Kinematics of the Isfjorden-Ymerbukta Fault Zone: a dextral oblique-thrust ramp in the Tertiary fold-thrust belt of Spitsbergen

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The NNE-trending Isfjorden-Ymerbukta Fault Zone is an oblique structural element within the NNW-trending Tertiary transpressional fold-thrust belt of Spitsbergen, Arctic Norway. It can be traced for nearly 50 km, and separates two different structural domains in the fold-thrust welt of Oscar II Land, Central Spitsbergen. The fault zone is more than 500 m wide and contains several segments of highly folded/rotated, faulted and cleaved Triassic through Paleocene rocks. Displacement across the fault zone can be decomposed into (i) a reverse, top-to-the-ENE component with a minimum 650 m vertical throw, and (ii) a horizontal dextral component of approximately 5–10 km. Displacement across the fault decreases northward along strike, where the fault zone merges into parallelism with a ramp-system of the fold-thrust belt. Inherited, underlying Devonian(?)-Carboniferous structures may have controlled the location of the fault zone.

Detailed studies of map and mesoscale faults and folds reveal complex geometries and varied kinematic signatures across the fault zone width. Along the southwest portion of the fault zone (Ramfjellet-Erdmannflya) three major fault segments record oblique-reverse (Morenekilen fault), combined oblique-reverse and oblique-normal (Straumhallet fault), and dextral strike-slip (Flydammane fault) movements, respectively. Further northeast (Mehøgda-Bohemanflya), a traverse from west to east of three structural domains shows; (1) thrusts and associated folds that record oblique-reverse kinematics, (2) steep faults with dextral strike-slip and conjugate strike-slip (extrusion) movements, and (3) thrusts and oblique-normal faults. The overall kinematics is consistent with mainly oblique-reverse and dextral strike-slip faulting, and subordinate local fault zone-oblique/parallel extension. Various geometries within the fault zone, as well as the variation in the direction of movement on the segments, can be explained from either (i) synchronous shortening and out-of-the-plane movement partitioning, or (ii) an effect of polyphase changes in the orientation of the overall shortening axes during the fold-thrust belt evolution. Either of these interpretations is consistent with the Isfjorden-Ymerbukta Fault Zone as an oblique-thrust ramp or transfer fault.

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Introduction

The Tertiary fold-thrust belt of Spitsbergen (e.g., Dallmann et al. 1993) makes up a nearly 150-km-wide province of dominantly contractional deformation (Fig. 1). This contraction affected both the Caledonian basement and a near-continuous Paleozoic to Paleogene cover sequence (for stratigraphy, see Steel & Worsley 1984; Nøttvedt et al. 1992). Formation of the fold-thrust belt probably was the result of transpressional decoupling associated with a major, intracratonic transform fault to the west (Hornsund fault) during opening of the North Atlantic–Arctic Ocean in Paleocene-Eocene times (Harland 1969; Lowell 1972; Talwani & Eldholm 1977; Maher & Craddock 1988; Faleide et al. 1988; Muller & Spielhagen 1990; Maher et al. 1995). In Spitsbergen, the Tertiary deformation belt is expressed as (i) a western basement-involved hinterland province characterized by complex interactions of orogen-perpendicular, -oblique and -parallel motions (Braathen et al. 1995; Maher et al. 1997), and (ii) an eastern foreland province of contractional, thin-skinned fold-thrust belt structures, where orogen-perpendicular transport directions dominate (Bergh & Andresen 1990; Wennberg et al. 1994; Bergh et al. 1997). This provincial variation can be attributed to spatial and temporal changes of successive transpressional strain events (e.g., Kleinspehn et al. 1989; Lepvrier 1992; Maher et al. 1997; Bergh et al. 1997; Braathen et al. 1999).

Along the northern shore of Isfjorden (Fig. 1c) a major NNE-striking fault zone obliquely truncates the NNW-striking fold-thrust belt structures that characterize the interior of Oscar II Land. This high-strain zone, herein named the Isfjorden-Ymerbukta Fault Zone, juxtaposes intensively folded and thrusted Mesozoic units in the hangingwall to the northwest with mildly deformed Cretaceous-Tertiary rocks to the southeast (Fig. 1b, c). Various structural interpretations of this fault zone have been proposed: Harland & Horsfield (1974) described it as a dextral strike-slip fault, the Isfjorden Fault, whereas Ohta et al. (1992) applied the name Ymerbukta Fault for the related reverse element. Other structural interpretations

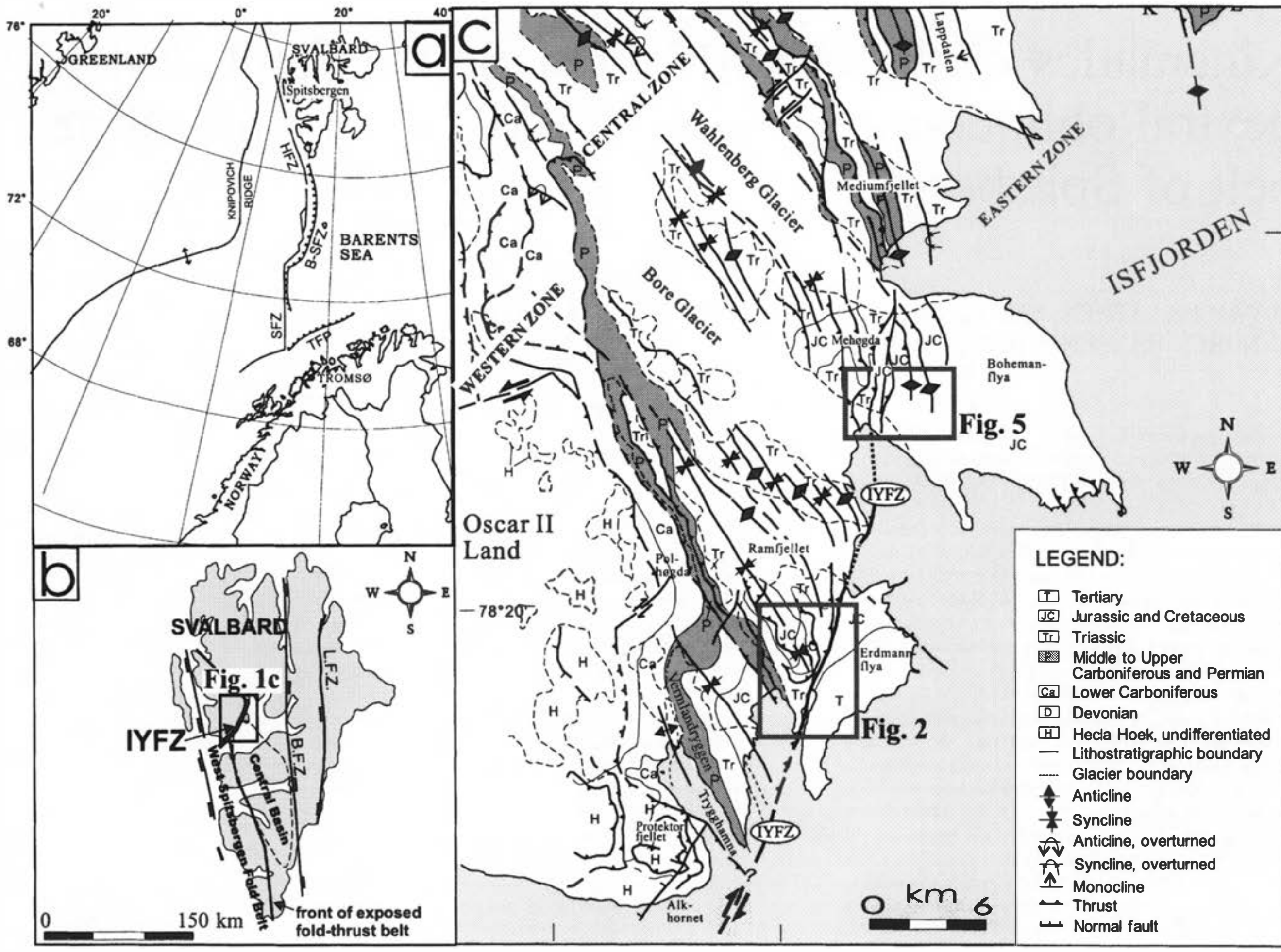

Fig. 1. (a) Regional location map of Svalbard and the northwestern Barents Sea shelf. Note that Spitsbergen is the main island on Svalbard. (b) Simplified geological map of Spitsbergen showing the extent of the Tertiary fold-and thrust belt (Dallmann et al. 1993). (c) Geological and structural map of Oscar II Land, Central Spitsbergen (after Bergh et al. 1997). The frames outline the Ramfjellet–Erdmannflya area (Fig. 2) and the Mehøgda–Bohemanflya area (Fig. 5). IYFZ = Isfjorden-Ymerbukta Fault Zone; BFZ = Billefjorden Fault Zone; LFZ = Lomfjorden Fault Zone.

include an oblique-thrust ramp (Bergh et al. 1988, 1997; Dallmann et al. 1993), a late thrust (Hanisch 1984), and an extensional (normal) fault (Lyberis & Manby 1993).

