Early Tertiary palaeostress distribution on Spitsbergen: implications for the tectonic development of the western fold-and-thrust belt

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Distribution and evolution of the Palaeocene–Eocene stress fields on Spitsbergen support a two-stage model of development of the West Spitsbergen Orogenic Belt, within a transpressive setting. A wrench-type tectonic regime developed first, adjacent to the intra-continental transform, then followed by a superimposed and widespread regime of strictly transverse compression. The tectonic nature of the belt is therefore composite. The clockwise change of trend of the average maximum horizontal stress from 10–20°N to 70–80°N (oblique to subnormal to the transform fault) is interpreted in terms of a progressive decrease in friction and shear stress along the plate boundary, and supports the idea of a partitioning of the components of transcurrent and convergent motions. Such a phenomenon is aided by the presence of deep ductile horizons.

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The Tertiary fold-and-thrust belt of Spitsbergen (Svalbard) is classically related to the dextral intra-continental transform movement, along the NNW–SSE De Geer line (Fig. 1), which developed by separation of the Greenland and Eurasian plates, during the first stage of the opening of the Norwegian–Greenland Sea and the coeval Eurasian Arctic Basin (Harland 1969; Birkenmajer 1972; Lowell 1972; Kellogg 1975). Deformation along Spitsbergen, in the West Spitsbergen Orogenic Belt (Harland & Horsfield 1974), is explained either in terms of a non-orthogonal relationship between the De Geer Line transform and the spreading ridges (Crane et al. 1982) or in terms of a major restraining bend along the transform boundary (Vågnes et al. 1988).

From magnetic anomaly data, it has been shown that the period of dextral transcurrent motion started during the late Palaeocene (anomalies 25–24) and was completed in earliest Oligocene (anomaly 13), when the relative plate motion across the two sliding plates shifted from NNW–SSE to WNW–ESE (Talwani & Eldholm 1977; Myrhe & Eldholm 1988). About 550 km of dextral strike-slip displacement took place during the initial 20–25 Ma period of shearing when Spitsbergen was sliding past northeast Greenland (Fig. 1).

The age of contractional structures in West Spitsbergen coincides with the pre-early Oligocene period of transcurrent motion and therefore supports the wrench-related nature of the belt. The existence of late Cretaceous compressional tectonic events, as suggested by Hanisch (1984), is not demonstrated. Tertiary strate are clearly involved in the tectonic structures. Furthermore, the tectono-sedimentary record documented in the Central Basin (Steel et al. 1981; Steel & Worsley 1984) has shown that the earliest events, marked by a significant uplift of the basement in the western area, started during the late Palaeocene and that maximum tectonic activity was achieved during the Eocene. The latest events are extensional and they are related to the post-Early Oligocene rifting period. In this article, the orientation and distribution of the Tertiary stress fields in Spitsbergen are examined with respect to the Greenland–Eurasia plate kinematics, and the implications of the tectonic model to development of the belt are discussed.

Tectonic structures and deformational regimes

The NNW–SSE trending tectonic structures, forming the West Spitsbergen Orogenic Belt, can be followed over 300 km on Spitsbergen, parallel to the western margin and the Hornsund Fault Zone (Myrhe et al. 1982). According to traditional understanding, these structures are associated with transpression (Harland 1969), marked by a dominant strike-slip component (Lowell 1972). Thrust faults have been interpreted as upthrusts related to strike-slip faults at depth, giving rise to a large positive flower geometry. The West Spitsbergen Orogenic Belt has therefore been considered to be a typical strike-slip belt of dextral transpressive origin (Lowell 1972).

However, recent structrual analysis (Maher & Craddock 1988) revealed that the standard characters of a typical strike-slip belt were not so obvious in Spitsber-

