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HISTORY AND TECTONIC DEVELOP-
MENT OF THE FORLANDSUNDET
BASIN, SVALBARD, NORWAY**



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Cover: Selvågen area towards northwest,
west side of Forlandsundet

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EARLY TERTIARY PALEOSTRESS HISTORY AND TECTONIC DEVELOPMENT OF THE FORLANDSUNDET BASIN, SVALBARD, NORWAY.

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Close to the West Spitsbergen margin, the Forlandsundet Paleogene basin is a NNW-SSE fault-bounded elongate and narrow zone, cutting into the pre-Devonian basement. Faulting analysis demonstrates that the graben not only represent a simple tensional feature, formed by downfaulting, but has experienced several episodes of faulting in a complex history of compressional and extensional episodes, marked by the influence of strike-slip to oblique-slip movements and depending of distinct paleostress fields. The sequence of events is as follows:

- Establishment of N20 transpression manifested by dextral lateral movements and as a consequence lengthening of the basin along NNW-SSE marginal faults.

- Clockwise rotation of the horizontal maximum stress component to a N70-80 orientation with a resulting compressional development expressed by strike-slip activity of quasi-conjugate cross-cutting faults, which cause the lateral offsetting of the bounded faults and a noticeable modification of the geometry of the basin.

- NNW-SSE extension, which was in the previous stage associated with the compression, and finally is marked as a distinct episode which overprinted and reactivated different faults and gave to the basin its present-day tensional feature.

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INTRODUCTION

On Spitsbergen (fig.1), Tertiary deposits are mainly preserved in the Central Basin which covers a large surface of the island, south of Isfjorden, and was probably in connection with the Kongsfjorden (Ny-Alesund) subbasin, to the north. Both are interpreted as foreland basins situated E or NE of the Spitsbergen fold and thrust belt by HARLAND, (1969) and STEEL et al. (1985). West of this major deformed zone, in an area of basement uplift, Tertiary formations occur in three other localities; from North to South: Forlandsundet, Renardodden (Kapp Lyell) and Øylandet (Sørkapp) basins.

Close to the present-day West Spitsbergen margin- less than 20km from the continent-ocean boundary, approximatively marked by the Hornsund Fault Zone (MYHRE and ELDHOLM, 1988)- the Forlandsundet Basin (ATKINSON, 1962; 1963) is a fault-

bounded elongate and narrow zone, about 20 km wide, which occupies the strait separating Prins Karls Forland in the West from the mainland (Oscar II Land) in the East (figs 1, 5). This graben-like structure is entrenched and cuts into the pre-Devonian basement along steeply dipping marginal master faults, probably inherited from Caledonian time, which are referred to the Western and Eastern Forlandsundet faults (HARLAND and HORSFIELD, 1974). These faults, which are not strictly linear but composed of segments showing slighty changing trends, run in average NNW-SSE . They parallel the Hornsund Fault Zone and line up the general strike of the Tertiary fold and thrust belt. They are intersected and offset, on Oscar II Land and Prins Karls Forland, by transverse cross-cutting NE-SW and ENE-WSW faults. Such fault pattern is also indicated by morphotectonic submarine features (OHTA, 1982).

The northern and southern terminations of the basin are not known, although NE-SW running oblique faults have been suggested, such as the Isfjorden Fault. Seismic-reflection profiles have revealed (EIKEN and AUSTEGARD, 1987) the existence of similar graben-like geometries, at the inner part of the shelf along the west coast, south of Isfjorden. They are believed to represent an offsetting continuation of the Forlandsundet basin. South of Bellsund, the Renardodden basin also occurs in a similar NNW-SSE tectonic setting (DALLMANN, 1989).

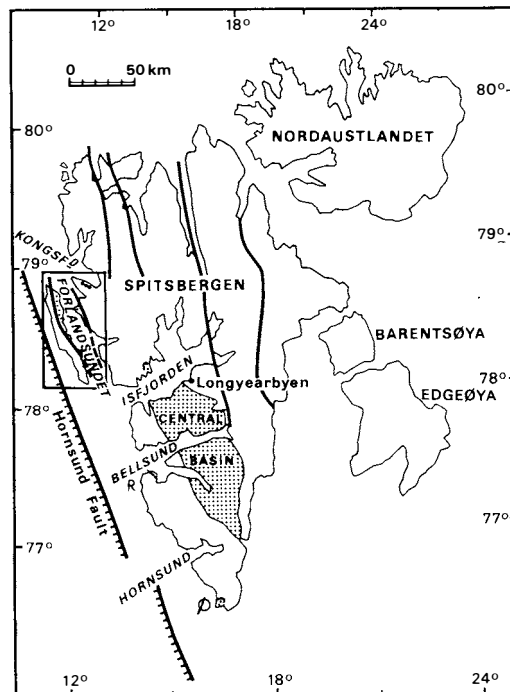


FIG.1- Main fault zones and Paleogene basins on Spitsbergen (dotted areas) with location of the Forlandsundet study area. R: Renardodden basin; Ø: Øylandet-Sørkapp basin.