In this paper we address this controversy in interpretation of the first-order structure by presenting new, detailed geometric and kinematic fault-fold data from two key locations where the fault zone is well exposed (Fig. 1c); (i) between Ramfjellet and Erdmannflya, and (ii) in the Mehøgda-Bohemanflya area. Our conclusion is that the Isfjorden-Ymerbukta Fault Zone is a dextral oblique-thrust ramp with complex internal strain patterns, including structures in support of reverse and strike-slip faulting, and subordinate, local fault zone-oblique/subparallel extrusion and extension.

Structural setting of the Isfjorden-Ymerbukta Fault Zone

The fold-thrust belt in Spitsbergen has its apparent maximum width in Oscar II Land, north of Isfjorden (Fig. 1b). Three distinct styles of deformation can be distinguished from west to east (Fig. 1c; see Bergh et al. 1997); (i) a western zone made up of a large-scale, basement-involved fold-thrust complex or antiformal stack, (ii) a central zone of thrust imbrication and upright folds above a Permian evaporite decollement, and (iii) an eastern 'thrust-front' (at Lappdalen) where the basal detachment ramps upsection into Triassic and Jurassic/Cretaceous shale units (Wennberg et al. 1994; Johansen et al. 1994), where it continues as bedding-parallel thrust (decollement zones). Farther east, thin-skinned structures are underlain by local, deep, basement-seated reverse faults (e.g., Haremo & Andresen 1992). The average tectonic transport direction is approximately N60E, and shortening estimates range from 20 to 40 km for the Oscar II Land transect (Wennberg et al. 1994; Bergh et al. 1997).

The Isfjorden-Ymerbukta Fault Zone can be traced through the western and central zones as a NNE-striking, clearly oblique-truncating feature. According to Bergh et al. (1997), the southwestern segment dextrally displaces the basement-cover contact in the range of 5 to 10 km. In the central zone, the Isfjorden-Ymerbukta Fault Zone

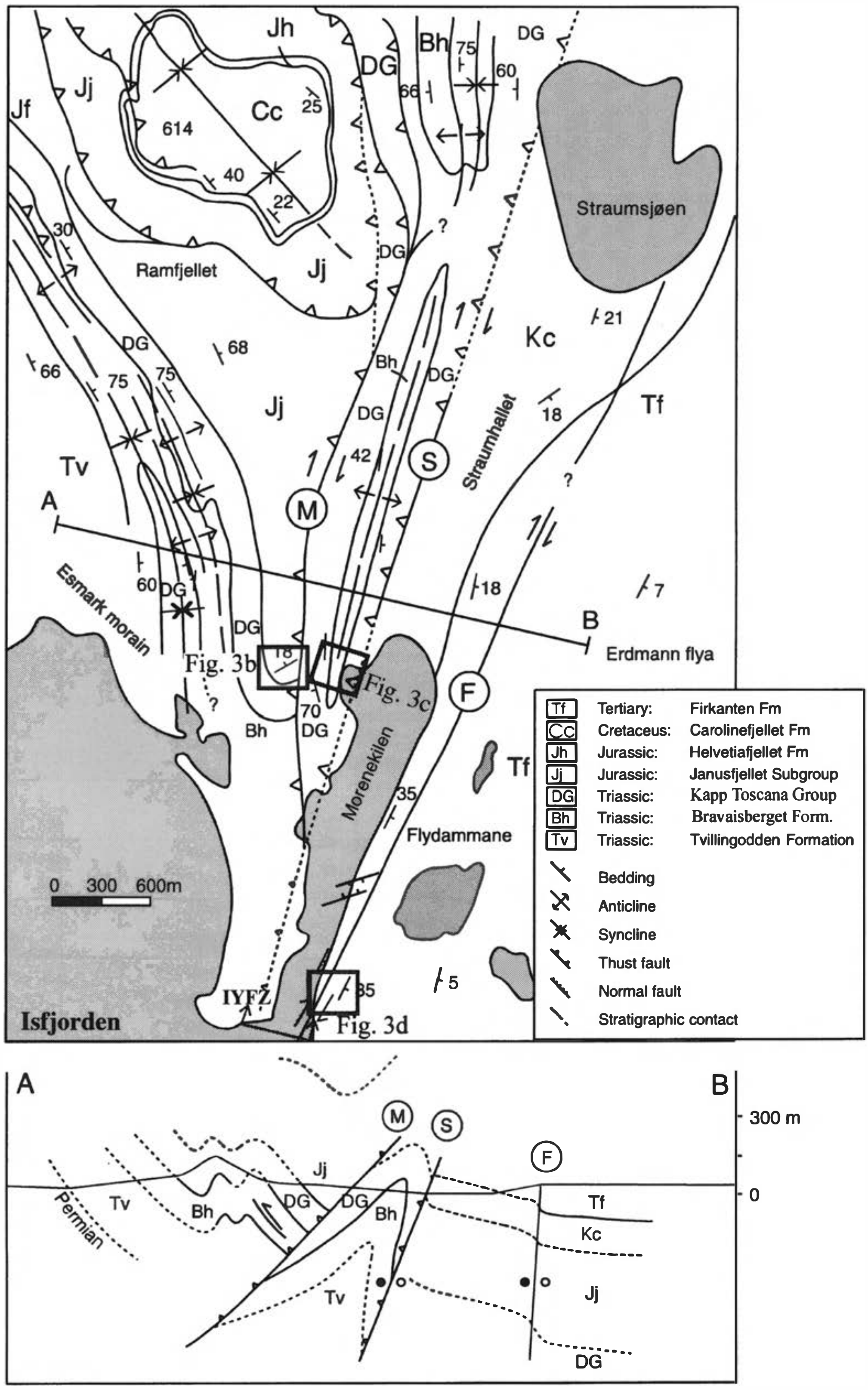

Fig. 2. Detailed geological and structural map and cross-section of the Ramfjellet–Erdmannflya transect outlining the main structures and provincial subdivision as described in the text. The map is modified from Bergvik (1990) and Hansen (1995). M = Morenekilen fault, S = Straumhallet fault, F = Flydammane fault. Filled dots – away; open dots – towards.

juxtaposes fold-thrust belt structures in Permian–Mesozoic strata against less deformed Cretaceous–Paleocene strata (Fig. 1c). On Erdmannflya the fault zone is made up of three moderately to steeply inclined fault strands, whereas further north, at Mehøgda–Bohemanflya, it broadens and is made up of a system of steep faults and thrusts. In the latter area, displacement along the Isfjorden-Ymerbukta Fault Zone diminishes as the faults merge into parallelism with