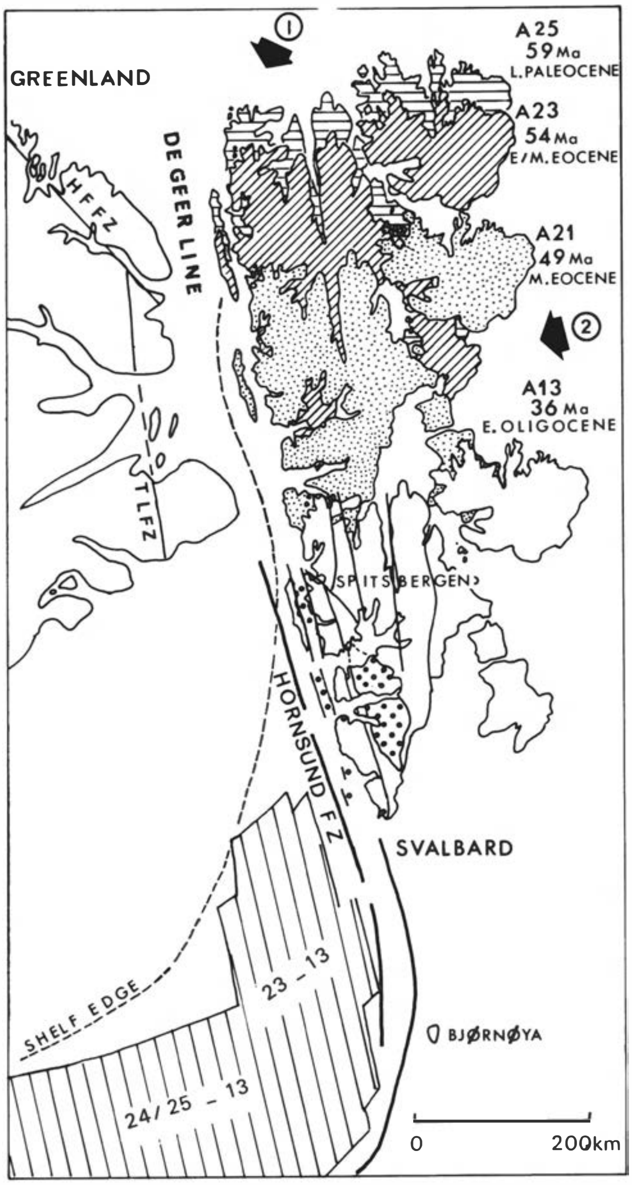

Fig. 1. Successive positions of Svalbard relative to Greenland, during the intracontinental transform period, from magnetic anomaly 25 to 13 (after Myrhe & Eldholm 1988). 1 and 2, Two successive orientations of the maximum principal stress σ_1 indicated by heavy black arrows; HFFZ, Harder Fjord Fault Zone; TLFZ, Trolle Land Fault Zone. The major fracture zones and Tertiary basins on Spitsbergen have been drawn on the A13 position, the latest position before the change in plate motion.

gen. In particular, the expected en échelon fold patterns could not be recognized clearly, or were found inconsistent with the expected dextral motion. Moreover, at least on the large scale, structural evidence for Tertiary strike-slip faulting along the major N–S to NNW–SSE trending tectonic lineaments, which dissect Spitsbergen in different blocks, was considered to be absent, even along the westernmost basement faults. The strike-slip dominating nature of the West Spitsbergen Orogenic Belt therefore has been questioned.

By contrast, according to increasingly accurate field investigations, as well as seismic reflection profiles from Spitsbergen's fjords, it became more apparent that the tectonic regime was dominantly compressive and that Tertiary deformation was not restricted to the westernmost area but had affected a wider zone than recognized previously (Faleide et al. 1988; Nøttvedt & Rasmussen 1988; Nøttvedt et al. 1988b). In east-central Spitsbergen, notably, the Billefjorden Fault Zone and Lomfjorden Fault Zone were reactivated as reverse faults (Andresen et al. 1988ab; Haremo & Andresen 1988; Nøttvedt et al. 1988a; Ringset & Andresen 1988). Thus the belt appeared as a strictly east-verging, compressional, foreland propagating fold-and-thrust belt, and the Central Basin as well as the Ny-Ålesund sub-basin were interpreted as typical foreland basins (Steel et al. 1985). Features analogous to the eastern front of the Canadian Rockies were first reported by Challinor (in Harland 1969). Deformation, in relation with an ENE–WSW direction of shortening, was both of a thin-skinned (detachment tectonics) and a thick-skinned (basement involved tectonics) nature (Maher et al. 1986, 1989; Bergh et al. 1988; Dallmann 1988; Maher 1988; Nøttvedt et al. 1988b; Bergh & Andresen 1989; Dallmann & Maher 1989). The eastward-directed tectonic migration was made possible by the presence of décollement horizons in the evaporites of the lower Permian Gipshuken Formation (Harland et al. 1988) and in the Mesozoic ductile shale layers, especially the Triassic Botneheia Member of the Barentsøya Formation and the upper Jurassic Janusfjellet Subgroup. Fault-bend folds, fault-propagation folds, flat-ramp geometries, imbricate fans, thrusts and duplex systems, which are all typical of foreland thrust-and-fold belt structures, are commonly described by many workers (Challinor 1967; Bergh et al. 1988; Dallmann 1988; Maher 1988; Bergh & Andresen 1989; Manby 1988; Maher et al. 1989). The total amount of shortening is not precisely estimated yet, but certainly averages several tens of kilometres.

