TERTIARY TECTONICS OF SVALBARD

Extended abstracts from Symposium held in Oslo 26 and 27 April 1988

"The problem of the driving force is still unsolved ..."
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PREFACE

The importance of Tertiary tectonics on Svalbard has currently been recognized by many academic and industrial geoscientists. Research on this topic is going on in many different areas by various groups of scientists. This symposium is a first attempt to bring together people interested in these problems and to try to synthesize our present state of knowledge.

Therefore, in December 1987, we decided to organize an informal symposium on a national level in order to exchange information and to discuss future foci of subjects and study areas. As seen from the number of abstracts, participation was extensive and much greater than expected. About 60 participants from 22 institutions and companies attended. Most of them were Norwegian or settled in Norway, but scientists from Denmark, Germany, England, France and the United States were also present.

The talks presented during the symposium included structural descriptions of many areas within southern and central Spitsbergen that were deformed in Tertiary times. Several seismic sections, both on-land and off-shore, were also presented. Possible contemporaneous deformation on northeast Greenland was discussed. Several speakers emphasized their considerations on the expected strike-slip movement between Svalbard and Greenland, and the meeting ended up with proposing and discussing models on the plate-tectonic evolution of the Greenland - Barents Sea plate boundary, the sequence and timing of events and the nature of the Spitsbergen thrust-and-fold belt.

Several of the talks dealing with central Spitsbergen emphasized that Tertiary deformation is more extensive and occurs further east than hitherto recognized. Much of the thrust displacement is thin-skinned with major décollement zones localized within incompetent late Carboniferous / early Permian evaporites and Triassic / Jurassic shales. The overlying Cretaceous and Tertiary strata have moved passively on top and show relatively little internal deformation. Deformation of the remaining upper Paleozoic strata and the Caledonian basement east of the fold belt is characterized by steeply dipping reverse faults (thick-skinned tectonics).
The general structural style of the fold belt is very similar to that known from marginal thrust-and-fold belts of compressive orogens. At various localities, balanced sections provided estimates of lateral shortening. However, how much of the thin-skinned shortening observed in the incompetent layers is really an expression of crustal shortening, and how much of the thickening is compensated by thinning elsewhere due to migration of material within a more rigidly behaving frame of competent lithologies, has not been studied quantitatively yet. The Lomfjorden and Billefjorden Fault Zones have undoubtedly been reactivated as steep reverse faults during the Tertiary movements.

There was a general consensus at the conference that the exposed part of the Spitsbergen fold-and-thrust belt cannot be explained as a part of a major flower structure as proposed previously. Folding and thrusting are generally due to convergent east-west movements causing a total shortening of several tens of kilometers. The mechanical problem of the driving forces turning the Tertiary transform movement between Greenland and Svalbard into a dominantly compressive deformation is not yet solved.

A model favoured by some participants explains the early Tertiary tectonics as decoupled strike-slip and compressive processes, where the major strike-slip faults were almost frictionless. The Forland area may represent a transitional zone with alternating extension and compression, although earlier attempts in explaining this history with one persisting stress regime now seem to have failed. Decoupling seems to be little developed along the southwestern Barents Shelf margin, the Hornsund and Knølegga Faults, where Tertiary transform movements mainly reactivated inherited lineaments along older block boundaries. Different stress fields were thus activated in different areas, giving rise to the contemporaneous formation of basins and ridges. Deep seismic sounding confirmed that the mantle-crust boundary was involved in the movements.

The general timing of the tectonic regimes in Svalbard and the Barents Sea as stated in the modern literature (transform movement with convergence from late Paleocene through Eocene, transform movement with passive margin formation from Oligocene onward) seems to be well established. The closer timing of individual deformation events, however, is still problematic, and the meeting did not succeed in pointing out distinct trends valid for more than local areas. The timing of events in adjacent parts of Greenland generally of Cretaceous age cannot be correlated with the deformation recognized on Spitsbergen at the time being.

One of the important subjects not touched upon at the meeting is the relationship between tectonics and the Tertiary sedimentary record. Detailed facies analyses of the Paleocene to Eocene sedimentary beds in different regions, determination of transport directions and heavy mineral analyses would help in reconstructing the development and migration of positive and negative structures associated with transcurrent movement between Greenland and Svalbard. This point should be stressed in future research and is supposed to be one of the foci of interest at future meetings.
The extended abstracts of the talks are listed in the order in which they were presented at the meeting. We are grateful to all participants for having enabled the success of the symposium. We thank 'Norsk Polarinstitutt' and the Department of Geology of the University of Oslo for sponsoring the symposium. The publication of extended abstracts was sponsored by the 'Samarbeidsprosjektet Norsk Hydro/Store Norske Spitsbergen Kulkompani'.

The interest in the subject of Tertiary tectonics on Svalbard documented by the participants of the meeting has encouraged us to envisage a subsequent meeting in 1990.

Oslo, July 1988

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The basement of Western Spitsbergen Orogenic belt has two important traits:
1) unconformities representing orogenic events, and
2) possible terrane boundaries formed during the Caledonian period.

1) The oldest orogenic event hitherto recognized is of Grenvillian age, which is marked by the Konglomeratfjella Conglomerate in Wedel-Jarlsberg Land and the Slingfjella Conglomerate in the Hornsund area. No radiometric age has been obtained for this age in W-Spitsbergen, but this event is constrained by lithostratigraphic correlation with other parts of Svalbard. The rocks below the unconformity are psammo-pelitic clastics and carbonates, varying from low grade phyllites in the Orvindalen area in the NW to amphibolite facies of Barrovan type in the NW and SE of Hornsund. Judging from the rocks just below the unconformity, the NW part around Orvindalen was eroded to a shallower level than the Hornsund area during late Grenvillian Orogeny. When the unconformity is restored into horizontal position, the Grenvillian structures are W-verging, overturned folds with a ESE strike and very gentle axial plunge. Bimodal plutonic rocks in NW Hornsund could be Grenvillian intrusives, but this is not proved yet. The pre-Grenvillian rocks are not exposed in the area north of Bellsund and south of Kongsfjorden.

Late Riphean shallow marine clastics and carbonates overly the unconformity. They are apparently thinner in the Hornsund area than in the north of Isfjorden, and are
2–4 km thick in the latter area. Overlying tilloids of Vendian age have some basic rocks and green phyllite layers in them.

Two unconformities with sub-Cambrian and sub-Ordovician stratigraphic hiatus, have been stratigraphically recognized in Hornsund. Two K/Ar ages of ca. 550–580 Ma may be due to the sub-Cambrian event, and the basic rocks in the tilloids may be related to this event. A late Precambrian event has been known as the Baikalian Orogeny in the circum Arctic areas and some U/Pb and Ar\(^{40}/^{39}\) ages from NW Spitsbergen and Rb/Sr ages from Nordaustlandet fall within this period. However, the nature and extent of this event is not yet clear in Svalbard.

Beside above two, Middle Ordovician, Middle Silurian, Latest Silurian-Early Devonian and Late Devonian events have been recognized within the Caledonian period. An oceanic suture, revealed by the Motalafjella high-pressure metamorphic complex, south of St. Jonsfjorden, was formed in the Middle Ordovician event and was overstepped by flyschoids of Late Ordovician-Early Silurian age. The Middle Silurian event strongly folded the flyschoids. Most migmatites and granites in northern Svalbard were emplaced during Middle Silurian and later. The Haakonian (Latest Silurian-Early Devonian) and Svalbardian (Late Devonian) events are essentially extensional and transcurrent faulting might also have occurred.

A N-S structural trend is common all over the Svalbard Caledonies, and a E-W compressive stress is inferred. A conjugate set of faults, NE-SW and NW-SE in strike and steep dips, were developed in a later stage. These two directions of faults and longitudinal faults are the essential fractures in the Caledonian terranes along the northern side of Svalbard.

2) The Late Caledonian event of Middle Silurian time is recognizable over the whole Svalbard, but the Early Caledonian event is of different age in W and NW Spitsbergen. The later area had a metamorphic event to form eclogite around 550–500 Ma ago, while the former area had a high-pressure metamorphism to form blueschists around 480-470 Ma ago. This infer that the amalgamation of these two areas is Middle Ordovician in time.

The oceanic rock assemblage and blueschist-eclogite metamorphism in the Motalafjella, reveal a narrow oceanic suture zone which may separate two terranes on either side of the zone. This suture is traceable as discontinuous
serpentinite bodies along the eastern boundary fault of the Forslandsundet graben for about 50 km to the north of St-Jonsfjorden in a NNW direction, while the southern extension is not clear. The zone occurs as a thrust slice with a gentle W-dip and form a part of a probable accretionary prism developed during Middle Ordovician time. The thrust imbricated structures, each thrust unit is 1-3 km in thickness, extend over the whole area from Isfjorden to Engelskbukska. It seems that there is no newly formed thrust in this area and all Tertiary stresses are accommodated by the reactivation of these Caledonian structures at varying scale, from large thrust to individual cleavage slips, in manners of non-affine displacement.

Similar thrust imbrication structures exist in the N-Wedel-Jarlsberg Land, while the Caledonian structures in the W Nordenskiold Land and Hornsund-Sørkapp areas are mainly steep in dip. These differences in the basement structure are reflected in the deformation of platform sediments of post-Devonian age; large thrust and complex overturned fold structures developed in the E Oscar II Land and E Wedel Jarlsberg Land, while relatively simple, large fault-propagation folds were formed in the W Nordenskiold Land and middle Sørkapp Land. Some Upper Paleozoic-Mesozoic beds overly the steep structured basement in the latter two areas. These younger beds do not show strong folding, but instead, are flat or weakly tilted by block faulting.

A typical thrust imbricated structure develops along Kongsfjorden with a NW-SE strike, and a large structural break has hitherto been inferred along the fjord. Recent field work shows that the Caledonian rocks show a gradational change from a high to low grade across the fjord. The axial plunge of Caledonian rocks in NW Spitsbergen is gently to the south and low-grade rocks can thus be expected on the southern side. Slivers of mylonitic granites and sillimanite-bearing gneisses in the southern side of the fjord indicate that high grade rocks similar to the northern side, underly in the Brøggerhalvøya area. The NW trend along Kongsfjorden appeared in the Late Paleozoic time as a boundary of sedimentary facies change and might have been accentuated during the Middle Cretaceous uplift of N Spitsbergen, to form a hinge of tilting along the fjord. This hinge zone developed as the Brøggerhalvøya thrust zone during the Tertiary deformation period.

Devonian extensional faulting occurred subparallel to the
Caledonian axial trend, in a N-S direction, and controlled the positions of Late Paleozoic sedimentary basins. The western boundary faults of the Devonian graben extend to the south to control the position of the present boundary between the basement and platform cover strata in Oscar II Land.
Tertiary tectonic movements in the archipelago to a large extent represent reactivation of a series of major lineaments with a long history of differential movement. The most important of these are the Lomfjorden/Agardhbuks, Billefjorden, Inner Hornsund and Paleo-Hornsund Fault Zones.

The late Devonian Svalbardian deformation has often been advocated as representing sinistral movements along the Billefjorden Fault Zone in the order of several hundred kilometres. Recent work has suggested that this is not the case, but a detailed reappraisal of the entire Svalbardian deformation zone is necessary.

The Carboniferous and Permian were characterized by the development first of isolated narrow grabens, then by ongoing regional transgression and increasing tectonic stability. This general trend was however interrupted by marked local basin inversions - e.g. in Hornsund and on Bjørnøya. These features, together with the possible en echelon arrangement of western depositional basins, may suggest lateral movements along the Paleo-Hornsund Fault Zone.

The late Permian to Cretaceous is generally characterized by flexuring and differential subsidence along most lineaments. More marked movements may have occurred along the Lomfjorden/Agardhbuks and Billefjorden lineaments around the Jurassic/Cretaceous boundary; these, together with penecontemporaneous intrusive and extrusive magmatic activity, may reflect late Kimmerian tectonism. The Svalbard platform was however a largely stable entity during the entire Kimmerian phase - major movements being taken up along the platform's southeastern and western margins.

An increasingly important constraint on depositional patterns from the late Triassic onwards was a general uplift of the platform's northern margins. This trend culminated in marked regional uplift and erosion during the late Cretaceous.
Detailed 1:10,000 mapping of ca. 20km² of Blomstrandhalvøya has revealed several previously undescribed outcrops of red sandstones and conglomerates which have, together with the underlying basement, been subjected to high-level post-Caledonian folding and thrusting.

Lithologically, the peninsula is dominated by low-grade, late Precambrian (Hecla Hoek) marbles and blue-grey calcareous to dolomitic schistose limestones. The schistosity of the marbles strikes N-S and dips steeply to the east. Fold axes within this fabric plunge mainly to the SW or NE, although some NW-SE and N-S directions are found.

The intersections of the earlier schistosity and later brittle fabrics causes these rocks to fracture, and it was this property which frustrated the London Marble Company's attempts to quarry the marbles for decorative purposes some 80 years ago.

In addition to the Old Red Sandstone outcropping along the eastern seaboard of the peninsula (Gjelsvik 1966) four other localities have been discovered. The largest, to the NE of London, is ca. 100m wide and about 20km long from N to S. Along the western flanks the red beds of all localities are in normal transgressive/erosional contact with the underlying Hecla Hoek marbles. However, along their eastern margins, they are overthrust by the marbles which exhibit thrust-related NW- to W-vergent folds, and the red beds themselves are imbricated by many small thrust faults. Therefore, whilst these red beds may have been deposited in a N-S trending graben-like structure, they have subsequently been displaced by N-NW directed thrust faulting. The transport direction of this thrusting contrasts with the N to NE high level (Tertiary) displacements seen on Brøggerhalvøya.

The age of the red beds on Blomstrandhalvøya is uncertain, but on the nearby Lovén Islands similar rocks contain Devonian plant remains. On Brøggerhalvøya, mid-Carboniferous microfossils are found in limestones associated with red beds. The high-level semi-brittle to brittle defor-
mation is clearly post-Caledonian, but is it the product of Svalbardian or later Tertiary strike-slip related tectonics?
Geoffrey M. Manby

TERTIARY FOLDING AND THRUSTING IN NW SVALBARD


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The Brøggerhalvøya-Engelsbukta area of NW Svalbard presents an excellent opportunity to assess the extent of basement (Hecla Hoek) involvement in the Tertiary fold and thrust belt. The principal structural features of the area from the thrust belt to the foreland are outlined (Fig 1a & b) and their implications for tectonic models are discussed.

The gross structure of the area consists of a series of N-NE vergent thrust nappes dominated by post-Devonian strata in the NW of Brøggerhalvøya and by the Hecla Hoek in the SE of the peninsula, Engelsbukta and northern Oscar II Land. A major N-S fault zone in the vicinity of Brøggerbreen (Fig 1a) separates the nappes in the NW from those to the SE and S but does not penetrate the structurally higher nappes to the S. This fault is interpreted as a transfer zone which has accommodated a more northerly displacement of the south-eastern nappes.

In the NW of Brøggerhalvøya the younger rocks are stacked into three major nappes. The broad open folding of the Brøggerinden fm, along the Kongsfjorden coastline indicates that the floor thrust to the lowest exposed nappe is ramping up at this point and may outcrop in fjord. The roof thrust to this nappe coincides with two N vergent duplex structures both in the Nordenskioldbreen fm, which are well exposed on the SE slopes Scheteligfjellet. The upper duplex is considerably more deformed than the lower. The omission of the Gipshuken to Tertiary strata suggests that this nappe is not lowest in the stack and thrusts cutting up-sequence should be present beneath the fjord. Although the floor thrust to the overlying nappe is in the Nordenskioldbreen fm, S, towards the hinterland, it cuts down sequence into the basement (Hecla Hoek). The narrow strip of Hecla Hoek along the shore SE of Kulmodden represents the lowest exposed segment of this nappe. The whole of this higher nappe is folded into an overturned (N vergent) anticline-syncline pair and a late thrust repeats part of the lower limb of the syncline carrying Gipshuken over Kapp Starostin strata. The highest of the three nappes in the NW contains a Hecla Hoek to Gipshuken sequence floored by a low angled S-SW dipping thrust. The high cut-off angle between this thrust and the steeply dipping, overturned hanging wall rocks indicates that overfolding preceded thrusting and that this is a fold nappe in contrast to the lower thrust nappes. At least 12km of crustal shortening are required to account for the deformation recorded in the uppermost nappe. Taken together the whole nappe sequence in NW Brøggerhalvøya must represent a minimum of 18km of crustal shortening.

