Tertiary structures in the platform cover strata of Nordenskiöld Land, Svalbard

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Maher, H. D., Jr., Ringset, N. & Dallmann, W. K. 1989: Tertiary structures in the platform cover strata of Nordenskiöld Land, Svalbard. *Polar Research 7*, 83–93.

Air photo interpretation along with limited field work is the basis of a compilation map of Tertiary structures in the Upper Paleozoic through Mesozoic platform cover strata of Nordenskiöld Land. Permian Kapp Starostin Formation strata form a continuous marker horizon delineating both a large NE-verging fold complex, which involves the basement (Hecla Hoek sequence) through basal Tertiary strata, and somewhat smaller scale folds, some of which may have formed in association with detachments and thrusts within the platform cover sequence. The map pattern is both a function of local structural plunge and changes in fold geometry along strike. Regional considerations suggest that subsurface basement-involved thrusts exist. In S Nordenskiöld Land, to the E of folded Kapp Starostin Formation strata, a 3.5 km wide zone of folding and thrusting in Triassic and Jurassic strata above a subhorizontal décollement is inferred to occur. Further E is the W limb of the central Tertiary basin syncline.

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December 1988 (revised May 1989).

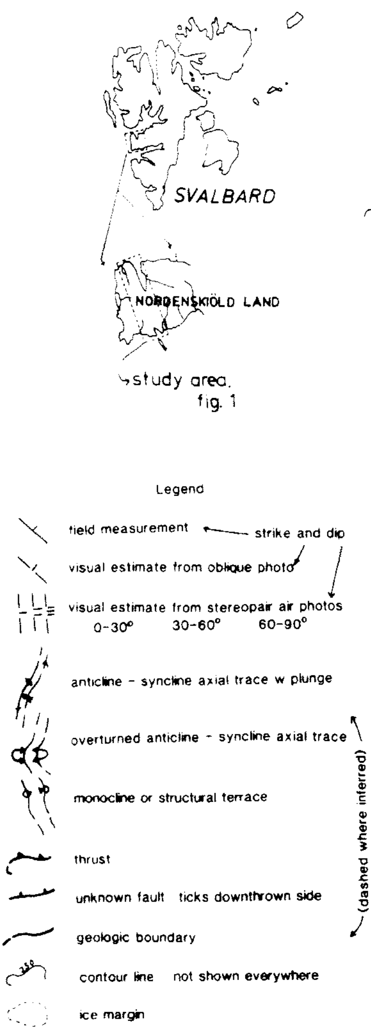
Orvin (1969) provided cross sections through N and S Nordenskiöld Land where the Tertiary structures are simplified as 2–3 NE verging, large folds that involve the basement and entire cover sequence. Considering the 1:1,000,000 map scale and early nature of this work (a 1969 reprint of a 1940 report), this was a state-of-knowledge interpretation for that time. Subsequent work which includes Nordenskiöld Land has largely focused on other areas than the western zone of Tertiary structures in Paleozoic to Mesozoic platform cover strata. Livšic (1965) describes the Paleogene strata and the broad, gentle fold and dome structures within them, as does Dalland (1979). The 1:100,000 geologic map sheet of Hjelle et al. (1986) and Hjelle (1988) delineates the detailed structural pattern in the Hecla Hoek basement rocks, but has limited structural data from the overlying platform cover strata. Yet, Svalbard's Tertiary structures, which formed during dextral transpression related to the opening of the Norwegian-Greenland oceanic basin (Lowell 1972), are of renewed interest (Dallmann et al. 1988). Ohta (1988) provides some of the most detailed descriptions of Tertiary structures in the N part of Nordenskiöld Land, and also discusses how surface data can be combined with seismic data.

In order to partially remedy the lack of description of Tertiary structures in this area, and as part of a larger compilation project, the following were used to produce structural maps (Fig. 1) and cross sections (Fig. 2): a) published literature, b) air photo interpretation of vertical, stereo-pair, black and white air photos (1:20,000) and a variety of oblique photos, c) helicopter spot checks in the southern part of Nordenskiöld Land, d) two weeks of mapping in the Grønfjorden area (by N. Ringset), e) two days of mapping in the Flathaugen area (by H. Maher and W. Dallmann). Original compilation was at a scale of 1:100,000.

This paper is mainly a presentation of our results on the structural style in the platform cover strata and is meant to supplement earlier publications (e.g. Hjelle et al. 1986). A discussion on the nature of changes in structure along strike, on the nature of basement involvement, and on similarities to Tertiary structures to the N and S of Nordenskiöld Land is also included, along with some suggestions for future research in the area.