In fact, strike-slip motion along the major NNW–SSE to N–S fault zones is not absent and can be documented at least on a mesoscopic scale.

1. In eastern Spitsbergen, even if the Tertiary kinematics of faulting in the Billefjorden Fault Zone and Lomfjorden Fault Zone are essentially compressional (resulting in the inversion of the intermediate upper Palaeozoic basin), some observations indicate an older component of right lateral strike-slip movement. This statement is supported, for example, by the en échelon arrangement of folds along the Lomfjorden Fault Zone (Andresen et al. this volume).
2. In northwestern Spitsbergen, such strike-slip kinematics have been demonstrated locally in the Forlandsundet Basin. Although frequently overprinted by the more recent movements (i.e. the transverse ENE–WSW compression and finally the WNW–ESE to NNW–SSE extension), horizontal striae are sometimes preserved and can be detected on fault surfaces. This occurs along the border faults of the graben (e.g. near Dahltoppen on the eastern edge, see location on Fig. 3) or within the Tertiary sequence itself (Lepvrier

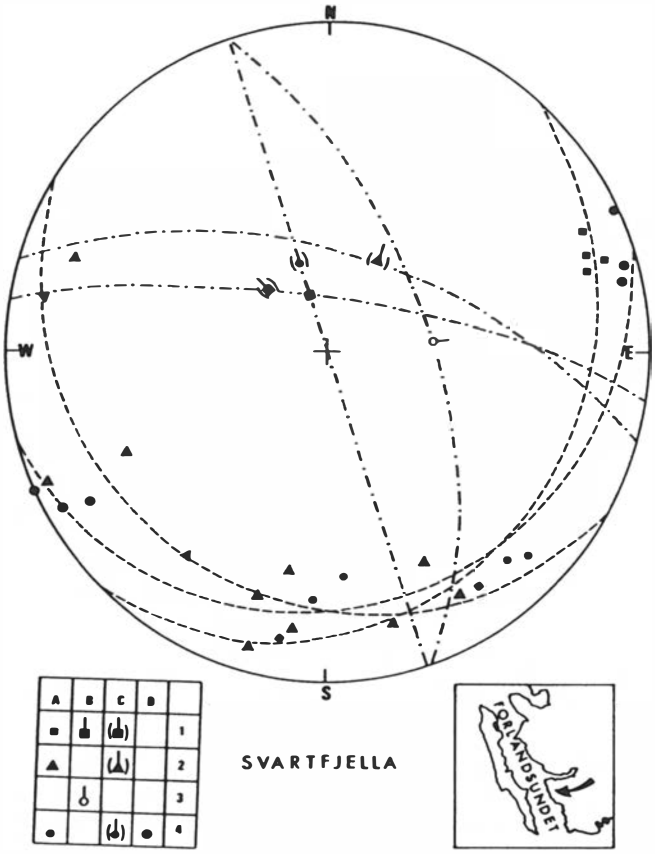

Fig. 2. Diagrams to illustrate metric to decametric cylindric folds with steep axes (1, 2, 3, 4) formed by dextral strike-slip faulting regime (slivers of Carboniferous rocks, Svartfjella, east Forlandsundet). Schmidt's projection, lower hemisphere: A, poles of bedding and their girdle distribution; B, C, fold axes, measured or graphically determined and cyclographic representation of the corresponding axial planes; D, poles of cleavage axial planar to the folds.

