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Tertiary tectonism and basin inversion of the St. Jonsfjorden region, Svalbard

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Abstract—Deformed basement and cover rocks of the St. Jonsfjorden area further define the character of Spitsbergen's Tertiary fold and thrust belt. Three major thrusts comprise a folded, *ca* N060° E-directed, foreland propagating thust stack, with likely additional subsurface thrust faults. The folded Vegardbreen–Robertsonfjellet Thrust is the most significant fault in the complex and re-emerges in the core of a disrupted synclinal structure in Triassic strata. Shortening across the area indicated from line length restoration is of the order of 13 km. Differences in stratigraphy between and within thrust sheets indicate the thrust stack initiated along the edge of a westward deepening Carbonbiferous basin with a fault-step margin and represents basin inversion. Early structures related to basin formation had a major control on later thrust sheet evolution and the complexity of inversion structures reflects the initial complexity of the basin geometry. Such basin inversion could characterize the length of the fold and thrust belt. The St. Jonsfjorden structures are primarily contractional, and together with areas farther southeast in the fold–thrust belt, indicate shortening took place perpendicular to the fold belt across much of the length of the evolving margin.

INTRODUCTION

IN western Spitsbergen, on the northwestern corner of the Barents Shelf, both crystalline basement rocks and overlying Carboniferous–Cretaceous platform cover strata are notably thust and folded within a NW-trending belt (Fig. 1). Although the age range of these structures is still a topic of discussion, evidence points to the majority of deformation occurring from Late Paleocene to Eocene. This is based on the following; local involvement of Tertiary strata in fold and thrust structures (Orvin 1934, 1940, Hoel & Orvin 1937), the 20° tectonic dip of Tertiary units in the *ca* 100 km long and several km wide western limb of the central basin syncline (Maher & Craddock 1988), the lack of angular unconformities at the base of the Tertiary sequence, and sedimentological signatures in the Tertiary foreland basin (Steel *et al.* 1986). On the basis of the temporal overlap between folding and thrusting and the early stages of opening of the Norwegian–Greenland Sea, Harland (1969) and Lowell (1972) interpreted an overall intracontinental, dextral transpressive transform setting for this deformation.

Subsequent mapping has brought to light a predominance of convergent, fold and thrust structures and a paucity of transcurrent features. This led to the suggestion that the dextral transpression must have been decoupled (Beck 1986, Mount & Suppe 1987) with the convergent portion exposed on western Spitsbergen (Haremo & Andresen 1988, Maher & Craddock 1988, Nøttvedt *et al.* 1988). Also, Andresen *et al.* (1988), and Haremo & Andresen (in press) describe thin-skinned contractional features along the southern portion of the Billefjorden fault zone (Fig. 1) and argue that these features are linked with the west coast structures to form a much more extensive (*ca* 100 km wide) fold and thrust belt than previously thought.

The St. Jonsfjorden area (Fig. 1) in northwest Spitsbergen, is well suited for studying the evolution of the fold and thrust belt because: (1) it is located on the transition between basement-involved folds and thrusts and thin-skinned deformation to the east within the platform cover; (2) a change in deformation style occurs along strike, with thrusts to the north and predominantly large monoclines and NE-verging folds to the south (Challinor 1967, Kellogg 1975, Maher 1988); (3) it is the site of several NE-dipping thrusts, which were thought to be either backthrusts or folded thrusts (Winsnes & Ohta 1988). Backthrusting has been described from the Bellsund area and has been proposed as an important component of the Tertiary fold and thrust belt (Dallmann 1988, Dallmann & Maher 1989).

This paper describes the structures and implied kinematics of the St. Jonsfjorden region, discusses the significance of structural plunge to changes along strike, and considers various mechanical controls on fold and thrust geometry and position. The latter includes the role of Carboniferous intrabasinal faults in controlling ramp positions and lithologies, which form important

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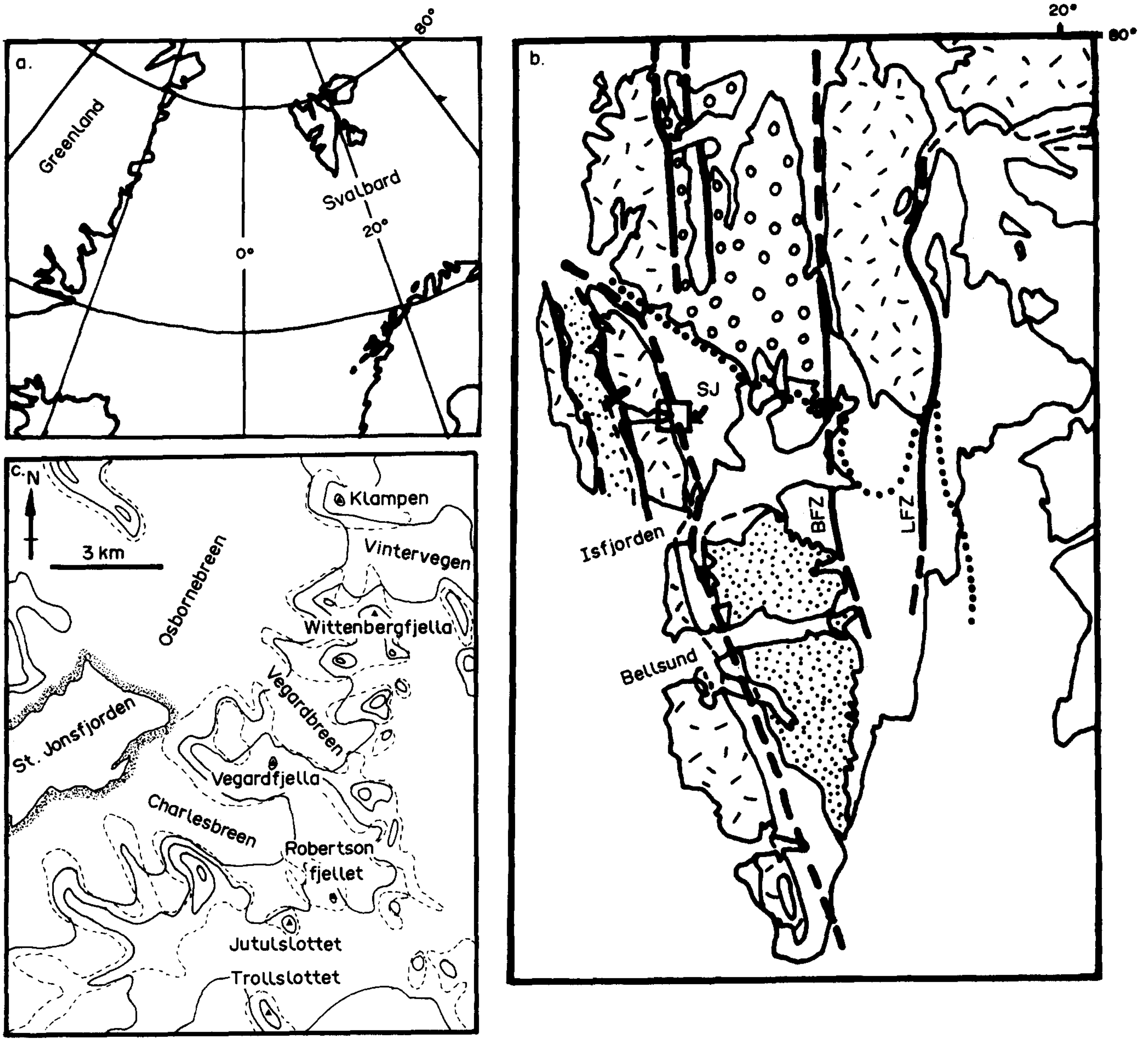

Fig. 1. (a) Location map for Svalbard. (b) Geologic map of Spitsbergen (largest island in Svalbard archipelago). Simplified from Winsnes (1988). BFZ = Billefjorden fault zone. LFZ = Lomfjorden fault zone. SJ = St. Jonsfjorden field area. Dot pattern = Tertiary basin fill. Unpatterned area = platform cover strata (see Fig. 2). Circles = Devonian basin fill. No pattern = basement rocks. Heavy dotted line = approximate known eastern extent of preserved thin skinned tectonics. Heavy dashed line = eastern extent of significant, thrust-ramp related uplift. Both BFZ and LFZ were reactivated in Tertiary (Haremo & Andresen in press). (c) Topographic map of the field area.

detachment horizons in the area. Implications of this data for regional tectonic modeling are also discussed.