Stratigraphy

The following description and nomenclature is taken primarily from Hjelle et al. (1986). Base-



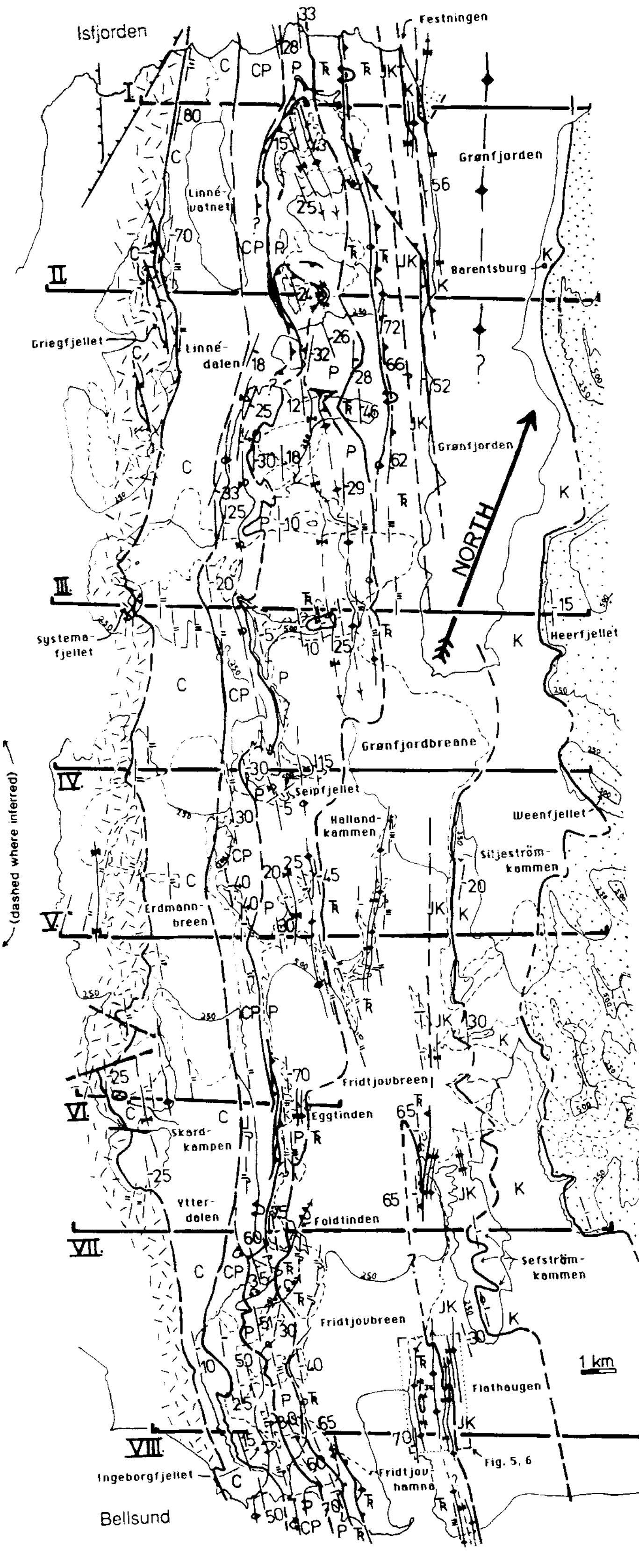


Fig. 1. Compilation map of Tertiary structures in the pre-Tertiary platform cover strata of Nordenskiöld Land. Original compilation base: Norsk Polarinstitutt 1:100,000 topographic map sheets. Map units in order of stratigraphic ascent: hatchured pattern – Hecla Hoek basement sequence; C – Carboniferous Billefjorden Group; CP – Carboniferous to Permian Gipsdalen Group; P – Permian Kapp Starostin Group; TR – Triassic Sassendalen and Kapp Toscana Groups; JK – Jurassic to Cretaceous Janusfjellet Formation; K – Cretaceous Helvetiafjellet and Carolinefjellet Formations; dot pattern – Tertiary clastics.