& Geyssant 1985; Lepvrier 1990). In addition, along the eastern edge of the Forlandsundet, slivers of upper Palaeozoic rocks showing steep fold axes (Svartfjella, Eidembukta, Figs. 2, 3), are thought to have been emplaced initially during the early Tertiary by a mechanism of strike-slip faulting, before being subjected to transverse compression (Lepvrier 1988). However, the possibility of middle Carboniferous movements of such nature cannot be excluded totally. In a similar way, Brøggerhalvøya is a zone of superimposed structures, with a dominant WNW–ESE strike (Challinor 1967). These structures resulted from initial N–S to NNE–SSW and from subsequent ENE–WSW compressions (Lepvrier & Geyssant 1984). WNW–ESE thrusts, NW–SE oblique reverse faults and pseudo-conjugate NNW–SSE to NNE–SSW strike-slip faults of tear nature (the latter finally reactivated as oblique-slip to dip-slip normal faults), are believed to have been formed, during a first stage, in a contractional relay zone, between two left-stepping dextral strike-slip faults (Lepvrier 1988). The tectonic style is both thick-skinned and thin-skinned with a décollement in the Gipsuken Formation. (Challinor 1967; Lepvrier 1988; Manby 1988). Spectacular duplex with sigmoidal horses (Lepvrier & Geyssant 1984), pop-up structures, etc, can be seen in the cliff along the coast, southeast of the Kongsfjorden.

In summary, the Tertiary tectonic regimes in Spitsbergen have been successively of transpressional and of compressional nature. Some authors, however, still suggest that compression occurred before transpression, possibly as early as late Cretaceous (Larsen 1988; Manby 1988). Since post-strike-slip Tertiary compressional tectonism is certainly present, this interpretation should imply the existence of two compressional events.

The Early Tertiary stress patterns

Early Tertiary stress patterns on Spitsbergen (Fig. 3) have been reconstructed from analysis of fault-slip data collected from different areas, in early Tertiary deposits as well as in the underlying post-Caledonian strata (Lepvrier & Geyssant 1984, 1985; Lepvrier 1990). Determination of the principal stress directions reveals a noticeable variation in space and through time and shows that the evolution was polyphase (Lepvrier et al. 1988). The palaeostress stratigraphy applied to the Tertiary Central Basin fill and to the underlying Cretaceous strata (Kleinspehn et al. 1989) better constrains the relative timing of events. The latest recorded event, oriented WNW–ESE to N–S, is extensional and is thought to be related to the rifting episode that occurred in earliest Oligocene times. In the previous stages, the maximum horizontal stress axis σ_1 is horizontal and shows two contrasting trends.

1. A well-defined 70–80°N direction of σ_1 is almost perpendicular to the strike of the palaeotransform fault zone represented by the Hornsund Fault. This direction accounts for purely compression or purely strike-slip compression, depending of the spatial orientation of the principal stress axes (σ_1 horizontal and σ_3 or σ_2 vertical). This state of stress has been documented in various areas and was probably present all over Spitsbergen. For example, in the westernmost zone, the Forlandsundet Basin has experienced this 70–80°N compressional strike-slip regime of deformation (Fig. 4), characterized by horizontal σ_1 and σ_3 axes (Lepvrier & Geyssant 1985; Lepvrier 1990). A similar compression, superimposed on a N–S to NNE–SSW transpression also is documented on Brøggerhalvøya (Lepvrier & Geyssant 1984). In the Central Basin, two types of stress tensors have been defined (Kleinspehn et al. 1989); they are characterized by a common 70–75°N azimuth of the σ_1 axis and an exchange between σ_2 and σ_3 axes. In eastern Spitsbergen, in the upper Palaeozoic rocks east of the Lomfjorden Fault Zone, a similar compression, attributed to the same Tertiary tectonics, has been determined (Figs. 3, 5, left). The same state of stress, also believed to be Tertiary in age, affects the eastern border of the Devonian basin, along Wijdefjorden:

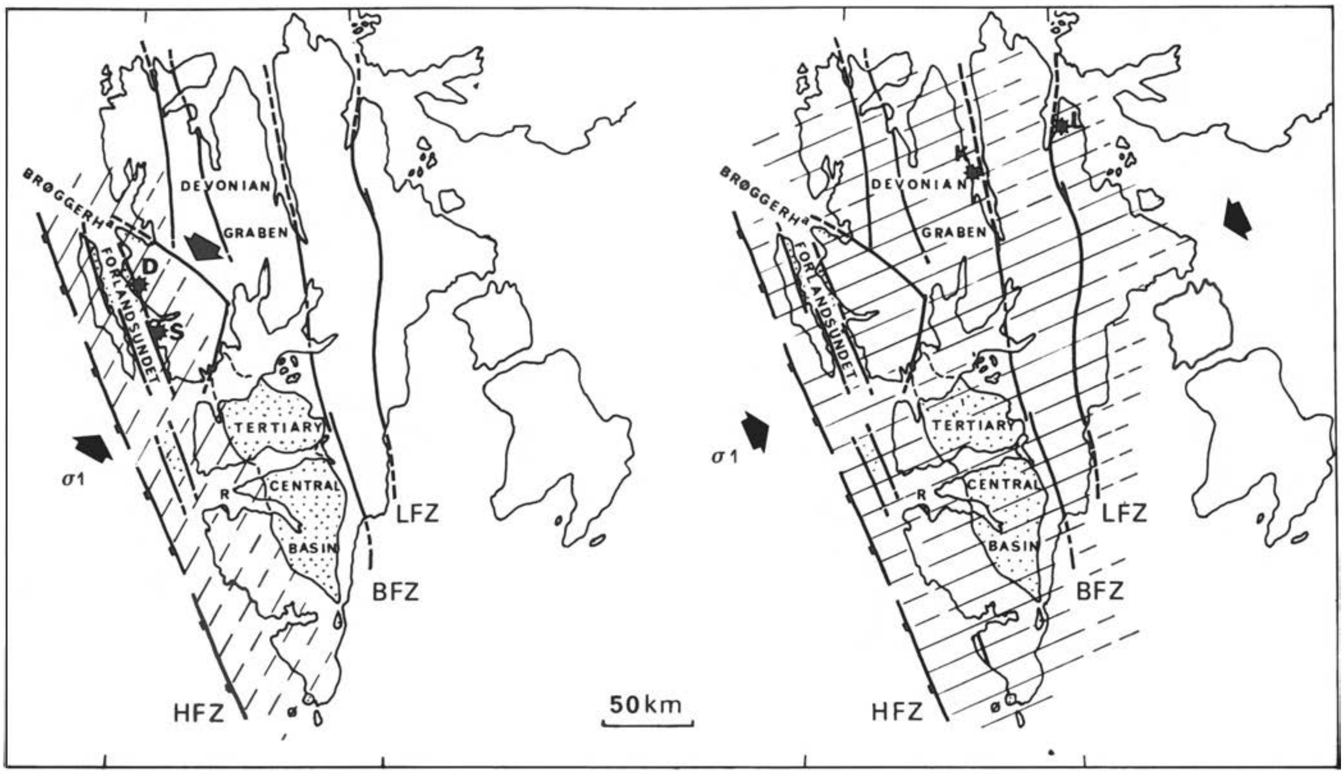

Fig. 3. Early Tertiary stress patterns on Spitsbergen: successive orientation and distribution of the horizontal maximum principal stress σ_1. HFZ, Hornsund Fault Zone; BFZ, Billefjorden Fault Zone; LFZ, Lomfjorden Fault Zone; R, (Renardodden) and Ø, (Øyrlandet) are Tertiary occurrences; stars indicate localities of mesoscopic structural data that are mentioned in the text; D, Dahltoppen; S, Svartfjella; K, Krosspynten; L, Lomfjorden.