STRATIGRAPHY

The platform cover stratigraphy of north Spitsbergen is summarized in Fig. 2 and is described in more detail by Hjelle & Lauritzen (1982) and Steel & Worsley (1984). The crystalline basement in the St. Jonsfjorden region consists of Caledonian nappes containing schists, marbles and diamictites (Morris 1988). The oldest rocks overlying the basement are Carboniferous Billefjorden Group conglomerates, quartz arenites and shales which vary in thickness from thrust sheet to thrust sheet and are locally absent. These clastic rocks contain abundant plant fossils, attesting to their non-marine nature, and are interpreted as predominantly fluvial, lacustrine and swamp deposits. Above the Billefjorden Group, or the Caledonian basement where the Billefjorden Group is absent, are the Petrelskardet marine shales. Increasing proximal sources are reflected in the deposition of the overlying Tårnkanten Formation, comprising shallow marine sandstones and conglomerates. The combined effect of sea level changes and the northward drift of Spitsbergen on sedimentation resulted in deposition of fossiliferous limestones of the Nordenskiøldbreen Formation, and sabkha facies of the Gipshuken Formation. Upper Permian and Lower Triassic sedimentation was characterized by deposition of cherts and cherty limestones, whilst the remaining Triassic deposits consist of shallow marine shales and limestones of the Sassendalen Group.

Lithostratigraphic equivalents to the St. Jonsfjorden Nordenskiøldbreen and younger units are widely distributed throughout Spitsbergen and are suggestive of general platform stability. In contrast and due to Carboniferous tectonism, considerable lateral variation occurs both within Carboniferous strata of the St. Jonsfjorden area, and between the St. Jonsfjorden area and other localities where Carboniferous rocks are exposed (Worsely 1986). Carboniferous tectonism is well documented for the Billefjorden fault zone (Fig. 1) and the accompanying basin to the east by Gjelberg & Steel (1981) and Steel & Worsley (1984), and is also described for Bjørnøya (Worsley 1986) and Greenland (Stemmerik *et al.* 1991). While the tectonic setting for the Carboniferous tectonism is uncertain, it probably included an element of rifting (Worsley 1986).

In St. Jonsfjorden the following attests to tectonism during deposition of the Carboniferous strata. An angular unconformity (up to *ca* 15° discordance) underlies the Nordenskiøldbreen Formation carbonates throughout the study area, and in places cuts out the entire Tårnkanten Formation (Welbon & Maher 1990). Gentle fold structures are truncated by the unconformity (e.g. on Robertsonfjellet, Fig. 7d), and at least one other angular unconformity also exists within the Carboniferous clastics underlying the Nordenskiøldbreen Formation. Local conglomeratic units are suggestive of a relatively proximal source. Significant facies changes (from sand dominated to shale dominated) occur within the Vegard through to Tårnkanten Formations, both along strike within a thrust sheet and from one thrust sheet to another. In some of the thrust sheets up to 500 m of Billefjorden Group orthoquartzites rest unconformably on the basement rocks while in others a relatively thin Tårnkanten Formation overlies basement rocks. Whilst details of the Carboniferous stratigraphy can be developed only after the thrust geometry has been established, in general the upper thrust sheets have thicker,

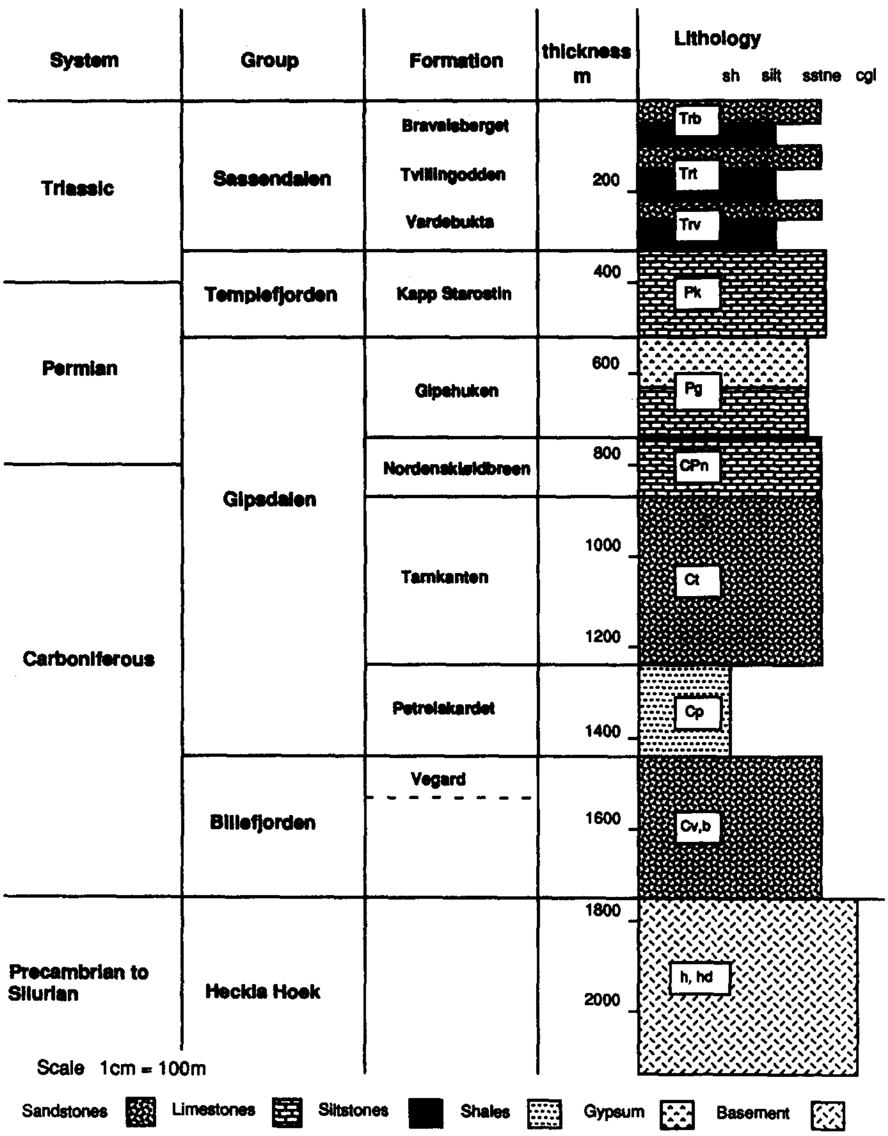

Fig. 2. A generalized stratigraphic column for the St. Jonsfjorden region. After Challinor (1967), Hjelle & Lauritzen (1982) and data from the present authors.

