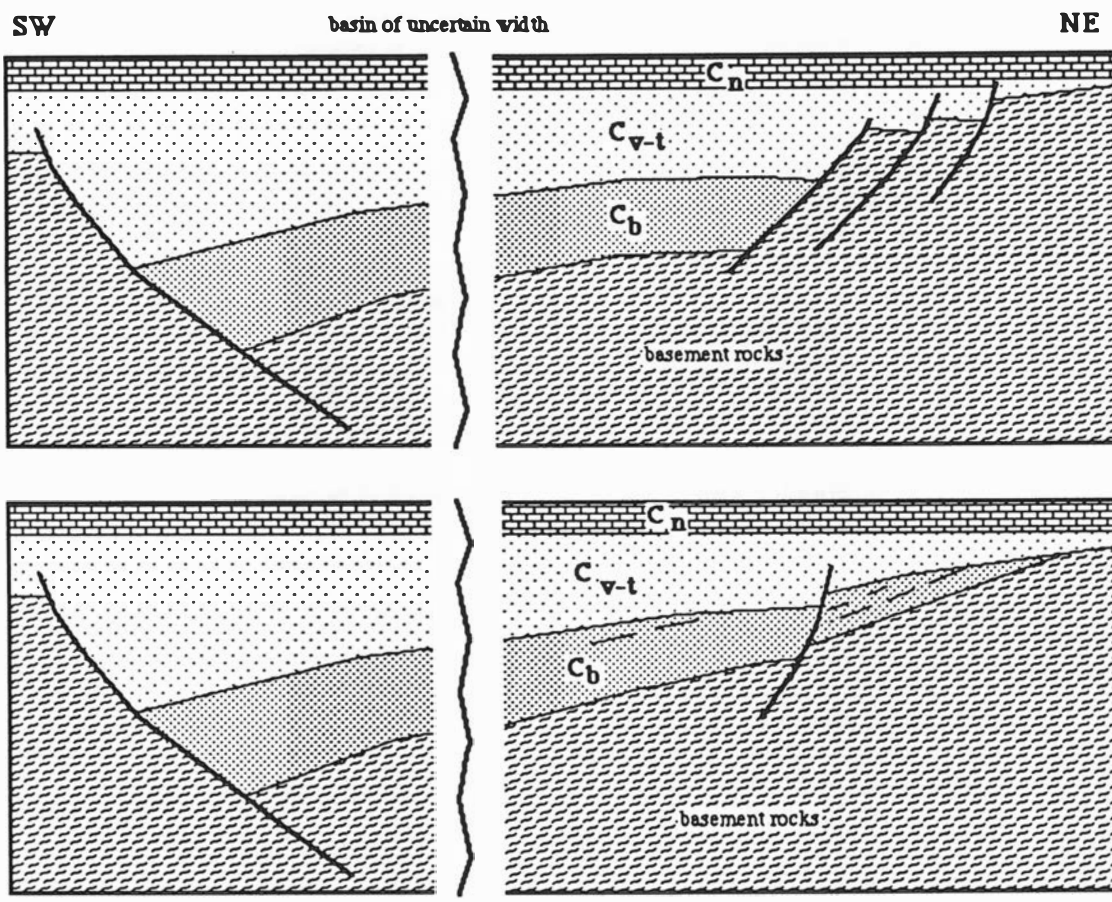

Fig. 4. A working model for the pre-Tertiary geometry of the St. Jonsfjorden trough. Upper section is for the St. Jonsfjorden area, while the lower is for the Bellsund area. Symbols as in Fig. 1.

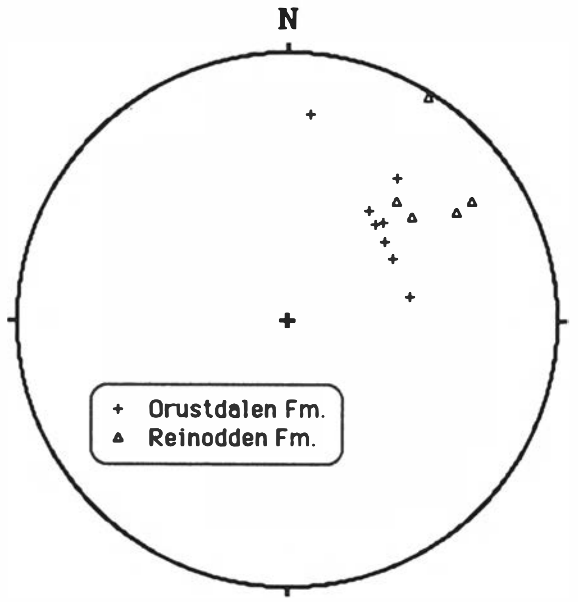

Fig. 5. Stereonet plot of poles to bedding in proximity (<40 m) to the contact between the Reinodden and Orustdalen Formations at Reinodden. If an unconformity exists here the consistently shallower plunge of Orustdalen poles to bedding suggests a northeast dip when younger Reinodden beds are restored to horizontal.