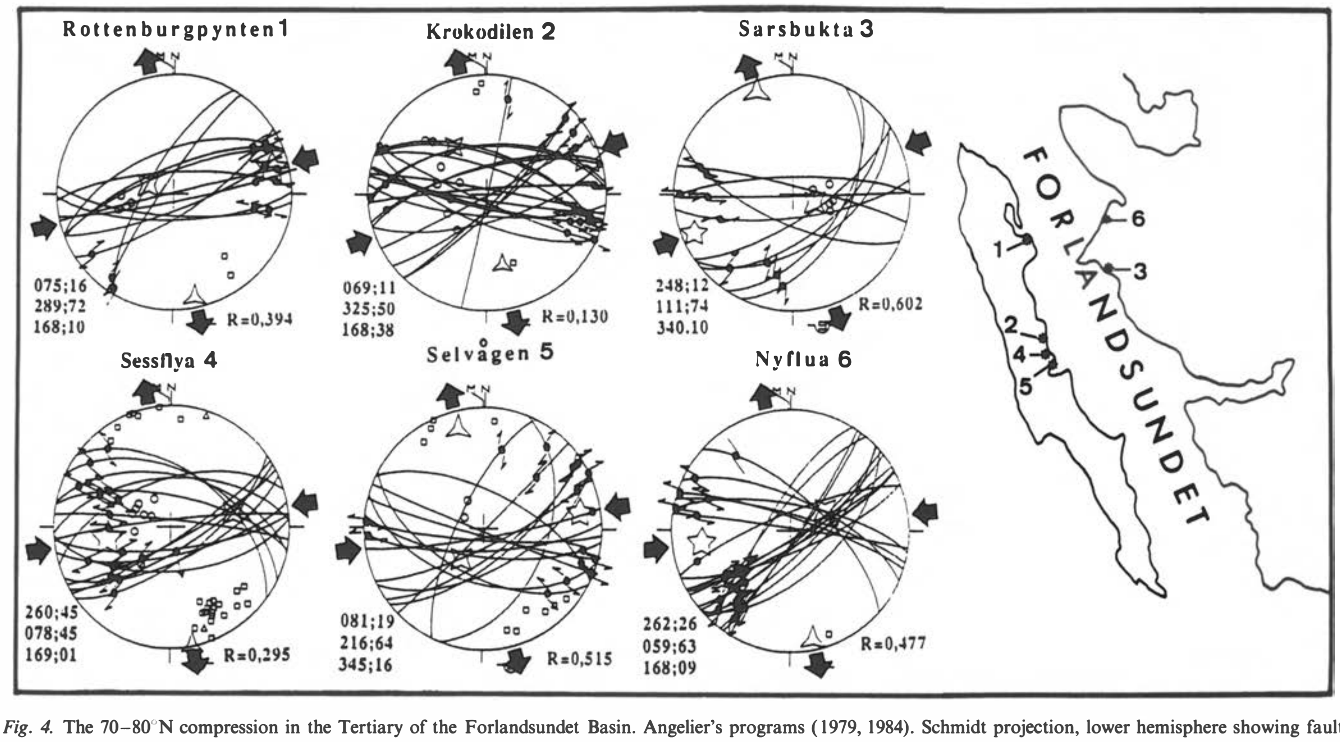

Fig. 4. The 70–80°N compression in the Tertiary of the Forlandsundet Basin. Angelier's programs (1979, 1984). Schmidt projection, lower hemisphere showing fault planes with striae (mainly strike-slip faults): small circles, poles of bedding; squares, poles of tension gashes; stars with 5, 4 and 3 arms, σ_1, σ_2, and σ_3 principal stress axes. Azimuth and plunge of the tensor axes are given on the bottom left of the diagrams. The ratio $R = \sigma_2 - \sigma_3/\sigma_1 - \sigma_3$ is noted on the bottom right. Heavy black arrows indicate the resulting directions of compression (convergent) and extension (divergent).