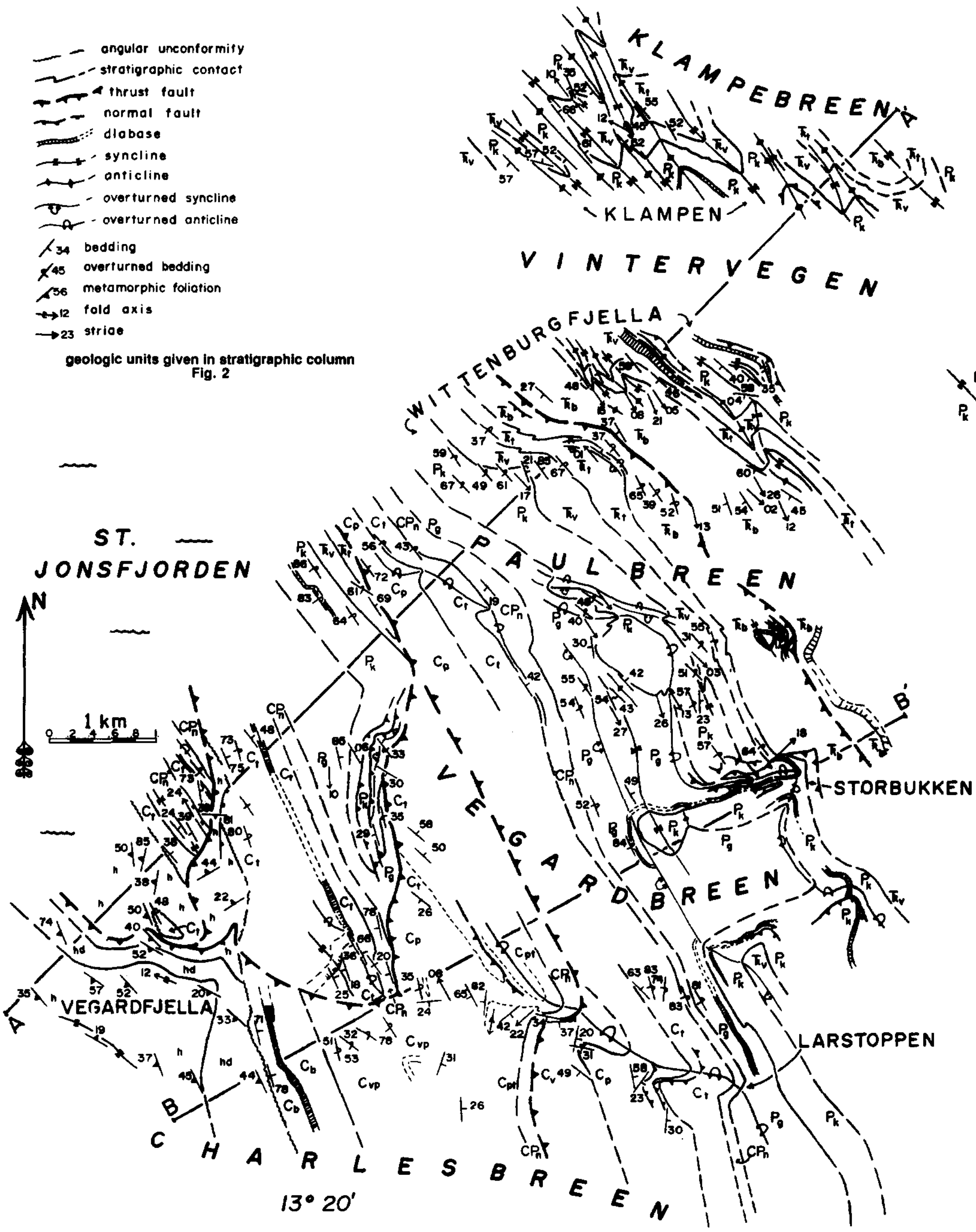

Fig. 3. Structural map of St. Jonsfjorden area. Sections A–A′ and B–B′ are found in Fig. 4.

more complete sections, suggesting a deepening basin to the west.

DESCRIPTION OF THRUST SHEETS

Three major bounding thrust faults of the St. Jonsfjorden area enclose thrust sheets with smaller-scale internal folding and faulting (Figs. 3 and 4). The major thrusts are in turn folded, most likely above a culmination produced by an underlying subsurface thrust geometry. While some changes in style occur along strike, the structures are best described in a cross-section perspective. The following description of bounding thrusts and the associated thrust sheets is from structurally lowest to the highest.

The Lower Vegardfjella Thrust

This thrust outcrops at lower levels on Vegardfjella's northwestern slopes and with a variable NE dip it becomes subsurface before the terminus of the Vegardbreen glacier. Its southwest termination is the Upper Vegardfjella Thrust. Where exposed the thrust cuts up-section to the northeast. For most of its exposed length there is a basement hangingwall flat parallel to foliation (Figs. 3 and 4). In the immediate hangingwall on the northern slopes of Vegardfjella, a Carboniferous fault, subparallel to the Tertiary thrust, juxtaposes Tårnkanten Formation strata (southwest side) against basement rocks (Fig. 4). In subsurface, the thrust is inferred to cut up-section until it forms a flat in the Gipshuken Formation (a common detachment horizon elsewhere in west-

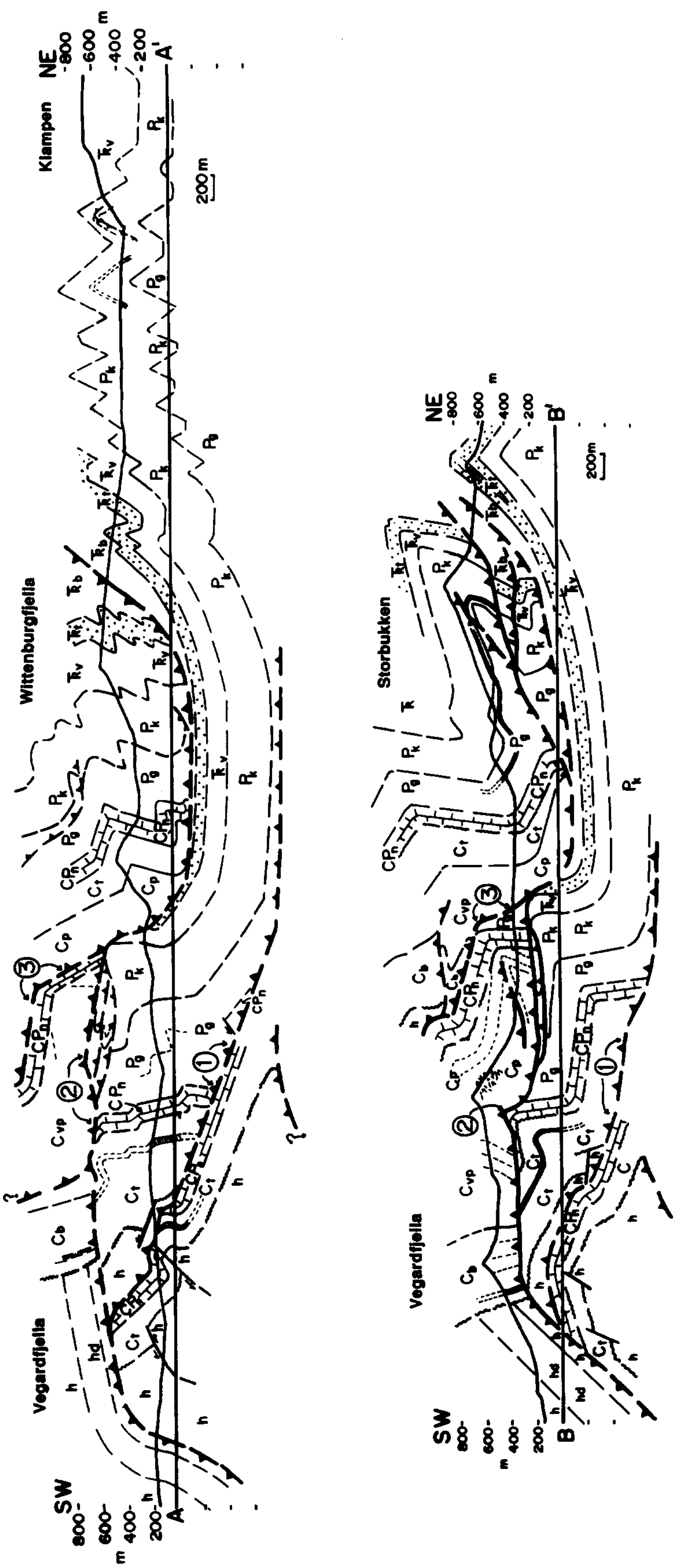

Fig. 4. Cross-sections A–A′ and B–B′ from Fig. 3. Thrusts numbered in order discussed in text. Nomenclature of thrusts is also shown in Fig. 8.

ern Spitsbergen). Hangingwall rocks continue as far as Wittenburgfjella, and the Lower Vegardfjella Thrust may join a major flat that underlies folded and thrusted Kapp Starostin and Triassic rocks of Klampen and which extends *ca* 10 km northeast of the study area (Maher 1988). In the footwall, a Nordenskiøldbreen Formation flat has local complexities which can be explained as local distruption by down-to-the-west Carboniferous normal faults (Fig. 4). It is important to note that the footwall sequence does not include the Billefjorden to Petrelskardet stratigraphic units. Nordenskiøldbreen cut-offs indicate *ca* 2 km of displacement for the Lower Vegardfjella Thrust. Other thrusts may join it in the subsurface to the east and increase displacement in that direction.