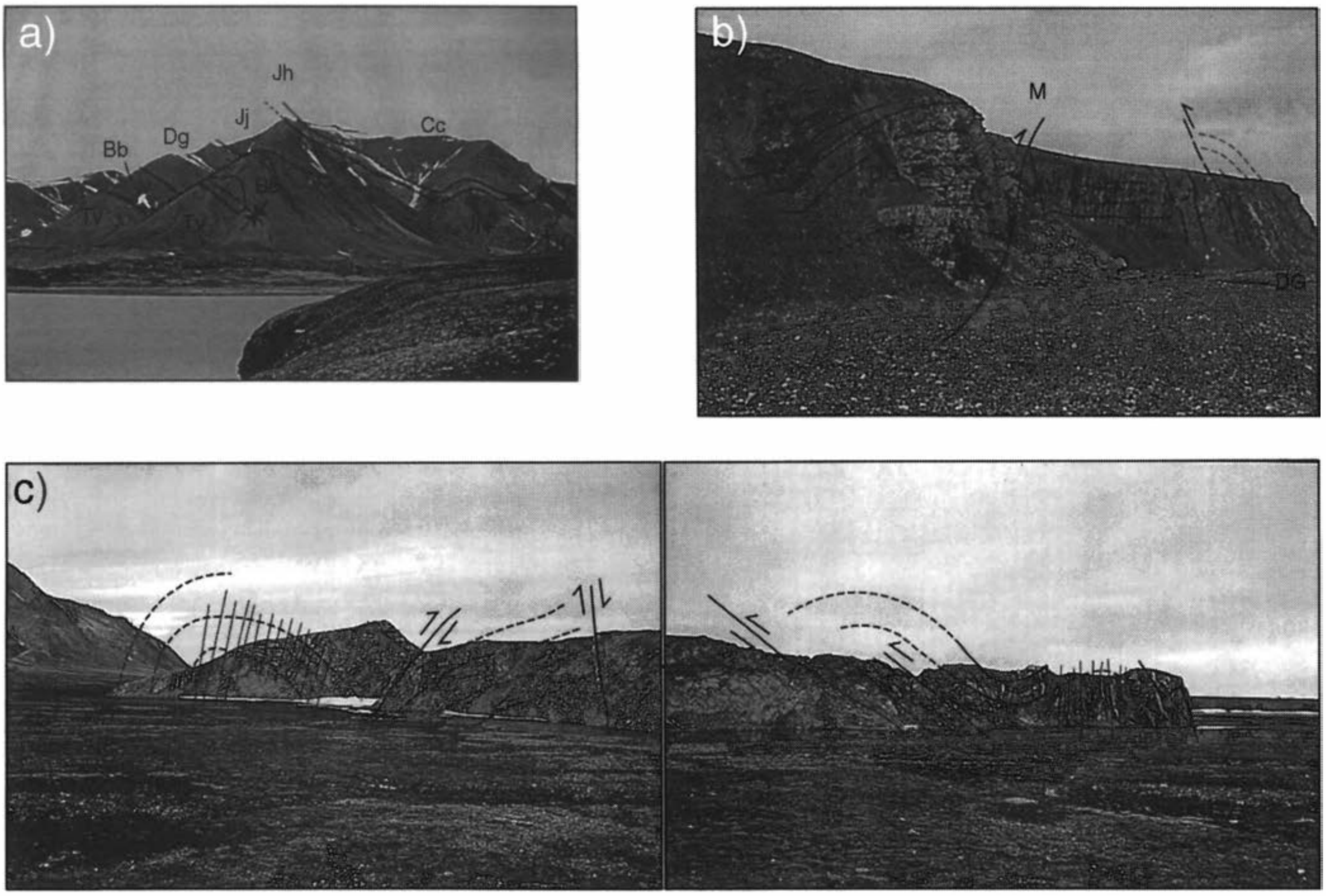

Fig. 3. Photographs (3b, c, d located in Fig. 2) with sketch interpretations of structures along the Isfjorden-Ymerbukta Fault Zone in the Ramfjellet–Erdmannflya area: (a) Northward view of the Ramfjellet Syncline and accompanied southwest and northeast-bounding thrusts-folds. DG equals the Kapp Toscana Group in Fig. 2. (b) Outcrop of the Morenekilen fault zone in sandstones–siltstones of the DeGeerdalen Formation (DG) and shales of the Janusfjellet Subgroup (Jj). Note doubly plunging hangingwall anticlines and thrusts along the main fault trace, numerous minor offsets of sandstone units near minor faults, and cleavage development in the shales. View is towards the north. (c) Tight, upright anticline (Morenekilen Anticline) in shales of the Janusfjellet Subgroup. Note well-developed, steep axial planar cleavage and reverse fault zones near the hinge zone. Locality west of Straumhallet, looking north. (d) Close-up view of the Flydammane fault in cliff-section east of Morenekilen. Rocks involved are sandstones–siltstones of the Paleocene Firkanten Formation. Note steep, complex fault systems with varied displacements (strike-slip, reverse and normal). The walls of the fault zone are defined by strike-slip faults.

NNW-striking thrusts of the fold-thrust belt (Fig. 1c). In the following, detailed geometric and kinematic patterns from the two transects along the fault zone are described.

Ramfjellet–Erdmannflya area

Geometric patterns

The fold-thrust system near Ramfjellet (Figs. 1c and 2), to the north of the Isfjorden-Ymerbukta Fault Zone, marks the boundary between documented basement-involved deformation of the western zone and thin-skinned tectonics of the central/eastern zones. The dominant feature is a macroscopic syncline (Ramfjellet syncline; Fig. 3a) bound by west- and east-verging thrusts and associated tight asymmetric folds, producing an overall pop-up structure (Bergh et al. 1988; Bergvik 1990; Hansen 1995). This fold-thrust system was likely formed above a west-dipping thrust-ramp in the subsurface (Bergh et al. 1997) that involved hinterland basement rocks and that stepped up into a decollement in Permian evaporites to the east. Hence, thrusts bounding Ramfjellet to the east represent minor thrust-ramp splays and out-of-the-syncline thrusts, while thrusts at the western margin of the Ramfjellet syncline formed as backthrusts.

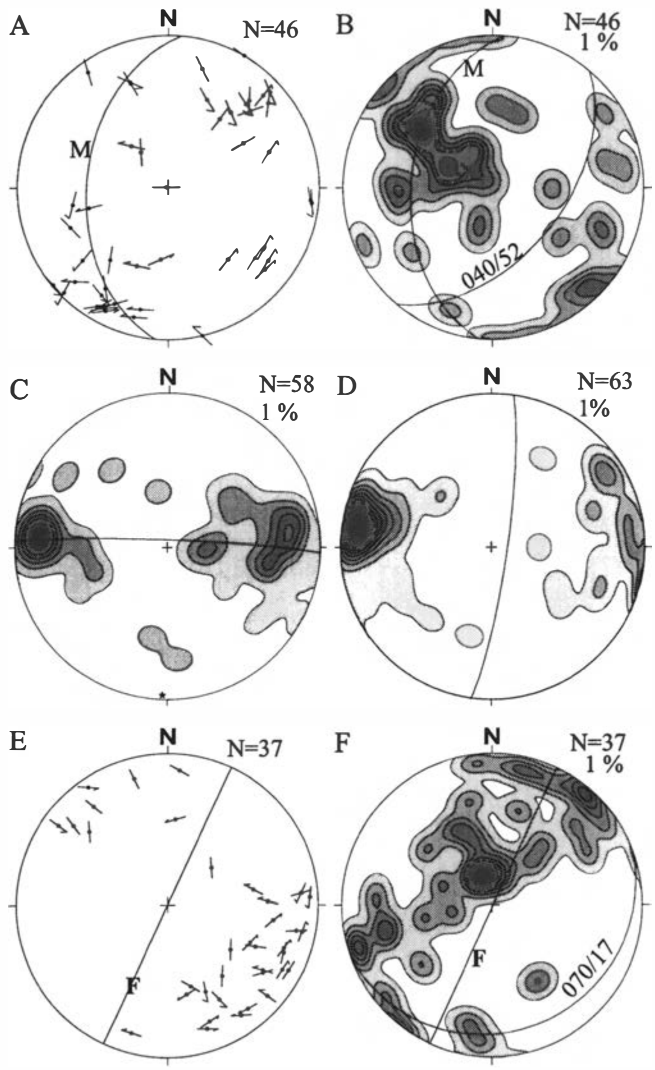

Fig. 4. Structural-kinematic data from the Isfjorden-Ymerbukta Fault Zone in the Ramfjellet–Erdmannflya area, presented in equal-area, lower hemisphere projection (Schmidt net). A: Slip-linear (arrow) and B: M-plane plots of mesoscale slickensided fault surfaces along the trace of the Morenekilen fault. Orientation of the fault is indicated [M]. C: Contoured poles to bedding and D: cleavage data of the Morenekilen Anticline, next to the Straumhallet fault. E: Slip-linear and F: M-plane plots of mesoscale faults of the Flydammane fault. Orientation of the fault is indicated [F]. The slip-linear plots (Aleksandrowski 1985; Goldstein & Marshak 1988) present the pole to the fault plane decorated by a line/arrow indicating the direction and sense-of-slip of the hangingwall. The arrow is parallel to the horizontal outgoing of a plane (M-plane or movement-plane) defined by the pole to the fault and the slip line.