movement phase (Mann & Townsend 1989). A member of such a fault set could explain the stratigraphic disparity seen to the south.

As a working model (Fig. 4), a listric, northeast-dipping normal fault could then explain both the geometry of the angular unconformity between Midterhuken Carboniferous stratigraphic units, facies relations within the Reinodden, and the large thickness of Billefjorden Group strata preserved on Nordenskiöld Land. Such a fault would have to lie offshore Bellsund since Billefjorden Group strata preserved in the presumed half-graben structure are found near to the west coast of Nordenskiöld Land (Hjelle et al. 1986; Hjelle 1988). Southwest dipping normal faults seen in Nordenskiöld Land and at St. Jonsfjorden could be included in the half-graben model as an antithetic set. Elsewhere, the lesser thickness of Carboniferous strata may be due simply to an erosional truncation of tilted Billefjorden Group strata. Such a geometry may be an approximation of the structural template that Tertiary tectonism inherited.

Other localities

Descriptions of other localities suggest a relation between Tertiary and Carboniferous structures. South of Bellsund, in interior Wedel Jarlsberg Land at Supanberget, facies changes in Carboniferous strata involved in basement-cored fold-thrust features are notable, and faults in thrust hanging walls may be Carboniferous in age (Dallmann & Maher, 1989). Further east, Triassic strata are repeated by folding with subhorizontal enveloping surfaces and by minor thrusts in a thin-skinned style, until the east limb of the Tertiary central basin syncline is reached.

Greater complexities in a Carboniferous structural template inherited by Tertiary deformation exist in the Hornsund region to the south of Wedel Jarlsberg Land. Birkenmajer (1964) and Dallmann (this volume) describe Middle Carboniferous unconformities that truncate underlying fold and fault structures. Worsely (1986) describes an Early Carboniferous basin, the Hornsund trough, which develops an inverted median element (uplifted) during the Mid-Carboniferous. Notable Tertiary folding and uplift occur near the eastern part of the inner Hornsund trough (of Carboniferous age) margin (Birkenmajer 1964; Gjelberg & Steel 1981; Worsely 1986; Dallmann this volume). A pre-Tertiary configuration for Hornsund would thus be more complex than schematically shown in Fig. 4.

In Nordenskiöld Land, where 1000+ m of Billefjorden strata occur, an eastern margin of the St. Jonsfjorden trough is not exposed and should lie in the subsurface to the east. The thrusts associated with the basement uplift, across which the same stratigraphic disparity as at Vegardfjella and Midterhuken might be seen, also are likely in the subsurface (Faleide et al. 1988; Ohta 1988). This is consistent with the overall northerly structural plunge in the Bellsund area and the southerly structural plunge in the Isfjorden area. Nordenskiöld Land is thus the structurally highest portion of the Tertiary fold-and-thrust belt (Maher et al. 1989), and only the very top of the thrust stack is exposed. The scale of the Carboniferous structures suggested by surface data at Bellsund and St. Jonsfjorden is such that these features might be resolvable in seismic sections in Isfjorden (Nøttvedt & Rasmussen 1988).

At Brøggerhalvøya, at the northwestern end of onland exposures of the Tertiary fold-and-thrust belt, Carboniferous stratigraphic complexities occur also (Dineley 1958; Fairchild 1982; Welbon et al. this volume) in general spatial coincidence with basement involved Tertiary thrusts (Challinor 1967). Some of the thrusts are folded and locally foreland-dipping, traits also seen at St. Jonsfjorden and Bellsund. The exact relationship between Carboniferous and Tertiary structures is largely uninvestigated at Brøggerhalvøya. However, as occurs to the south, greater thicknesses of Billefjorden Group strata lie to the west and in higher thrust sheets (Orvin 1934; Challinor 1967). Welbon et al. (this volume) describe a Mid-Carboniferous angular unconformity as responsible for the westward thickening, and which has a similar geometry to the one on Midterhuken.