SE of the Brøggerbreen fault the lowest nappe contains Tertiary down to Brøggerinden strata folded into a broad NW plunging syncline which is itself overthrust by the recumbent Zeppelinfjellet syncline (Fig 1a). Throughout this thrust sheet there are many examples of small scale imbricates, duplex structures and folded thrusts. The overlying thrust is topographically at its highest above the Zeppelinfjellet syncline but to the SE it cuts down through the syncline removing it altogether before Sherdahlfjellet. The Hecla Hoek rocks in the
overthrust sheet are high grade schists, migmatitic gneisses, phyllonites and marbles of the Kongsvegen Group (Harland et al. 1979). The whole sequence is characterised by strong (Caledonian) shearing fabrics and mylonitic zones refolded on all scales by N-NE vergent crenulation type folds consistent with the Tertiary deformation of the lower nappe.

Separating this and the overlying Trondheimfjellet nappe are two thin slices of Breggerlinden and Culm rocks (Fig la & b) both of which are very strongly cleaved. The Caledonian S metamorphic (greenschist facies) fabric of the Trondheimfjellet phyllites, psammites and flaggy limestones with diamictite horizons is refolded by a large N vergent antiform-synform pair. The folds, accompanied by a spaced pressure solution (S2) cleavage, have distinct box-like to chevron profiles with accommodation structures typical of locked-up flexural slip folds.

Above the Trondheimfjellet nappe is a strongly imbricated sequence of light grey Moefjellet marbles. On the narrow col at the head of Nordenfeldsskebreen these marbles are unconformably overlain by a synclinally folded and cleaved sequence of Culm-type pebbly conglomerates and coarse sandstones. The Culm rocks are then overthrust by the Haaken tillitic succession (Waddams 1983). However SE of the col the Haaken and Moefjellet rocks are repeated by thrusting in which Dahlbreen (Harland et al 1979) marbles also become involved. The incorporation of post-Devonian rocks in these higher nappes combined with the identical vergence directions in both rock sequences clearly indicates the Tertiary age of the later deformation in the older (Hecla Hoek) rocks.

In the triangle of mountains between Comfortlessbreen and Sarsøyra the wide expanse of ground occupied by the Haaken tillites reflects the shallow SW sheet dip of these rocks. These and the succeeding dark grey calcareous slates, white marbles and phyllites are well exposed on the southern shore of Englesbukta. Here again the Caledonian S foliation is refolded by open box-like folds overturned to the NE and associated with a steep SW (81/220) dipping S2 pressure solution cleavage.

To the west of Kapp Graarud Tertiary conglomerates lie above the Hecla Hoek and both sequences are cut by steep west dipping to vertical faults. In the conglomerates small scale sinistral and dextral displacements of pebbles occur in association with anastomosing fractures parallel to the faults. On similarly oriented fault surfaces in the Hecla Hoek close to the contact with the Tertiary sediments slickensides show both reverse slip and down-dip movements to have occurred.

Post Caledonian deformation of the foreland
On most maps of NW Svalbard the northern limit of the Tertiary fold and thrust belt is shown to be coincident with a WNW-ESE fault zone located in Kongsfjorden-Kongsvegen. However folding and thrusting of the Permo-Carboniferous rocks on the nunataks in Kongsvegen, N of the supposed fault, is at variance with this assumption. The presence of N-S fault controlled Devonian breccias and conglomerates has long been recognised on the foreland. Recent fieldwork on the Lovenøyane and Blomstrandhalvøya has brought to light several previously unrecognised post-Caledonian deformation features. On Blomstrandhalvøya, in a narrow strip east of Bratliek, strongly cleaved (SE dipping) Devonian breccias and conglomerates are overthrust to the E by Hecla Hoek marbles exhibiting a NW vergent fault-bend fold. The orientation of this fold and the cleavage in the Devonian rocks are consistent with sinistral transpression along the N-S lineaments. A well exposed fault surface on the western edge of Juttaholmen exhibits near horizontal slickensides with a clear sinistral sense. Red sandstones and conglomerates on Observasjonsholmen are also weakly folded, cleaved and imbricated. Whilst a Svalbardian age for this deformation cannot be ruled out it is interesting to note that the controlling N-S faults have the same orientation as the Brøggerbreen transfer zone which is effectively a sinistral fault.

In several localities over Blomstrandhalvøya and particularly well developed in the Hecla Hoek marbles NW of London are high level imbricate thrust fans with a consistent northerly vergence. Because these imbricates have the same transport sense as those to the S it seems reasonable that they are expressions of Tertiary shortening on the foreland. The development of the imbricates requires the presence of floor thrust, probably at no great depth, which could be the sole thrust to the Tertiary folding and thrusting. There is no evidence to suggest that this thrust breaks the surface to the N and it is presumed to be blind.

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It is not yet known to what extent the N-S faults have influenced the progression of these imbricates on the so-called foreland.

Figure 1. Sketch map and cross-section of the Brøggerhalvøya-N Oscar II Land area.
Conclusions and discussion.

The Tertiary folding and thrusting in NW Svalbard like that in foreland fold and thrust belts is characterised by the development of imbricately stacked thrust nappes in which older deeper sections of the stratigraphy have been emplaced above younger sections in the direction of the foreland. Successively higher nappes are more deformed and contain basement (Hecla Hoek) rocks. The highest, basement dominated nappes, occasionally incorporate discontinuous slices of younger rocks which are folded and cleaved in the same style and with the same sense of vergence as the D₂ structures developed in the older rocks. The post metamorphic D₃ deformation of the Caledonian D₁ fabric in the Hecla Hoek rocks is therefore assigned to the Tertiary event. The active involvement of the older rocks demonstrates the thin-skinned to thick-skinned nature of the Tertiary folding and thrusting in NW Svalbard. The stacking of the lower grade Trondheimfjellet nappes above the high grade Kongsvegen rocks is somewhat anomalous and may be due to Tertiary backthrusting, to the N-NE, of earlier SW directed Caledonian nappes stacked in order of increasing metamorphic grade.

Throughout the fold belt there are a number of features which are not readily accounted for by published flower structure or transpressional models. For example major thrusts rather than steepening towards the supposed axis of the flower structure usually have fairly shallow dips. The folding and thrusting of the Hecla Hoek described here demonstrates that these rocks, rather than acting as passively upfaulted blocks, have actively participated in the Tertiary deformation. En echelon arrays of folds with transecting cleavages and thrusts are not the rule and, except for the anomalous N-NE transport in the NW sector, deformation is generally east directed.

The Tertiary fold belt as whole is dominated by E-W compression and minor changes in transport directions (e.g. in the NW) may reflect differences in the degree foreland directed transport along surging thrust fronts, or evidence lateral ramping and/or the presence of transfer faults.

It is suggested that the bulk of the deformation in the fold and thrust belt was accomplished by collision of Greenland and Barents Sea platforms brought about by the clockwise rotation of Greenland as the Mid Atlantic ridge began to propagate northwards in Oligocene time(?). Modification of the initial E-W compressional structures, particularly along the western margin of Svalbard, by dextral strike-slip motion on N-S faults coincided with the separation of Greenland and Svalbard. In this scenario the Forlandsundet graben could have formed as a northward migrating extensional basin between two parallel right-stepping dextral wrench faults possibly coincident with present bounding faults. Rotation and reactivation by the intervention of a left-stepping dextral wrench fault array could alternatively explain the apparently anomalous N-NE verging nappes in the NW. With the development of the Knipovich ridge most transpressive stresses would be expected to have been absorbed by the Greenland-Svalbard transform and subsequent tectonism on Svalbard be dominated by extensional faulting to the present day.
Winsnes, T. S. and Y. Ohta

FOLD STRUCTURES OF CARBONIFEROUS TO TRIASSIC ROCKS IN THE INNER PART OF ST. JONSFJORDEN


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Between Isfjorden and Kongsfjorden a wide zone of folded Carboniferous to Triassic sequences form characteristic long and narrow mountain ridges, like Gestriklandkammen and Jentlandkammen. From a short stay in the area of inner St. Jonsfjorden for geological mapping purposes and profiles further south by D. L. Dineley, produced more than 20 years ago, an impression of the fold structures is obtained.

The border between the Hecla Hoek and younger rocks does not form a straight line but shows a step-like trend, where the north part has been pushed farther to east-northeast (Fig. 1). At the junction more complicated tectonic structures are seen, including strike-slip faults, overthrusts and folded thrust planes. Between Isfjorden and Kongsfjorden four such breaks are seen.

Between them north-northwest running, more regular fold patterns are met with. They consist of open and stacked folds, monoclinal and overturned (Fig. 2). The eastern limbs are mostly steep and small thrusts are also seen. East of the head of St. Jonsfjorden the shortening along the border between Perman and Triassic sequences is about 20 % towards east. The fold axes mostly climb gently towards north and the Triassic exposures narrow this way. To the north most of the tectonic movements are restricted to major thrust and faults where slices of Devonian and Lower Carboniferous can be seen.

The general tectonic picture is one of compression. No indication of extension was seen.

An anticlinal axis of a step-fold extends from Trygghamnna to Vegardfjellet and forms a complex of thrust-overfolds, involving the basement rocks.

On the B section (Fig. 3), an overturned syncline occurs in the north and steep younger faults, possibly extensional ones, cut the lower limb of the fold in the south. Two bed-slip thrusts occur in the limb, moderately dipping eastward. The A section (Fig. 3) to the north of B has two
Fig. 3

LA: calc-argill.suc., OA: qz-t-argill.suc., VS: schistose volcanics

Or: Orustdalen Fm.
Vg: Vegaard Fm.
Pt: Petrelskardet Fm.
Tå: Tårnkanten Fm.
G: Gipsdalen Gr.
KS: Knapp Starostin Fm.
R: Triassic strata

Triassic strata
gently eastward dipping thrusts and the sandstones of the Tärnkanten Fm. overlie the Kapp Starostin Fm.. The A section is possibly situated on the eastern extension of the axial part of the overturned syncline of the B section. A composite profile of A and B is presented in C, Fig. 3, to show the structure prior to the steep extensional faulting.

At three localities, the D, E and F sections, Fig. 3, the basement rocks overlie the Carboniferous white sandstones of the Orustdalen Fm.. The Vendiann tilloid unit horizontally overlies by thrust steeply folded Carboniferous sandstones in the D section. In the E and F sections, pelite phyllites and basic metapyroclastic rocks of Late Riphean age, respectively, overlie the Carboniferous quartzitic sandstone by thrust faults with moderate to gentle easterly dips. These occurrences of Carboniferous rocks under the basement rocks, can be explained by a successive folding of thrust sheets which involve the basement rocks, as shown in G-1 and G-2, Fig. 3. The eastward dipping thrust surfaces observed in all sections, are interpreted to be the result of successive rotation result of initially westward dipping surfaces. The inferred positions of the sections are shown in the idealized cross-section, G-3, Fig. 3.

If a dextral transpression system is assumed along the basement-platform boundary, the Brøggerhalvøya area is a restraining, contractional area, while the inner St. Jonsfjorden area may be a releasing, extensional site. But all observed structures, except for the later steep faults, in the latter area are undoubtedly compressive ones, produced by an ESE directed stress. Thus, a local deviation of the main compressive stress is inferred, from W to E in the north and WNW to ESE in the south of St. Jonsfjorden. Isolated narrow wedges of Carboniferous rocks in the northern part of Fig. 1 are the roots of thrust sheets, and main parts of thrust-folded Carboniferous rocks which might have had similar structures as in Vegardfjellet, may have been removed by erosion. Occurrences of two narrow Devonian rocks in NW Osbornebreen and E Løvenskioldfonna (Fig. 1), indicate that the western boundary faults of the Devonian graben extend to the south into the present area, and controlled the position of the basement-platform boundary.

Legend of Fig. 1

1) Triassic strata, 2) Kapp Starostin Fm., 3) Gipsdalen Group, 4) Lower to middle Carboniferous clastic rocks, 5) Devonian sandstones, 6) Vendian tilloids, 7) Calc-argillaceous succession, 8) Quartzite-argillite succession, 9) Basic, meta volcanic rocks. 7, 8 and 9 are of the Late Riphean age.
Yoshihide, Ohta.

STRUCTURES OF CARBONIFEROUS STRATA AT TRYGHAMNA AND ALONG THE SE MARGIN OF THE FORLANDSUNDET GRABEN


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(1). Trygghamna region.

The eastern and northern sides of Trygghamna are composed of subvertical Carboniferous-Triassic strata and an anticlinal crest is expected to the west. A coal-bearing, white sandstone occurs on the inner-west coast of Trygghamna and a limestone-sandstone alternation forms Knulven to the west (Fig. 2). The strata show folds of less than 100 m wavelength and the beds often show an inverted position. Tight overturned folds are well exhibited on the eastern cliff of Knulven, with NW-SE striking, gente SW dipping axial planes. A distinct thrust occurs in the same direction. The rocks are faulted down at least 750 m by a ESE-NWN trending fault along the northern slope of Protektor-aksia.

To the south and west of the Carboniferous rocks a thick Precambrian limestone-pelitic phyllite succession occurs with gentle W-dipping structures. Both limestone and pelite layers often include small scale isoclinal folds and preferred orientation of constituent minerals defines the cleavages. Gentle W-dipping thrust faults develop in the limestone-pelite succession (Fig. 1.), locally showing discordant, ascending sections (Fig. 3-1). Several overturned folds with E-verging structures are associated with the thrusts. The compositional layering and cleavages are folded, while a new generation of cleavage is very weak. One fold at Alkhornet is an overturned synform with a few, E-dipping backthrusts under major thrusts. Another on the SE-ridge of Daudmannen (Fig. 3-2) shows brittle box-shaped folds, contrasting the strongly ductile Caledonian deformation. When the Carboniferous rocks of Knuvlen are restored to the position before the ESE-WNW normal faulting, the SE-Daudmannen thrusts are on the southern extension of the Knuvlen thrust. Thus, the Daudmannen thrusts are inferred to be of Tertiary in age, or at least reactivated in the Tertiary time. The brittle nature of associated folds is consistent with this interpretation. Extending this interpretation, most W-dipping thrusts in the
Precambrian rocks on the northern coast of Isfjorden also reactivated in the Tertiary deformation period. These thrusts do not show steepening to the west up to the subvertical graben margin faults near Daudmannsodden, where the latter clearly cut the gentle structures.

(2). SE margin of the Forlandsundet graben.

At least two horst-graben pairs occur along the margin from St. Jonsfjorden to Daudmannsodden, and a narrow (max. 1.5 km wide) sliver of Carboniferous rocks occupy the eastern graben. The eastern border of the Carboniferous rocks is a steep fault, while the western one is locally a fault and locally an unconformity (Fig. 4-1). The unconformity is preserved at the northern side of Eidembukta and south of Tordenskioldbukta to Kapp Scania, with gentle E-dips. The strata involved in the graben are from Orustdalen Fm. to the Nordenskioldbreen Fm., a max. thickness = 1415 m. The source area is estimated to be to the west from the current directions.

Two types of folding have been recognized, 1) tight-isoclinal, E-ENE verging folds with local, spaced axial plane cleavages without new mineral growth (Fig. 4-2), and 2) open folds with sub-vertical axial planes, roughly parallel to the marginal faults. The 2) can be explained by down-throw of the graben zone, but the 1) can not. The 1) indicate definite compressional structures which are older than the graben faulting.