The Upper Vegardfjella Thrust

This thrust can be traced from the southern part of Vegardfjella (within basement rocks) to Vegardbreen, where it is interpreted to have a leading edge termination against a roof thrust (the Vegardbreen Thrust described below) (Figs. 3 and 4). At its southwestern end, a SW-dipping hangingwall and footwall foliation flat within basement occurs. To the northeast there is a complicated geometry of hangingwall and footwall cut-offs (Fig. 4). These cut-offs form a major ramp, with minor flats, that climb up to the Triassic Bravaisberget Formation where the thrust joins a major flat (reactivating the Vegardbreen Thrust flat—discussed later). Apart from footwall repetition due to the Lower Vegardfjella Thrust, stratigraphic climb of the Upper Vegardfjella Thrust is clearly to the NE for both the hangingwall and footwall. At the NE end of the thrust, footwall imbrication of Kapp Starostin Formation lithologies forms a small duplex with horses 50–100 m thick.

A notable feature of this thrust is the presence of 400 m of Billefjorden Group and an indeterminable thickness of Petrelskardet Formation in the hangingwall, which are absent in the footwall, where basal Tårnkanten Formation rests directly on basement. Since a significant thrust flat does not appear to exist within the Carboniferous rocks (Fig. 3), the hangingwall and footwall sections were in general proximity prior to thrusting. This suggests that the Upper Vegardfjella Thrust either nucleated close to or reactivated a Carboniferous fault and inverted part of the Carboniferous basin. On the basis of Nordenskiøldbreen Formation cut-offs (a thin distinctive unit relatively unaffected by Carboniferous tectonism) the displacement is *ca* 1.5 km in this section.

The Vegardbreen Thrust

On the ridge between Vegardfjella and Larstoppen (Fig. 3), the Vegard Formation is thrust on top of the Nordenskiøldbreen Formation. Hangingwall rocks are continuous to the North, where, at outcrops on the NE side of the Vegardbreen terminus, Petrelskardet Formation rocks are in thrust contact with the Triassic Tvillingodden Formation. The footwall rocks at this northern locality are also the footwall rocks to the Upper Vegardbreen Thrust, and therefore the Vegardbreen and Upper Vegardfjella Thrusts must joint somewhere to the southeast of this point, underneath Vegardbreen. We interpret the Vegardbreen Thrust to be the roof thrust that the Upper Vegardfjella Thrust merged with. Hangingwall cut-offs of the Vegardbreen Thrust cut up-section to the NE, from Carboniferous to Triassic strata (Fig. 4), and indicate this is a tilted NE-directed thrust. Like the Upper Vegardfjella Thrust the fault has a variable dip, mainly to the NE.

At Wittenburgfjella and Storbukken, farther northeast, a major syncline exists with abundant small folds and thrusts on the overturned SW limb and in the core. A continuous core is not evident in the Bravaisberget Formation despite excellent exposures on Wittenburgfjella. In cross-section constructions, the most likely place for emergence of the Vegardbreen Thrust is the core of this syncline, consistent with the disruption and minor structures observed in the field. This implies the syncline structure actually consists of a long, mainly subsurface, footwall flat in the Bravaisberget Formation, and a hangingwall cut-off of Tårnkanten through Tvillingodden Formations. Matching Tvillingodden cut-offs across this portion of the thrust indicates *ca* 3.2 km of displacement in the direction of the cross-section (Fig. 4). More displacement is indicated by the folds in the Tvillingodden Formation that remain after matching the cut-offs. These folds can be explained as early fault propagation features, which were later cut by continued fault tip propagation. Considering that this 3.2 km+ offset is northeast of the branch line with the Upper Vergardbreen Thrust (which has *ca* 1.5 km of displacement), some 1.7 km is suggested for the Vegardbreen Thrust southwest of the junction.

The following indicates the Vegardbreen Thrust probably connects with a major thrust exposed on Robertsonfjellet (Figs. 1 and 5) to the south: (1) the two thrusts have a similar orientation and are on strike with each other across the intervening glacier; (2) they both have Nordenskiøldbreen Formation rocks in the footwall; and (3) the Robertsonfjellet Thrust carries Billefjorden and basement rocks in the hangingwall, consistent with a continued cutting down-section to the southwest. As a combined major fault this thrust can then be traced some 10 km along strike and could continue to Trollslottet to the south (Fig. 1) where basement rocks overlie Billefjorden Group quartzites with an intervening subhorizontal thrust (Ohta personal communication).

Definition of thrust sheets

On the basis of the three major thrusts described above four major thrust sheets can be defined. From structurally lowest to highest these are as follows.

Thrust sheet 1. This lies beneath the Lower Vegardfjella Thrust. In that the folding and general NE dips of the NE-directed overlying thrusts is most easily

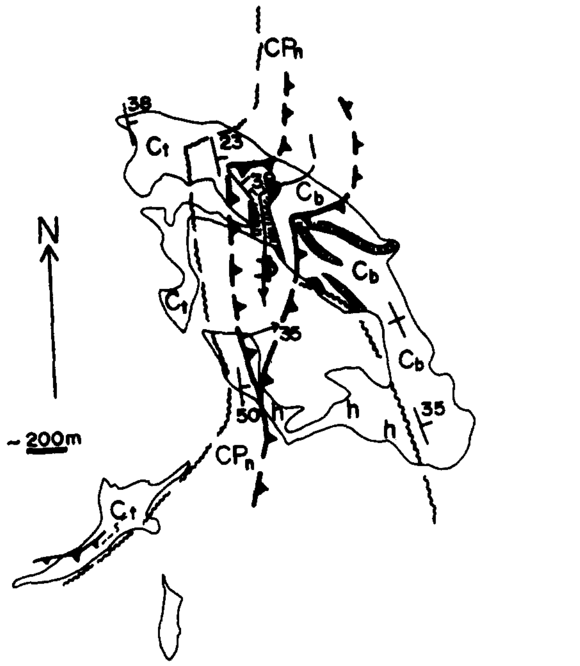

Fig. 5. Geologic map of the nunatak Robertsonfjellet to the south of the area depicted in Fig. 3. See Fig. 1 for relative locations.

explained by tilting above underlying thrusts, this thrust sheet probably overlies a major, subsurface thrust fault. This is also suggested by the shortening in the Klampen area (discussed later) and farther northeast (*ca* 6.6 km, Maher 1988), which is much greater than can be ascribed to the lower Vegardfjella Thrust alone (Fig. 4). In the Vegardfjella area this thrust sheet has undergone a minimum of 600 m vertical uplift.

Thrust sheet 2. This lies between the Upper and Lower Vegardfjella thrusts, and includes basement through to Triassic Bravaisberget Formation strata, and has inferred (not exposed) Gipshuken Formation lower and Bravaisberget Formation upper thrust flat boundaries for much of its length.

Thrust sheet 3. A wedge-shaped thrust sheet between the Upper Vegardfjella and Vegardbreen thrusts which includes basement through to Nordenskiøldbreen Formation rocks (including Billefjorden Group strata).

Thrust sheet 4. This lies above the Vegardbreen Thrust and contains basement (in the Robertsonfjellet area) through Bravaisberget Formation rocks and a large overturned fold pair.

There are several additional sites of thrusting in the St. Jonsfjorden area. Within thrust sheet 3, on the upper ridges of Vegardfjella, Billefjorden Group strata are relatively intact, while overlying Carboniferous sandstones and shales to the east are folded and faulted with abundant slickensides and striae. This discrepancy suggests the existence of a footwall thrust flat just above the intact Billefjorden Group strata. In addition, long flats are common in the gypsiferous Gipshuken Formation just above the Nordenskiøldbreen Formation elsewhere in the fold and thrust belt, and in cross-sections (Fig. 4) there are some notable thickness changes. Cryptic thrust flats may exist at this stratigraphic level (e.g. between the Gipshuken cut-offs of thrust sheet 2).