A pronounced clockwise change in the strike direction of the fold-thrust belt at Ramfjellet, from northwest into north and northeast, is notable when approaching the Isfjorden-Ymerbukta Fault Zone (on Erdmannflya; Fig. 2). Similarly, fold hinges bend and turn into steeply plunging attitudes, and the strata are cut by successively more north- to NE-striking faults. The Isfjorden-Ymerbukta Fault Zone itself is a 500 to 700 m wide, complex deformation zone of variably rotated fault blocks, and folded-faulted and sheared/cleaved Triassic to Cretaceous shales, siltstones and sandstones (Tvillingodden and Bravaisberget formations, Kapp Toscana Group, plus Janusfjellet Subgroup). The fault zone rocks reveal variable attitudes, but on average dips of bedding exceed 45°. The southeastern boundary of the Isfjorden-Ymerbukta Fault Zone brings Triassic-Jurassic shales in the hangingwall against overall subhorizontal Upper Cretaceous and Paleocene strata in the footwall. The latter strata are affected by gentle macrofolding and gradational steepening of dips, from 10 up to 35° close to the fault zone boundary.

In the Morenekilen–Straumhallet area (Fig. 2), the Isfjorden-Ymerbukta Fault Zone consists of three branching and linked fault-fold sets, striking variably north to northeast. The westernmost *Morenekilen fault* (M in Fig. 2) strikes north and dips moderately (ca. 55°) to the west. It juxtaposes a footwall flat and a hangingwall ramp within shales of the Kapp Toscana Group–Janusfjellet Subgroup, and hangingwall strata are folded into an asymmetric and upright anticline (Fig. 2). In outcrop, the Morenekilen fault is defined by a network of minor faults with both reverse and oblique slip signature (Fig. 4A). Within a 20-m-wide zone of Janusfjellet Subgroup strata, distinct sandstone marker beds are offset and dismembered, and locally folded into steep to subvertical, tight to isoclinal structures (Fig. 3b).

The *Straumhallet fault*, exposed north of Straumsjøen (S in Fig. 2; Bergvik 1990), dips ca. 65–70° northwest as indicated from attitudes of related minor faults and folds (Fig. 4C). The fault truncates bedding in footwall and hangingwall ramps. Shales in the Bravaisberget Formation of the hangingwall are folded into a major tight, upright and gently south-plunging anticline (Morenekilen anticline). Numerous mesoscopic reverse faults dissect the anticline, and a north-striking, steep west-dipping, penetrative axial planar cleavage is developed near the hinge zone (Figs. 3c and 4d). Locally, steep, conjugate oblique/strike-slip and normal faults and veins occur. Displacement on the Straumhallet fault has to exceed 650 m, given the stratigraphic separation between Triassic strata in the hangingwall, and footwall lower Cretaceous strata (Bergvik 1990).

The *Flydammane fault* crops out near the eastern shoreline of Morenekilen (F; Figs. 2 and 3d). The fault zone is approximately 10 m wide, strikes north–northeast and dips steeply (70–80°) west–northwest. It crosscuts gently dipping Paleocene sandstone units, which south–westwards generally dip 35° to the southeast. The internal fault zone fabric is complex, including rotated fault blocks, sigmoidal fold patterns, and dismembered and fractured sandstone units embedded in a strongly cleaved shale and coal matrix (Fig. 3d). Sense-of-shear estimates on minor faults indicate oblique-, normal-, reverse-, and strike-slip movement (Fig. 4E; see below).

Kinematic patterns

In the Ramfjellet–Erdmannflya area, the kinematics of the Morenekilen, Straumhallet and Flydammane faults can be established through abundant mesoscopic fault sets, folds and cleavages. The north-striking *Morenekilen fault* is dominated by minor, northwest-striking oblique-reverse faults, as outlined by attitudes of slickenlines (e.g., grooves, fibers and steps; Hancock 1985; Petit 1987) on the fault surfaces. Three separate fault populations are distinguished using slip-linear fault plots; (1) a fault set that dips moderate to steeply to the northeast with a dextral-oblique to reverse sense-of-shear, (2) a fault set dipping steeply southwest and with a dextral-reverse sense-of-shear, and (3) a subordinate fault set with north- to NNE-striking, steep dextral strike-slip fault character (Fig. 4A). The first two populations of faults (1–2) are interpreted as oblique backthrusts and forethrusts, respectively, oriented at a high angle to the Morenekilen fault, whereas the strike-slip faults (3) are parallel with the main fault. When the entire fault data set is plotted as M-planes (Fig. 4B), an average movement plane is apparent, which strikes N40E and dips moderately southeast. This M-plane is a three-dimensional expression of the average direction of movement on the Morenekilen fault (for a description of the method, see Goldstein & Marshak 1988). The oblique nature of the movement plane relative to the Morenekilen fault suggests that the Morenekilen fault represents an oblique-dextral thrust.

The kinematics of the NNE-striking *Straumhallet fault* have been interpreted from bedding-cleavage orientations and associated fault patterns (Fig. 4C, D). An E–W shortening axis is inferred from cleavage and a great-girdle pattern of poles to bedding in the Morenekilen anticline. Recorded oblique-normal faults and veins that strike north–northeast and dip steeply east–southeast are consistent with an additional component of oblique-normal sense-of-shearing on the Straumhallet fault. The oblique shortening axis (E–W) with respect to the NNE-striking main fault indicates a dextral component of movement.

Mesoscopic fault-slip data of the *Flydammane fault* indicate variable reverse-, normal-, and strike-slip movements that can be ascribed to at least two kinematically different fault populations (Fig. 4E); (1) north to NE-striking, steeply west-dipping dextral strike-slip and oblique-reverse faults, and subordinate (2) normal faults that strike northeast and dip both to the northwest and southeast. The strike-slip faults are most abundant near the fault contacts on both sides, and constitute the walls of the fault zone (Fig. 3d), while the interior of the fault zone reveals the more complex normal and oblique-reverse fault signatures. Our interpretation addresses a common east–northeast shortening axis (Fig. 4E); the observed normal faults are oriented subparallel with this axis, whereas the oblique-reverse faults strike at a high angle to this shortening axis. These complex kinematic patterns may reflect rotation of fault blocks and successive deformation within the fault zone that is bound by strike-slip faults (see discussion below). The M-plane plot of mesoscale faults (Fig. 4F) reveals an average plane that is subhorizontal and strikes N70E, i.e. oriented at an oblique angle (30–40°) to the strike of the main Flydammane fault. This, in conjunction with a dominant dextral strike-slip/oblique-slip fault character on the subvertical fault zone and drag folding of strata next to the fault, supports an overall interpretation of the Flydammane fault as a dextral strike-slip fault.

Summary. – The three fault-branches along the Isfjorden-Ymerbukta Fault Zone within the Ramfjellet-Erdmannflya transect, from west to east, are interpreted as: an oblique-dextral thrust (Morenekilen fault), a reverse fault with a possible dextral component and subordinate transport-parallel extension (Straumhallet fault), and a dextral strike-slip fault (Flydammane fault), respectively.

Mehøgda–Bohemanflya area

Geometric patterns

The fold-thrust system of western Bohemanflya can conveniently be divided into three domains (western, central, eastern; Fig. 5), separated by and/or containing faults that are at either low or high angle to bedding (Karlsen & Bergh 1999). Characteristically, all structures merge with the NNW trend of the fold-thrust belt as they are traced northward; i.e. the average strike changes from NNE to NNW (Fig. 1c).

The western domain is characterized by NNW-trending detachment folds and thrust-splays that are developed above a probable basal detachment in the Bravaisberget Formation (e.g., fault 1 in Fig. 5). A cleavage is locally developed in the fold hinges.