The main objective of the study was to document the structural development of the basin by means of faulting analysis. The aim was to assess the role of strike-slip components and determine the evolution of paleostress during Paleogene time. An earlier study of RYE-LARSEN (1982) focused on the more sedimentological aspects. Careful observations have been carried out on both sides of the basin and numerous fault-slip data including striated surfaces, joints of different types, calcite-filled fissures, tensional gashes, have been collected in various sites. Detectable offsets have been observed due to mismatching pebbles of conglomerates. The classical criteria of fault analysis described in PETIT (1987) were used to identify the sense of movement and to decipher different episodes of faulting, although preserved superimposed striations were not so frequent. Reconstruction of the stress tensors has been made employing computer programs of ANGELIER (1979, 1984). The preliminary conclusions of this work have been reported (LEPVRIER and GEYSSANT, 1985). However, much more detailed data and illustrations are present in this paper. The method of paleostress stratigraphy recently used in the Central Basin (KLEINSPEHN et al, 1989) was not applicable in the study area because of fragmentary exposure of the sedimentary succession and the lack of precise stratigraphic subdivisions and dating (see below). Therefore, the defined stress tensors concerned the entire sequence.

THE FORLANDSUNDET SEDIMENTARY SUCCESSION

Most of the Tertiary deposits of the Forlandsundet Basin are below sea-level. They crop out, on both sides, in the northern half of the strait and are exposed over a distance of about 50km. These formations are dipping basinwards 15 to 50° and up to vertical along Trocaderostranda. They are in lateral faulted-contact with the basement but this contact is frequently covered by Quaternary deposits. In the SW, a primary basal unconformable contact can be observed: the Selvagen conglomerates rest directly over the Caledonian metamorphic rocks.

The Forlandsundet sedimentary succession displays a thick accumulation of continental to marine clastic sediments, ranging from coarse conglomerates of debris-flow origin to sandstones, siltstones and shales. The cumulative stratigraphic thickness of the sedimentary pile is almost 5km (RYE-LARSEN,1982), with a maximum accumulation against the western marginal fault.

These deposits have been interpreted (RYE-LARSEN, 1982; STEEL and WORSLEY, 1984), as marginal alluvial fan in the Selvagen Fm. at the south western edge and in the Sarsbukta and Sarstangen fms. to the East. They interfinger laterally with fan-delta in the Sesshøgda and Reindhardpynten Fms. Near-shore to shallow-marine sediments are present in the Krokodilen and Marchais Laguna Fms. Submarine fans in the Aberdeenflya Fm. occupy occupying the northern axial zone of the basin.

The Forlandsundet sedimentary sequence, named the "Forlandsundet Group" (HARLAND, 1969), is thought to be equivalent or even younger in age than the uppermost formations preserved in the Central Basin (ORVIN,1940; ATKINSON,1962; 1963; HARLAND,1969). Age estimates are Eocene to Early Oligocene (MANUM, 1962; LIVSHITS, 1974), but the age of the youngest strata is still disputed (FEYLING-HANSEN and ULLEBERG, 1984). Foraminifera assemblages contained in the Sarsbukta Fm. indicate an Oligocene age. However, new biostratigraphic evidence, based on Dinoflagellatae in the Sarstangen Fm., are in favour of a Middle to Upper Eocene age for the entire sequence (MANUM and THRONDSSEN, 1986). In spite of this uncertainty regarding the age of the youngest sediments, it appears that the post-Early Oligocene deposits are only to be found in the offshore basins predominantly floored by oceanic crust, west of the Hornsund fault zone (SCHLÜTER and HINZ, 1978; STEEL et al., 1985).

THE ORIGIN OF THE BASIN.

Whereas the Central basin represents a foreland basin relatively to the east-vergent Spitsbergen fold and thrust belt, the Forlandsundet basin appears as an asymmetric trough of graben-type bounded by high angle dip-slip marginal faults.