FOLD STYLES

As outlined above, several scales of folding, together with along-strike changes in structure are found in the study area. However, it is possible to generalize about the character of folding, and how fold styles vary from one thrust sheet to another.

In thrust sheets 2–4 (excluding the Klampen area) angular, NE-verging, monoclinal to overturned folds, with interlimb angles from *ca* 135° to 45°, have a consistent southerly plunge (Fig. 6). In contrast, folds in thrust sheet 1 (the northeastern part of the study area) have a slight northerly plunge. Truncation of overturned hangingwall limbs suggests fault-propagation folds were later cut by continued thrust tip propagation, or transported in their entirety during development of a deeper splay. Whilst most folds appear to be approximately cylindrical, locally folds in thrust sheet 3 were visibly conical in the field and the stereonet plot of poles to bedding also indicates a strong non-cylindrical distribution (Fig. 6).

The leading anticline of thrust sheet 4 displays instructive changes in structural style from Wittenburgfjella to Storbukken (compare cross-sections, Fig. 4). On Wittenburgfjella and the next ridge to the south, the overturned limb, which is truncated by the Vegardbreen Thrust, has folds with wavelengths from *ca* 10 to 100 m, and axial planes inclined at 45° SW. The fold axes have a consistent southerly plunge (Fig. 6). Within the major overturned limb, the Kapp Starostin Formation is commonly extended by minor normal faults (Fig. 7a). At Storbukken smaller-scale folding is diminished on a shorter overturned limb, where there are also thrusts with displacements of 50–300 m. These may represent formation of an imbricate fan or duplex along the Vegardbreen Thrust, although any roof thrust present has been eroded away. This relationship, where folding decreases while thrusting increases along strike, is consistent with a fault-propagation fold mechanism (vs prethrust fold formation).

In eastern Wittenburgfjella and Klampen to the east (foreland portion of thrust sheet 2) the fold style changes. The folds are very angular in style (chevron to conjugate), have limbs hundreds of metres long, plunge *ca* 7° to the NW, are upright, and have interlimb angles of *ca* 60° (Fig. 7b). Minor, low-angle thrust ramps, often in hinge regions within the Kapp Starostin Formation, are also folded. These folds are interpreted as a response to layer-parallel shortening above an extensive major thrust flat within underlying Gipshuken gypsum (Harland & Horsefield 1974, Maher 1988). If there was significant stratal cover during thrusting, this may be a large fold duplex with a roof thrust in the Triassic Sassendalen Group black shales. As discussed earlier, the Lower Vegardfjella Thrust may join the major thrust flat carrying the Klampen fold structures.

One fold within thrust sheet 3 is worth special mention. On the ridge between Vegardfjella and Larstoppen, a NE-verging open fold within Nordenskiøldbreen Formation limestones is cored by a tight fold under the

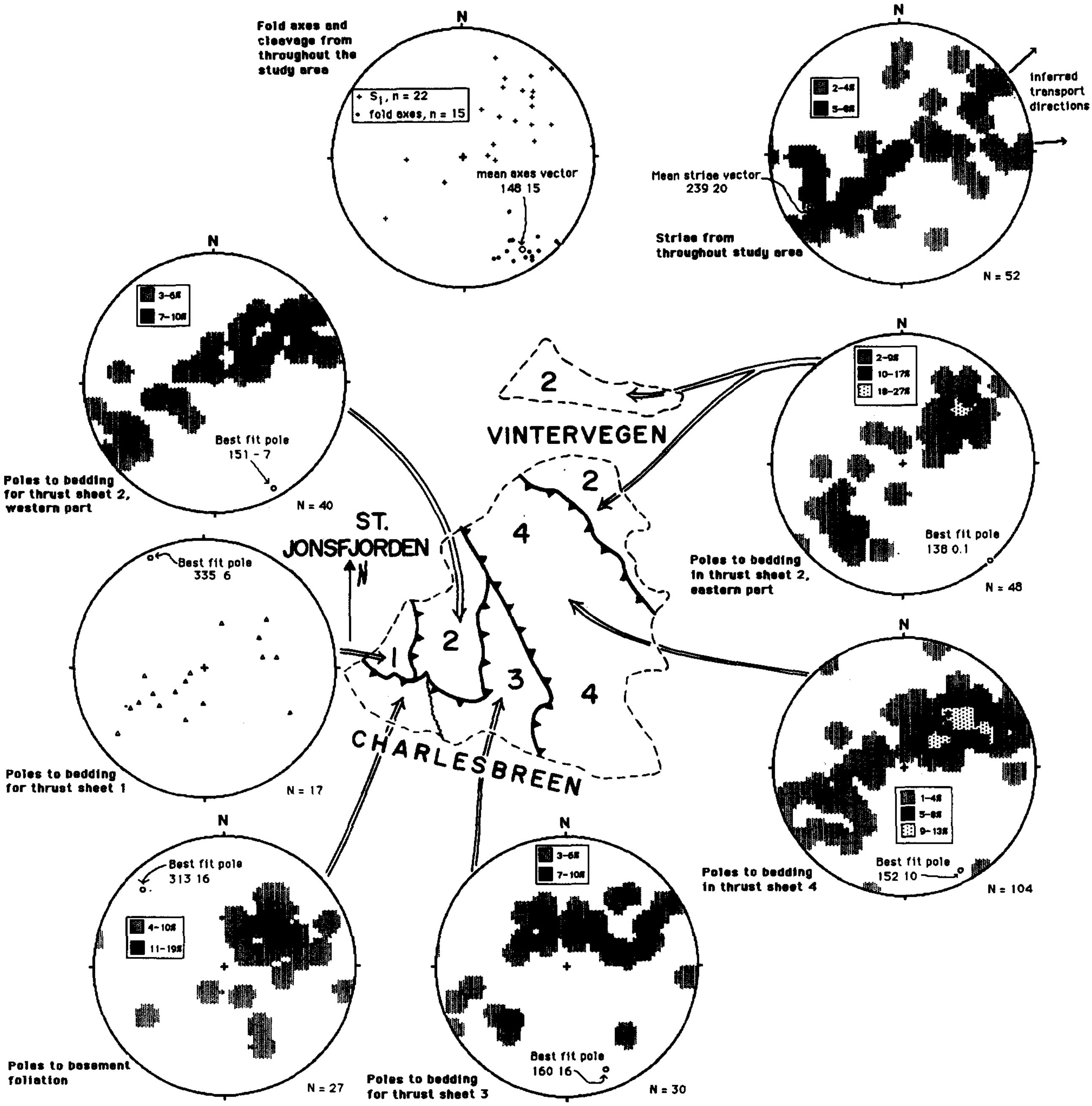

Fig. 6. Equal-area stereonet plots of bedding in thrust sheets 1–4, and plots of fault plane striae, fold axes and cleavage locally developed in Triassic strata.

sub-Nordenskiøldbreen unconformity (Fig. 7c). This unconformity is of similar age to that on Robertsonfjellet, described in the stratigraphy section.

KINEMATICS

While folding can be problematic as a kinematic indicator (due to local folds associated with oblique or lateral ramps), in the St. Jonsfjorden area fold axes generally have a strike either along a trend of 320°–140° or 340°–160° with a mean and maxima orientation of *ca* 148°. A transport direction sub-perpendicular to the fold axis trend is consistent with that indicated by fault striae (Fig. 6), where the mean is *ca* 060°. There is a significant striae sub-population direction at *ca* 080°. The second population comes primarily from two areas, Robertsonfjellet and the Vegardbreen Thrust and overlying thrust sheet 3 along the ridge from Larstoppen to Vegardfjella. This probably represents an early, anomalous transport direction of the Vegardbreen–Robertsonfjellet Thrust (see later). The variation in thrust directions means perfectly balanced cross-sections are not to be expected. This anomalous trend was used to project an approximate position of Robertsonfjellet structures on to the southern cross-section (Fig. 4). The inferred overall transport direction of *ca* 060° is the same as found farther south in the Tertiary fold and thrust belt (Bergh *et al.* 1988, Dallmann 1988, Maher *et al.* 1989).