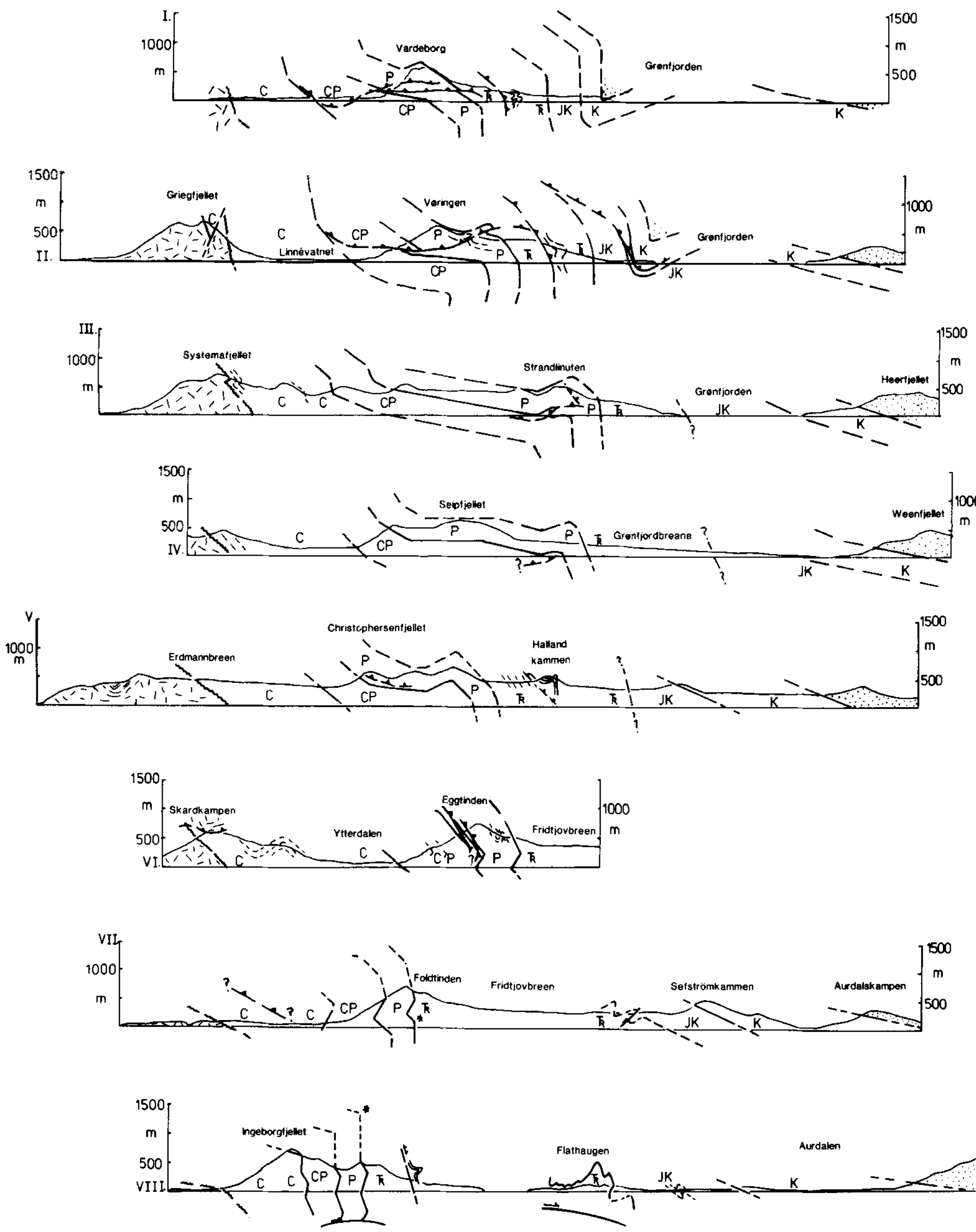


Fig. 2. Serial cross sections from Fig. 1. No vertical exaggeration. Units same as in Fig. 1.

ment is composed of phyllites, quartzites, marbles, and minor metavolcanic rocks of Riphean(?) age and metatilloids of Vendian age (referred to collectively as the Hecla Hoek sequence). Unconformably overlying these are about 1100 m of Carboniferous age Billefjorden Group quartz arenites and minor black shales and coals. These represent the basal stratigraphic division of some 3700 m of platform cover strata. Overlying Gispdalen Group light-grey dolomites, dolomite breccias and subordinate anhydrite, quartz arenites and basal conglomerates are cumulatively 360+ m thick. The equivalent strata on Midterhuken (just S) are 370–470 m thick

(Cutler 1981). Above these strata are 400 m of predominantly dark, spiculitic cherts and light coloured, fossiliferous limestones of the Permian age Tempelfjorden Group (equivalent here to the Kapp Starostin Formation). This unit is easy to distinguish both in the field and on air photos. Triassic age, Sassendalen Group, marine, recessive siltstones and sandstones (about 700 m thick) are the next unit with stratigraphic ascent, and are overlain by terrestrial and shallow marine clastics of the upper Triassic and Jurassic Kapp Toscana Group (300–350 m thick). A distinctive, thin conglomerate, the Brentskardhaugen Bed, separates Kapp Toscana Group strata from Jurassic through Cretaceous age, black, marine shales of the Janusfjellet Formation (the lowest unit in the Adventdalen Group). Overlying these shales are terrestrial sandstones, siltstones, and minor coals of the Cretaceous age Helvetiafjellet Formation (50–100 m thick), and deltaic and proximal marine clastics of the Carolinefjellet Formation, both also within the Adventdalen Group. In the N part of Nordenskiöld Land, Middle to Upper Cretaceous erosion has removed all of the Carolinefjellet Formation, and Tertiary strata rest directly on Helvetiafjellet Formation strata. In the S part, several hundred meters of the Carolinefjellet Formation are preserved. Paleocene to Eocene clastics of the Van Mijenfjorden Group occur mainly to the E of the study area, within the central basin Tertiary syncline. Further stratigraphic description can be found in Buchan et al. (1965), Cutbill & Challinor (1965), and Steel & Worsley (1984).