The tectonic setting has led to the suggestion that the formation of the basin was simply due to downfaulting, although HARLAND (1969) envisaged that the graben could be bounded by strike-slip faults or that a rift basin developed above a deeper transcurrent zone. The Forlandsundet Basin was then earlier believed to be a late-tectonic structure with respect to the main phase of folding and thrusting of the Tertiary orogeny (HARLAND and HORSFIELD, 1974; KELLOGG, 1975). Similarly, BIRKENMAJER (1972; 1981), suggested that the Forlandsundet basin represents an intramontane rift valley subsequent to the main deformation. More recently, OHTA (in MAHER and CRADDOCK, 1988) estimated that the eastern border fault of the Forlandsundet Basin postdates the main compressional tectonics, since the fault truncates fold structures in adjacent Carboniferous strata. Kinematics of opening of the northern Greenland Sea after anomaly 13 time - Eocene-Oligocene boundary (TALWANI and ELDOHLM, 1977) - with the resulting installation of a transtensional rift regime, as well as the lack of precise stratigraphical data, render such interpretation plausible.

However, as pointed out by STEEL et al. (1985), the fact that the Tertiary succession in the graben is slightly deformed, proves that the basin developed prior to or during the last deformational phase. Fault analysis and paleostress reconstruction have already demonstrated (LEPVRIER et GEYSSANT, 1985), that the basin did not develop in a simple tensional regime but has experienced several periods of faulting, including both compressional and extensional episodes. The post-tectonic aspect of the graben is only the consequence of the latest extensional phase. Before, the basin has been subjected to the same phase of suborthogonal compression which produced fold and thrust structures in the adjacent belt and also affected the Spitsbergen island far to the East. Moreover, a strike-slip activity with a dextral sense of motion along NW-SE to N-S faults has been evidenced in the basin as a first faulting event (LEPVRIER and GEYSSANT 1985), although frequently obscured by later extensional movements. According to STEEL et al. (1985), the Forlandsundet probably formed from a collapse of the crest of the orogenic belt or from extension adjacent to a curved strike-slip fault zone. In the same way, LEPVRIER and GEYSSANT (1985) and LEPVRIER (1988) envisaged a pull-apart mechanism of formation: the basin generated as an extensional relay zone between two right-stepping dextral wrench faults.

This view has received support from sedimentological studies which also challenged the hypothesis of entirely post-tectonic development of the basin. These studies clearly indicate the influence during deposition of lateral movements along marginal faults. Such strike-slip fault activity explains cumulative stratigraphical thickness of the sequence, high sedimentation rate, as well as the observed facies sedimentological pattern. All these features indicate that the basin developed as a southerly migrating trough in an oblique structural setting (STEEL et al. 1981; RYE-LARSEN, 1982; HJELLE and LAURITZEN, 1982; STEEL and WORSLEY, 1984). Sediment infilling is thought to have started in Late Paleocene in the northern part and migrated southwards mainly during Eocene.

FAULT DEVELOPMENT AND PALEOSTRESS SUCCESSION.

Fault analysis and paleostress determination reveal that the tectonic development of the basin is polyphase. Relative timing of the stress tensors are settled with certainty.

Within the Paleogene deposits, two orientations of the maximum horizontal stress component σ_1 , shifting from NNE-SSW (azimuth N20) to ENE-WSW (azimuth N70-80) and corresponding to transpressional (wrench) and compressional regimes, have been discriminated. Fault activity is essentially expressed by strike-slip movements. During the first event, NW-SE to N-S faults were mobilized in a dextral sense. The second compressional episode was marked by movements on quasi-conjugate N30-50 dextral and N80-110 sinistral strike-slip faults. Such succession of events has also been observed locally along the eastern Forlandsundet Fault, for example in Dahltopp (East of Sarsbukta section): N150-180 fault-surfaces affecting Hecla Hoek metamorphic limestones and showing dextral movements are cut and displaced laterally by N20 dextral and N95-120 sinistral fault systems, depending of distinct stress conditions.

As a consequence of these two successive regimes of strike-slip faulting, two orthogonal and subordinate directions of extension are associated with the directions of compression. These two distinct directions of the minimum horizontal stress component σ_3 are materialized by two systems of tensional gashes with calcite infilling, N0-30 and N60-80, which can be observed preferentially in the Tertiary shaly formations. The NNW-SSE to N-S extension finally gave rise to a prevailing and distinct episode which clearly postdates the two transpressional and purely compressional stages. This latest event is essentially manifested by oblique-slip movements on previous strike-slip faults and rarely by purely dip-slip striations on newly formed normal faults. The approximately E-W extension, induced by the N20 transpression (by reference to the NNW-SSE trend of the paleotransform), also exists as a distinct event. It is however, generally difficult to separate this first extensional stage from the final phase of extension.