The marginal faults have a NNW-SSE strike and steep dips. Regional structures including Precambrian rocks appear to be NNW tapering wedges, the tips of which are at about the St. Jonsfjorden coast and north of Eidembukta. The faults inside the Carboniferous zone at the latter area show a sinistral wedging. The structures of Precambrian rocks are distinctly different in trend on either side of the zone and this difference existed before the formation of the graben zone.

The faults cutting the Carboniferous rocks form two groups; one group at a small angle to the marginal faults, with mainly a normal throw, and may be splay faults to the marginal ones, and the other group at a high angle to the marginal faults, with both normal and reverse displacements, and some of which have gently plunging slip striations indicating strike-slip movement.

An attempt to explain all these structural parameters by a single sinistral transpressional system is shown in Fig. 5. However, the orientations of some faults and many observed fold axes do not fit with this model. An alternative interpretation is that these structures were formed under different stress fields at different times; 1) the E-ENE converging folds formed by a compression from the W, and 2) the extensional graben faulting, 3) weak compressional stage to producing a conjugate set of faults in NE-SW and NW-SE strikes, which cut the graben margin faults. If this is the case, the compressional tectonic regime, typically developing along the basement-platform boundary about 20 km to the east, occurred in this area, before the formation of Forlandsundet graben.
Audun Hjelle

1. Kapp Linne

A prominent NNE/SSW-trending fault passes to the east of Strokdammane-Tunajoen (Fig.). No Paleozoic or younger rocks which would indicate the absolute or relative age of the fault occur here. The rocks on the east side of the fault most likely belong to the ‘pre-Vendian limestone beds with phyllite’ (‘unit 8’ of Hjelle & Lauritzen 1986). On the west side Vendian tillites occur and suggest a downthrow to the west of more than 200 m. Due to the straight course of the fault a young, probably Tertiary age is assumed.

To the west the fault cuts older curved faults of NNW/SSW trend. These less pronounced faults split the western area into at least 3 blocks. The patterns of bedding, cleavage and mesoscopic folds differ significantly from one block to another. If these structures primarily developed during the Caledonian deformation the faults are of post-Caledonian age, probably Tertiary. The fault passing just east of Kapp Linné contains breccias and strongly developed slickenside on local fault planes and is easily recognized in the field. The local fault planes dip c. 60° towards the WSW.

Faults with downthrow to the NW can also be seen to the south of Kapp Linné. A sinistral movement between the two western blocks might explain the structural difference between them.

Uncertain observations of sandstone with possible plant remains from a skerry to the SW of Kapp Linné suggest that late Paleozoic rocks could have been preserved due to near-shore faults. A small basin revealed by seismic profiling some 5 kilometres to the NW of Kapp Linné (Eiken & Austegard 1987) might be related to such faults.

2. Orustosen

A narrow wedge of Carboniferous sandstone with thin shaly, plant bearing horizons occurs here in the basement rocks (Fig.). The beds are striking c. NW-SE i.e. parallel to the trend of the wedge, with dip c. 65° NE. The calculated stratigraphic thickness of the sandstone is c. 400 m. and the lithology suggests a correlation to the Orustdalen Fm. of the Billefjorden Group. Basal conglomerate or other primary depositional contact to the basement rocks is not observed.

Basement rocks to the south of the sandstone are faulted and brecciated and their mesoscopic structures show scattered patterns compared to those of surrounding areas, probably due to splitting up of the area in numerous small blocks by faulting. As a whole, this area is the most dissected and structurally least homogenous one seen in the coastal area between Isfjorden and Bellsund. The sandstone is also partly brecciated, especially...
at its NE contact to the basement rocks, and, except for a few outcrops, only occurs as loose blocks from underlying beds. The Carboniferous rocks are thought to be preserved as a half-graben by faulting on its NE side.

Several thrust faults close to and parallel to the southern sandstone-basement contact and the lack of a Carboniferous basal conglomerate indicate that the contact here might be of fault origin. Extensively developed slickenside to the south of the sandstone and the Orustosen outlet suggest thrusting towards the NE. To the SW of the Carboniferous sandstone the structures in the basement rocks bend into parallelism with the trend of the basement-sandstone-contact. The lithology and assumed stratigraphical position of the basement rocks are similar on both sides of the sandstone wedge, and the displacement due to thrusting therefore does not seem to be great.

Considering the observations mentioned, the Orustosen faults are of post-Billefjorden age, probably Tertiary. Assuming a fault plane dipping 75° towards the SW the relative downthrow in the suggested half-graben may have exceeded 320 m. The deformation of basement rocks to the SW of the sandstone, with chlorite on slaty cleavage surfaces might have developed during the Tertiary, and reworking of older structures should not be precluded. The faulting and the bend of the common NNE-SSW trend of the basement rocks into the WNW-ESE direction suggest a SW-NE compression combined with left simple shear.

3. Kapp Martin

A narrow NNW-SSE trending outcrop of conglomerate, and sandstone with plant remains occurs to the north of Kapp Martin along the east side of Lågnesrabbane (Fig.). The outcrop is c. 5 km long and of max. 250 m width. The bedding parallels the outcrop, with a dip of c. 50° to the ENE and a calculated max. thickness of c. 130 m. Lithology and fossil content suggest correlation with the Orustdalen Formation of the Billefjorden Group. Similar Carboniferous rocks are preserved by faulting c. 5 km to the east. Basal conglomerates in the lowest part of the Carboniferous succession suggest a primary contact. The eastern boundary reveals breccias and a main NNW-SSE fault is assumed. If the fault plane dips c. 75° WSW the relative downthrow must exceed 120 m. E-W sinistral faults displace the main fault.

Comparing the basement rocks to the west and east of the main fault, a contrast occurs in both lithology and structure which at present is explained by faulting. Much less variation occurs in the Carboniferous rocks. This suggests that the main observed differences in lithology and structure of the basement rocks could have been established in pre-Carboniferous time and was reactivated during the Tertiary orogeny, preserving the Carboniferous rocks by faulting.

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AN ADDITIONAL PRESENTATION ON THE BASEMENT-PLATFORM BOUNDARY STRUCTURES IN NW NORDENSKIØLD LAND

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1. Sinistral extensional faulting along the basement-platform boundary, west of Linnédalen.

The sub-Carboniferous unconformity is subvertical at the Isfjorden coast, ca. 1 km west of Linnéelva, and extends to the N ridge of Griegaksla, then along the eastern foothill of Griegfjellet. A small, NNW-SSE trending Culm sandstone-conglomerate sliver within Precambrian rocks has been mapped and two more slivers of the same rocks are clearly seen on vertical airphotos. These rocks have a moderately E-dipping unconformity surface along their western margins, while the eastern margins are steeply W-dipping normal faults. The structures inside the slivers are NNW-SSE striking, moderately E-dipping monoclines, while the basement rocks between the slivers have a N-S strike and steep W-dipping cleavages.

The echelon arrangement of these Carboniferous slivers with normal faults borders, infers an extensional event, possibly a result of a sinistral transpressional stress system. The timing of this event is not clear, but the moderate E-dips of the unconformity surfaces, contrasting to the steep dip of the same surface in adjacent areas, may indicate that this event preceded the major compressive event.

2. Southern Isfjorden profile off Kapp Starostin.

A seismic profile has been presented by Gudlaugsson and Faleide, along a ENE-WSW striking line a few km off the coast. The profile shows that the Carboniferous-Permian strata exists about 3-4 km below sea level, while the same strata are exposed on the surface of shoreline. Thus, the strata occur at two different levels in the profile.

These general profile structure obtained from the surface data and oblique airphotos along the coast, has been projected on the seismic profile, and their structural relation were considered. The surface structures show a step-like fold geometry, with some subordinate folds on the gentle limb, one steep limb along the western side of Linné dalen and another along the west coast of Grønfjorden. The most probable structural interpretation is that the steep limb along Grønfjorden is cut by many W-dipping thrusts which push up the shallow rocks onto the underlying Upper Paleozoic strata. A large part of the resultant strain was probably absorbed by complex imbrication structures within ductile Triassic shaly strata. This profile agrees very well with those of adjacent areas both to the north and south along the basement-platform boundary.
While the dextral transcurrent component of the Tertiary, intracontinental, transpressional zone within the then-contiguous Greenland-Barents Shelf area is constrained by geophysical seafloor data, the convergent component must be constrained by evidence from crustal structures on Svalbard and Greenland. No evidence of significant wrench tectonics occurs on Midterhukken. Indications of transport direction are sub-perpendicular to the present shelf margin, and by inference to the overall zone of dextral transpression. Dextral and convergent components were likely decoupled. Therefore, a cross section of Midterhukken structures (Fig. 1) can provide minimum constraints for crustal shortening in this segment of Svalbard's Tertiary fold-and-thrust belt. Significant structures and related shortening are discussed below from W to E.

The E-dipping Midterhukhamna fault (MF) has a footwall flat of Nordenskioldbreen Fm. strata and a hangingwall flat of Billefjorden Grp. strata. Down dip it splits into the shallowly E-dipping Bravaisknatten fault (BF) which offsets Kapp Starostin strata 1.2 km, and a continuation with normal stratigraphic relations across the fault (i.e. Gipshuken Fm. hangingwall). This set of faults is best interpreted as a foreland rotated flat (MF) and ramp (BF). A minimum estimate of 800-1000 m of slip on the flat is given by the dip-length of the exposed fault with Billefjorden Grp. hangingwall strata plus the stratigraphic interval traversed in order to produce the observed stratigraphic inversion. Notable folding and small scale faulting within the rocks overlying the MF (Fig. 1) indicate stratatal shortening of some 900 m above the underlying flat; i.e., restoring hangingwall internal deformation and then reversing MF movement moves a point in the hangingwall some 1.7 km up-dip with respect to a point

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MINIMUM ESTIMATE OF TERTIARY SHORTENING SUGGESTED BY SURFACE STRUCTURES EXPOSED ON MIDTERHUKEN, BELLSUND, SPITSBERGEN


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below the inclined footwall flat. While some 1.2 km of this transport was transferred to the BF the rest must have been accommodated along the flat continuation. Due to an original angular discordance between Billefjorden Grp. and overlying younger strata across an angular unconformity, movement along the MF also tilted hangingwall rocks farther E some 30-35 degrees (Fig. 1). The BF projects into the subsurface to the E, probably as a flat within Botneheia Fm. strata. Its connection with overlying structures here is a critical aspect of kinematic models.

The steeply E-dipping Midterhuken decollement (MD) lies at the base of Botneheia Fm. strata. Overlying upper Triassic and Jurassic strata strata are notably folded, while underlying strata are tilted, but mostly unfolded. Sinuous bed estimates of shortening (5 cross sections) are all within the 1600-1800 m range. A S shore cross-section shows a notably lower value and represents an anomaly (discussed later). Offset of a dike on the N side of Midterhukfjellet on some of the lower slip surfaces that characterize the MD suggests hanging-wall down movement.

Three possible models for these structures with different implications for their contribution to shortening are: 1) they are E-directed structures which formed over an originally subhorizontal thrust-flat and were later rotated into their present position (e.g. Ringset, this vol.); 2) they are gravity induced structures that formed after or during tilting of their present steep position (Maher and others, 1986), or 3) they are structures above a backthrust (Dallmann, this vol.), i.e. slip was up-dip and syn-tilting. Observations made by Dallman (this vol.) on Berzeliustinden to the S indicate that folding above a NE-dipping detachment also at the base of the Botneheia folding a backthrust associated with the Berziuliustinden thrust. Since the Berzeliustinden thrust produced the tilting of the overlying Triassic strata (including the Botneheia), folding and detachment with a geometry very close to that on Midterhuken occurred syn- or post-tilting. In summary the first model is inconsistent with the best argument for relative timing of tilting versus detachment and folding, while the third model is inconsistent with the dike offset, leaving the second model by default.

However, the third model also explains a structural anomaly as a result of a subsurface connection between the BF and MD. On Midterhuken’s S shore two important changes occur. First, there is an overall swing in the structural trend of the rocks and structures above and below the MD to a more N-S trend. This suggests less offset on the BF (arrows – Fig. 2). Second, there is a change from a distinctly cylindrical to a distinctly conical fold form, with folds diminishing along axis to the SW. In the first two models this would be coincidence, but it would be a consequence of the backthrust model with a decrease in movement along the BF connected to the MD producing the conical forms. The dike offset will be reinvestigated – perhaps more than one dike exists in the area.
Farther E a series of folds in Helvetiafjellet and Carolinefjellet Fm. sandstones have subhorizontal enveloping surfaces, a sinuous bed shortening of 800-1000 m, and an underlying decollement estimated to lie some 1200 m under the Festningen sandstone within the synclinal keels (i.e., about 800 m below sea level). Janusfjellet Grp. shales exposed below the sandstones show a complexity of small scale E and W directed thrusts and tight folds. These structures likely represent the accommodation of slip above a subsurface thrust within Botneheia or deeper strata. A lack of marker horizons within the Janusfjellet Grp. makes estimation of stratal shortening of these structures difficult. It should be equal to or greater than that of the overlying Cretaceous sandstones.

Farther E Carolinefjellet Fm. and Tertiary strata dip moderately to shallowly E as the W limb of the central basin syncline. Recent work by Nottvedt and Rasmussen (1988) and Nottvedt and others (1988) indicates that Tertiary structures extend under these tilted but otherwise mostly undisturbed strata. On a speculative note, assuming conservation of area and different depths to a flat basal decollement estimates ranging from 2.0 to 8 km can be made for the amount of blind subsurface shortening necessary to cause the observed W-limb tilting. A basal detachment within the Triassic would imply 4-5 km of shortening.

What subsurface structure(s) produced uplift and tilting of the basement Hecla Hoek rocks unaccounted for by surface structures? The Berzeliumstinden thrust to the S (an extension of which may very well underly Midterhuken – Dallmann, this vol.) indicates basement involvement is in the form of of an earlier-formed, high-angle, fault propagation fold that later moved over a low-angle ramp and/or flat within Triassic strata. Taking a simple anticlinorium arch and an angular, fault-bend fold style (Fig. 1) as endmember geometries, and assuming a range of reasonable depths to autochthonous basement, shortening of the unconformity surface can be bracketed between 1 km to 6 km. While the subsurface geometry is poorly constrained, several kilometers of shortening are likely associated with basement uplift and tilting. Importantly, related thrust faults must be blind since surface structures to the E are inadequate and already accounted for in terms of the overlying BF. Structures underneath the W limb of the central syncline may represent eastern accommodation of fault movement responsible for basement uplift.

In summary, at least 4 km of stratal shortening are required by Midterhuken structures. If model 1 for the MD is adopted, an additional 1.6-1.8 km is required. Up to 8 km of shortening is permitted by the mapped structures. Considering that this is only a partial transect of Tertiary deformation and that Tertiary structures may exist farther W and E of the segment described here (e.g. Haremo and Andresen, this vol.), total shortening is probably significantly greater than this (tens of km with a simple extrapolation).
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Figure 1: Midterhuken cross section identifying major structures. HH - Hecla Hoek basement, Cb - Billefjorden Grp., Pk - Kapp Starostin Fm., J - Janusfjellet Grp. Small dots - Kapp Toscana Fm. (Triassic), large dots - Helvetiafjellet Fm. Several geometries for fault-bend uplift and tilting of HH depicted - see text for discussion.

Figure 2: Geologic map of Midterhuken's S shore area. BF and MD as in text. Pk - Kapp Starostin Fm.
Narve Ringset

THE FOLD AND THRUST SYSTEM OF MIDTERHUKFJELLET, BELLSUND

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The fold and thrust system of Midterhukfjellet, Bellsund. Norsk Polarinstittutt Rapport No. 46, 39-42.

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The exceptional exposures on the north face of Midterhukfjellet provide a display window of the structural styles of the Tertiary fold and thrust belt of Spitsbergen on the whole range of stratigraphical levels.

Structures in the Mesozoic rocks were interpreted by Maher et. al. (1986) as a possible result of gravity gliding. An alternative model for the evolution of these structures is presented here.