Definition of the St. Jonsfjorden trough

Dineley (1958) originally noted that 'considerable variations in character take place' in Carboniferous and Permian rocks along Spitsbergen's west coast. Gjelberg & Steel (1981) defined the St. Jonsfjorden trough with an eastern boundary that ran from Brøggerhalvøya, through inner St. Jonsfjorden, into western Nordenskiöld Land (their fig. 1). A continuation of their border to the south would pass through Midterhuken and continue to the southeast. This configuration is very close to the zone of Carboniferous structures described above. Therefore, we believe this zone to be the eastern margin of the St. Jonsfjorden trough in Mid-Carboniferous times.

However, Steel & Worsely (1984) subsequently redefined the eastern margin of the St. Jonsfjorden trough to trend more towards the west, and to follow the Pretender lineament (Fig. 1), significantly to the east of the St. Jonsfjorden area. This configuration is utilized by Bergh & Andresen (1990), who argue that Carboniferous structures associated with the Pretender lineament may have affected the Tertiary structural style in east Oscar II Land. In the redefined basin geometry the western boundary of the trough passes near the St. Jonsfjorden area (Steel & Worsely 1984; Bergh & Andresen 1990). Two difficulties exist with this margin configuration. Welbon et al. (this volume) investigated the Pretender lineament at Pretender (just east of Brøggerhalvøya) and found no evidence of Carboniferous structures. Also, the Tertiary structures at St. Jonsfjorden are northeast directed, and therefore the Carboniferous basin was thicker to the west, not the east (see above). If the rotated, northeast dipping thrusts had been misinterpreted as southwest directed structures, then the St. Jonsfjorden trough could be interpreted to lie to the east, but this is not the case. Therefore, we believe the original definition of the St. Jonsfjorden trough (Gjelberg & Steel 1981) is more useful, and we would extend it at least to southern Bellsund. Carboniferous structures that affected Tertiary tectonism in Oscar II Land (Bergh & Andresen 1990) would then represent another zone unrelated to the St. Jonsfjorden trough.

Limited data available suggest that the trends of Carboniferous and Tertiary structures are subparallel. A subhorizontal rotation axis for tilting of Billefjorden strata underneath the Mid-Carboniferous unconformity at Midterhuken is subparallel to the rotation axis associated with Tertiary deformation. At St. Jonsfjorden gentle folds truncated by Carboniferous unconformities have subparallel axes to Tertiary folds (Welbon & Maher 1989, 1992). While the westward thickening of Carboniferous clastics and the associated Carboniferous structures seen at Brøggerhalvøya, St. Jonsfjorden, Midterhuken and the south shore of Bellsund could be associated with different basin margins, the above data and parsimony leads us to postulate they are all part of one basin margin. The nature of the eastern margin of the Carboniferous basin is likely segmented along strike, with step faulting at some locales, and tilting and erosional truncation (a hinge margin) at others.

Billefjorden Group orthquartzites at St. Jonsfjorden and Bellsund slow little evidence of being proximal to a fault during deposition. They are well sorted, rounded sandstones and minor conglomerates with notable compositional maturity. In contrast, Gipsdalen Group clastics show compositionally immature facies that suggest notable relief and easily could be proximal to syndepositional faults (e.g. Gjelberg & Steel 1981; Steel & Worsley 1984). We therefore use the term St. Jonsfjorden trough for the Gipsdalen and not the Billefjorden Group. The original geometry of the basins during Billefjorden times is very difficult to establish.

Discussion

In summary, at both St. Jonsfjorden and Bellsund our studies indicate Tertiary thrust stacks with basement involvement are spatially coincident with transported Carboniferous structures. Carboniferous clastics on the west side of these older structures are thicker and more stratigraphically complete than those on the east side. To the east of this zone a thin-skinned style of Tertiary deformation exists. Thus, we infer that the margin structures of a continuous(?) Carboniferous basin (the St. Jonsfjorden trough of Gjelberg & Steel 1981) controlled in some manner the large-scale architecture of the northeast directed and propagating Tertiary fold-and-thrust belt. In at least one case (St. Jonsfjorden) Carboniferous faults were directly reactivated. In that, what was once a basin margin is now the edge to the zone of basement uplift by Tertiary thrusting, the basin has been inverted.