1-N20 transpressional event (figs 2, 3)

Within the Tertiary succession, this wrenching regime has only been detected on the western margin of the basin and in different sites. Preserved horizontal striae, also noted by STEEL et al. (1985) as a result of a N60W contemporaneous extension, are locally visible. From North to South:

- in the Aberdeenflya Fm. (from Carmichaelpynten to Mac Vitiepynten, along the coast line), the layers which strike N-S to N20W and dip 35-40° eastwards are intensively affected by two sets of N160-180 and N15-35 fractures, both dipping 50-80° westwards, probably as a consequence of a later tilting of the beds (Carmichaelpynten site, fig.3 top). Clear brittle shear zones are visible, limited by purely dextral strike-slip faults forming the first set, N50 sinistral faults being less frequent. The other N15-35 set probably represents Riedel-type fractures which are however frequently seen as normal-sinistral and then indicate a following episode of oblique extension (see fig.6, Mac Vitiepynten site).

- in the Marchaiselaguna Fm., around Marchais Laguna where beds are oriented N125-155 and dip 30-35° basinward, sandstones are densely cut by NW-SE to N-S trending set and by W-dipping striated fractures which show right-lateral movements in relation with a N20 direction of compression. Nice shear zones marked by Riedel fractures can be observed in the vicinity of Innerodden (fig.2, left). Comparable observations have been made in equivalent white sandstones present at the bottom of Krokodilen (fig.3, middle): in addition to N-S dextral strike-slip faults, N40-55 sinistral to reverse faults can be observed, both related to the same N20 maximum horizontal stress σ_1 .

- along Sessflya (fig.2, right and fig.3, bottom), the same stress regime is manifested by an echelon arrangement of N20-30 tensional gashes along N05 dextral and N55 sinistral directions. Veins of calcite parallel to this direction were reactivated in a dextral sense by a later ENE-WSW compression.

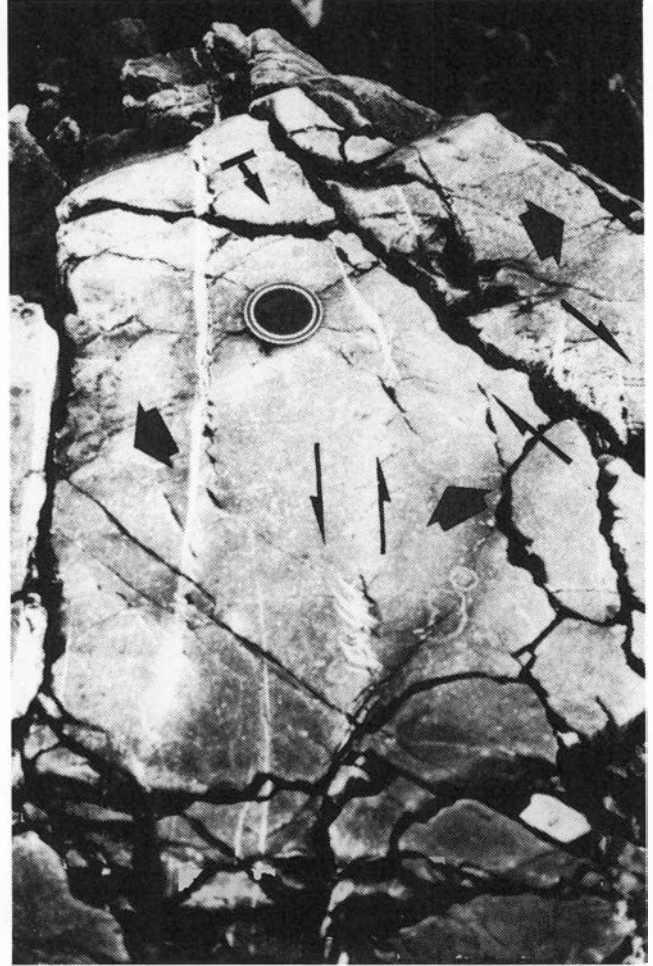
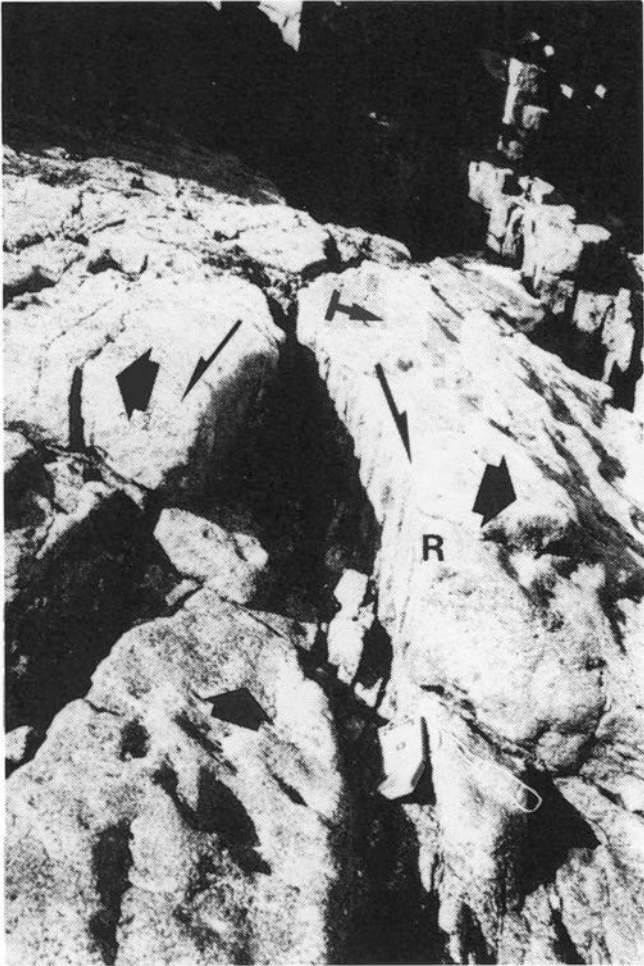