In the central domain, which hosts the main part of the Isfjorden-Ymerbukta Fault Zone, upright fault-propagation folds, low-angle thrusts (faults 4 and 5, Fig. 5) and the moderately dipping bedding are truncated by three steep fault zones. The westernmost zone consists of two subvertical faults (faults 2 and 3) that bound a pop-up (or positive flower) structure with approximately 50 m uplift of the core (Fig. 6a). Further east, the next fault zone contains two steeply east-dipping fault strands that show ca. 50 m west-side-up separation (faults 5 and 6). The easternmost structure is a major steep fault zone that juxtaposes the Bravaisberget Formation to the west with the Janusfjellet Subgroup (fault 7, Fig. 5). Here, separation is consistent with a throw of 600 m.

The eastern domain, east of the main Isfjorden-Ymerbukta Fault Zone, differs from the other domains in that the amount of strain is significantly lower. The Triassic–Cretaceous section is folded into an upright, open N–S trending anticline with parasitic flexures. This folding probably occurs above a deeper-seated detachment, e.g., in gypsum of the Kapp Starostin Formation (see Bergh et al. 1997). Only one map-scale fault is observed in the domain; this structure has a moderate dip to the west, truncates bedding in a foot- and hangingwall ramp, and has approximately 100 m reverse throw (fault 9, Fig. 5). A much more complex pattern is recorded by mesoscopic faults (Fig. 6b, c), especially when approaching the central domain (see below).

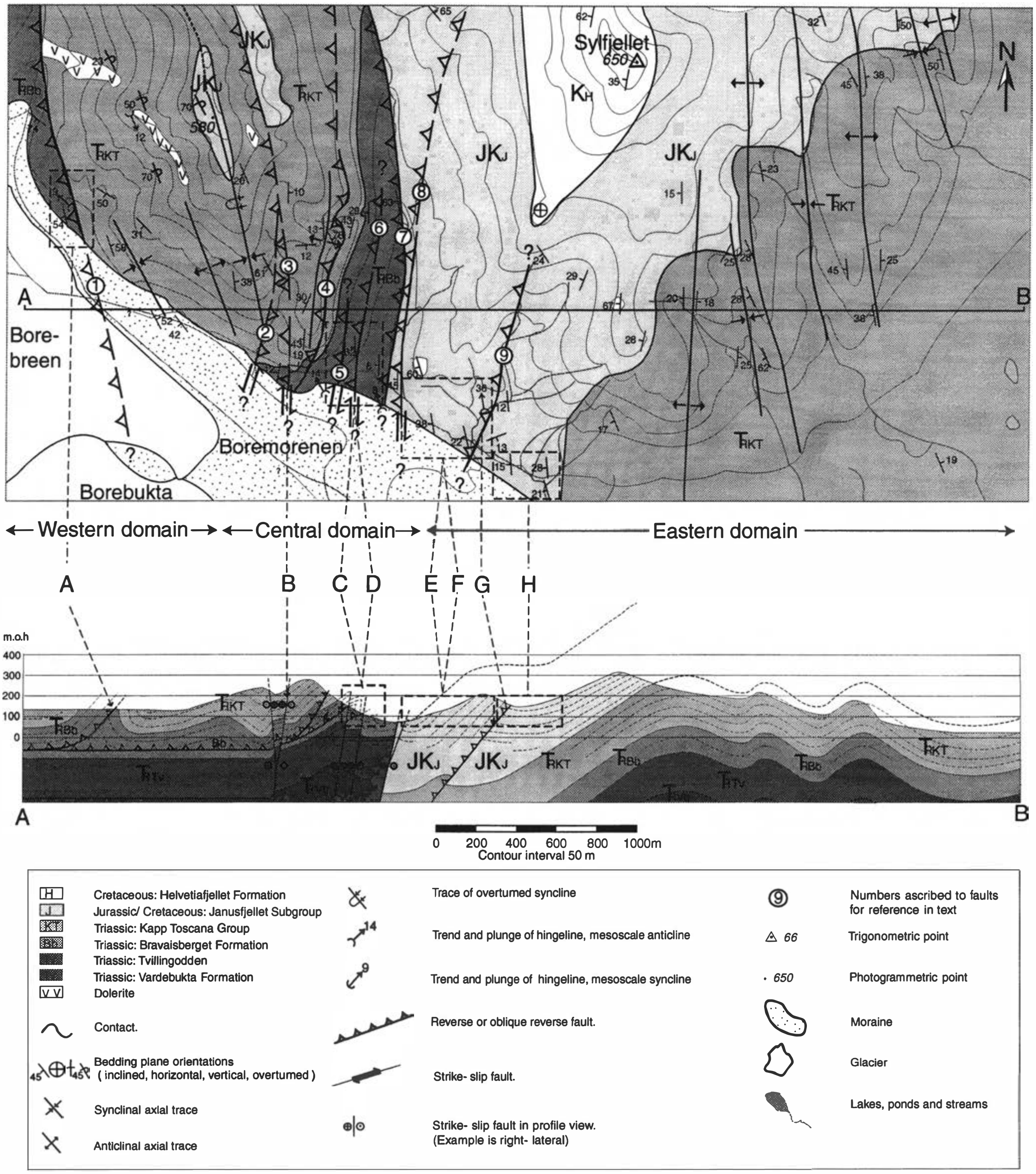

Fig. 5. Geological and structural map and cross-section for a transect across the Isfjorden-Ymerbukta Fault Zone in the Mehøgda–Bohemanflya area. Letters A–H with corresponding dashed frames locate the respective kinematic data presented in Fig. 7. The faults are numbered 1–9 (from west to east) on the map.

Kinematic patterns

The three domains of the Mehøgda–Bohemanflya transect record distinctly different kinematic patterns. In the western domain (Fig. 7A), detachment folds plunge gently NNW. Associated mesoscopic faults dip steeply westward, and contain slickenlines consistent with oblique-dextral, reverse movement.

In the central Isfjorden-Ymerbukta Fault Zone domain, the mesoscopic strain patterns are complex. The western-