Two décollement zones are located in Mesozoic strata in the Midterhukfjellet area. The lower Midterhukbreen Décollement (Maher et. al. 1986, fig. 1), or the floor thrust, is located in the Triassic Bravaisberget Fm. The upper Nordlikollen Décollement (fig. 1), or the roof thrust, is located near the Jurassic / Cretaceous border, or between Agardhfjellet and Rurikfjellet Mbs. of the Janusfjellet Fm. The intervening strata are extensively deformed. Two principal styles of deformation are recognized, both of which are controlled by lithology (fig.1).

The Triassic/Jurassic Kapp Toscana Group is concentrically folded. A dominant, competent sandstone, sandwiched between two thin-bedded, incompetent sequences controls the fold geometry. This style of deformation requires detachment zones both above and below the folded strata, as showed in fig. 2. The detachment zone below the fold train may be identical with the floor thrust, and an upper detachment may be located in the lowermost part of the Agardhfjellet Mb. (fig. 1).
The basal beds of the shale-dominated Agardhfjellet Mb., lying below this detachment zone, fills the cores of the concentric synclines. They show minor out-of-syncline fashion drag folds.

The Bravaisberget Fm., underlying the Kapp Toscana Group, fills the cores of the concentric anticlines. Its incompetent, thin-bedded strata are characterized by chevron folds, as well as numerous slippage zones and imbricate thrusts. These imbricate thrusts branch out from the floor thrust (Midterhukbreen décollement), which is parallel to the Lower Triassic/Permian foot wall strata.
Between the concentric fold train and the roof thrust, Janusfjellet Fm. contains several imbricate thrusts, joining the roof thrust asymptotically. The roof thrust is parallel to the bedding of the relatively undeformed hanging wall.

In westerly exposures of Janusfjellet Fm., these imbricate thrusts are interpreted to branch out from the detachment zone above the folded sequence. Eastwards, the amplitude of the concentric folds decrease, and the floor thrust probably cuts up section. In its easternmost exposure, the Kapp Toscana Group is involved in an imbricate thrust sheet. From this point and eastwards, the imbricate thrusts are interpreted to branch out from the floor thrust in the Bravaisberget Fm. Thus, we have here a classic duplex (Dahlstrom 1970), causing a significant shortening and thickening of the shale-dominated Jurassic sequence.

The effect of this fold and thrust system is to transfer the eastwards propagating displacement gradually from the lower Miderhukbreen décollement to the higher stratigraphic level of the Nordlikollen décollement. This comprises roughly a doubling of the stratal thickness between the two décollements.

The two described décollement horizons exhibit easterly dips, and folds are overturned towards east. This feature may be interpreted as a result of folding above an antiformal stack (Boyer & Elliot 1982), produced by the development of younger, deeper thrusts. These thrusts involved Late Palaeozoic strata, and eventually the structural basement, Hecla Hoek rocks. Folding of the strata above the antiformal stack induced out-of-syncline directed shear, which caused the development of small, west-vergent thrusts and drag folds on the east-dipping limb (fig. 3).

The duplex in the Janusfjellet Fm. shales continues eastwards at the same stratigraphical level, but dips under sea level at Lågkollane. Thus, the Tertiary fold
and thrust belt does not stop abruptly, as supposed by Maher et. al. (1986). Instead, it continues underneath the Central Basin, to reappear at the surface along the Billefjorden Fault Zone.

The structural assemblage at Midterhukfjellet includes low angle reverse faults, décollement, duplexes, folded thrusts and concentric folds. These are structures that can be expected in a classic, foreland prograding fold and thrust belt. They indicate that the tectonic scenario in the vicinity of Midterhukenfjellet can be ascribed to eastward thrusting. This thrusting presumably happened in Late Eocene time, as Eocene strata in the Central Basin are folded above the duplex thrust zone.

When attempting to construct balanced cross sections through the thrust belt, a pin line must be placed some 150 km east of Midterhukfjellet, in the Storfjorden-Edgeøya region. Since Mesozoic strata show a great deal of displacement for a long distance eastwards, cross sections through this part of western Spitsbergen must show Palaeozoic strata in excess at depth, as they are piled up in the core of the Midterhukfjellet antiformal stack.

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THRUSt TECTONICS SOUTH OF VAN KEULENFJORDEN


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In the area between Hornsund and Bellsund (SW Spitsbergen, Fig. 1), the boundary between the Caledonian and post-Caledonian strata is complicated by thrusting in Early Tertiary times. Later tilting of ca. 1° of southern Spitsbergen to the north-northwest exposed continuously lower structural levels of the Tertiary orogen to the south. An approximately 1 km depth interval of the thrust belt structure can thus be observed. Restoring the section of this interval, it is shown that the Caledonian unconformity dipped moderately eastward prior to the onset of thrusting. Furthermore, thrusts have been progressively rotated causing more gen-

Fig. 1: Location map of major thrust faults (1-4) between Bellsund and Hornsund.
1: Bravaisknatten T. F.
2: Berzeliustinden T. F.
3: Saussureberget T. F.
4: Hornsund-Zittelberget T. F.
tle westerly, and finally easterly dip (Fig. 2) at higher structural levels, indicating that thrusting happened at progressively lower levels, and that the Caledonian basement was continuously rising during that time.

Fig. 2: Hypothetic composite section across the western margin of the platform area. Heights are 3x exaggerated. Numbers 1 to 4 correspond to thrusts faults indicated on Fig. 1.

One of the thrust faults, the Berzeliuslinden Thrust Fault (no. 2 on Fig. 1), and its associated structures are well exposed and have been analysed in detail. The thrust fault ends blind in the Triassic strata, and deformation is accommodated by fold-propagation folds in the Middle and Upper Triassic strata, and by different systems of shear zones in the Jurassic/Lower Cretaceous black shales (Fig. 3). Structures within the overlying strata (stratigraphical repetition, décollement zone, westward and eastward vergent shear zones at different levels) suggest interacting backthrust movement within two black shale formations (the Middle Triassic Bravaisberget, and the Jurassic/Lower Cretaceous Jannusfjellet Formations). The Berzeliuslinden Thrust Block is thus wedging into the foreland strata, splitting it along stratigraphic horizons of very low shear strength. Basement shortening is thus, at least partly, transferred to the hinterland side of the thrust within the Cretaceous and Tertiary strata. This model does not exclude that parts of the shortening may have been transferred eastward (Fig. 2).

This sort of wedging may be an important, but not the only mechanism controlling deformation of the western margin of the Central Tertiary Basin of Spitsbergen. The structural thickening of parts of the Jurassic/Early Cretaceous black shales and the progressive uplift of the overlying more competent strata to the west as confirmed by seismic sections can be explained by this model (Faleide et al., this volume).

The thrusting and folding within the post-Caledonian strata of the western margin of the Central Tertiary Basin must consequently be regarded as a response to progressive basement uplift in the west. Structures along this margin suggest mostly compressional tectonics, whereas the uplift of the basement itself may be caused by transpressional movements along the plate boundary between Greenland and the Barents Shelf.

Reference:
Fig. 3: Block diagram of the Berzeliustinden - Reinodden area. Note the stacking of thrusts: The Berzeliustinden Thrust Fault (no. 2 on Figs. 1 and 2) occurs at a higher level than the Saussureberget Thrust Fault (beneath Hermelinberget, no. 3 on Figs. 1 and 2). In front of the Berzeliustinden Thrust Block deformation is accommodated by fault-propagation folds, backthrusts and décollement structures.
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SEISMIC STRUCTURE OF SPITSBERGEN: IMPLICATIONS FOR TERTIARY DEFORMATION


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Seismic reflection data from Spitsbergen's fjords, acquired by Nordisk Polarinvest in 1984 and 1985, show that the post-Caledonian succession may be divided into two different, superimposed and detached structural regimes: Pre-mid Carboniferous sediments are preserved in an extensional structural setting whereas mid-Carboniferous to Paleocene rocks form a sedimentary platform later deformed by compression, or transpression related to the early Tertiary opening of the Norwegian-Greenland Sea.

Structural features revealed by the seismic data and attributed to Tertiary compression are:

1. A wedge of thrust slices underneath the Cretaceous-Tertiary layers at the western rim of the Central Basin. The wedge is bounded above by bedding-parallel décollement surfaces within Late Jurassic shales and below by similar surfaces within Late Paleozoic and Triassic layers.
2. Internal deformation structures within the platform sequence such as thrusts, reverse faults, low amplitude folds and anticlines cored by duplexes.
3. A tilting of the sedimentary platform west of the Billefjorden Fault Zone towards the margin.
4. There is a systematic decrease of compressional deformation in the platform sequence eastwards from the exposed orogenic front across the Central Basin. In Isfjorden compressional features are lost beneath the limit of seismic resolution some distance west of the Billefjorden Fault Zone.
5. The Late Paleozoic extensional relief beneath the platform cover is almost totally unaffected by the compression evident in the layers.
above. The presence of important sub-horizontal décollement surfaces is thus implicit in the overall structure of Spitsbergen.

The pure compressional style of deformation has led several investigators to suggest a phase of more E-W oriented compression prior to the latest Paleocene-Eocene transpressional phase. There is, however, no evidence in the seismic data across the Central Basin for a Late Cretaceous-early Paleocene onset of the Spitsbergen Orogeny as suggested by analogy to the Wandel Sea Basin in NE Greenland (Håkansson, this volume). In fact the Cretaceous-Tertiary sequence boundary is perfectly conformable within the limits of resolution of the seismic data. The abovelying early-mid Paleocene formations are also devoid of any signs of synsedimentary tectonic activity. The whole sequence of Cretaceous and early-mid Paleocene rocks is bent upward by later compressional movements to form the western rim of the Central Basin.

The cause of the Tertiary deformation of Spitsbergen is thought to be the wedge driven by plate tectonic forces into the upper crustal layers along the western margin of the island. The upper, brittle, crust can be divided into three main units based on differences in overall mechanical properties and response to Tertiary compression:

(1) The lowermost unit consists of autochtonous Late Paleozoic sedimentary rocks and underlying Hecla Hoek basement.

(2) The middle unit, which consists of Late Carboniferous-Jurassic layers, shows significant internal deformation indicating eastward transport. Soft, organic rich, marine shales within the Triassic and Jurassic, and gypsum layers within the Permo-Carboniferous carbonate platform have acted as décollement surfaces. Movements on ramps connecting these surfaces have caused considerable disruption of this unit.

(3) The uppermost unit, which consists of Cretaceous and Tertiary layers, is relatively competent and reacted to the eastward directed compression by flexural upbending at the western margin without much internal deformation.

The structure observed on seismic sections beneath the western rim of the Central Basin adds a few kilometers to the minimum estimates of total crustal shortening in the orogeny based on structures exposed along the western coast. This part of the crustal shortening is accommodated within the middle unit in the form of eastward movement of its upper part with respect to the lower parts across the Central Basin and tectonic thickening through imbrication. Because of the detachment at the base of the uppermost unit, its movement relative to the substratum is not easily determined, but some backthrusting towards the west relative to the middle unit is likely and is easily compatible with the observed structures.

New data from various sources enable us to test Harland's (e.g. 1969) hypothesis of a transpressional origin for the Spitsbergen Orogeny, as well as Lowell's (1972) model for the deformational mechanism within it. The plate tectonic aspects of the formation of the Spitsbergen fold and thrust belt are discussed by Vågnes et al. (this volume). As far as overall geometry is concerned, the belt is readily
explainable in terms of transpression. An average maximum crustal shortening across the orogeny of 30 km may be accommodated within known constraints.

Lowell's (1972) interpretation of the orogeny as a large-scale flower structure, in which the roots of the orogeny are directly coupled with marginal thrusts through fault planes that steepen with depth, implies a substantial strike-slip component on the marginal thrusts. Structural relationships implied by this model are neither substantiated by surface mapping nor seismic investigations. Because of this and because Lowell's mechanism is highly inefficient in accomplishing the deformation caused by the independent along-plate-boundary and across-plate-boundary components of lithospheric deformation, we suggest a different model for the formation of the Tertiary Spitsbergen fold and thrust belt:

In this model, horizontal slip along the plate boundary occurs on a vertical strike-slip master fault through the lithosphere. Lithospheric shortening due to compression across the plate boundary is accommodated in different ways above and below the brittle-ductile transition. The lower ductile part of the crust forms a root by downward flow. The upper, brittle, part of the crust forms a thin-skinned fold and thrust belt floored by a sub-horizontal décollement surface at the brittle-ductile transition. Movement in the belt is all in a vertical plane normal to the plate boundary. The fold and thrust belt is generated as an imbricated stack of thrusts on several inward dipping ramps.

Thus, the components of deformation normal and tangential to the plate boundary are accomplished through separate deformation mechanisms that coexist at the plate boundary but that are both linked to the primary plate tectonic cause of the orogeny i.e. transpressive rotation of the plate boundary as Greenland slides past Svalbard. The model is in agreement with both the plate tectonic history and structural evidence from Svalbard. Such a mechanism has recently been invoked to explain the seismically active fold and thrust belt in the San Joaquin Valley east of the San Andreas Fault in central California (Mount & Suppe, 1987; Namson & Davis, 1988).

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TERTIARY THIN-SKINNED COMPRESSIONAL DEFORMATION ON OSKAR II LAND, CENTRAL VEST-SPITSBERGEN


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Structural mapping of Paleozoic and Mesozoic rocks in Oskar II Land, central Vest-Spitsbergen, reveals a system of major, asymmetric to overturned, east-verging folds with NNW-SSE-trending axes, accompanied by thrust faults and imbricated faults with a shallow to moderate southwesterly dip.

Most of the major folds display asymmetric styles with wavelengths up to 2 km. Others display typical chevron and box-like geometries. Such folds probably overly frontal ramps/thrust detachments in competent Permian-Carboniferous strata. During upsection movements along frontal ramps complex folds, stacked imbricate thrusts and associated backthrusts and backfolds were developed in the Mesozoic (Triassic) cover. A genetic relationship between folding and thrusting is demonstrated in the Mesozoic rocks by thrusts dying out or passing along strike into major folds. Most of the imbricate thrusts developed by forelimb cutoffs of inverted major folds. The imbrications have produced numerous repetitions of sand-dominated Triassic formations in the area north of Erdmannflya. Most of the mapped frontal ramps cut through the competent Permian layers while they seem to flatten out in the less competent shaly Mesozoic formations, such as the Botneheia and Janusfjellet Formations. Similar complex deformation and staircase flat-ramp geometries of thrusts are typical for many classic buried foreland fold-and thrust systems (Dunne & Ferrill 1988).
A major NE-SW-trending fault, separating strongly contorted Mesozoic rocks to the NW from almost flatlying Cretaceous/Tertiary rocks to the SE on Erdmannflya (termed The Isfjorden Fault by Harland & Horsfield 1974), is interpreted as an oblique ramp. The rocks adjacent to the fault, including both Cretaceous and Tertiary strata, are characterized by numerous minor reverse faults/imbrications and tight upright folds with axial cleavage. Throw associated with this fault is about 400 m since the Jurassic-Cretaceous boundary lies 400 m stratigraphically higher on the hanging wall than on the footwall block.

The Tertiary deformation in Spitsbergen is normally placed in Lappdalen where a system of reverse faults cut the surface. The rocks involved in the thrust front include stacked and imbricated Permian strata, with associated hanging wall folds, placed on top of little disturbed, almost flatlying Triassic units to the east along a major sole thrust fault. An intensely deformed, about 100 m thick, Permian anhydrite/gypsum layer (i.e. the Gipshuken Formation) is present in the core of a collapsed hanging wall anticline near the basal sole thrust. This thrust, which displays a smooth, listric curved surface geometry, is interpreted as a basal detachment/decollement layer, emerged to the surface near a leading imbricate fan. The gypsum layer may have provided an excellent glide zone for thrusting. The presence of monoclinal structures and imbrications in Mesozoic shales east of Ekmannfjorden, indicate that decollement thrusting may continue even farther east.