FIG.2- Illustrations showing strike-slip structures related to the N20 tranpressional episode. (Innerodden, West Forlandsundet). Convergent black arrows indicate the direction of compression, divergent ones the direction of subordinate extension.

Left: Plan-view of brittle shear zone developed in sandstones layers (azimuth 005, dip 25E). Note the dextral shear, N148 oriented, associated with the en échelon Riedel fractures (R), trending N173.

Right: Upper surface of a bed (azimuth 120, dip 32N), showing two conjugate sets of sigmoidal tension gashes striking N30 in average, with N05 dextral and N55 sinistral arrangements. Note on the left side of the picture the opening of calcite veins along the N55 trend in relation with the subordinate extension. N.B.- this vein is also affected by dextral striae- not visible on the document- which correspond to a reactivation during the following N70-N80 compressional stage.

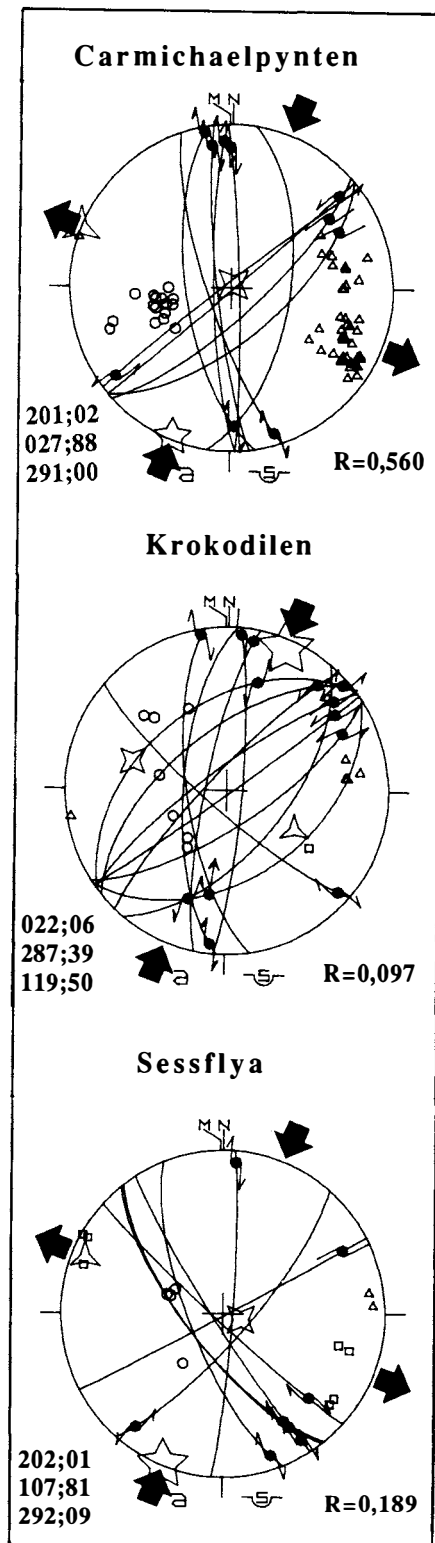


FIG.3- Diagrams related to the first episode of faulting documented along the western edge of the basin and indicating a paleostress field characterized by a N20 maximum horizontal compressive axis.

Legends of diagrams: Schmidt's projection, lower hemisphere, of strike-slip faults with striae (double arrows) and computed paleostress; maximum compressional stress: 5-arm asterisk, minimum stress: 3-arm asterisk, intermediate: 4-arm asterisk; $R = (\sigma_1 - \sigma_2) / (\sigma_1 - \sigma_3)$, also visualized by the relative size of the asterisks; small circles: bedding poles, small squares: poles of tension gashes, small triangles: poles of joints. Large convergent and divergent arrows indicate resulting direction of compression and extension. Azimuth and plunge of the tensor axes σ_1 , σ_2 , σ_3 are given on the bottom left of each diagram; R value is noted on the bottom right. See fig.5 for location.