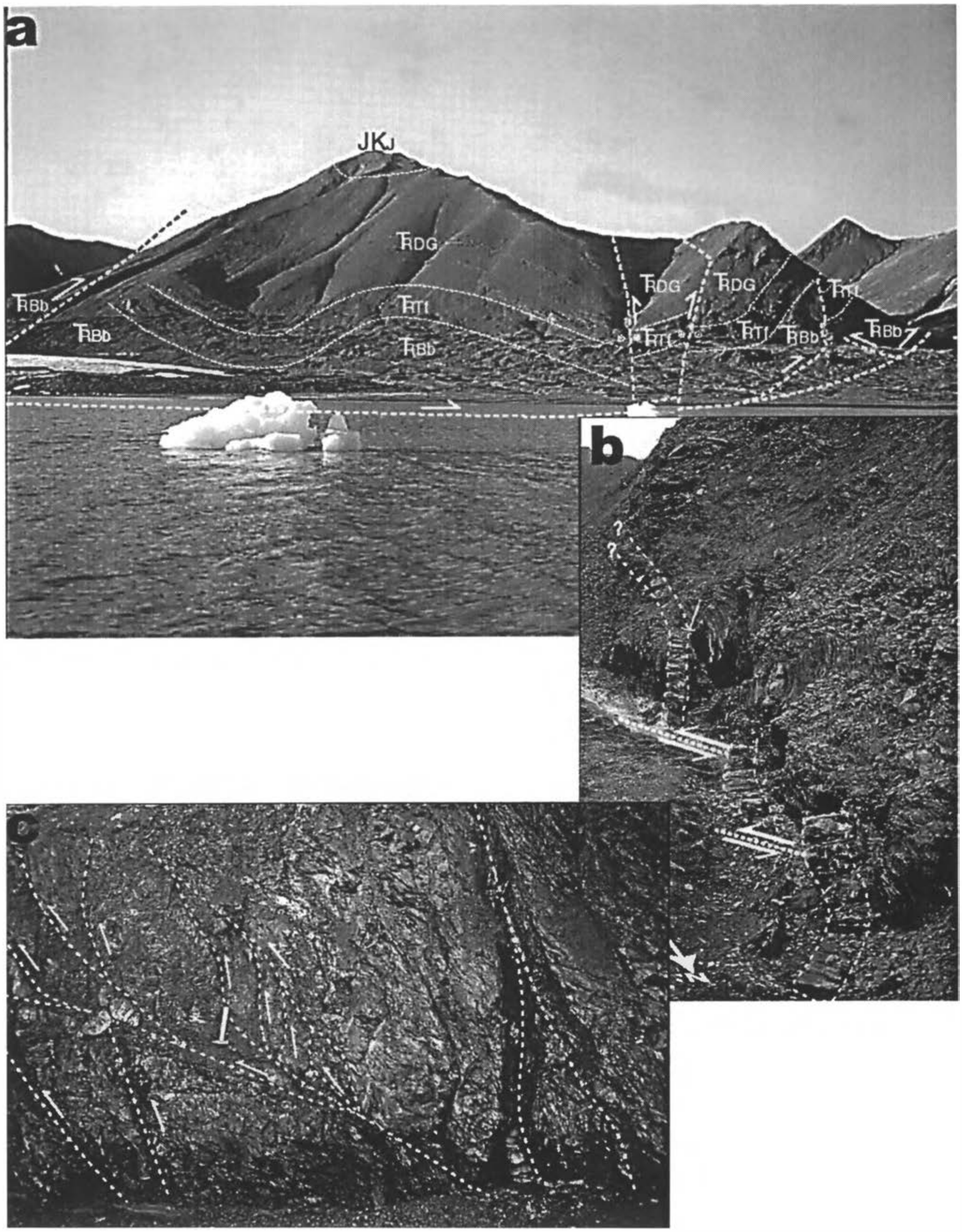

Fig. 6. (a) Peak 580 m viewed from the south with sketched interpretations. Thin dotted lines show stratigraphical boundaries, while thick dotted lines show approximate fault trajectories (compare with the western part of geological cross-section in Fig. 5). T_{RBb} = Triassic Bravaisberget Fm; T_{RTf} = Triassic Tschermakfjellet Fm; T_{RDG} = Triassic De Geerdalen Formation; JK_J = Jurassic–Cretaceous Janusfjellet Subgroup. (b) NW-striking (330°) sinistral strike-slip faults that offset subvertical siltstone bed in the Janusfjellet Subgroup. The outcrop is located along fault 8 just north of Boremorenen (Fig. 5). For orientation data, see plots D and E in Fig. 7. (c) East-verging duplex structure and steeply dipping, NW-striking fault zone developed in shales of the Janusfjellet Subgroup, viewed from the north. These structures are located just north of Boremorenen between faults 8 and 9 in Fig. 5. For orientation data, see plots E and F in Fig. 7.

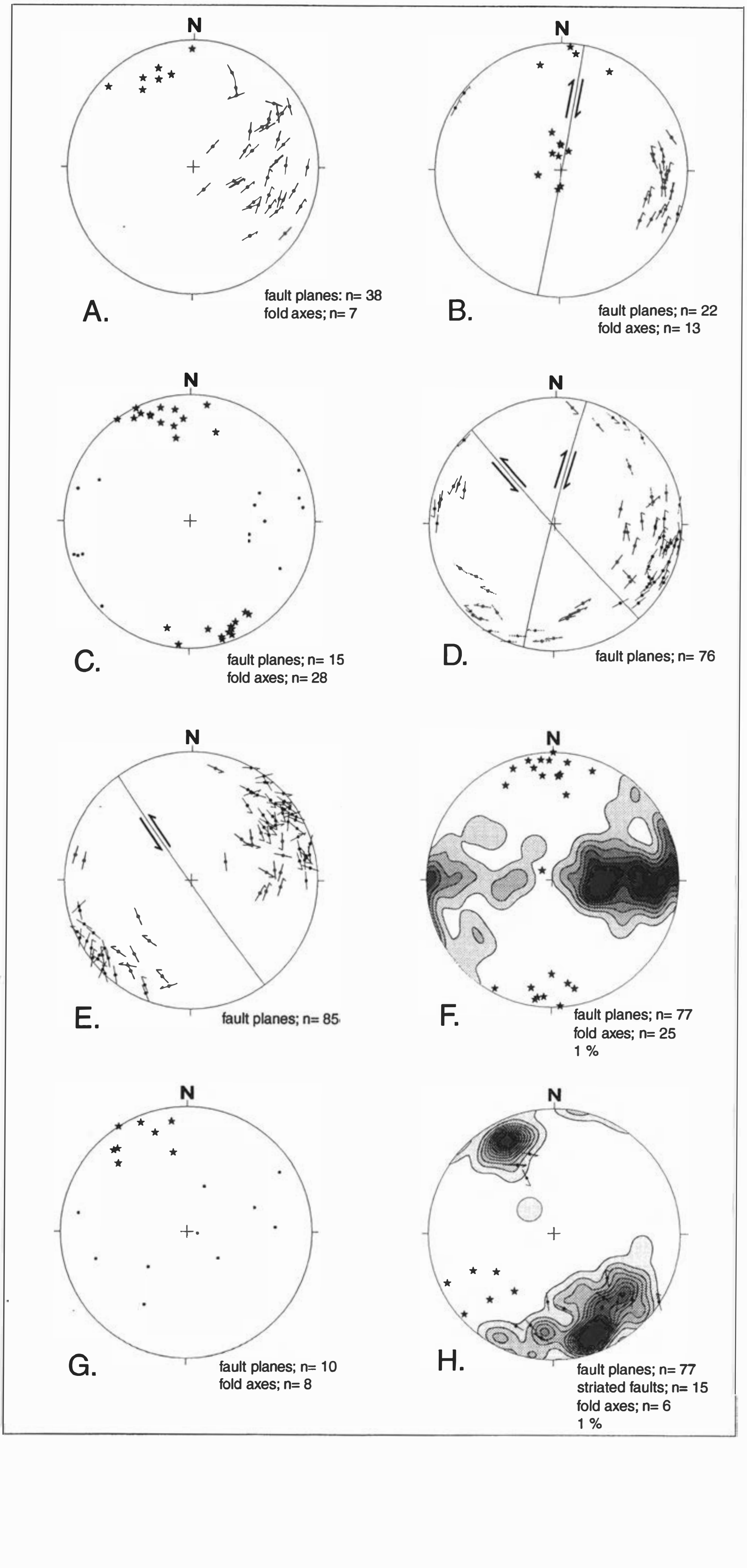

Fig. 7. Structural-kinematic data from a transect across the Isfjorden-Ymerbukta Fault Zone in the Bohemanflya–Mehøgda area, presented in lower hemisphere, equal area projections. See dashed reference frames in Fig. 5 for location of the data. A: Combined plot of mesoscopic fold axes (stars) and fault-slip data (slip-linear). B: Combined plot of mesoscopic fold axes (stars) and fault-slip data (slip-linear). Great circle represents average girdle to fault planes, and arrows indicate average sense of slip. C: Combined plot of poles to fault planes (dots) and mesoscopic fold axes (stars). D: Slip-linear plot with associated average girdles from striated fault surfaces, outlining two populations of NNE-striking dextral and NW-striking sinistral strike-slip faults, respectively. E: Slip-linear plot and associated girdle to fault planes of dominantly NW-striking sinistral strike-slip faults. Note subordinate NNE-striking dextral strike-slip faults. F: Combined plot of mesoscopic fold axes (stars) and contoured pole to fault surfaces. G: Combined plot of poles to fault planes (dots) and mesoscopic folds axes (stars) from fault 9. H: Contoured pole to plane plot for a conjugate set of normal faults. Stars denote fold axes of associated drag-folds. Striated fault-surfaces are plotted as slip-linears.