Folding of the Kapp Starostin Formation

The Kapp Starostin Formation (Hjelle et al. 1986; Cutbill & Challinor 1965) behaves as a relatively competent unit S of Isfjorden (e.g. Maher et al. 1986), and in Nordenskiöld Land provides a continuous marker horizon from the N to the S shore delineating a variety of folds. A large scale anticlinal fold structure in the N is composed of an upper limb with shallower to moderate NE dips and a lower, subvertical to overturned limb (Fig. 2). In some ways it resembles the 'step folds' described from Oscar II Land to the N (Harland & Horsfield 1974; Bergh et al. 1988; Maher 1988b). Steeply dipping Tertiary strata on the W shore of Grønfjorden (Hoel & Orvin 1937) indicate that they are involved in this large structure, and also constrain the timing of deformation to Paleocene or younger. The involvement of Hecla Hoek basement through basal Tertiary rocks gives this large structure a decided 'thick-skinned' character, as portrayed by Orvin's (1969) and Ohta's (1988) cross sections.

For the length of Grønfjorden, a smaller anticline-syncline pair, with an amplitude of 60–70 m and a wavelength of 100–250 m or less, is found in the Kapp Starostin Formation strata of the upper, shallowly-dipping limb of the fold belt on the W side of Grønfjorden (Fig. 1). While they were originally thought to be continuous (Ohta 1988; H.M. this report), detailed mapping (N.R. this report) suggests that at least two separate syncline-anticline pairs exist. Also, while fold structures are evident on the adjacent mountain sides, there is no reversal of dip at lower levels within Kongressdalen (Fig. 2, immediately S of cross section II). Their size, discontinuous nature and the inability to trace them into lower strata suggest they formed above detachments near to and below the base of the Kapp Starostin Formation. Detachments in a similar position are documented by Bergh et al. (1988) in equivalent strata N of Isfjorden. Both on Vardeborg and Vøringen (Fig. 2 – II + III), low-angle, NE-directed thrusts can be seen to cut basal Kapp Starostin Formation strata. A simple interpretation for the structures is that they represent a duplex system with NE transport that has later been rotated to its present position on the upper limb of the large, above-mentioned fold. An out-of-sequence thrust truncating an earlier fold structure might be an alternate working hypothesis. However, the footwall truncation is not evident.

Folds in the Kapp Starostin Formation of the southern half of Nordenskiöld Land are more variable in style. Seipfjellet (Fig. 2 – IV) is characterized overall by open folding and shallow dips, but in nunataks along strike to the SE these folds have a larger amplitude. Foldtinden and Folddalen provide an excellent exposure of a northeast-verging chevron fold-pair with an overturned limb some 400 m long (Fig. 2 – VII, 3). The structural higher axial plane is subhorizontal and the axis is NW-SE (parallel to the overall trend of Tertiary structures). The structurally lower axial plane is exposed low on the N side of Folddalen (roughly at the level of the valley floor) and fairly high on the northern slopes of Grå-

Fig. 3. View of Foldtinden looking NW. Dark strata at peak are Kapp Starostin Formation, and lighter grey in the fold core to the W are dolomites of the Gipshuken Formation (Gipsdalen Group). The less resistant strata to the right are Triassic Sassendalen Group. Relief is approximately 550 m.

Fig. 4. View of Sundhøgda and the E end of Ingeborgfjlellet. View to the NW from over Van Mijenfjorden. Same strata as in Fig. 3. Note fold in Triassic strata (arrow).

nutane (ridge defining the S side of Folddalen). This pattern indicates a local 15–20° northward dip of the axial plane. The northern ridge of Grånutane is subparallel to the NNE-plunging fold axis. This complex axial plane geometry suggests that in a cross section view (Fig. 2 – VII) the axial planes converge within Triassic strata to the SE, and that along strike to the NW the fold structures change in the subsurface (the overturned limb length should increase).

Comparable folds with moderately to shallowly NE-dipping limbs and with subvertical to overturned lower limbs continue from Foldtinden to the S shore of Nordenskiöld Land, and are evident in the southern slopes of Ingeborgfjellet (Fig. 1, 4). As far as can be ascertained from the air photo interpretation, they have shallowly NW plunging axes and shallowly to moderately, SW dipping axial planes. At both Ingeborgfjellet and Foldtinden (Fig. 2, 3, 4), both the overlying Sassendalen Group strata and the underlying, grey dolomites of the Gipsdalen Group are involved in the folding. The degree to which the underlying, Lower Carboniferous Billefjorden Group strata are also involved is not known, but along the S shore, NE dips of up to 50 degrees of these strata (Hjelle et al. 1986) indicate partial involvement.