The structural geometry is consistent with a foreland-propagating thrust sequence with upper thrusts being

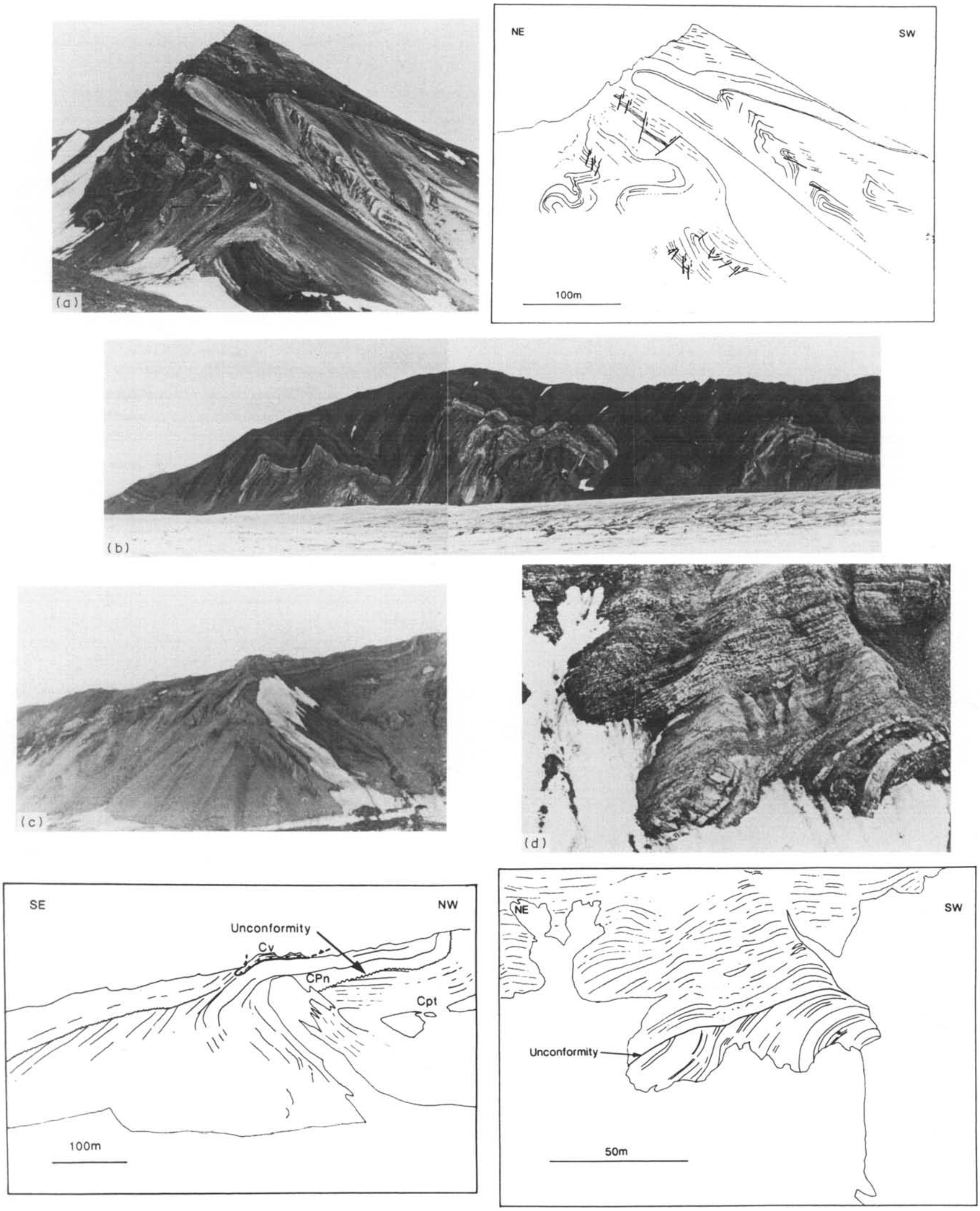

Fig. 7. (a) Photograph and line drawing of folding and extensional faults on the overturned limb of the large fold on the mountain south of Paulbreen. The core of the fold consists of Gipshuken Formation evaporites enclosed within the Kapp Starostin Formation cherty limestones. (b) A photograph, looking northwest, of folds within the Kapp Starostin Formation and Sassendalen Group lithologies on Klampen. Height of cliff *ca* 400 m. (c) A NE-verging fold (note view is oblique) on the ridge between Larstoppen and Vegardfjella. The open fold contains an unconformity enclosing a tight fold, indicating reactivation of a Mid-Carboniferous fold structure during Tertiary folding. (d) An unconformity beneath Nordenskiøldbreen Formation limestones truncating fold structures, Robertsonfjellet. The unconformity is accessible from the right-hand side of the outcrop. Fabrics underneath the unconformity related to the folds (cleavage, pressure solution) are truncated by the unconformity and are absent from the overlying rocks. Clasts of the underlying sandstones are found within the limestone above. Weathering textures are common in a zone 1 m deep beneath the unconformity.

folded on lower thrusts (Fig. 8). From oldest to youngest the thrusts are; Vegardbreen, Upper Vegardfjella, Lower Vegardfjella, and subsurface thrusts that fold the overlying thrusts. This sequence explains the NE dip of the major thrusts in this area.

Cross-sections allow the following approximate estimates of offsets for the major thrusts: (1) 2.3–2.8 km for the Nordenskiøldbreen Formation cut-off across the Lower Vegardfjella Thrust; (2) 1.4–1.7 km for the Nordenskiøldbreen Formation cut-off across the Upper Vegardfjella Thrust; and (3) a minimum of 1.7 km for the Nordenskiøldbreen Formation cut-off across the Vegardbreen Thrust (the footwall cut-off is not controlled, and must exist in the vicinity of Jotulslottet) (Fig. 1). Given that the frontal part of the Vegardbreen Thrust was reactivated by the Upper Vegardfjella Thrust, the combined displacement on the Vegardbreen and Upper Vegardfjella Thrust hinterland of their junction should equal that of the reactivated thrust immediately beyond their junction (some 3.4 km based on Tvillingodden Formation cut-offs). However this does not include folding or other wallrock strain and is therefore a minimum estimate. Bed length estimates of layer parallel shortening on Klampen yield an estimate of 2.4 km.

DISCUSSION

Two explanations for the previously described northeast dip of the thrusts in the St. Jonsfjorden area (Maher 1988, Winsnes & Ohta 1988) are that they are backthrusts or folded NE-directed thrusts. Consistent stratigraphic climb of the thrusts and minor structures unequivocally indicate the latter geometry, as Winsnes & Ohta (1988) suggested. The structure of the area, is, in part, an antiformal stack, with progressively lower displacement on later thrusts deeper in the stack causing a foreland dip of the strata within the overlying thrust sheets (e.g. the Upper Vegardfjella and Vegardbreen thrusts and thrust sheets 3 and 4, respectively). However, some of the foreland dip also appears to be due to the Upper and Lower Vegardbreen thrusts having a common root within the basement (Fig. 4). This structural pattern has similarities with that described by Challinor (1967) from 50 km further north on Brøggerhalvøya.

A line-length restoration of the Nordenskiøldbreen and Kapp Starostin Formations in section A–A′, including bedding projected above the topographical surface, gives shortening values of 69 and 42%, respectively. The Nordenskiøldbreen Formation shows *ca* 11 km shortening, a minimum estimate based on restoring both cut-offs and folds. Also included in the estimate is the line-length of an extended thrust sheet 4 or its overlying thrust sheets, extending from known outcrop on Wittenburgfjella to west of Vegardfjella, where the Vegardbreen Thrust must root due to continuous outcrop of thrust sheet 3 on Vegardfjella. Since the uplift of basement in thrust sheet 1 and folding of overlying thrusts can be explained by basement involved thrusts below the present exposure level, shortening is likely to be greater than calculated above.