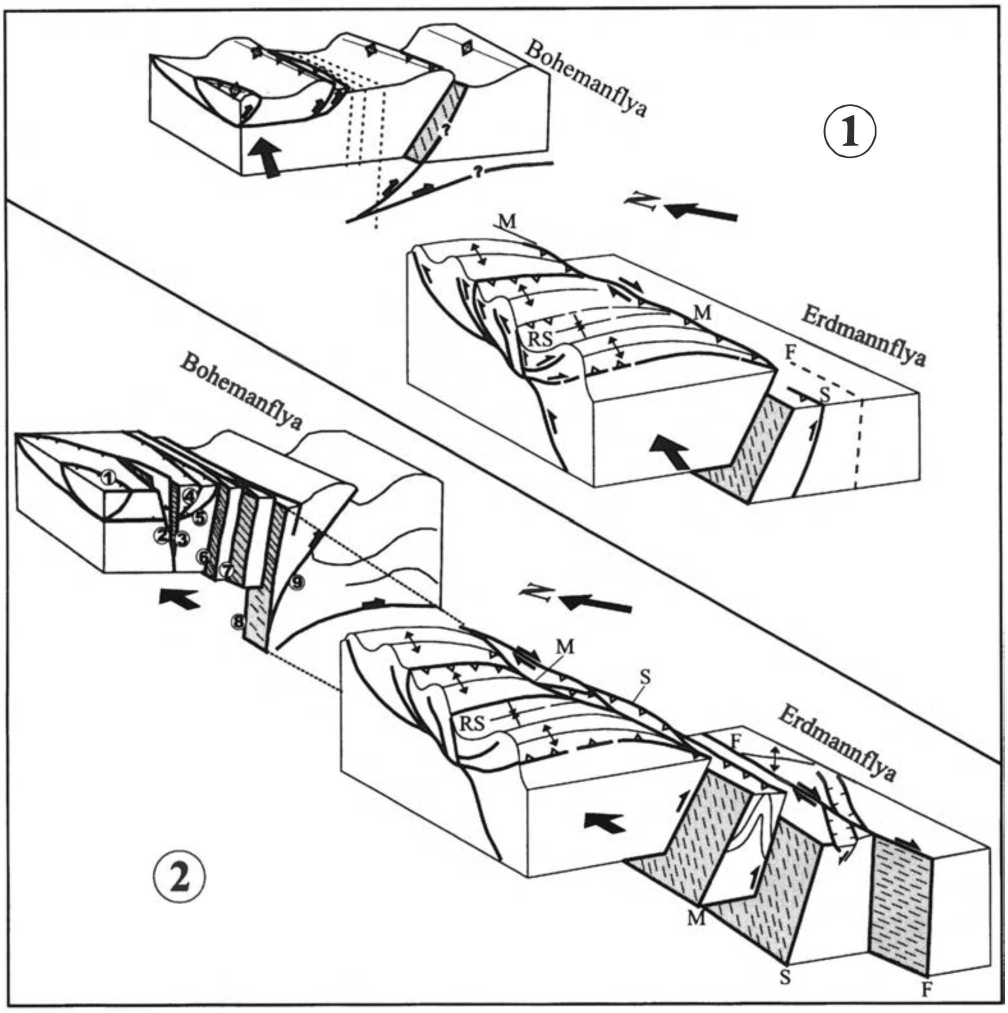

Fig. 8. Simplified, two-stage oblique-thrust ramp (tear fault) model of displacement along the Isfjorden-Ymerbukta Fault Zone, addressing change from weakly oblique-thrusting to highly oblique, dextral strike-slip movements. Regional shortening axis (arrow) and local strain conditions are illustrated. An alternative interpretation of the Isfjorden-Ymerbukta Fault Zone addresses formation during a single event, with a consistent strain field, which is further discussed in the text.

most fault zone (i.e. the pop-up or flower structure) contains numerous, steeply WNW-dipping faults with slickenlines consistent with dextral strike-slip movement (Fig. 7B). Data from the next fault zone to the east reveal two fault-fold populations (Fig. 7C, D). One is consistent with ENE-directed thrusting, the other defines an apparent set of conjugate, subvertical strike-slip faults, with NW-striking sinistral faults and NNE-striking dextral faults, the latter parallel to the first-order fault. Hence, the mesoscopic strike-slip faults reveal a bisecting WSW-ENE shortening axis and NNW-SSE extension axis consistent with (i) dextral movement on the leading fault zone, and (ii) accompanied stretching and/or lateral extrusion subparallel to the main structure. The strike-slip faults truncate the thrust-structures, as evident in the map- and cross-section pattern (Fig. 5).

The easternmost, major fault zone of the central domain is poorly exposed, and mesoscopic data have been recorded at nearby exposures. In the eastern, footwall section, abundant steep NW-striking faults show slickensides consistent with sinistral strike-slip faulting (Figs. 6b and 7E), whereas a subordinate set of NNE-striking faults are characterized by dextral slip. The dominant sinistral fault-set is clearly oblique to the main fault and, in combination with the dextral fault-set, is similar in orientation to the abovementioned conjugate strike-slip fault system.

The eastern domain reveals a distinctly different pattern of mesoscopic faults and folds, which can be separated into two populations: One with N–S striking mainly moderately west-dipping reverse faults and gently north and south plunging contractional folds (Fig. 7F, H), the other with steep WSW-ENE striking normal faults, some with downdip striation, and subhorizontal SW-plunging folds (Fig. 7G). The latter fault-system is consistent with conjugate normal faults and associated drag-folds along the symmetry axis, and with a total strain-pattern of NNW–SSE extension. The reverse faults and associated folds reflect E–W contraction.

Summary. – The Mehøgda–Bohemanflya transect is characterized by a western domain with structures indicating NE-directed, dextral-oblique thrusting, a central domain that contains structures formed by a combination of dextral strike-slip faulting and N–S extension/extrusion, and an eastern domain dominated by structures consistent with E–W contraction and subordinate NNW–SSE extension.

Discussion

The map, cross-sections and character of fold-fault patterns, in conjunction with the fault-slip data presented above, can be used to evaluate the kinematic character of the Isfjorden-Ymerbukta Fault Zone. We interpret this fault zone to be a dextral oblique-thrust ramp or tear-fault system (see Price et al. 1978), in accordance with Dallmann et al. (1993) and Bergh et al. (1988, 1997), for the following reasons. First, the fault zone obliquely separates two contrasting domains in southern Oscar II Land (Figs. 1c, 2 and 5), marked by a significant reduction in shortening on surface structures from north to south across the Isfjorden-Ymerbukta Fault Zone, consistent with a tear fault geometry. However, seismic reflection data from Isfjorden (Johansen et al. 1994; Bergh et al. 1997) confirm that fold-thrust belt structures of Oscar II Land can be traced southwards beneath the Central Tertiary Basin (Fig. 1b). Secondly, on Erdmannflya the Isfjorden-Ymerbukta Fault Zone is a distinct truncating feature with narrow blocks or fault segments joined by north- and NE-striking fault and fold patterns. It also affects the fold-thrust belt structures at Ramfjellet, which bend and steepen into the Isfjorden-Ymerbukta Fault Zone plane. Thirdly, northward, at Bohemanflya, the fault zone widens and both truncates and merges with the typical fold-thrust belt structures, as it is responding to a decrease in displacement and termination of the fault. Finally, the mesoscopic fault and fold data support an overall dextral-oblique thrust or strike-slip character on the fault zone.

Others have argued for (i) pure strike-slip faulting (Harland & Horsfield 1974), (ii) a mainly contractional fault zone contemporaneous with (Ohta et al. 1992) or late in the fold-thrust belt evolution (Hanisch 1984), or (iii) a normal fault (Lyberis & Manby 1993). The geometric and kinematic pattern of individual structures along the Isfjorden-Ymerbukta Fault Zone may, in isolation, permits the various interpretations. However, taken together the data are certainly consistent with a combination of reverse and dextral motion on the fault zone. The subordinate extensional structures are found in distinct domains, they have strikes at high angles to the fault zone, and they reveal a stretching axis that is oblique to near parallel to the trend of the Isfjorden-Ymerbukta Fault Zone. Hence, an interpretation of the fault zone as a normal fault is inconsistent with the geometric and kinematic data. Subordinate normal faulting in contractional regimes is not a contradiction, as discussed below.