We suggest a kinematic model of Tertiary compressional deformation being transferred eastwards across Oskar II Land by a combination of fault-bend/fault-propagation folding and thin-skinned decollement thrusting. The westernmost areas may represent a "buried/blind thrust system" characterized by major folds overlying frontal ramps and imbrications, whereas farther NE the deformation is typically that of an "emerged thrust system" with fault-propagation folds and thrusts reaching the surface (Fig. 1). Structures typical of compressional thin-skinned deformation, e.g. imbricate thrust stacking, thrust ramps and flats etc., are also observed in Mesozoic strata in Nordenskiöldland and along the Billefjorden and Lomfjorden Fault Zones of eastern Spitsbergen (Andresen et al. 1988, Haremo et al. 1988, Nøttvedt et al. 1988). This suggests a model of eastward transmittance of stress from the Vestspitsbergen Orogenic Belt by thin-skinned decollement thrusting for the Tertiary deformation in central Vest-Spitsbergen, a model which is also confirmed by seismic data (Nøttvedt & Rasmussen 1988).
Fig. 1: SW-NE geological cross-section between Trygghamna and Lappdalen, in Oskar II Land.

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Black and white air photos (scale approx. 1:17,000) were used along with published maps and literature (e.g. Orvin, 1934; Challinor, 1967; Flood et. al., 1971 and Hjelle and Lauritzen, 1982) and with field maps and recollections of Norsk Polarinstittutt geologists (Ohta, Winsnes and Kielen) to compile a map (1:100,000) of Tertiary structures (Fig. 1). Eight stratigraphic divisions were distinguished from air photos on the basis of color, slope, topographic character (smooth vs. irregular), and structural context. Although a greater degree of interpretation is involved in this map than in a conventional geologic map, the air photos allowed an area, much of which consists of nunatuks with difficult mapping conditions, to be quickly covered in a reconnaissance manner. The air photos, by their resolution, also act as a filter, focusing attention in on the larger structural pattern. On the basis of this compilation three zones can be recognized within the deformed platform cover sediments.

The western most zone, with a min. width of 8 km, is characterized in the N by a complex geometry of thrusts emplacing Hecla Hoek basement rocks into and over the lower platform cover strata (from the Broggerhalvoya area to St. Jonsfjorden). In the S it is characterized by a series of stacked monoclinal to overturned, shallowly S-plunging, folds of Kapp Starostin Fm. strata that form a 'staircase' type pattern in profile, descending to the E (from Isfjorden up to the E end of St. Jonsfjorden). These folds are readily traceable on the air photos. Their structural position and style indicate they are fault-propogation folds. The geometry of the underlying, basement involved faults is significant in estimates of the contribution of these structures to overall Tertiary shortening.
The 9-km wide central zone consists mainly of Kapp Starostin Fm. cherts and limestones and Triassic clastics. Folds with wavelengths of several 100 m up to 1 km are the predominant structure. Since many of these folds have subhorizontal enveloping surfaces and since roughly the same stratigraphic interval is exposed in cross section view of the zone the deformation is very likely thin-skinned, with a detachment horizon within the Gipshuken Fm. gypsums as suggested by Harland and Horsfield (1974). The gypsum is also probably responsible for unusually tight folding (interlimb angles of < 60 degrees) of the Kapp Starostin Fm. by allowing flowage into the fold core. Kapp Starostin Fm. strata act in a very competent manner elsewhere. Exposures of mainly Kapp Starostin strata in the N part of this zone change along strike to the S to mainly Triassic strata - this indicates the basal decollement has a component of dip to the SE. Conservative estimates indicate that 20% shortening exists in this zone. Since these folds appear to be 'buckle' folds and not of a fault-bend style, the associated shortening should not have been translated farther E, i.e., associated motion on the basal detachment is blind.

The 10 km wide frontal zone consists of Gipshuken Fm. through upper Triassic strata involved in at least two, major, W-dipping thrusts. Along Lappdallen a major thrust emplaces Gipshuken Fm. strata on Triassic strata and therefore has an absolute minimum displacement of 500 m (the stratigraphic throw) and a possible displacement in excess of 3 km. To the W of Sveabreen another major thrust locally (Mediumfjellet) repeats the Kapp Starostin Fm. with a hanging-wall flat and has a minimum displacement of 1100 m. Locally, the thrust geometry is more complex (Fig. 2). This frontal zone represents stratigraphic ascent of the basal detachment to a level whose structures would lie farther E but are no longer preserved.

From S to N in the study area there is a notable thinning of the middle zone. Changes along strike in map pattern may be due to erosion patterns, changing thickness of platform cover along strike, differing availability of incompetent horizons along which flats could form, a higher thrust sheet covering underlying structures, changes in transport direction, or some combination of these factors. It is suggested that the 2nd and 3rd factors are significant in this area.

Shortening estimates of this segment of the Tertiary fold-and-thrust belt from airphoto interpretation and map compilation indicate a minimum of 4 km, suggest 6.6 km and permit 9 km. Further discussion can be found in Maher (1988).

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Figure 1: Simplified map of major Tertiary structures in Oscar II Land. Box outlines study area of airphoto interpretation and map compilation. Dashed horizontal lines represent the edge of Hecla Hoek basement outcrops to the W. Small inset box is area shown in Fig. 2.
Figure 2: a) Portion of Norsk Polarinstitutt airphoto # S70-4932. View is of ridge between Sveabreen to the E (right side) and Wahlenbergbreen to the W. Tall mountain in the lower center is Triryggttoppen.

b) Interpretation of air photo. Pk - Kapp Starostin Fm. Tr - Triassic strata.
TERTIARY STRESS EVOLUTION ON SVALBARD

_Norsk Polarinstitutt Rapport nr._ 46, 59-61.

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Tertiary stress fields on Spitsbergen have been determined from processing of fault-slip data collected from several areas (West Spitsbergen Fold Belt, central and eastern platform areas). Measurements have been done in Early Tertiary deposits (Central Basin, Forlandsundet, Ny-Ålesund and Renardodden outcrops) and in the post-Devonian strata. The evolution is polyphased: four stress regimes have been discriminated and their succession deduced from classical microtectonic criteria. They correspond to compressional phases of NNE-SSW and ENE-WSW directions and are followed respectively by two episodes of subsequent and suborthogonal E-W and NNW-SSE extension. The change from compression to predominant extension can be explained by a permutation between the two principal stress axes \(\sigma_1\) and \(\sigma_2\).

The first compressional (transpressional) event is essentially expressed in northwestern Spitsbergen. Faulted structures related to this stress pattern are NWW-SSE to N-S dextral, NE-SW sinistral strike-slip faults and NW-SE oblique-slip faults as well as development of thrusts on Brøggerhalvøya. In Central Spitsbergen this initial wrench regime has only been noted along the southern continuation of the Billefjorden Fault Zone (Flowerdalen area) showing preserved dextral strike-slip movements.
The stress pattern corresponding to the ENE-WSW compressional event is widespread and is recorded as far as the eastern coast of Spitsbergen. The induced faulted structures consist of east- or west-dipping high angle reverse faults, low angle thrusts, flat-lying decollement surfaces and conjugate tranverse strike-slip faults (NE-SW dextral and E-W to ESE-WNW sinistral). In easternmost Spitsbergen such small-scale strike-slip faults are developed in the Mesozoic (Aghardbukta area) or late Paleozoic formations (east of Lomfjorden), possibly in relation to the reversal nature of the adjacent Lomfjorden Fault Zone.

Only the latest NNW-SSE extensional event is supposed to be related to the rifting regime which took place after the change in the spreading direction at anomaly 13 time (Eocene-Oligocene boundary). The three previous stages correspond to the transcurrent regime which started at anomalies 25-24 (late Paleocene).

It is assumed that the structures on Brøggerhalvøya and Forlandsundet have been produced concurrently during the NNE-SSW transpressional stage as a consequence of lateral offsets between basement wrench faults. The former is interpreted as a contractional relay zone, between two left-stepping dextral strike-slip faults and represents a natural example of a combination of dip-slip and strike-slip duplexes. In the same way, the slices of Upper Paleozoic rocks within the Hecla Hoek (SE of Engelsbukta, S of St. Johnsfjorden) are considered as shear lenses or minor Riedel-type duplexes. For the same reasons the Forlandsundet is thought to have originated as an extensional relay zone between right-stepping dextral faults.

Towards the end of the wrench regime the clockwise rotation from NNE-SSW to ENE-WSW of the direction of maximum stress $\sigma_1$ gives rise to transverse strike-slip faults and eastwards vergence structures and deformation propagates further east by means of decollement in incompetent horizons.
Post-Devonian strata

Devonian basin

Calabrian basement

N 18-20 first compression stage

N 70-80 second compression stage

SPITS BERGEN

BARENTSØYA

EDGEØYA

TERTIARY STRESS PATTERN

NORDAUSTLANDET

Compressed amplitudes of the extreme stress axes.

Approximate orientation of compression or extension (convergent or divergent arrows)

Site of fault slip data

Fault with strike-slip motion

Undifferentiated faults

Thrust and reverse faults
In spring 1986 Statoil carried out one of the first seismic reflection surveys on the glaciers of Svalbard. Four lines, totalling 55 km, were acquired in Statoil's licence area at Grimfjellet (Torell land) between Van Keulenfjorden and Hornsund. The contractor was Geco. Geoflex was the primary energy source. Processing of the data was performed by SSL.

Statoil also collected a total of 1450 km of marine reflection seismic data in Isfjorden and Van Mijenfjorden/Bellsund in 1984 and 1985. This data was of a relatively poor quality but has recently been reprocessed with considerable improvements.

The interpretation of the Grimfjellet data was partly based on field mapping, and also by correlation of the seismic character and interval thicknesses with seismic lines shot in Van Mijenfjorden that tie to the exploration well at Ishøgda.

Six good reflectors were mapped: 1) Base of Billefjorden Group (Top Devonian or top Basement), 2) Base of Nordenskiöldbreen Formation (Upper Carboniferous), 3) Base Sassendalen Group (Top Permian), 4) Top Dolerite sill (intruded approximately at the top of Sassendalen Group), 5) Base Adventdalen Group (mid Jurassic) and 6) Base Helvetiafjellet Formation (Lower Cretaceous). In the area Cretaceous rocks of the Helvetiafjellet Formation crop out at the surface.
The anticlinal axis at Grimfjellet is located about 10 km east of the thrust front, as expressed on the western side of Storbreen, and the axis strikes exactly parallel with the reverse faults in the area.

Four reflectors were digitized and depth converted, and contour maps drawn. At all four levels the surface structure of the Grimfjellet anticline can be seen. At the surface the anticlinal ridge strikes about 325° and the crest of the anticline is in the Grimfjellet area. The anticline seems to be symmetrical in an E-W direction at the surface. This pattern change in depth where the anticline becomes more asymmetric, with the steeper limb towards the east. At depth the strike of the fold axis also rotates anti-clockwise to about 315°.

Several reverse faults can be seen on the seismic data, and some minor normal faults. Most faults have dip at a small angle towards the west, and seem to flatten out at deeper levels. Some larger faults have a slightly steeper dip westward and involve the basement. Smaller duplexes and wedge shaped (delta-) structures can also be seen. Many of the faults are blind in the Cretaceous level. The large thrust fault that forms the Grimsfjellet anticlinal thrust front also terminates within the Cretaceous sediments. The top of the Grimfjellet anticline, at most levels, is about 1500 m above the same beds in the gentle syncline to the east, and indicates the amount of uplift. The shortening in the area is in the order of 2 - 3 km. This, together with the fact that the fault is blind should, suggests that the flat lying beds in the Mesozoic sediments east of the Grimfjellet anticline should contain many small flat thrusts with minor ramps (below detection limits of the seismic data).

We conclude that the Grimfjellet anticline is an anticlinal structure formed just in the front of the Tertiary fold belt, and that in the area as the first basement-involved thrusts do not travel to the present surface. The parallel strike of the anticlinal axis with the fold belt indicates a compression perpendicular to the structures, with a compression stress axis oriented at about 50°. This setting can hardly be explained by transpression. It strongly indicated pure compression pre-dating transpression and transtension in early Tertiary times on Svalbard.
Fig. 1: Structural geoprofile - seismic line GR-002 Grimfjellet, Svalbard.
Fig. 2: Linedrawing of seismic line GR-002.
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THE GIPSHUKEN FAULT SYSTEM -
EVIDENCE FOR TERTIARY THRUSTING ALONG
THE BILLEFJORDEN FAULT ZONE.

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The N/NW - striking Gipshuken Fault is the main tectonic
element of the Billefjorden Fault Zone at Bünsow Land
(McWhae 1953, Harland et. al. 1974). The best exposed,
upper part of this reverse fault is subvertical, off­
setting upper Carboniferous and Permian sediments. In its
southern part, at Gipshuken, it has a westerly downthrow
of 350 m. At Cowantoppen, in its northern part, the throw
of the Gipshuken Fault has decreased to about 120 m.

Part of this reduction is taken up by a NE dipping, high
angle reverse splay fault, the Cowantoppen Fault. This
fault has a W downthrow of 80 m, and diverges from the
middle part of the Gipshuken Fault with a NW strike. On
Brisingefjellet, E of the Gipshuken Fault, minor reverse
faults (back thrusts) with a composite E downthrow of 100
m occur.

Downwards, in the less competent, Middle Carboniferous
strata, these two faults appear to flatten gradually
eastwards.

A distinct asymmetric anticline, the Anservika Anticline,
forms the W limit of the studied segment of the Bille­
fjorden Fault Zone. It is interpreted as a fault pro­
pagation fold (Suppe 1985) in front of a blind thrust. As
the fold is cut by the Cowantoppen Fault, the fold
presumably is older than the fault.
A less prominent anticline in Gipsvika, just E of Gipshuken Fault, may also be a fault propagation fold, truncated by the Gipshuken Fault. It is seen only to-fold Nordenskiöldbreen Fm. The overlying Gipshuken Fm. is thickened E of the Gipshuken Fault. Apparently, anhydrite beds of the Gipshuken Fm. are piled up against the Gipshuken Fault. This is due to imbricate reverse faults that merge with the main fault updip. The thickening causes rotation of the overlying Kapp Starostin Fm., which shows increasingly steep E dip towards the fault. It also implies that the throw on the Gipshuken fault must decrease downdip, so that some of the vertical displacement is transferred on a horizontal component.

The tectonic structure in the area is dominated by imbricate reverse faults. These occur on both sides of the main fault, but most frequently close to its eastern side. Some of these reverse faults have lineations plunging down-dip, indicating dip slip movement. Minor folds occur in the hanging walls of small thrusts. Neither normal faults nor indications of strike slip faults have been found.

The geometries of the Gipshuken Fault and its associated major and minor faults and folds clearly show that they formed in a compressional setting. The reverse faults are interpreted to branch out from a low angle (or bedding parallel) floor thrust, located in evaporites of the Ebbadalen Fm. As this floor thrust propagates towards W, it approaches lateral equivalent fan delta conglomerates near the western margin of the Carboniferous Billefjorden Trough. This lithological inhomogeneity causes the floor thrust to ramp upwards. New reverse faults develop in the hanging walls of older ones, and the thrust system propagates towards the hinterland, forming a trailing imbricate fan (Boyer & Elliot 1982). The position of this thrust system at the Billefjorden Fault Zone is thus indirectly controlled by a Carboniferous structure (Fig. 1).

The timing of this thrusting event is not well constrained. The Anservika Anticline folds a dolerite sill of probable Early Cretaceous age, indicating a Cretaceous or Tertiary age of deformation. Along the Billefjorden Fault Zone south of Sassenfjorden, a phase of eastward thrusting involves Lower Cretaceous/Palaeocene rocks. These (Eocene?) thrusts appear to truncate the Flowerdalen Fault, which probably is a southerly continuation of the Gipshuken Fault. Andresen et. al. (1986) interpret the Flowerdalen fault as an Early Tertiary compressional feature, slightly older than the thrusts.
If an Early Tertiary age is assumed for the Gipshuken/Flowerdalen Faults, they may possibly have controlled the sedimentation of the lower part of the Tertiary succession of the Central Basin (Firkanten to Grumant Fms.). If so, an Early to Middle Paleocene age is indicated. This event may be connected to the onset of transpression along the continental De Geer transform fault. Compression along this zone may have been transferred eastwards to the Lomfjorden Fault Zone through a deep-lying décollement zone. The Gipshuken Fault system may then be interpreted as a back thrust, developed above this décollement zone.
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Previous investigations along Billefjorden Fault Zone (BFZ), one of Spitsbergen's most prominent lineaments (Fig. 1), suggest a complex tectonic history (e.g., Harland et al., 1974). It is interpreted to have been a tectonically active fault zone in 1) Late Devonian, 2) Early to Late Carboniferous, 3) Late Jurassic/Early Cretaceous and 4) Tertiary.