The total shortening in Spitsbergen's fold and thrust belt is estimated from cross-sections to be at least 18 km to the north (Manby 1988, Brøggerhalvøya area), and on the basis of a plate tectonic model possibly at 30 km (Vågnes *et al.* 1988). Since the Upper Vegardfjella and Vegardbreen thrusts emerge in Triassic rocks of Wittenburgfjella (Fig. 4) the shortening associated with them and with hangingwall structures is in addition to that in the footwall rocks to the northeast. However underlying thrusts and structures probably represent shortening that was translated farther northeast. Maher (1988), on the basis of air photograph map compilation, suggested a minimum shortening of 6.6 km for the width of the fold thrust belt to the northeast, and detailed mapping and cross-section constructions by Bergh & Andresen (1990) yielded a conservative estimate of 4 km for a complex frontal ramp duplex exposed in the Mediumfjellet–Lappdalen area on the north side of Isfjorden. This area may represent the emergence of the basal detachment below the Klampen structures (within the gypsiferous Gipshuken Formation). Combining the shortening above the Upper Vegardfjella and Vegardbreen thrusts with that estimated by previous work from footwall to the northeast provides a very crude minimum estimate of 15 km of shortening across the fold–thrust belt in Oscar II Land. This is consistent with the results of Vågnes *et al.* (1988). To this can be added any possible basement shortening from west of the restored St. Jonsfjorden structures, and any shortening in the Billefjorden region (Haremo & Andresen in press) unaccommodated for by movement on the lower St. Jonsfjorden structures.

Several lines of evidence indicate pre-Tertiary structures and lateral stratigraphic changes in the St. Jonsfjorden area controlled Tertiary tectonism. Figure 8 illustrates the control of Tertiary thrust evolution by basin geometry and early structures on a sequentially restored sketch cross-section. Although thrust ramps often localized around Carboniferous faults, in at least one case the actual Carboniferous fault surface was reactivated. The Upper and Lower Vegardfjella thrusts both root in a foliation flat in phyllites underneath a distinct sequence of more competent Precambrian dolomites and tillites. Note that the foliation and platform cover strata in this area have subparallel strikes (Fig. 6). Farther up-section, a difference in Carboniferous stratigraphy across the Vegardfjella thrusts has already been noted. There is also a steep cut-off angle in the hangingwall and footwall Carboniferous rocks of the Upper Vegardfjella Thrust. A larger offset across this fault between post-rift stratigraphic units, relative to smaller offset of the basement contact (Fig. 4), shows the inclusion of early displacement produced by an intrabasinal fault. The absence of a footwall shortcut or slice of cover preserved in the hangingwall of the Upper Vegardfjella Thrust also illustrates the actual normal fault surface was reactivated, and the thrust was not just

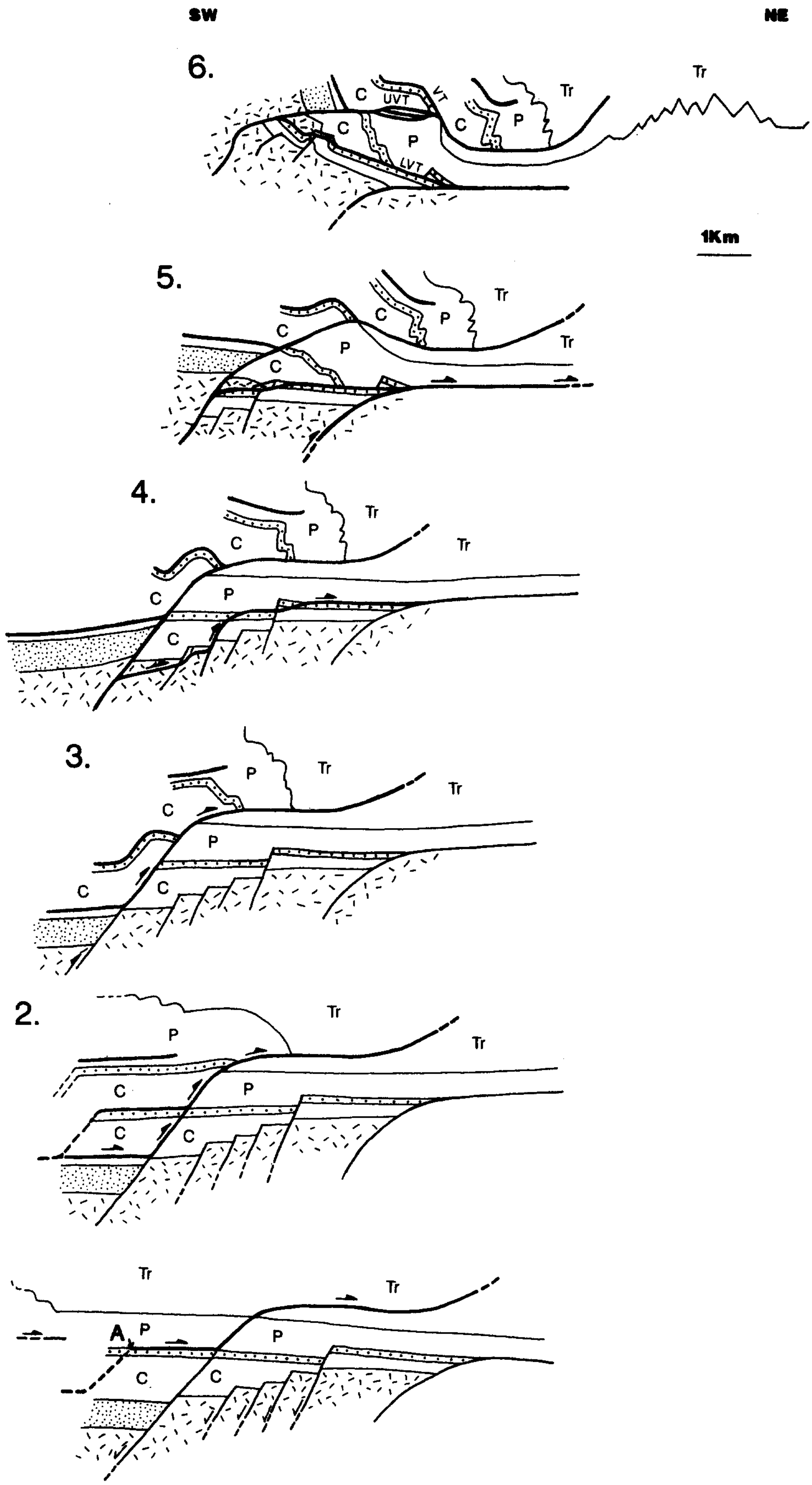
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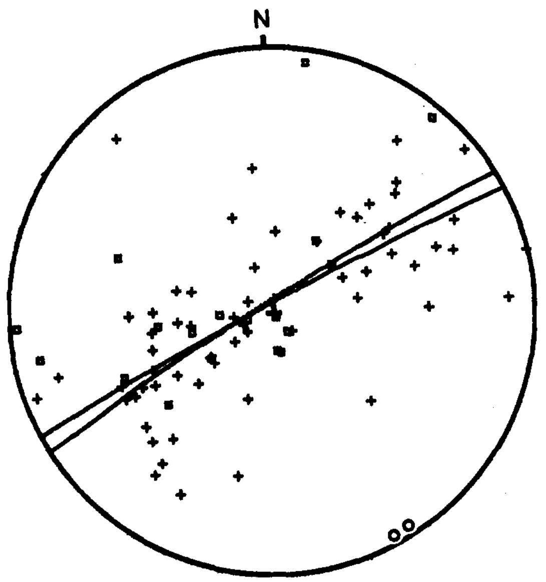
Fig. 8.



N = 80

Fig. 9. An equal-area stereonet plot of Tertiary structures and Carboniferous structures. Key: crosses = Tertiary bedding, squares = Carboniferous bedding and cleavage. Also shown best-fit great circles and pole to best-fit great circle. The Carboniferous structures have had the Tertiary tilt removed. All data is represented as poles, and the poles to the best-fit great circle plot within 5° of one another.

localized into the area around the fault. On the basis of the parallelism of the basement fabric, the Carboniferous fault and the Tertiary thrust, it is suggested that the basement structure localized Carboniferous age faults (normal or transcurrent with a normal component), which in turn were reactivated during Tertiary thrust development.

In addition to nucleation of later structures at or around syn-depositional normal faults, fold structures have also been the focus for reactivation, e.g. within thrust sheet 3 (Fig. 7c). There is a pronounced similarity in orientation between these earlier folds and later folds. In Fig. 9, the pre-Tertiary orientation of Carboniferous folds beneath the basal Nordenskiøldbreen unconformity on Robertsonfjellet is compared with that of Tertiary folds. They have bedding girdle poles within 5° of each other.