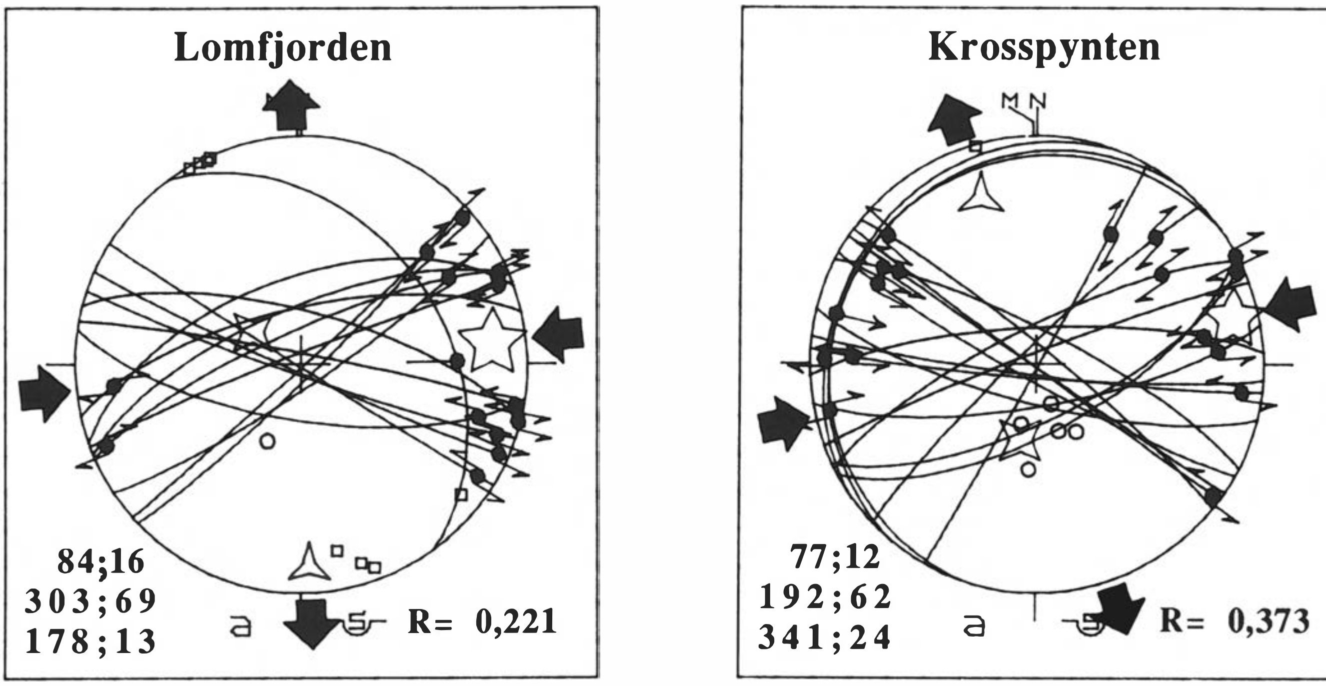

Fig. 5. The 70°–80°N compression in northeast Spitsbergen (see location of the two sites on Fig. 3). See Fig. 4 for legend.

relevant pseudo-conjugate transverse strike-slip faults and low-angle thrust-faults are well exposed near Krosspynten (Figs. 3, 5, right), defining a regime of strike-slip compression. They affect not only the Devonian sedimentary strata but also more recent volcanic rocks, which are intrusive parallel to a widespread submeridian cleavage.

According to palaeostress stratigraphy in the Central Basin, the age of this compressional event is post-lower to upper Paleocene. According to the stratigraphic age of the deformed Sarsbukta Formation in the Forlandsundet sedimentary sequence (Manum & Throndsen 1986), this event could have persisted until the upper Eocene.

2. A regime of dextral transpression, essentially documented in northwestern Spitsbergen (Fig. 3), precedes the regime of purely transverse compression. In the Forlandsundet Basin, this oblique-slip regime, generally expressed by strike-slip faults and by some oblique-reverse faults (Krokodillen Formation) corresponds to 20°N azimuth of the σ_1 axes (Lepvrier & Geyssant 1985; Lepvrier 1990). On Brøggerhalvøya, the stress tensors reconstructed for this earliest event have similar azimuths for the σ_1 axes (Lepvrier & Geyssant 1984).

This regional distribution and this change through time of the principal stress directions in Spitsbergen are strikingly similar to the states of stress documented along the San Andreas Fault system in central California (Mount & Suppe 1987). Pleistocene to Holocene orientation of the maximum horizontal stress also is nearly perpendicular to the strike of this transform boundary, thus indicating a regional compressional deformation, whereas in the Miocene this orientation was oblique to the fault. Similar observations have been made in other transpressive settings, such as the active left-lateral Northern Carribean strike-slip fault, where the maximum horizontal stress also is subperpendicular to the trend of the plate boundary (Calais et al. 1990).

Tectonic models

The decoupling model

In contrast to the coupling model proposed by Lowell (1972), an alternative kinematic model has been envisaged recently by different authors (Faleide et al. 1988, Haremo & Andresen 1988, Maher & Craddock 1988, Nøttvedt et al. 1988b). By comparison with the San Andreas Fault system (Mount & Suppe 1987), the oblique convergence along the De Geer transform can be resolved into components of transcurrent and convergent motion, respectively parallel and normal to the transform boundary, each of them being active independently. According to this concept, the Hornsund Fault Zone was an almost frictionless interface (Haremo & Andresen 1988). This situation led to the juxtaposition of two subparallel belts: a strike-slip belt developed adjacent to the shear zone, passing eastwards to a compressional fold-and-thrust belt (Nøttvedt et al. 1988b). In an intermediate zone, strike-slip and compressional structures could coexist (Maher & Craddock 1988). Most of the structures relevant to the strike-slip regime are believed to be located offshore or to be represented in the Greenland fold belt (Maher & Craddock 1988; Nøttvedt et al. 1988b).