2- N70 80 compressional event. (figs 4, 5)



FIG.4- Illustration of the ENE-WSW (N70-80) compressional episode (west side of the Forlandsundet).

Top- Rottenburgpynten-Murraypynten area: offsetting of pebble in conglomerates (Selvagen formation), cut and displaced left-laterally by a set of N88 subparallel strike-slip faults.

Bottom- Reinhardpynten- Selvagen area: conjugate strike-slip faults, N52 dextral and N90 sinistral, with steps of calcite (white), developed in slaty formation.

See also diagrams in Fig.5.

This event was responsible for the basinward dip of the Tertiary strata; it gave a general synform structure to the graben. A well-defined direction of the maximum horizontal stress axis σ_1 - comprised between 70-80 in azimuth - has been reconstructed essentially from quasi-conjugate strike-slip faults affecting the Tertiary deposits. Deformation related to this compressional phase is similar on both sides of the graben. Rarely tight folds or thrust-faults comparable to those produced in the adjacent belt can be recognized. A slight dip-slip component of movement towards the axis of the basin can be observed at some sites, conformable with the dip of the layers; this demonstrates that strike-slip faulting preceded the tilting and constituted the earliest stage of deformation under this stress regime.

eastern flank of the basin:

Along the eastern edge of the basin the alluvial fan conglomerates of the Sarsbukta-Sarstangen Fms., are clearly affected by two sets of strike-slip faults. In the area of Sarsøyra, near Kapp Graarud and Nyflua, a set of N35-70 dextral and another one N100-130 sinistral, steeply dipping to the S and the N respectively, are present, with striae showing a fairly important normal component westwards, caused by the later tilting of the strata (fig. 5). Pebbles of the conglomerates are cut and display a lateral offset of about 1-2 cm. The faulted contact of the Tertiary strata with the basement is at Kaap Graarud expressed by a N130 sinistral fault active during this episode.

In the Sarsbukta section itself (stream running along the northern moraine of Aavatsmarkbreen), similar sets of faults also exist but extension (NW-SE to N-S, the latest one) is generally dominant, marked on them by oblique to normal striae (see Sarstangen site, fig.6).

western flank of the basin:

On this side of the basin, the same stress pattern has been evidenced in several localities.

- Between Rottenburgpynten and Murraypynten a N75 direction of σ_1 has been determined, from the existence of two sets of transverse (with respect to the general trend of the basin), strike-slip faults. Some pebbles of the conglomerates are intersected and displaced laterally (photo fig.4 , bottom).

- Along Sessflya, the Reinhardpynten Fm., also provides a very good illustration of the same stage of stress, expressed as usual by a prominent system of left and right-lateral strike-slip faults underlined by steps of calcite (photo, fig.4 top). Tensional gashes, striking N60-70, with a double en echelon arrangement, are also well-developed in this black shaly formation. Locally a synsedimentary vein of sandstone within the shales, N100 oriented, has also been reactivated in a sinistral sense during this phase, as indicated by the steps of calcite present on its flanks.

3 ESE-WNW and NNW-SSE to N-S extensional phases (fig.6):

Faults related to each of these extensions are sometimes rather difficult to discriminate.

The final NNW-SSE to N-S extension is of course easier to distinguish, particularly when manifested by oblique to dip-slip movements on the two sets of previous strike-slip faults. Associated with the ENE-WSW compression, this extension finally becomes a distinct event. Several examples on both sides of the graben provide convincing evidence of this succession; for example in Marchais Laguna site, N60-75 and N95-115 faults which transect NW-SE to N-S faults, show oblique striae towards west which are therefore not due to tilting but to a N167 direction of extension. (see diagram on fig. 6).