The coincidence of St. Jonsfjorden trough's eastern margin and the margin of the Tertiary basement uplift raises the question as to the mechanics of localization and reactivation. With folded, foreland-dipping, northeast directed thrusts the eastern margin of thick-skinned tectonics can be treated in part as a complex, foreland-propagating antiformal or thrust stack (Maher et al. 1986; Welbon & Maher, 1992; Bergh & Andresen, 1990). Consideration of the different stratigraphic levels at which basement-involved ramps bent into a major flat may provide insight into the localization process. Both at St. Jonsfjorden and Midterhuken (Upper Vegardbreen and Bravaisknatten thrusts, respectively) the thrust that most clearly reactivates or nucleates close to a Carboniferous fault associated with the basin margin is a ramp that climbs up to a flat within Triassic strata. They bypass horizons of the Nordenskiöldbreen and Gipshuken Formation which form such prominent long flats both to the northeast and southwest of the basin margin (e.g. the Vegardbreen thrust, which emerged from within the Carboniferous basin, has a notable flat near the top of the Nordenskiöldbreen Formation).

This behaviour is predicted by Wiltschko & Eastman (1983) and Schedl & Wiltschko (1987). Using field studies, photoelastic models, and finite element analysis of a stepped basement cover contact they conclude that a basement fault can: (1) concentrate stress above the basement fault in the cover and therefore localize ramps, and (2) produce a stress shadow in the cover strata on the up side of the basement fault. As the Tertiary fold-and-thrust belt on Svalbard propagated northeastward, Carboniferous basin margin structures likely exerted a mechanical control as a stress riser that produced longer ramps with greater stratigraphic ascent, thereby increasing the component of uplift and inverting the St. Jonsfjorden trough. Potential flats on the eastern side of the margin were bypassed because of the effect of the stress shadow. Inversion of the basement step (Carboniferous basin) by thrusting and uplift would ostensibly remove the stress shadow. After such inversion a greater differential stress could then be transmitted in the foreland direction and thrusts developing foreland (E) of the margin could resume joining deeper flats (within Gipshuken Group, Fig. 2a). These would then fold and rotate the earlier formed margin-associated thrusts.

Boyer & Elliot (1982) and Mitra & Boyer (1986) describe a general scheme for the development of thrust duplexes, of which antiformal stacks represent a special case where s (spacing between imbricate slices) is approximately equal to u (the amount of displacement on each thrust). While the thrust stacks discussed here differ significantly from their general scheme (they involve basement, they do not ascend to common flats, and they may not all have a common root), it may serve as a useful guide. From a least energy perspective, hinterland-dipping duplexes (where $u < s$) are favoured, and these are found in the thin-skinned section of the fold and thrust belt in Oscar II Land (Bergh & Andresen 1990). At the basin margin, however, s may have been controlled by the pre-existing Carboniferous faults, and Tertiary thrusts concentrated in the same zone of weakness that controlled localization of the Carboniferous faults. The local reduction in s could then produce an antiformal stack instead of hinterland dipping duplexes.

In addition to the above mechanisms, at Midterhuken the Carboniferous angular unconformity clearly played a specific role where thrust flats within Billefjorden shaley horizons had an uplift component due to the original southwest dip. Detachment horizons available within the St. Jonsfjorden trough below the unconformity (at shaley horizons) would by necessity ramp up into the younger platform cover strata at the basin margin, also locally aiding in basement uplift and the inversion of the trough. With more detailed seismic sections from Bellsund the role of the above-mentioned factors might be better evaluated.

Conclusions

In summary, from interior Wedel Jarlsberg Land in the south to Brøggerhalvøya in the north, a Tertiary thrust stack has transported and telescoped stratigraphy and older structures that suggest significant westward thickening of a Carboniferous basin. This zone of Carboniferous structures and associated thickening conforms with early (Gjelberg & Steel 1981), but not later depictions of the St. Jonsfjorden trough. A more thin-skinned Tertiary deformation style exists to the east of this thrust stack. Hence, the Carboniferous structures appear to have controlled the large-scale architecture of the Tertiary fold and thrust belt. The trough margin may have localized the Tertiary thick-skinned margin and produced thrust stacks and associated uplift by: (1) a 'stress riser' effect owing to basement steps along the margin, where ramps bypassed lower potential flats within the Gispdalen Group and instead joined flats in the Triassic units (2) direct reactivation of Carboniferous faults and a decrease in spacing between ramps, and (3) ramping from flats within the St. Jonsfjorden trough (absent to the east) to flats higher in the stratigraphic section.

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