Character of basement involvement

Where exposed in Nordenskiöld Land the basement-cover contact dips consistently and moderately to steeply to the NE, and is only cut by minor transverse faults or by normal faults (E slope of Griegfjellet, Fig. 2 – II) of uncertain age. The basement could be viewed simply as an uplifted, tilted block. Two areas indicate at least minor basement involvement in the Tertiary folding and thrusting. On the NE cirque wall of Systemafjellet (Fig. 2 – III), a NE verging fold in Billefjorden Group strata is indicated on air photos in such close proximity to the basal unconformity that it seems likely they are also affected. Also, the peak of Skardkampen (Fig. 2 – VI) consists of Hecla Hoek basement overlying Billefjorden Group strata (Hjelle et al. 1986), and this may represent an erosional klippe of thrusted basement. The ridge SE of Skardkampen also shows a reversal of dip, indicating relatively upright folds in the Billefjorden Group strata. The size and proximity of these again makes it seem reasonable that the basement rocks might be involved.

It is curious that exposures of the basement-cover contact for the width of Nordenskiöld Land show no significant changes in dip, while Kapp Starostin Formation strata to the E are involved in folds that change along strike and plunge, and have overturned limbs. This observation hints that many of these folds formed above detachments within strata below the Kapp Starostin Formation, but above basement rocks. The following points are also consistent with such an idea: 1) some Gipsdalen Group cross section thicknesses (e.g. Fig. 2 – VI, VII) are up to twice the stratigraphic thickness given by Hjelle et al. (1986) (360+ m) for Nordenskiöld Land. This suggests either consistent map boundary misplacement, notable undocumented stratigraphic thickness changes, or possible tectonic repetition; 2) tectonic repetition and detachments have been described in the same strata on Midterhuken, just to the SE (Maher 1984; Maher et al. 1986), as well as further N in Oscar II Land (Bergh et al. 1988); 3) axial planes of some of the folds in the Kapp Starostin Formation appear to converge within Billefjorden Group strata, well above the basement contact (Fig. 2, S sections); 4) minor low-angle thrusts with some tens of meters of movement occur on the NW slopes of Eggtinden (Fig. 2 – VI), repeating basal Kapp Starostin Formation strata; 5) air photos suggest that stratal disruption may exist in shallows along the Isfjorden shore near the Billefjorden-Gipsdalen Group contact, an appropriate stratigraphic level for a detachment.

Major, basement involved overthrusts in Nordenskiöld Land, similar to those at Berzeliustinden to the S (Hauser 1982; Dallmann 1988) and St. Jonsfjorden to the N (Winsnes & Ohta 1988), are not known to us. However, both recent seismic studies (Faleide et al. 1988) and structural field studies (Andresen et al. 1988; Bergh et al. 1988; Haremo & Andresen 1988) imply that basement involved overthrusts occur in the subsurface of Nordenskiöld Land, as suggested by Ohta (1988). These would be necessary as part of a thrust system that continues under the central Tertiary basin syncline and emerges along the trace of the Billefjorden fault, where up to 3 km of stratal shortening has been reported (Andresen et al. 1988; Haremo & Andresen 1988). The Bravaisknatten thrust exposed on Midterhuken to the S (Maher et al. 1986; Maher 1988a) may continue under Akseløya and southern Nordenskiöld Land as one of these subsurface thrusts.

Structures in Triassic strata

Kapp Toscana Group sandstones in the E ridge of Sundhøgda (S shore of Nordenskiöld Land, E of Ingeborgfjellet, Fig. 2 – VIII, 4) show a style of folding very similar to that described on Midterhukfjellet to the S (Maher et al. 1986). Parallel folds with moderately to shallowly, SW dipping axial planes, and without a prevailing asymmetry occur above a NE dipping décollement within the Sassendalen Group. Conflicting models for the kinematics of these folds are discussed in Maher et al. (1986), Maher (1988a), and Ringset (1988), but will not be repeated here. Hoel & Orvin's (1937) description of the Festningen section along the N shore of Nordenskiöld Land indicates that small scale folding and thrusting occurs in Triassic strata here. It is likely that these folds also formed between bedding-parallel slip planes and that they represent a continuation of this structural style.

Further E of Sundhøgda, Fridtjovhamna, and along strike, Fridtjovbreen cover a 2 km or greater width of structure (Fig. 1, 2). At Flathaugen, on the NE side of Fridtjovhamna, tight, upright, doubly-plunging folds with subhorizontal enveloping surfaces repeat Kapp Toscana strata (Fig. 5, 6) in a geometry consistent with formation above a décollement in the underlying Sassendalen Group (likely within the shales of the Botneheia Formation). Crude sinuous-bed estimates indicate some 700–800 m (roughly 40%) of stratal shortening in the immediate Flathaugen area. Since folding continues to the E, this represents a minimum estimate. Along strike to the NE, just W of Sefströmkammen (Fig. 2 – VII), helicopter reconnaissance indicates a possible thrust of Kapp Toscana Group sandstones into the black shales of the overlying Janusfjellet Formation.