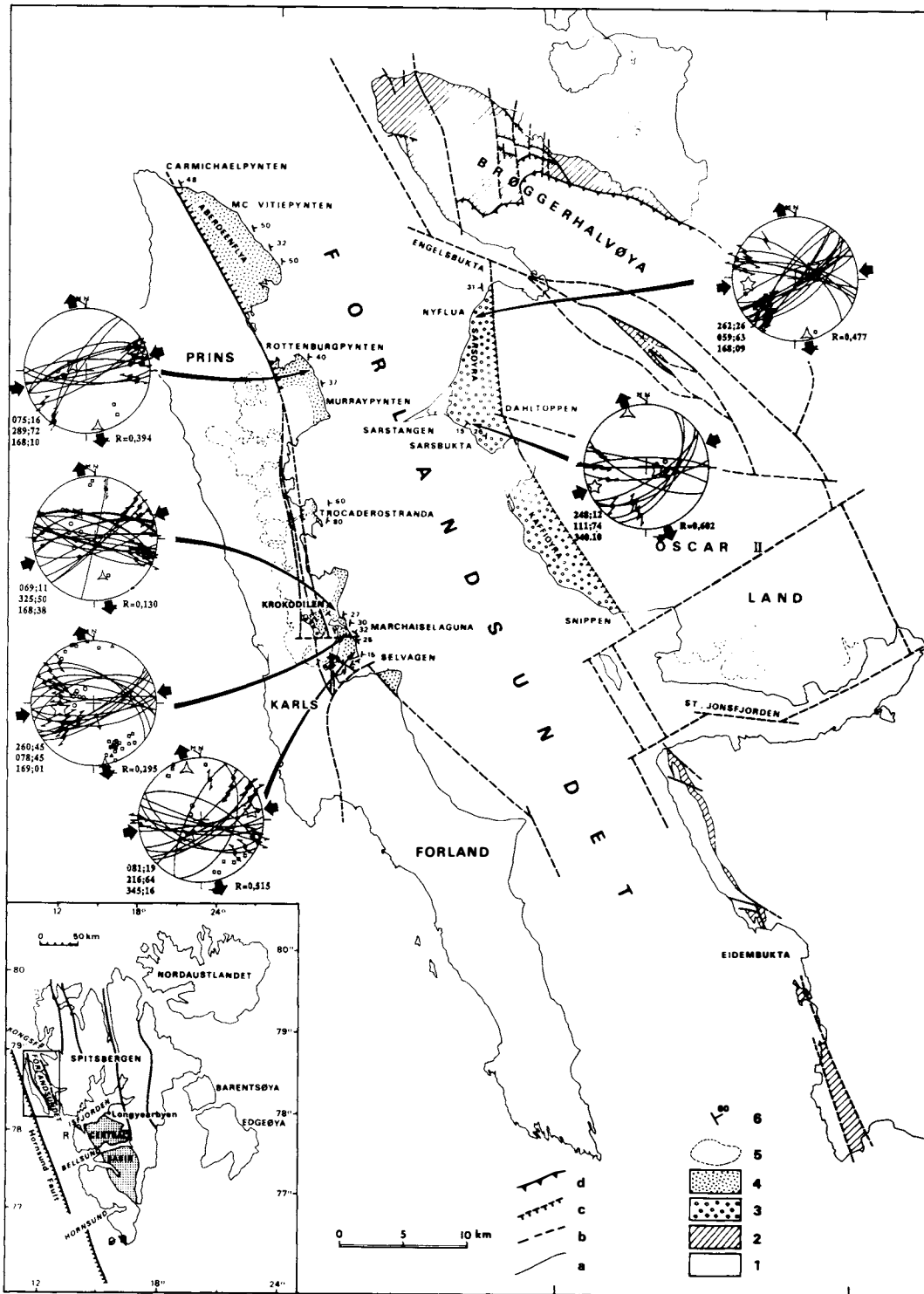


FIG.5- The N70-80 compressional episode in the Forlandsundet basin: diagrams related to different sites within Tertiary deposits. Legends of diagrams as for Fig.3. Note that this event is essentially expressed through strike-slip faulting along two transverse, quasi-conjugate sets of faults; pitches of striae are generally basinwards as a consequence of progressive tilting of the layers during the same episode. Note also the tendency to reactivation of previous strike-slip faults into oblique-slip ones (normal-dextral or normal-sinistral), as a result of the NNW-SSE extension becoming dominant.

1: basement; 2: upper Paleozoic; 3: Paleogene deposits, Selvagen Formation; 4: other Paleogene deposits; 5: limits of the main glaciers; 6: strike and dip of the Tertiary layers; a: stratigraphical contact; b: faults undifferentiated; c: present-day normal boundary faults; d: thrusts faults.

In rare cases (Selvagen area) it has been possible to see overprinted striae on the same fault-plane, or to observe on different fault-planes of the same attitude, a progressive evolution of the dip of the striae from purely strike-slip to oblique and dip-slip. This seems to reflect a progressive change in the stress conditions instead of a simple permutation between σ_1 and σ_2 (as revealed by the R value in the Selvagen site, σ_1 and σ_2 are not so close to one another to allow such a permutation). The NW-SE to N-S extension causes also renewed movements in an oblique way on the previous NW-SE dextral faults: this explains why the marginal faults of the basin are presently normal faults.