Influence of a ductile layer at depth on the partitioning of fault motion

Faulting experiments have used physical analogue models (with sand for brittle and silicone putty for ductile behaviour), in order to investigate the development of structures produced in deep-seated convergent wrench zones (Richard & Cobbold 1989). Results show that partitioning of fault movement is favoured when a basal ductile layer exists. In that case, faults which develop in the brittle sedimentary cover, above a reactivated subvertical basement wrench fault, are generated as separated, steep, purely strike-slip faults and gently dipping purely reverse faults. In contrast, with sand only, a flower geometry is formed. In Spitsbergen, the presence of upper Palaeozoic evaporites above the basement, near the base of the post-Devonian strata, has certainly reduced the basal drag and has thus favoured the proposed decoupling. The ductile lower crust probably has played the same role, as suggested by Faleide et al. (1988). In addition, when uplift also is combined with wrenching, experiments show the development of a shifted simple graben in the elevated block (Richard 1990). This could provide an explanation for the origin and for the peculiar inner position of the Forlandsundet Graben (Fig. 3).

A two-stage model

A two-stage model of formation of the West Spitsbergen Orogenic Belt is suggested by the existence of superimposed tectonic structrues in northwestern Spitsbergen. Two distinct directions, 10–20°N and 70–80°N, of the maximum horizontal stress axis, σ_1, may be recognized before the latest extensional events took place.

A wrench-type simple shear mechanism of deformation is suggested to have taken place during a first episode with the development of contemporaneous strike-slip faulting and thrusting. The average regional direction of σ_1 was about 10–20°N, approximately at an angle of 45° to the direction of the palaeotransform trend. During this phase, transcurrent and convergent components of movements could have been partially coupled, but a significant amount of strain was accommodated by strike-slip motion. Deformation was strongly controlled by pre-existing basement faults and occurred preferentially in relay zones, producing either contractional or extensional structures along the westernmost faults. Some amount of strike-slip motion and some related structures could have been initiated along the central-eastern Billefjorden and Lomfjorden Fault Zones. It is suggested that this regime of wrenching was established during the late Palaeocene or even earlier during the late Cretaceous. One must note, however, that the early Palaeocene sinistral movements documented in the Central Basin (Kleinspehn et al. 1989) are not interpreted directly within the framework of this model; they may have a local significance only as suggested by these authors.

During the second episode, the obliquely convergent displacement was preferentially accommodated by dip-slip movements on thrusts faults or by strike-slip movements on transverse faults. The trend of the maximum horizontal stress σ_1 changed to 70–80°N, becoming suborthogonal to the shear zone. This probably was a response to decoupling, itself the result of a decrease in shear stress (Mount & Suppe 1987). The tectonic regime was dominated by pure transverse compression, producing overprinted structures in the western zone and affecting the central eastern zone, giving rise to a foreland-propagating fold-and-thrust belt. Deformation was transmitted eastwards in the sediment cover through detachment structures. The Billefjorden Fault Zone and the Lomfjorden Fault Zone were reactivated as reverse faults. This stage can be dated tentatively as Eocene, as shown in the Central Basin, and also in the Forlandsundet Basin where upper Eocene sediments are affected by transverse compression. This episode persisted until the earliest Oligocene plate reorganization.

Conclusions

The early Tertiary stress distribution and evolution in Spitsbergen are very consistent with the states of stress that develop close to typical active convergent strike-slip faults. Despite the polyphase character of tectonism during Palaeocene–Eocene times the change in the attitude of horizontal maximum principal stress on Spitsbergen does not necessarily imply any change in the relative direction of motion between Greenland and Eurasia (Myrhe & Eldholm 1988). Rather, this evolution may be related to variation of friction along the transform boundary. Accommodation of the obliquely convergent displacement was then achieved through a dominant compressional deformation. With a possible exception of shearing during the first stage, decoupling between the transcurrent and convergent components of motion probably was the rule. This partition was made easier by the presence of ductile horizons at the basement–cover interface.

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