The Tertiary tectonic activity associated with BFZ, has been related to the Eocene(?)-transpressive Vest-Spitsbergen Orogeny which is associated with movement along an intracontinental transform fault zone between

Figure 1: Simplified geological map of Svalbard. BFZ: Billefjorden Fault Zone, LFZ: Lomfjorden Fault Zone, Elsfjorden, VM: Van Mijenfjorden.
Greenland and Spitsbergen. However, neither the geometry nor the kinematics of the Tertiary structures along BFZ, in particular how they relate to the narrow belt of intense deformation along Vest-Spitsbergen, have been thoroughly described. From recent detailed structural mapping along BFZ south of Isfjorden (Andresen et al., 1986; Haremo et al., 1988, Fig.1) it seems clear that Tertiary deformation is more extensive than hitherto recognized and that Late Jurassic/Early Cretaceous faulting, as suggested by Parker (1966), is only minor or non-existent in the area.

Tertiary deformation in the Mesozoic and younger strata along BFZ south of Isfjorden is characterized by compressional tectonics, which has led to development of two N-S trending tight anticlines in the Festningen Sandstone and overlying sand/shale sequences of the Helvetiafjellet- and Carolinefjellet formations. The underlying shale dominated Janusfjell Subgroup (Jurassic/Cretaceous) is thickened in the core of the two anticlines by; reverse faulting with formation of duplexes and imbricate fans, and folding, locally isoclinal. East-west cross-sections illustrating the main structural features across BFZ north of Adventdalen and north of Reindalen, are presented in Figure 2 (for location see Figure 1).

Geometry and orientation of folds and faults indicate tectonic transport of upper plate rocks from west towards east, although "back-trusts" occur locally. Out of sequence thrusts are observed and are interpreted to be responsible for the reduced thickness of the Janusfjell Subgroup in the inner Adventdalen area (Fig.2a). The two anticlines are not recognized below the Janusfjell Subgroup, suggesting that the latter acted as a major decollement zone during compression. Construction of detailed cross-sections show approximately 3 km of shortening of the Festningen Sandstone across BFZ. Local imbrication of the Triassic DeGeerdalen- and Wilhelmøya formations indicate that another decollement zone is present at a deeper structural and stratigraphical level. Shortening associated with these structures are at least 0.5km. Data from outside the study area (Andresen et al., 1988) suggests that this decollement zone is localized to the shaly Botneheia Member of the Barentsøya Formation.

Development of the Tertiary structures associated with BFZ are most likely controlled by high angle, east-dipping reverse faults in the pre-Mesozoic basement (Fig.2). A westward facing monocline involving the entire Mesozoic sequence is the only indication of this proposed early
Tertiary faulting activity in the study area. However, eastward dipping reverse faults in the Permian strata at Gipshuken (Andresen et al., 1988; Ringset & Andresen, 1988) support this interpretation.

Our own observations suggest that both decollement zones can be traced eastward to Storfjorden. They are also inferred to continue westwards and link up with the major reverse faults recognized at the same stratigraphical levels (units) around Midterhuken. The obvious thin skinned tectonic style recognized in the Mesozoic strata along BFZ south of Isfjorden, indicating a shortening of at least 3km, has to be considered when Tertiary shortening calculations, based on balanced sections across Spitsbergen, is carried out. We believe that the calculated shortening is related to decollement zones that go all the way to the west coast, and accordingly should be added to layer shortening observed further west. However, existing and new seismic data from Isfjorden and Van Mijenfjorden will hopefully prove whether this model is correct, or if the decollement zones are related to steep basement faults somewhere between BFZ and the west coast. Furthermore the lack of obvious strike slip deformational structures along the Vest-Spitsbergen Foldbelt as well as along the BFZ is indicative of two things; 1) that the main strand of the Hornsund Fault Zone was located considerably west of the present west coast of Spitsbergen and/or 2) that the Hornsund Fault Zone was a nearly frictionless interface, which caused the Tertiary
transpressive plate motion to be decoupled into a low stress strike slip component parallel to the fault and a high stress compressive component normal to the fault as has been proposed for the San Andreas Fault (Mount & Suppe, 1987).

References:


Lomfjorden Fault Zone (LFZ) (Flood et al. 1971) is, together with Billefjorden Fault Zone (BFZ), one of the few areas outside Vest-Spitsbergen where Tertiary deformation is inferred to have taken place. Whereas numerous papers have dealt with the tectonic history of BFZ (Harland et al. 1974), considerably less is known about the geometry and kinematics of LFZ. Kellogg (1975) stated that most of the Cenozoic compression along the west coast of Spitsbergen resulted in block faulting in the central and eastern areas, and that most of the deformation took the form of folding over (reactivated (?)) basement faults.

Throughout most of its length LFZ is a down-to-the-east fault, which to the north brings Upper Paleozoic rocks in contact with pre-Caledonian rocks (Hjelle & Lauritzen 1982). Southward, where pre-Mesozoic rocks are not exposed, LFZ is seen as a prominent flexure or asymmetric anticline. In the vicinity of Agardhbukta the steep limb is locally overturned (Kellogg 1975). The details of this flexure (Eistraryggen anticline, named after a mountain north of Agardhdalen), particularly its termination south of Agardhdalen, is described herein.

In its type area the Eistraryggen anticline is seen to involve Triassic and Jurassic strata. Southward, across Agardhdalen, Lower Cretaceous sediments, including the Festingen Sst, are involved in the deformation. The structure is in this area, no longer a simple anticline as appear to be the case at Eistrarøyggen.
GEOLOGY OF THE KLEMENTIEVFJELLET AREA, EAST-SPITSBERGEN

Formation boundary
Thrust
Anticline
Syncline

Fig. 1
Mapping of the east-facing slopes of Klementievfjellet show that two asymmetric closed, chevron-like anticlines with an intervening syncline are developed in the Mesozoic De Geerdalen-Wilhelmøya Fms (Triassic) and overlying Janusfjellet Subgroup (Fig. 1). The eastern (short) limbs of the anticlines are locally overturned; amplitude is at least 100 meters. Numerous minor revers faults, all indicating tectonic transport of the hanging wall block towards east, are developed in the core of the folds. Southward the two anticlines apparently degenerate into an open asymmetric anticline at the structural and erosional level of the Janusfjellet Subgroup (Fig. 2). Constructed foldaxes suggest that the Eistraryggen anticline around Klementievfjellet has a N-S trend with a gently southward plunge.

Structural observations along Rurikdalen (Fig. 1) show that the folded and faulted De Geerdalen and younger formations involved in the Eistraryggen anticline at Klementievfjellet sit structurally on top of flat-lying strata of the lower part of the Agardhfjellet Formation of the Janusfjellet Subgroup (Fig. 2). A reasonable interpretation is to consider the Eistraryggen anticline as being formed above a reverse fault ramping up through the sandy competent Wilhelmøya-De Geerdalen Fms. The fault is interpreted to turn into a flat further eastward, following bedding at the base of the Agardhfjellet Formation (Fig. 2). Its geometry at depth is unclear. It may be rooted in one of the steep basement faults recognized further north towards Lomfjorden (Andresen et al. 1988). On the other hand, local duplex development in
the Botneheia Mb of the hanging-wall block at Eistraryggen indicate that it westwards may level out in a flat following the Triassic shales. Shortening calculations based on length of folded beds (Breitkardhaugen Bed) indicate a minimum shortening of 700-800 meters across the Eistraryggen anticline around Klementievfjellet.

Offset (down to the east) of the Festningen Sst within the hanging-wall block south of Rurikdalen (Fig. 1), cannot be directly linked to the folds and reverse fault discussed above, and is interpreted as a separate reverse-fault (ramp) at a higher structural level, rooted in a flat within the Janusfjellet Subgroup. Apparent offset across this reverse fault decreases southward and is interpreted to die out as a blind thrust in a fold north of Ingelfieldbukta. Although not well exposed, local development of reverse-faults, all with a westerly dip, particularly at the base of Agardhbukta Formation, support this interpretation. It is tentatively suggested that this upper decollement zone continues westwards and links up with the decollement zone recognized at this stratigraphic level or a lower one along BFZ and within the Vest-Spitsbergen Orogenic belt.

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Recent work has increased our understanding of and modified our models for the Tertiary deformation on Svalbard. Seismic and field data gathered by NORSK HYDRO/STORE NORSKE show the need to reject a simple strike-slip model for the West-Spitsbergen Orogenic Belt (WSOB) (Fig. 1). A foreland fold and thrust belt model is required to account for the increasing evidences of extensive thin-skinned thrusting eastwards in the Central Spitsbergen Trough (CST), possibly as far east as Edgeøya (Nøttvedt & Rasmussen, 1988; Nøttvedt & Rasmussen in prep.). Major thrusting and asymmetric folding within the WSOB pass eastwards, across the orogenic front, into horizontal decollement surfaces and associated minor thrust ramps in the CST (Bergh et al., 1988, Nøttvedt & Rasmussen, 1988).

Similarly, previously proposed Mesozoic block faulting on the Billefjorden Fault Zone (BFZ) and Lomfjorden Fault Zone (LFZ) have been demonstrated to be overall unimportant. Post-Paleozoic tectonism on these two fault zones, on east-central Spitsbergen, relates predominantly to compression during the Tertiary (Andresen et al., 1988; Nøttvedt et al., 1988). A sequential model of Tertiary deformation is suggested, involving early, at least partly basement rooted, inversion of the old Paleozoic basin element between the BFZ and LFZ (Fig. 1) (Nøttvedt et al., 1988). These major reverse movements are clearly overprinted by, and decoupled from, younger, shallow rooted thrust ramps. On central Spitsbergen, the BFZ reverse fault is interpreted to have been cut and displaced eastwards for some 4 km by successive shallow thrusting.

Discussions on timing of deformation have recurred frequently the past few years. Despite speculations on a late Cretaceous phase of compression on Svalbard, however, seismic data and field observations of thrust ramps involving lower Tertiary stratigraphy and coal mining notes on numerous, similar striking folds and minor reverse offsets within the Paleocene coal-bearing strata are evidence of a Tertiary (Eocene) age of CST foreland deformation (Fig. 2), as is the thickness of Tertiary fill in the basin itself (cfr. Harland et al., 1976; Manum & Throndsen, 1986). It seems logical to assign a similar age also to...
the WSOB orogenic deformation proper, though an eastward progression in the age of thrusting is expected and more westerly structures may be older.

In order to work out a tectonic model for the Tertiary deformation on Svalbard, some key issues must be resolved:

1. What is the large scale geometry of the WSOB, and how does it relate to the Greenland-Svalbard suture shear zone?
2. What are the mechanics and kinematics of foreland deformation, with special notes to the BFZ and LFZ lineaments?
3. How does our new tectonic understanding affect the model of the Central Tertiary Basin (CTB) evolution?

It is our view that a general foreland fold and thrust belt model for the Tertiary deformation on Svalbard calls for expanded thoughts and refinement. Plate tectonic evidences of early Tertiary shearing between Svalbard and Greenland are persuasive from several lines of research, and the angle of relative compression is likely to have been very low (3 - 4°) (Nøttvedt et al., in press). From such conditions a strike-slip belt is to be expected (cfr. Lovell, 1972). Yet, prolonged weak compression is believed to have caused a total crustal shortening greater than previously anticipated.
We believe that a strike-slip welt may have initially formed (Figs. 2, 3). But, as the welt grew larger and the amount of shortening increased, master low-angle thrust faults developed, giving rise to a compressional fold and thrust belt on the flank of the strike-slip welt. It is important in this respect that most collision zones tend to be asymmetric, with one plate overriding the other. One should therefore not be surprised that Cretaceous compressional shear on Greenland is not widely recognized on Svalbard, and that the Vest Spitsbergen Orogeny cannot be traced on Greenland (cfr. Håkansson & Schack Pedersen, 1982; Hanisch, 1984; Håkansson, oral. presentation - this meeting). As these large thrust nappes became also successively locked, the main strain was transmitted stratigraphically upwards and taken up in horizontal decollement planes in ductile Mesozoic shales and to some extent, in upper Paleozoic gypsum layers (Fig. 3)(Nøttvedt & Rasmussen, 1988; Andresen et al., 1988; Bergh et al., 1988; Harland et al., 1988).

This stratigraphic control on deformation style explains the curvature and narrowing of the WSOB southwards across Isfjorden (Fig. 1), as due partly to a southerly plunge of the orogenic structure. It may further be speculated if the apparent bending of the deformation front offshore Kongsfjorden (Orvin, 1940; Challinor, 1967; Harland, 1969) is a second order feature and that the fold belt proper strikes more N-S, with the possibility of Tertiary compressional overprinting also in the Hecla Hoek (- Devonian) complex of northwest Spitsbergen (Fig. 1).

Similar examples of oblique-slip deformation have been documented elsewhere. Typically, strike-slip deformation is dominant close to the shear zone and compressional deformation becomes increasingly important away from the shear zone, due to rotation of the σ stress vector across the shear zone. But, what is the position of the WSOB relative to principal suture shear zone in this general model (Fig. 3)? Assuming a paleo-suture root zone onshore West Spitsbergen (Fig.
Fig. 3 Schematic model of Tertiary deformation of Svalbard. The figure is not to scale. Note asymmetry of the Central Spitsbergen Trough (CTB), due to buckling and tectonic loading by eastwards propagating orogenic belt (WSOB). Overthrust are expected to become older westwards. BT - Billefjorden Trough (Paleozoic). For other abbreviations, see Figs. 1 and 2.
1), one should expect significant evidences of obliquely striking, downward steepening thrust faults within the present fold belt. On the contrary, placing the suture shear zone along the Hornsund Fault Zone (HFZ)(Fig.1), would allow for mostly compression in the WSOB, as an eventual strike-slip welt (typically few tens of km wide) would then be expected to be buried below sea. We favour the latter, or at least an offshore location of the shear zone. In fact, previous workers nicely demonstrate the compressional aspects of the fold belt (Harland, 1969; Lovell, 1972; Kellogg, 1975; Birkenmajer, 1981; Maher et al., 1986), but mostly fail to give other than circumstantial arguments to support major strike-slip movements. Recent marine deep-seismic across the fold belt (O. Eiken, oral presentation - this meeting) points to the same conclusion.

Evidence of thin-skinned thrusting within the post-Devonian cover confirm this aspect of CST style of deformation. Yet, the inverted nature of the block element between the BFZ and LFZ on central Spitsbergen calls for basement involved mechanisms of deformation. More data is needed in order to explain the geometrical and kinematic relationships involved, but, basically, we believe there are two plausible models that should be tested, though they may augment each other:

1. The block is a pop-up structure generated by compressional block faulting, with genuine reverse vertical movements (6-800 m) on the LFZ and mainly hinging and (?) shallow rooted backthrusting (2-400 m) along the BFZ.

2. Inversion relates to basement involved, thick-skinned thrusting below the CST foreland deformation, with major ramping along the LFZ and antithetic hinging and backthrusting on the BFZ.

The integration of this new tectonic information have some important bearings on the CTB evolution. A general understanding exists, that the incipient evolution of the CTB was in response to gentle warping and weak extension on the Greenland - Svalbard shear zone (Fig. 2) (Paleocene)(Kellogg, 1975; Steel et al., 1981). Recent work further shows that with increased compressional shear (Eocene), the CTB evolved into a foreland basin, with subsidence now being controlled by isostatic loading of both thrust plates and sediment fill (Helland-Hansen, 1985; Steel et al., 1985). Tectonic models presented herein, makes it likely that the CTB passed into a third and final stage of evolution as the basin block, including its thin-skinned deformation, were caught between the upthrusted WSOB and thrust ramps along the BFZ/LFZ (Figs. 2, 3).