From these observations, and using Midterhuken's N shore as a parallel (Maher 1984; Maher et al. 1986; Ringset 1988), the zone from the end of Sundhøgda through Flathaugen is thought to represent a 3.5 km wide structural 'terrace' where Kapp Toscana Group strata are repeated above a subhorizontal décollement mainly by folding but also by thrusting, as part of a composite duplex system (Fig. 2 – VII). The duplex roof would lie within Janusfjellet Formation black shales. Simple extrapolation of the estimates from Flathaugen would infer some 1.4 km of shortening across this zone. This structural terrace widens consistently to the S on Midterhuken and Wedel Jarlsberg Land, but is not apparent in the northern half of Nordenskiöld Land, although it could underlie Grønfjorden.

West limb of the Tertiary central basin syncline

On the eastern edge of the study area (Fig. 1), upper Janusfjellet Formation shales and Helvetiafjellet Formation sandstones dip consistently some 30 to 15 degrees to the NE to form the W limb of the asymmetric central Tertiary basin syncline. Dalland's (1979) structure contour map on a Paleogene horizon shows that the dip change on the W limb does not form an arc, but has a hinge through Nordenskiöld Land occurring along a line some 6–8 km E of the eastern edge of the study area (Fig. 1) from Hollendarbukta (N) to Svartodden (S). By combining the above mentioned Isfjorden seismic work (Faleide et al. 1988) with regional considerations of the structural style at deeper levels, this line may be thought to represent a tip line and/or ramp-flat junction associated with a fault system that underlies and is responsible for the central basin west limb.

Just NE of Sefströmkammen (Fig. 2 – VIII) air photo interpretation indicates the presence of a fold with SW vergence. Similar folds occurring on Midterhuken are thought to be related to backthrusting associated with insertion of wedge shaped blocks (Dallmann & Maher 1988).

Evaluation of an en echelon fold pattern

The documentation of en echelon patterns in the Tertiary structures of Svalbard is especially important in light of the transpressive plate tectonic setting (Harland 1969) and Lowell's (1972) flower structure model for the large scale crustal architecture. Parts of the map pattern (Fig. 1) are suggestive of an en echelon structural pattern associated with dextral transcurrent movements, but the following two points indicate that alternate interpretations are needed.

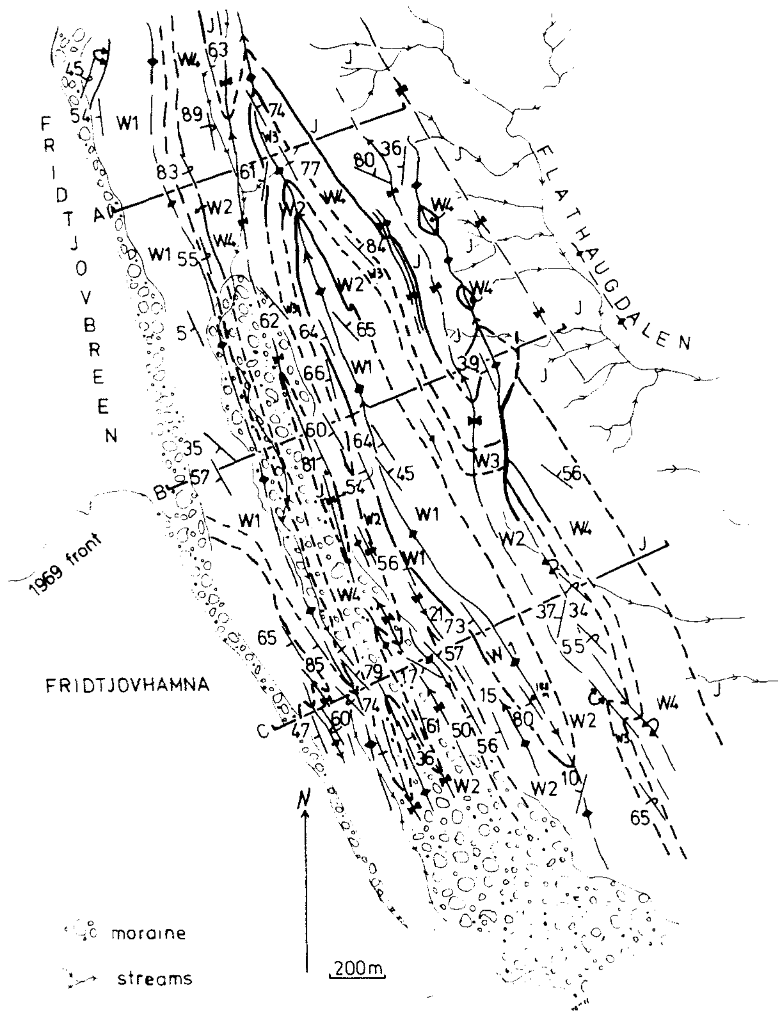


Fig. 5a. Detailed map of Flathaugen area (Fig. 1 inset for location). Symbols as in Fig. 1.