The interaction of pre-existing structure and faults developing in the fold and thrust belt led to the formation of a major antiformal stack structure (Fig. 8). To the east of this, the fold and thrust belt has a more conventional style. Thrust sheets dip to the hinterland and fold structures indicate layer parallel shortening (Klampen) rather than folding from below by basement culminations. This is supported by evidence of the duplex geometry from the Lappdalen region (Bergh & Andresen 1990).

This pattern outlined for St. Jonsfjorden may exist along most of the length of the Spitsbergen fold and thrust belt, which can be divided into a western, more thick-skinned portion (basement involvement, greater uplift, more thrust ramps) and an eastern more thin-skinned (detachment dominated) portion (Dallman & Maher 1989). In Bellsund (Fig. 1), hangingwall blocks also have Billefjorden Group strata, that are absent in the footwall, indicating an influence of basin structure on the development of the thrust system (Maher & Welbon in review). Foreland migration of inclined thrusts (dipping foliation flats in basement rocks which continued into ramps within the Carboniferous basin fill) continued until the basin margin was reached, after which folding and thrusting was mostly restricted to rocks above flats within the Gipshuken Formation and within the Sassendalen Group. These have been documented as common detachment horizons in many other parts of the fold and thrust belt: Brøggerhalvøya (Challinor 1967), Oscar II Land (Harland & Horsefield 1974, Bergh *et al.* 1988, Maher 1988), Midterhuken, Wedel Jarlsberg Land (Dallmann 1988) and Billefjorden fault zone (Mann & Townsend 1989, Haremo & Andresen in press).

A remaining question is the placing of the root to the Robertsonfjellet–Vegardbreen Thrust in the Hecla Hoek, somewhere to the southwest of Robertsonfjellet. A thrust at Trollslottet (a nunatak *ca* 4 km to the SSW within Eidembreen, Fig. 1) has a basement hangingwall and Billefjorden Group footwall flat (Ohta personal communication 1988) and may be a continuation of the same thrust. The rooting of the thrust farther west indicates more extensive basement imbrication within the western basement outcrop belt (Fig. 1) as suggested by Manby (1988) and Ohta (1988), which is inconsistent with a simple uplift of a basement block as suggested by Mann & Townsend (1989).

Tertiary kinematic indicators in the St. Jonsfjorden area suggest an early 080° transport direction for the uppermost thrust and a later 060° direction for the other thrust sheets. The later direction is common for Tertiary thrusts throughout Svalbard, and is approximately orthogonal to the strike of the fold and thrust belt and the Tertiary transcurrent plate margin. The early direction is clockwise of the general orogenic trend and is therefore incompatible with an en échelon character in a

Fig. 8. Diagram of sequential cross-section development of cross-section A–A′. The arrows indicate the next thrust to move. Key: Stippled = basement, light dots = Billefjorden Group (excluding Vegard Formation), C = Carboniferous, heavy dot = Nordenskiøldbreen Formation, P= Permian, Tr = Triassic. LVT = Lower Vegardfjella Thrust, UVT = Upper Vegardfjella Thrust, V = Vegardbreen Thrust. (1) Pre-deformation template. A Carboniferous basin fill thickens to the west across extensional faults. The Vegardbreen Thrust cuts along the Gipshuken Formation, links into a major extensional fault and then flattens out within Triassic rocks. A on (1) is the minimum distance to the Gipshuken Formation cut-off derived from the known length of a footwall flat in the Nordenskiøldbreen Formation. (2) The upper part of the Upper Vegardfjella Thrust develops and reactivates the foreland part of the Vegardbreen Thrust. (3) The lower part of the Upper Vegardfjella Thrust forms by reactivation of the basement normal fault and the Vegardbreen Thrust. (4) Lower Vegardfjella Thrust forms by cutting through basement tilt blocks, partially reactivating one of the normal faults and cutting through the Gipshuken Formation. (5) A lower thrust sheet tilts all earlier formed thrusts. (6) Present-day geometry. UVT = Upper Vegardfjella Thrust, LVT = Lower Vegardfjella Thrust, VT = Vergardbreen Thrust.

dextral transpressive setting as suggested by Harland (1969) and Lowell (1972). A model with clockwise rotation of thrust sheets over time producing the different movement directions is also incompatible with a dextral setting. The St. Jonsfjorden area is another locality which strengthens the conclusion that the Tertiary fold and thrust belt is primarily a contractional feature (Harland & Horsefield 1974, Maher *et al.* 1986, Maher *et al.* 1989, Bergh & Andresen 1990, Welbon *et al.* in review), and that the transcurrent component required by plate reconstructions must be spatially decoupled from it.

The shallow, but consistent southerly fold plunge that exists throughout much of the study area, and continues to Isfjorden, give insight into significant along strike variations in the fold and thrust belt. Major basement involved thrusts with 1 km or more of movement that cut through overlying platform cover strata are not evident farther southwest in Oscar II Land or Nordenskiøld Land, except possibly at Trygghamna (Bergh *et al.* 1988) and instead large monoclines to overturned folds predominate (Maher 1988). Extrapolating the pattern seen in St. Jonsfjorden, these folds probably represent a higher structural level, with thrusts similar to those exposed in the St. Jonsfjorden area below and to the west of them. Extensive glacier cover in the critical areas and the difficulty of distinguishing Tertiary from older thrusts within basement rocks make detection of these thrusts difficult. However, a thrust duplex system in basement rocks of Protektfjellet (northwest Isfjorden shore), may represent such thrusts, below and west of the large, steep monocline at Trygghamna (Ohta 1988).

CONCLUSIONS

(1) Three major thrusts exist in the St. Jonsfjorden area, the most significant in length and displacement is the Vegardbreen–Robertsonfjellet (to Trollslottet) Thrust. Cross-section constraints and minor structures indicate this thrust emerges in a disrupted syncline composed of Triassic strata on Wittenburgfjella. We suggest the cores of other large, overturned synclinal structures in Triassic strata elsewhere might be considered as potential sites for thrust emergence (footwall flat–hangingwall cut-off geometry).

(2) Minor structures, map pattern, and stratigraphic cut-out patterns indicate that the NE-dipping thrusts noted by Winsnes & Ohta (1988) are not backthrusts, but folded thrusts with northeasterly transport.

(3) The structural style of the St. Jonsforden area is complicated, but is essentially a northeast verging thrust stack in the Vegardfjella region with a series of NE-verging folds and smaller thrusts above detachments in the Gipshuken Formation (Klampen area) and Bravaisberget Formation (Wittenburgfjella area) to the northeast.

(4) Caledonian basement foliations and subparallel lithological contacts, and mid-Carboniferous faults (dip-slip and possibly strike-slip) and folds were either reactivated or acted as stress risers during Tertiary shortening. The thrust stack thus formed along a westward thickening Carboniferous basin with several fault steps, and represents basin inversion. Specifically, the common basement root of the Upper and Lower Vegardfjella thrusts is a major Carboniferous fault that defined this basin margin.

(5) Approximately 13 km of shortening is indicated by surface exposures in the study area (adding the Nordenskiøldbreen Formation and Klampen area line length estimates). Subsurface thrusts which are likely responsible for the NE-dipping thrusts and lower parts of the thrust stack would increase this amount.

(6) The 060° transport direction is very similar to that in areas to the southeast. An inferred early 080° direction also exists.

(7) A southerly structural plunge exists in the St. Jonsfjorden region and is responsible for changes in structural style along strike.

(8) The St. Jonsfjorden fold and thrust belt structures are predominantly northeastward verging, and the tectonic style changes from basement imbrication in the hinterland to dominantly thin-skinned tectonics within platform cover strata towards the foreland. The kinematics of the St. Jonsfjorden region is consistent with a model of decoupling for the whole continental margin, whereby Tertiary transpressional motion between Greenland and Spitsbergen is decoupled into shortening components across western Spitsbergen forming the fold and thrust belt, and strike-slip components on major faults elsewhere in the transpression zone.

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