References


The Tertiary tectonic development of Svalbard is analysed based on information from three sets of data: a) marine geophysical data and plate-tectonic analysis, b) sedimentological models for the Tertiary basins, and c) structural field-geological observations.

Talwani & Eldholm (1977) and later Myhre et al. (1982), from plate-tectonic analysis, stated that the Greenland Sea margins, between the Greenland-Senja and Spitsbergen Fracture zones, evolved from a regional shear zone in Early Tertiary times (anomaly 24/25, 56 Ma) to a rifted passive margin in earliest Oligocene times (anomaly 13, 36 Ma).

The Tertiary sediments in the Central Basin of Spitsbergen (Van Mijenfjorden Group) are Paleocene to early Eocene in age, and the basin is interpreted as a forland basin to the Tertiary mobile belt (fold belt) of the western Spitsbergen.

Knowledge of the foldbelt in Spitsbergen comes mostly from structural observations on land, although in the last few years reflection seismic data has also been available.

Lowell (1972), based on Harland (1965, 69 & 73) and Harland et al. (1974), called the foldbelt of western Svalbard a "strike-slip orogenic belt" (as distinct from a "subduction orogenic belt"), and described it as a Tertiary compressive dextral (transpressive) strike-slip system. The en-echelon fold pattern, the narrow deformation zone (5-20 km), the involvement of basement, the pattern of the profiles ("upthrust"), the short thrust distance, and the lack of ophiolites and of metamorphism were the reasons Lowell used as evidence for his interpretation.
During the 1986 field season it became clear that the eastern part of Svalbard was also affected by Tertiary reverse faulting. In this area only late normal faulting had been described previously. Eastward directed reverse faults were observed in Statoil's licence area in the Agardh area, on both sides along the Lomfjord fault zone (Fig. 1), and in the Sassendalen area (Fig. 2). In the Agardh area intense reverse faulting was observed in the Botneheia Mb. black shales of the Barentsøya Fm. some few km west of the Lomfjord fault. The reverse faults were easily seen in the deformation of thin more competent sandstone beds within the shale. The strikes of the reverse faults were about 140 - 160° W and the dip about 15 - 30° W. This could indicate an eastward thrusting with a direction about 60°. The middle and upper part of the Botneheia Mb. acted as a flat thrust plane in a ramp-flat geometry. Similar observations were also made in different parts of Sassendalen. Here pronounced monoclines also occur. In Moskushornet in the inner part of Sassendalen a large monocline has an axial strike of about 5-10° and an azial plunge about 10° N. In the bend of the monocline, that occurs in Permian Kapp Starostin Fm. beds, slickensides indicate a compression with an axis towards the east at about 75°. East of the Lomfjord fault zone, towards the north, clear ramp situations occur in Kapp Starostin Fm. chert/shale/limestone approximately 10 km east of the fault zone (Fig. 1). This ramp area is as much as 100 km to the east of the front of the fold belt in western Spitsbergen. The reverse faults in this ramp zone east of Lomfjorden fault zone can be followed in a zone approximately about 2 km wide. The westward dip of the reverse fault planes varies from 15° to 45°, generally around 30°. The relative uplift of the flat-lying beds is in the order of 50 m on a single fault. Several faults can be seen in the zone and uplifts in the order of 200 m, and shortening of 500 m or more is possible over this exposed fault zone alone.

These observations, together with a reanalysis of the fold pattern along the mobile belt, reflección seismic data, and field information on Bjørnøya, lead us to the interpretation that there has been a compressional tectonic phase on Svalbard, prior to the transpression, transtension and spreading phases in Tertiary times. The width of the reverse faulted zone, 100 - 200 km, and the parallel orientation of the folds to the faults are the two strongest arguments.

The parts of the stratigraphy that most often acts as weak zones, where the thrusting occurs, are in the two evaporite horizons (Ebbadalen and Gipshuken Fms.), and the black shales of the upper part of the Sassendalen Group (Botneheia Mb.) and Janusfjellet Fm.
It seems clear that basement is involved in the reverse faulting tectonics even as far east as Lomfjorden fault zone. This zone is today a reverse fault with the eastern block lower than the western. The faultplane has a steep dip (60 - 80°) towards the west, and is not a normal fault as marked on most maps. In this fault zone steep dipping tectonised evaporites occur in the fault plane itself.

The unanswered question as of today is exactly when the compressional phase started and ended. Most observations indicate that the Paleocene, and maybe the uppermost part of Cretaceous and the lowermost part of Eocene, was the time of compressional tectonics, a tectonic phase that merges into a transpressive phase, a phase that we have only vague evidences of on-land Svalbard.


Fig. 1: Field sketch from east of the Lomfjorden Fault Zone. Ramp area in Kapp Starostin Fm.

Fig. 2: Field sketch from the Agardh area. Fault-bend fold and minor reverse faults.
A. Austegard, O. Eiken, T. Stordal & E.C. Evertsen

DEEP-SEISMIC SOUNDING AND CRUSTAL STRUCTURE IN THE WESTERN PART OF SVALBARD


About 2000 km of deep-crustal reflection seismic profiles (16 sec TWT) were acquired in Svalbard waters during the “Mobil Search” program for Norwegian Universities. 830 km of these were recorded as two-ship operations in conjunction with University of Bergen’s “Håkon Mosby”, obtaining wide-aperture reflection and refraction profiles with particularly deep penetration. Together with the Seismological Observatory’s earlier acquired seismic data, it forms a basis for understanding the transition from continental to oceanic crust. The data are in an early stage of processing and interpretation, however, some initial results are presented.

East of the Tertiary fold- and thrust-belt we observe generally a reflective lower crust, with an abundance of diffraction hyperbolas. In Isfjorden a fairly horizontal and continuous reflection at about 11 sec. TWT may originate from the crust/mantle transition or from a low-velocity layer in the upper mantle (Chan and Mitchell 1981). This reflector gets deeper at the fold belt at the mouth of Isfjorden, but further west the reflections are obscured by coherent noise, and the shape of crustal thickening below the fold belt is not established. Our interpretation disfavours the earlier proposed block-model of the crust in central Spitsbergen (Pajchel et. al. 1982). We do not observe deep-crustal involvement in the Tertiary thrusting in central Spitsbergen, either.

Reflections are hard to see in the fold- and thrust belt, but from the two-ship wide-aperture data a detailed refraction velocity profile is obtained down to 3-4 km depth. The belt is characterized by very high velocities, exceeding 7 km/s at 3-4 km depth. Its subcrop width is narrow, since Tertiary grabens are present immediately west of the coast line. We cannot rule out, however, that a western aprt of the fold-and thrust belt now forms the basement beneath these later developed grabens.
Offshore of the west coast the features are extensional: The crust is thinner, and a system of shallow (2-4 km deep) N-S trending grabens or half-grabens up to 30 km wide extends from Forlandsundet and southward at least to Hornsund. They have sedimentary infill from both sides, exhibit syn-sedimentary movements and the whole sequence is weakly compressed. These structures are interpreted mainly as extensional features, although a strike-slip model of graben-formation cannot be ruled out. The grabens are probably of late-orogenic or post-orogenic age. Based on lateral velocity variations and the thickness of post-rift sediments on the outer shelf and slope west of Spitsbergen, we assume 1-2 km of Tertiary sediments have been eroded from the offshore basins and 3 km in central Spitsbergen since the early-middle Tertiary.

The Hornsund Lineament, originally defined on basis of seismic velocities, bounds the thick basin of middle-late Tertiary sediments to the east. At deeper levels the lineament is a less prominent boundary. Extensional features are prominent. West of Isfjorden thinned continental crust with rotated basement blocks in the shelf area extend to about 35 km west of the Hornsund Lineament. However, significant structural variations occur along the margin. At 77°, west of Hornsund, the basement seems to be downfaulted in a single fault with 6-9 km throw. North of Prins Karls Forland the basement is more gently sloping to the west. We cannot trace continental basement all the way to oceanic-type crust. A 20-30 km wide zone with thick, unpenetrated sediments is limited to the west by a prominent basement high, presumably a part of the oceanic crust, paralleling the Hornsund Lineament at about 2000 m water depth.

North of Kongsfjorden the lower-crustal reflections become shallower, suggesting a much thinner crust in NW-Spitsbergen. Possibly the trend of the fold- and thrust belt changes to a NW-SE direction at Kongsfjorden, leaving NW-Spitsbergen more or less unaffected by early Tertiary compression.

We observe few signs of shear movement along the margin, in contrast to what has been expected from plate-tectonic models. The inner-shelf grabens as well as the thinned continental crust can mostly be explained by extensional movements. Possibly the shear features are overprinted by later movements, or possibly the zone of major shear was situated further west.

References:
A PRELIMINARY INTERPRETATION OF THE HORNSUND FAULT COMPLEX BETWEEN SØRKAPP AND BJØRNØYA

The term Hornsund Fault Complex is used to describe the faulted margin between oceanic crust and the relatively stable platform area of the Stappen High. The margin was strongly deformed in the Tertiary, probably with the main phase in the Oligocene. There is no evidence for strong tectonic movement in the Late Cretaceous.

The NPD is presently covering the area north of 74°30' with a regional seismic grid, and the margin has been mapped using a small amount of new data and some reprocessed old seismic lines. As line spacing north of Bjørnøya is 10-20 km and the data quality is fair to poor, only regional mapping is possible. However, the structural development in the area west and south of Bjørnøya can be taken as a model for the northern part north to approx. 76°.

The Hornsund Fault Complex is dominated by one master fault, the Knølegga Fault, defining the eastern boundary of the margin (fig. 1). The throw of this fault is greatest in the Bjørnøya area, where it separates Triassic to Permian rocks of the Stappen High from a very thick Tertiary and Mesozoic sequence to the west. The fault seems to be a listric normal fault associated with huge roll-over structures, and soling out at large depth.

In the main study area, the Knølegga Fault is also very well developed, but the roll-over geometry is not so obvious at the down-thrown side. Instead, one can define a zone of domes and rotated fault blocks west of the fault, fig.1, dome area. The dome area is separated from probable oceanic crust by a steep slope, and this boundary is associated with a strong positive gravity anomaly.
The Late Tertiary clastic wedge which was deposited across the continent-ocean boundary can be divided in two parts. The northern part is built up of stacked prograding sequences and reaches thicknesses of 4 - 4.5 sec TWT. The southern part is thinner and characterized by slumping.

The main structural problem of the area is the transition from the Spitsbergen folded belt to the mainly extensional Knølegga fault. As indicated in Fig. 1, this transition seems to take place close to Sørkapp, and it is linked to the change in direction of the Continent - Ocean boundary. The amount and quality of the seismic data available does not permit any detailed structural model. However, knowledge of the nature of this transition is important to understand the Spitsbergen Tertiary history.
Structurally, the Barents Sea continental shelf is dominated by ENE-WSW to NE-SW, NNE-SSW to NNW-SSE, and locally WNW-ESE structural trends. In the southern part, the ENE-WSW-trend is defined by the fault complexes bordering the Hammerfest and Nordkapp Basins. This trend is subparallel to a fault zone to the north defined by the Helgøya High and the fault complexes separating the Loppa High from the Bjørnøya Basin.

To the west and northwest the N-S-trends are dominating (Ringvassøy-Loppa Fault Complex, Knølegga Fault, Hornsund Fault Zone). This part of the Barents Sea have been the tectonically most active throughout in the latest Mesozoic and Cenozoic times. In contrast, the eastern and northeastern parts are dominated by stable platforms with less pronounced tectonic activity.

Few data exist on the pre-Devonian structural history of the Barents Shelf. However, reflection seismic data indicate that all the known main structural trends were established by Permian times.

In the subsequent structuring of the Barents Sea area, activity was associated with these important elements. This led Gabrielsen (1984) to propose a classification of faults according to their basement involvement and degree of reactivation. In this type of model the area is divided into separate fault blocks corresponding to the major highs and basins, delineated by deep-seated fault complexes. When stress is applied to this system of blocks, a complex pattern of relative movements between the individual blocks will take place.
Fig. 1 shows the main structural features of the Barents Sea region. In this picture, the following structures are believed to represent the principal, deep-seated fault lines: Troms–Finnmark, Måsøy, Thor Iversen, Nordkinn, Kalvsundet, Ringvassøy–Loppa and Bjørnøyrenna Fault Complexes. In addition, The Helgøy High and the Senja Ridge are probably underlain by deep zones of weakness.

In recent works in the area, indications of strike-slip movements and inversion have become evident, and shear movements have been proposed to be of importance for the structuring in late Devonian, Permian, mid Jurassic (Rønnevik et al. 1982, Rønnevik & Jacobsen 1984), late Jurassic – early Cretaceous (Riis et al. 1986, Berglund et al. 1986, Gabrielsen & Færseth in press), and Tertiary times (Riis et al. 1986).

Of these events, the early Cretaceous deformation is best documented. Strike-slip related deformation associated with several of the major lineaments has been suggested at this point in time (Fig. 1), and the most vigorous deformation seems to have taken place along the Bjørnøyrenna Fault Complex. The observation that the deformation is associated with the principal fracture systems seems to support the above principal model.

For the early Cretaceous deformation, Riis et al. (1986) suggested sinistral shear along the Bjørnøyrenna Fault Complex, and synthetic movements on a deep fault zone in the central part of the Tromsø Basin. In our opinion, this model may explain most of the structural features observed in the Bjørnøyrenna Fault Complex, provided that a compressional element is assumed for the strike-slip movement (transpression). However, sinistral shear fails to explain the compressional structures seen at the northwestern tip of the Senja Ridge, as well as the extension recorded in the Ringvassøy–Loppa Fault Complex at this point in time (Fig. 2a).

As an alternative model to explain inversion of the western part of the Kalvsundet Fault Complex may be a slight clock-wise rotation of the Hammerfest Basin fault block (Fig. 2b). This model would be in accordance with reactivation of the Trollfjord–Komagelv trend in the eastern part of the Hammerfest Basin, local inversion along the easternmost segment of the Troms–Finnmark Fault Complex (Gabrielsen & Færseth in press), and contemporaneous extension along most of the Ringvassøy–Loppa fault Complex.

In conclusion, several stress configurations may fit the strain pattern as recorded in isolated parts of the area. However, at the present stage in the exploration of the Barents Sea region, there are difficulties in defining a
successful synergetic structural model. It is considered likely that important pieces in this puzzle are to be found in the structural geology of Svalbard.

REFERENCES


FIGURE CAPTIONS

Figure 1
Main structural elements of the Barents Sea region. Arrows indicate late Jurassic - early Cretaceous tectonic activity. Structural features after Gabrielsen et al. in prep.

Figure 2
Simplified regional structural model for late Jurassic - early Cretaceous deformation of the Barents Sea region, implying sinistral shear along the Bjørnøyrenna Fault Complex and clock-wise rotation of the Hammerfest Basin. Note that the mode fails to explain inversion in the northern part of the Senja Ridge.
Fig. 2
Structural investigations in Kronprins Christian Land, eastern North Greenland, form the basis for the suggested model of tectonic deformations preceding the main transform dextral displacement of Svalbard relative to North Greenland.

Three major tectonic events of the Wandel Hav Strike-Slip Mobile Belt are recognized. An early extensional event (the Ingeborg Event) seems to affect Late Paleozoic carbonates and clastic sediments. The structures comprises normal listric faults accompanied by the development of slaty cleavage. The deformation probably took place during the Jurassic and created depocentres, which governed the Late Jurassic - Early Cretaceous accumulation in the order of 1,000 m or more.