First, the zero elevation contour lines on both the basement unconformity and the base of the Tertiary succession are fairly linear and subparallel. Any en echelon pattern is restricted to the intervening platform cover strata, and as described above, would be associated at least in part with low angle thrusts.

Second, the overall left-stepping pattern of folds in Kapp Starostin strata in the southern part and the more northerly trending axis of the Foldtinden structure (clockwise instead of counterclockwise of the general structural trend), in particular, would be more consistent with a sinistral movement component. It is instructive that folds in the N which may show a 'dextral' pattern plunge to the SE, while those with an apparent 'sinistral' pattern plunge to the NW, i.e. a consistent en echelon pattern does not exist. Plunge in part explains the map pattern. Transfer of slip from one structure to another along strike may explain the discontinuous nature of many of the structures. Detailed mapping is necessary to delineate transfer zone and mechanisms.

A model of kinematic decoupling (Maher & Craddock 1983, 1988; Haremo & Andresen 1988; Nøttvedt et al. 1988) can explain a predominantly compressive (movements perpendicular to the overall structural trend) character of Svalbard's

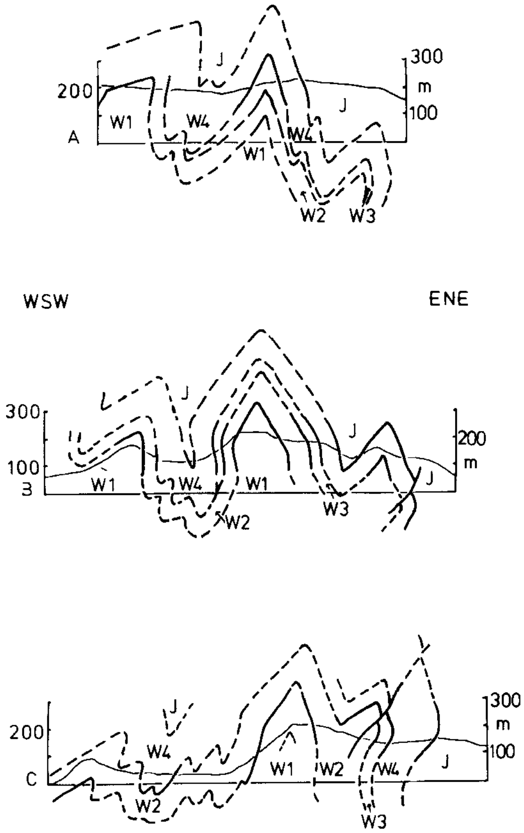


Fig. 5b. Cross sections from Flathaugen. W1 through W4 are an informal division of the upper Triassic strata (Kapp Toscana Group). W1 – white, quartz arenite; W2 – brown, cross-bedded sandstones; W3 – white quartz arenite; W4 – multi-colored (black, reddish, orange) shales and thin carbonates; J – black shales of the Janusfjellet Group. Complex facies relations exist between W2 and W3. Map base was black and white air photo # 69-2575 (1:20,000) Norsk Polarinstitutt.

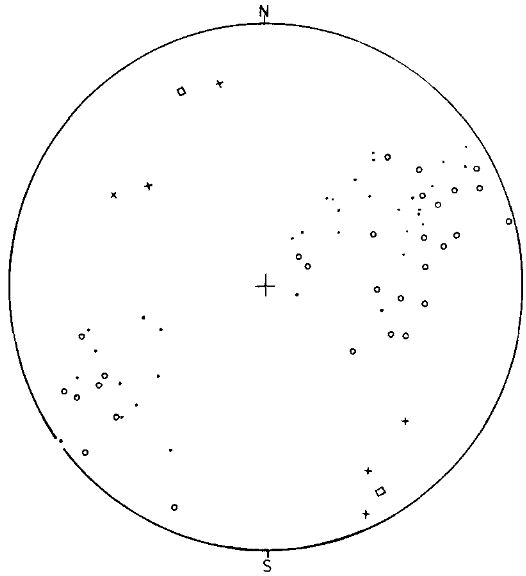


Fig. 6. Lower hemisphere, stereographic projection plot of structural elements from the Flathaugen area. Open circles – poles to bedding from the northern half. Dots – poles to bedding from the southern half. Crosses – measured fold axes. Squares – estimates of map-scale fold axes from the N and S halves of the map (doubly-plunging overall structure).

Tertiary fold-and-thrust belt. Structures in Nordenskiöld Land as known at present are consistent with this model.