Deflection of marginal structures is described from many fold-thrust belts, containing lateral ramp and/or tear faults. Typical patterns include interference and superposition of frontal and lateral folds, resulting in variable plunges that are oblique to the tectonic transport direction (Alvarez-Marron 1995). In addition, stretching of lateral folds in the direction of tectonic transport may, locally, trigger extension in the roofs of lateral culminations (Butler 1982; Apotria 1995; De Lamotte et al. 1995). Along the Isfjorden-Ymerbukta Fault Zone, evidence of stretching subparallel to the transport direction is recorded in two ways. First, by a conjugate set of strike-slip faults in the central domain of Bohemanflya, which reveals a strain pattern consistent with N–S extension or extrusion nearly parallel to the trend of the main fault zone. Second, by the normal faults in the eastern domain of the Mehøgda–Bohemanflya transect, which show a NNW–SSE stretching axis. This axis is slightly oblique (counter-clockwise) to the strike-slip fault in the area, and subparallel to the possible N–S extrusion axis discussed above. Hence, in this area transport-subparallel stretching within the mainly strike-slip fault zone seems to be important.

At Erdmannflya, the kinematic pattern is partly different. Again, strike-slip and oblique-reverse structures dominate. Normal faults appear only near the Straumhallet fault, where they are associated with reverse faults. Both these fault-sets are oriented subparallel to the axis of the hangingwall (Morenekilen) anticline, which supports an interpretation of localized stretching and shortening due to flexural slip within a contractional fold system.

Normal faults also develop along strike-slip fault zones (e.g., Sylvester 1988; Richard et al. 1995; Westaway 1995). Typically, they develop obliquely to the main fault trace (as tensional fractures) or at releasing overlaps and fault zone bends. No recorded, major structures along the Isfjorden-Ymerbukta Fault Zone are readily assigned to such a setting. However, internally, in some of the strike-slip fault zones, for example the Flydammane fault, observed normal faults fit an interpretation as tensional fractures parallel to the shortening axis.

The above discussion clarifies that a transfer-fault interpretation is supported by the kinematics of the Isfjorden-Ymerbukta Fault Zone, showing atypical orientations (NNE–SSW) and kinematic signatures (variable oblique-reverse and dextral strike-slip, subordinate oblique-normal) compared to the more uniform ENE shortening direction of the fold-thrust belt. The kinematic data (Figs. 4 and 7) also suggest non-plane strain across the fault zone boundary, a pattern that is commonly observed near oblique-thrust ramps (Apotria et al. 1992), where strain is distributed according to the position relative to the main fault. Non-planar strain distribution may, for example, be inferred from the change in fault kinematics between the northwestern Morenekilen fault (dominantly oblique-reverse movement) and the southeastern Flydammane fault (dominantly dextral strike-slip character) that likely developed in order to reduce compatibility problems across and along (?) the fault zone (Woodcock 1987). The Isfjorden-Ymerbukta Fault Zone responded by complex strain accommodations across the domain boundaries, i.e. it served as a buffer that partitioned the overall shortening strain of the fold-thrust belt into transport-normal (thrusts and folds) and transport-parallel (strike-slip faults) motions across the fault zone boundary.

The observation that steep dextral faults consistently post-date the more oblique-thrust-faults can be explained by the evolution of the oblique ramp-tear system. Initial thrusting would be to the ENE. As thrust sheets to the north moved farther than counterpart structural levels to the south, an incipient fault zone developed by rotation of earlier thrust structures and development of oblique-ramp thrusts. With continued differential movement and accumulation and concentration of strain, steep strike-slip faults organized into a tear system. Irregularities along strike produced variation in local kinematics, including stretching and extrusion near parallel to the fault zone.

The above discussion entertains a one-event model with a consistent overall strain field for formation of a lateral-ramp/tear-fault zone. In the case of Spitsbergen, a two-event evolution may be equally adequate. This complementary model attempts to place the Isfjorden-Ymerbukta Fault Zone in the documented polyphase evolution of the fold-thrust belt (e.g., Kleinspehn et al. 1989; Lepvrier 1990, 1992; Braathen & Bergh 1995; Teyssier et al. 1995; Bergh et al. 1997; Braathen et al. 1999). A regional and multistage chronology of Tertiary tectonic events includes (1) northward directed shortening, (2) major ENE-directed contraction (in-sequence thrust propagation), (3–4) linked transcurrent faulting, oblique transtension and NE-directed out-of-sequence thrusting, and (5) late E–W oriented extension/transtension (Braathen & Bergh 1995; Bergh et al. 1997). Of certain relevance for the Isfjorden-Ymerbukta Fault Zone is the difference in tectonic transport directions ascribed to the main stages 2 and 3/4 of the fold-thrust belt, a feature that can also be recorded in the change of kinematic movement plane directions across the Isfjorden-Ymerbukta Fault Zone (Figs. 4 and 7). If these deformation events affected the Isfjorden-Ymerbukta Fault Zone, the overall shortening axis of the fold-thrust belt relative to the strike of the Isfjorden-Ymerbukta Fault Zone rotated counter-clockwise (northeastward), from weakly oblique to highly oblique through time. Consequently, the first movement along the Isfjorden-Ymerbukta Fault Zone (stage 2) had a dominant shortening and subordinate dextral strike-slip component, while the dextral strike-slip component increased during the later stages (stages 3 and 4) of the deformation. As illustrated in Fig. 8, this model may fit the kinematics of the Isfjorden-Ymerbukta Fault Zone. In order to justify a polyphase evolution, cross-cutting relationships become important. For example, bending and subsequent truncation of folds and thrusts adjacent to the Isfjorden-Ymerbukta Fault Zone can be interpreted as drag folding of earlier fold-thrust belt structures, resulting from lateral uplift during oblique-thrust reactivation.

In view of the relative timing, the Isfjorden-Ymerbukta Fault Zone may have been established during the main contractional event (stage 2) and later reactivated as a combined thrust and strike-slip tear fault (stages 3 and 4) contemporaneous with oblique and out-of-sequence thrusting (Bergh et al. 1997). This kinematic pattern suggests oblique subsurface buttressing and deflection across the Isfjorden-Ymerbukta Fault Zone boundary zone of the tectonic transport direction, from its uniform direction in Oscar II Land. As Triassic and Cretaceous-Tertiary strata close to the fault zone were thrust towards the ESE, the fold-thrust belt structures were rotated clockwise. Finally, NE-directed oblique thrusting and dextral strike-slip displacement took over on the Isfjorden-Ymerbukta Fault Zone (Fig. 8).

Possible buttressing, and hence location of the Isfjorden-Ymerbukta Fault Zone, may be a consequence of subsurface structural grain. Interpretations of seismic sections from Isfjorden indicate the presence of a significant basement (Hecla Hoek)–Devonian–Carboniferous ridge and basin relief (Eiken 1994; Figure 13 of Bergh et al. 1997). Notable are (i) basins and ridges flanked by normal faults that, on average, strike northeast in central–western Isfjorden, and (ii) the basin fills pinch out to the northeast and northwest (Bergh et al. 1997). We postulate that the structural grain and the lateral thickness variations of the basins not only controlled the shape of the fold-thrust belt, but also controlled partitioning of strain along obliquely oriented structures. Lateral ramps are likely to be induced by subsurface (basement) heterogeneities, by lateral strength variations along the fault plane, or in the surrounding rocks (Wiltschko & Eastman 1983). We suggest that one or more of the NE-striking Carboniferous basin-bounding normal faults acted as lateral ramps or zones of mechanical weakness, that accommodated oblique-thrust reactivation and out-of-plane movements.

Although the kinematics and relative timing of movement(s) on the Isfjorden-Ymerbukta Fault Zone are constrained by our data in the Ramfjellet–Erdmannflya and Mehøgda–Bohemanflya transects, the absolute dating of movement with respect to the established chronology of plate-tectonic events for the Tertiary deformation in Spitsbergen (e.g., Talwani & Eldholm 197; Muller & Spielhagen 1990; Braathen & Bergh 1995) is less clear. The Isfjorden-Ymerbukta Fault Zone, however, is clearly partly younger than the Paleocene rocks of the Firkanten Formation (Ohta et al. 1992), because these rocks are affected by the transfer-faulting event (see Maher et al. 1995; Bergh et al. 1997). Furthermore, the termination of the fault zone by bending into the main fold-thrust belt structures argues for a chronological linkage. It is therefore reasonable to assume that the Isfjorden-Ymerbukta Fault Zone was formed in Early Paleocene–Middle Eocene times, contemporaneously with the main ENE–WSW shortening episode of the fold-thrust belt (Maher et al. 1995).

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