The second transtensional event (the Kilen Event) faulted the Late Jurassic and Early Cretaceous clastic sediments. Listric normal faults displace features related to the first event, and calcite-veins with ankerite and siderite are often developed along the fault-surfaces. Furthermore, mylonitic deformations affected Caledonian rocks in the main strike-slip lineament. The deformation took place in the mid Cretaceous and preceded deposition of between 500 m to 5 km Late Cretaceous clastic sediments in local, disconnected basins.

The third event is a main compressional - transpressional tectonism which was responsible for the structural inversion of the basins, it is here referred to as the Kronprins Christian Land Strike-Slip Orogeny. Three structural phases are recognized. The first phase is an anastomosing, penetrative shear jointing formed during initial transpressional shearing. The second phase is characterized by en échelon dome folding. Along the flanks of the domes thrust faulting appeared, and in the third phase the domes are torn apart by dextral strike-slip faults. The dextral faults are responsible for the final dissection of the area into rhomb-shaped fault blocks. Second order sinistral faults with off-sets of a few meters are related to the first order dextral faults. The transpressional event is dated to Late Cretaceous - earliest Tertiary times.
Figure 1. Three main structural events have been recognized in the Wandel Hav Strike-Slip Mobile Belt in eastern North Greenland. The Jurassic Ingeborg Event affected the Late Paleozoic - Early Mesozoic platform sediments by extensional normal listric faults leading to sub-basin formation. In the Kilen Event superimposed extensional faulting displace the Late Jurassic and Early Cretaceous marine clastic sediments, and several pull-apart basins developed. Finally the transpressional Kronprins Christian Land Strike-Slip Orogeny resulted in the structural inversion of the sediment basins with formation of characteristic en échelon dome folds.

For location of geographical names mentioned see Håkansson this volume.
DID TERTIARY COMPRESSIONAL TECTONICS AFFECT NORTH GREENLAND?
Summary of the evidence.


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Post-Paleozoic compressional tectonics in North Greenland have been the subject of two regional models differing somewhat in their conceptual time frame. One model relates compression in North Greenland entirely to Late Paleocene - Eocene events in the West Spitzbergen and Eurekan Orogenies (1), while the alternative model, based solely on North Greenland data, suggests that compression here is essentially Late Cretaceous (to possibly earliest Paleocene) in age (2).

In the latter model the structural setting governing events in North Greenland became well established some time in the late Jurassic during the first extensional event of the Wandel Hav Strike-Slip Mobile Belt, in the formation of the Trolle Land Fault System. Subsequently, in the second extensional event of this mobile belt, a number of pull-apart basins developed across North Greenland, with highly varied infill. Finally, in the compressive culmination of the Wandel Hav Strike-Slip Mobile Belt, these basins along with the rest of eastern North Greenland were severely folded and thrusted. Later events are solely tensional (2, 3, 4, 5).

In a broader, plate tectonic context the time differences implied in the two models are of fundamental importance; consequently this brief review is concerned primarily with the timing of events in North Greenland — temporarily ignoring the interesting aspects of the regional geological implication of these events.

Three structural entities in particular hold information pertinent to the assessment of the timing of the compressional regime in North Greenland.

A. In northern Peary Land the Kap Cannon Thrust Zone is an imbricate thrust fault fan with wedges containing a.o. all known occurrences of the Kap Washington Group. The thrust zone further affects a dense, N-S oriented dyke swarm. Dating of the dominantly volcanic Kap Washington Group is based on mixed paleontological and radiometric data: Partly intrabasaltic sediments from near the base have yielded poor macroplants indicative of Late Cretaceous ages (6), intrabasaltic sediments some
3 km above the base contain a restricted Campanian or Maastrichtian flora (6), while rhyolithic lavas at the top yield Rb/Sr-ages of 64±3 ma (7). The dyke swarm is most likely of (?)Late Cretaceous age; previously reported K/Ar-dates of dykes and retrograded micaschists from this area must be considered unreliable at this point (8).

B. The Harder Fjord Fault Zone in central Peary Land is a long-lived E-W oriented linear feature containing, along with older strata, variously disturbed sediments of Late Permian to possibly Paleogene age in an up to 5 km wide tectonic melange.

Centrally in the zone *Inoceramus* bearing Late Santonian strata were intruded by somewhat irregular basic dykes prior to upthrusting into the present vertical position. Associated with the compression, both magmatic and sedimentary rocks were subject to severe thermal alteration. Subsequently the entire disturbed sequence was intruded by a generation of N-S oriented basic dykes, which have undergone no thermal alteration.

Further to the east a tilted, unfolded sequence of fluvio-deltaic origin referred to the Herlufsholm Strand Formation has been thrust over strongly deformed rocks of the Franklinian Fold Belt; no direct age determination has been possible due to a complete thermal degradation of all organic-walled microfossils. A very limited occurrence of continental strata with a very restricted pollen flora suggesting a Paleogene age has also been reported from this part of the fault zone (9). The orientation of these strata is unknown, but the fact that they do contain reasonably preserved microfossils in spite of their location in the middle of the fault zone, is taken to indicate, that the two sequences were separated in time by the thrusting event.

Volcanic necks and breccia pipes previously referred to the same magmatic provenance as the Cretaceous dykes and Kap Washington Group volcanics were deformed in the mid-Paleozoic Vølvedal Orogeny (2, 10).

C. The Trolle Land Fault System is a complex of largely parallel, NW-SE oriented faults with anastomosing E-W oriented, second order faults which stretch across eastern North Greenland from Peary Land to Kronprins Christian Land. A great variety of data has been gathered along this system.

In East Peary Land a sequence of Carboniferous through Middle Triassic sediments were deformed in the first Wandel Hav Strike-Slip Mobile Belt event, in what was here most likely a sinistral strike-slip regime. The resulting block mosaic was transgressed in the Middle Oxfordian, and, after an interval of continental deposition starting in the Valanginian, marine conditions were reestablished in the Aptian-Albian period. Subsequent to this, fluvio-deltaic sediments of the Herlufsholm Strand Formation accumulated in a basin close to the junction between the Harder Fjord and Trolle Land Fault Zones. This area was later subjected to fairly strong domal folding in an event which probably also led to the complete thermal degradation of the microflora. Apart from the presence of deciduous leaves and wood indicating a Late Cretaceous or Early Tertiary origin (11), no age determination has been possible in this basin, neither regarding the sedimentation nor the deformation. However, by comparison with the neighboring basin in the Harder Fjord Fault Zone and the overall structural frame, a Late Cretaceous age is considered most likely.
On the north coast of Kronprins Christian Land very gently folded marine sediments are found containing a fairly diverse bivalve fauna indicative of a Late Cretaceous age. Locally extensional faults of probable Tertiary age are abundant with associated, quartz filled tension gashes giving evidence of a substantial increase in heat flow. Throughout the area organic walled microfossils are lost completely in this late episode, and neomorphic envelopes are typically developed around all non-quartzose sediment grains.

On the east coast of Kronprins Christian Land, at Kilen, a Late Jurassic to Albian marine sequence of substantial magnitude is developed somewhat parallel to the sequence in east Peary Land. This sequence is disturbed by normal listric faults of the second extensional event in the Wandel Hav Strike-Slip Mobile Belt prior to a Turonian transgression. Marine sediments with abundant ammonites and inoceramids continued to accumulate into the Coniacian, but a significant portion of later Cretaceous sediments at the top of the sequence has so far not been more precisely dated. In the final compressional culmination of the Wandel Hav Strike-Slip Mobile Belt the entire sequence at Kilen was severely disturbed in a series of domal folds and thrusts.

On the west coast of Kronprins Christian Land Permian sediments as well as Caledonian nappes were strongly faulted and folded in several episodes prior to the deposition of a clastic sequence in an alluvial fan to coastal plain setting. The macroflora from these sediments is associable with the Early Tertiary floras of Svalbard and the Sverdrup Basin, and from microfloral evidence a (?Late) Paleocene age can be assumed for the North Greenland strata. The Paleocene cover sequence is unfolded and cut by extensional faults only. Together with older strata the Paleocene sediments have been affected by the late episode of strong heat flow increase centered on the north coast of Kronprins Christian Land.

Summing up the evidence, I find it reasonable to maintain that post-Paleozoic compression in North Greenland may well have been concluded entirely within the Late Cretaceous period. The inviting parallel to the West Spitzbergen Orogeny in Svalbard therefore becomes very intricate, since compression here is mostly agreed to be of Paleocene age. Whether this discrepancy reflects an actual difference in the plate tectonic significance of the two orogenic belts, or whether it merely reflects difficulties in dating events and strata in Svalbard, has yet to be established.

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(3) Birkelund & Håkansson; Zitteliana, 10, 7-25.
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Structural and depositional elements in the Wandel Hav Strike-Slip Mobile Belt.

Stratigraphy of the Wandel Hav Strike-Slip Mobile Belt.
Erling Vågnes, Per Arild Reksnes, Jan Inge Faleide and Steinar Thor Gudlaugsson:

PLATE TECTONIC CONSTRAINTS ON THE FORMATION OF THE SPITSBERGEN FOLD AND THRUST BELT


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The formation of the Spitsbergen fold and thrust belt was related to the breakup of the North-American, Greenland, and Eurasian plates at the Yermak triple junction, and the subsequent ~550 km of dextral strike-slip along the Hornsund Transform in the Eocene. It is generally accepted that the fold and thrust belt resulted from transpression (e.g. Harland 1969; Lowell 1972). However, dating problems, and uncertainties regarding the exact geometry of the plate tectonic evolution of the Greenland Sea, have made exact correlation between geologic observations and plate tectonic predictions problematic. New evidence eliminates earlier discrepancies and enables an integrated discussion of structural geology and plate tectonics. It also opens the possibility of an alternative interpretation of the earliest part of the orogeny.

Models for the plate tectonic movements between Greenland and Eurasia are converging (Talwani & Eldholm 1977; Reksnes & Vågnes 1985; Srivastava & Tapscott 1985). Generally the model of evolution of the Norwegian-Greenland Sea put forward by Talwani & Eldholm (1977) is confirmed. In particular the direction of movement between Greenland and Eurasia from late Paleocene to early Oligocene was constant, thus excluding shifts in the direction of plate movement as an explanation for the Tertiary orogeny on Spitsbergen. The poles of rotation obtained by Reksnes & Vågnes (1985) are the starting point for the following analysis.

The dating of the orogeny now seems well constrained; onset in the latest Paleocene is indicated by the shift from an easterly to a westerly source area in the Central Basin (Steel et al. 1985; Manum & Throndsen 1986). The orogeny must have continued at least until deposition of the syn-orogenic Eocene formations. The latest Paleocene
onset of the orogeny may predate the onset of sea-floor spreading in
the Norwegian Greenland Sea in the earliest Eocene, but the
discrepancy is near the limit of resolution of the datings available,
and may be an artefact. On the other hand part of the orogeny may
have been a response to movements pre-dating the breakup of
continents.

Late Cretaceous to early Paleocene (?) dextral strike-slip movements
are reported from the Trolle Land Fault Zone in the Wandel Sea Basin
(Håkansson & Pedersen 1982). Major Late Cretaceous subsidence and
deposition is observed in the basins off central Norway. This is in
striking contrast to the southwestern Barents Sea where little coeval
deposition is observed. In reconstructed positions the Trolle Land
Fault Zone and the Senja Fracture Zone are aligned. We suggest that
the Late Cretaceous extension to the south was taken up as dextral
strike-slip movements along the "Trolle Land-Senja Fault Zone", thus
shielding the southwestern Barents Sea from Late Cretaceous
extension. These movements caused no deformation on Spitsbergen
(Faleide et al. this volume).

A latest Paleocene/earliest Eocene rifting episode formed a major
Tertiary basin along the Senja Margin in the southwestern Barents Sea
(Faleide et al. in prep.). The onset of the Spitsbergen Orogeny was a
part of the same tectonic episode, a result of pre-drift movement
between Greenland and Eurasia. Along the Harder Fjord Fault Zone
(HFFZ) ~20 km Tertiary dextral strike-slip has been reported (Higgins
1985). Furthermore, when Eurasia and Greenland are reconstructed to
their late Paleocene positions the trend of the HFFZ intersects the
Svalbard margin at the southern termination of the Spitsbergen fold
and thrust belt. The HFFZ also had a more westerly azimuth than the
post-breakup direction of movement between Greenland and Eurasia (~20
deg.). These observations are consistent with a model in which a
wedge of crust, limited to the south by the HFFZ, became squeezed
between the Greenland plate to the south and the Eurasian to the
north. This resulted in transpression along the HFFZ. At this time
the Spitsbergen Orogeny may be seen as the southeasternmost part of
the Eurekan Orogeny (Fig. 1a).

Increasing movement forced a break between Greenland and Eurasia,
initiating large scale strike-slip (~2 cm/yr) between Eurasia and
Greenland and producing the post-breakup part of the orogeny. The
geometry of the initial plate boundary was probably a compromise
between the direction of plate motion and the HFFZ trend. The larger
the impact of the Harder Fjord trend on the initial plate boundary,
the more transpression on Spitsbergen. An average of 30 km of
shortening along the fold and thrust belt may easily be accommodated
in such a model (Fig. 1b).

The fold and thrust belt does not cover the full length of the paleo-
transform. A trend-shift in the plate boundary off Kongsfjorden would
explain its northward termination. Evidence for such a northward
shift in the azimuth of the present ocean-continent boundary has been
reported (Eiken & Austegard 1988).
Figure 1. Schematic illustration of the interaction between plate movement and the plate boundary during Tertiary orogenesis on Spitsbergen. (YTP= Yermak Triple Junction, HFFZ= Harder Fjord Fault Zone).
Major orogenic activity ended in late Eocene (~40 Ma) when Greenland had slid past Svalbard a distance equal to the length of the fold and thrust belt (~375 km). At that time the plate boundary had become parallel to flow-lines along the whole Spitsbergen fold and thrust belt. The pre-Oligocene Hornsund trend was thus a product of transpression (Fig. 1d).

In earliest Oligocene the Greenland plate became part of the North-American plate. The Yermak Triple Junction became extinct and extension became dominant between Spitsbergen and Northeast Greenland, probably overprinting some of the compressive structures. The present lineaments along the Hornsund trend and the Forlandsundet Graben are likely a result of post-orogenic extension, which may have commenced in the late Eocene. Important information regarding the orogeny, particularly the position of the main transform fault, was probably erased by this event.

References:

Tertiary deformation of Svalbard includes: (1) reciprocal formation of the West Spitsbergen Uplift and the Central Basin on a fold-thrust boundary structure in the Early Tertiary; (2) formation of the Forlandsundet and Outer Shelf basins in the Middle and Later Tertiary; (3) Some reactivation of older more easterly fault zones, especially the Lomfjorden fault; (4) southward regional tilting; (5) regional uplift; (6) a small pullapart under a volcano.

The cross-sectional geometry of the West Spitsbergen Uplift is best displayed at its north end where it plunges southward into the ground. Alternatives are considered for both the map-view and cross sectional configuration of the northern end of the uplift. The Thrust Belt east of the basement exposure is made up of thin-skinned imbrications forced ahead of the basement thrust. Southward termination of these imbrications does not occur at Isfjorden, rather they are likely to plunge southward under the Central Basin. The en echelon map pattern of the imbricated zone is more related to this southward plunge than to an en echelon pattern imposed by the strikeslip component.

Plunges are important to deciphering deformed belts and end-member possibilities are presented. The southward plunge at the north end of the uplift reverses itself in the area of Bellsund, but becomes southward again at inner Hornsund. The outcrop of lower Hecla Hoak north of outer Hornsund contrasts with that of Carboniferous and Triassic south of it, indicating a large transverse ramp as the cause. There are two alternatives, depending on whether or not these exposures ride on the same thrust plate and whether plunges are northward or southward. Bear Island's faulted central basement uplift plunges north and seems to be a smaller scale replica of the West Spitsbergen uplift. A significant part of its development seems to be Tertiary.
Several additional points are covered including: (1) Alternative causes for the Forlandsundet Basin; (2) smaller-scale deformation along the thrust front and out into the Central Basin; (3) possible reactivation of older faults; (4) the causes of the vertical history of the area; and (5) some aspects of the plate setting.