Possible Middle Carboniferous unconformity

An angular unconformity exists on Midterhuken between Lower Carboniferous Billefjorden Group strata and Upper Carboniferous to Permian Reinodden Formation strata (Maher 1984; Maher & Craddock 1984; Maher et al. 1986). The extent of this unconformity is important in light of Birkenmajer's (1964) Middle Carboniferous Adriabukta phase based on observations in Hornsund. Visual reconnaissance of Ingeborgfjellet on the N shore of Bellsund indicated that a similar angular unconformity could exist in Nordenskiöld Land (Maher 1984). The overall map pattern is suggestive, with an implied thinning of the Billefjorden Group to the S. Also, in Linnédalen (Fig. 1), the red bed Vegard Formation, which overlies the grey quartzites of the Orustdalen Formation within the Billefjorden Group, is often absent. However, an angular unconformity was not directly observed by us. Townsend & Mann (1988) reported finding unconformities within the Billefjorden Group in Nordenskiöld Land, but details are not given. Given the character of the unconformity on Midterhuken and assuming it was the result of tilting caused by listric normal faulting formed during an extensional event (Gjelberg & Steel 1981), it can be inferred that it is not a fault that bounds the eastern limit of Billefjorden Group strata in the western outcrop belt of central Spitsbergen, but an erosional pinch out instead. The major Carboniferous basinal fault margin could be expected to the W.

Future research mapping

We suggest that mapping of the cover strata between the basement and ridges with folded Kapp Starostin strata would be most useful. This area is strategic for recognizing lower detachments and in constraining the nature of basement involvement. Because of a lack of distinctive marker horizons, air photo interpretation has limited use in delineating structures in these strata. Also, the possibility of angular unconformities within the Carboniferous strata can be evaluated in that area. Mapping of the Janusfjellet Formation strata beneath the western limb of the central basin syncline may help find possible back thrusts and roof thrusts associated with major duplexes.

Discussion and conclusion

In NW Nordenskiöld Land, Hecla Hoek basement rocks through basal Tertiary strata are involved in a large NE verging fold. Regional considerations and seismic studies (Faleide et al. 1988) indicate basement involved thrusts exist in the subsurface at the base of this structure (Ohta 1988). Otherwise, major basement involved thrusts are absent in Nordenskiöld Land. Folds similar in scale and style occur in Oscar II Land to the N. In addition, smaller scale folds of Kapp Starostin Formation strata evident in Nordenskiöld Land display uncertain basement involvement. A simple interpretation is that they formed above detachments within underlying Carboniferous strata, and were rotated to their present NE-dipping position. A consistent en echelon pattern is not discernible and changes along strike can be explained both by a disharmonic fold style with local structural plunge and by along-axis changes, perhaps due to slip transfer processes, in a system with a dominant N60E transport direction. Detailed mapping is needed to elucidate the exact character of the changes.

Based on limited mapping and regional comparisons, to the E of these folds in S Nordenskiöld Land we infer the existence of a 3.5 km wide zone where Kapp Toscana Group and overlying Janusfjellet Formation strata are repeated by folding and possibly by imbricate thrusting. While a large portion of this zone is covered by Fridtjovbreen, outcrops along the glacier's margins (e.g. Sundhøgda and Flathaugen), along with similar structures at Midterhuken to the S, are the basis for postulating the existence of this zone. It likely represents a composite duplex complex with subhorizontal constraining surfaces.

Further E is the W limb of the central Tertiary basin syncline. Backthrusting or a roof thrust are speculated to exist within the incompetent Janusfjellet Formation black shales immediately below the more competent sandstone-dominated sequence (Helvetiafjellet Formation and above) of the W limb. Such structures would serve to transfer movement represented by the structures immediately to the W, either up-dip into the air (backthrusting), or beneath the Tertiary basin.

Finally, with a consistent, although slight structural plunge to the S north of Isfjorden, and to the N south of Bellsund (Dallmann 1988), Nordenskiöld Land represents the highest preserved level of the Tertiary fold-and-thrust belt. Much of the shortening is accommodated either in the subsurface, evident in the formation of the W limb of the central syncline and in more subtle structures within the Tertiary strata of the central basin, or in the thin-skinned structures along the trace of the Billefjorden fault as described by Andresen et al. (1986, 1988) and by Haremo & Andresen (1988). Knowledge of the basement configuration is crucial to estimating the magnitude of Tertiary tectonism.

Acknowledgements. – H. Maher would like to thank NTNF for providing fellowship support, Norsk Polarinstitutt for providing office, material and logistical support, and the University of Nebraska for providing leave-of-absence support. Narve Ringset thanks Norsk Olje A/S for permission to publish their field data. Y. Ohta is also thanked for providing useful discussion and feedback. We are also grateful to two anonymous reviewers for providing valuable criticisms and suggestions.

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