The WNW-ESE extension is also well-documented (fig.6), alternatively marked by oblique-slip or dip-slip movements (Snippen, Peter Winterbukta sites), also with evidence of oblique-normal movements on very low-angle dipping fault-surfaces (Reinhardpynten).

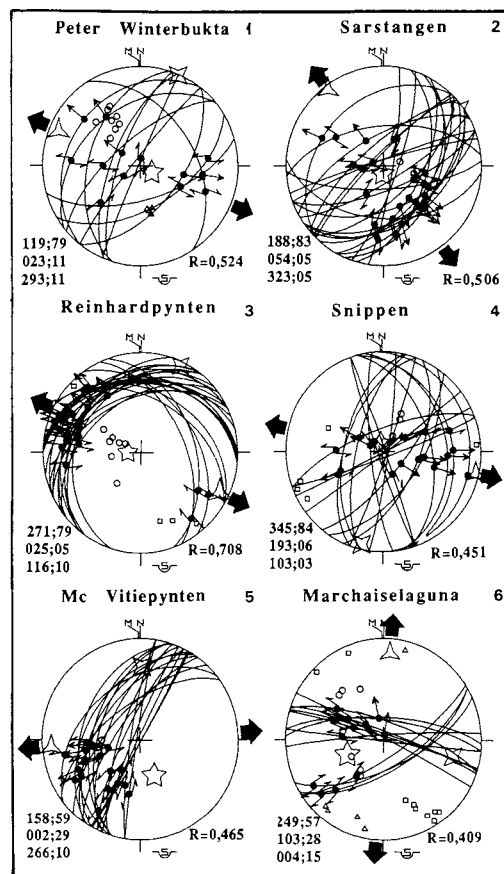


FIG.6- Different aspects of extension affecting the Tertiary deposits in the Forlandsundet basin.

- The latest NNW-SSE to NS event is clearly expressed (site 6, Marchais laguna), by oblique to normal striations which correspond to a reactivation of previous transverse strike-slip faults. (see in comparison diagrams of fig.5).

-The WNW-ESE extension is similarly marked (site 5, Mc Vitiepynten), by normal-sinistral movements on NNE-SSW faults wich are believed to represent previous dextral Riedel fractures active during the first transpressional episode. The same extension is also manifested by low-angle normal faults (site 3, Reinhardpynten) or by oblique-slip to normal-slip on faults of various attitudes (sites 1 and 4). In site 2, a combination of fault-movements relative to the two extensional events cannot be excluded.

SUMMARY AND CONCLUSIONS.

Detailed faulting analysis and paleostress reconstructions have shown that the Forlandsundet basin is not a simple tensional area of post-tectonic origin, but has developed through a complex succession of changing stress regimes: (1) transpression, (2) purely orthogonal compression which are both essentially manifested by strike-slip movements). Each of these compressional events were associated with, and then followed by, extensional episodes. Confirming the sedimentological evidence, these structural investigations undoubtedly prove in particular the role played by strike-slip movements in the initial phase of development of the basin. They also demonstrate, even if deformation remained weak, that the basin has suffered the same orthogonal N70-80 compression which gave rise, east of this area, to the major structures of the Spitsbergen fold and thrust belt, affected the Central basin (KLEINSPEHN et al. 1989) and produced notable effects far to the East by a mechanism of thin-skinned tectonics.

The basinal evolution is characterised by the following succession of stages:

- Instauration of a N20 regime of transpression and, consequently, dextral strike-slip generation of the basin along NW-SE to NNW-SSE inherited marginal faults. The basin originated and developed as a pull-apart, possibly in a releasing zone between two right-stepping segments. A subsequent orthogonal extension is associated with this first episode. Slivers of Upper Paleozoic rocks are believed to have been emplaced along the eastern border of the basin by such a mechanism of strike-slip faulting. This suggestion is supported by the existence of drag folds (Svartfjella, Eidembukta areas), squeezed and refolded later on, during the second compressional episode.

- Change to orthogonal compression oriented N70-80. As a result of clockwise rotation of the maximum compressional stress σ_1 , shifting from NNE-SSW to ENE-WSW, the basin geometry was modified and complicated: transverse strike-slip faults, probably also inherited from the basement, caused the lateral offsetting of the major boundary faults.

- Final NNW-SSE to N-S extension which was subordinate to the compression in the previous stage, and then became dominant. This last episode overprinted and reactivated the preexisting structures, in particular the bounded faults: the basin became a tensional structure and appears now as a simple graben.

This history can be compared with paleostress stratigraphy data obtained from the Early Paleocene to Eocene Central Basin and from the immediate Cretaceous strata (KLEINSPEHN et al. 1989). The same succession of events has been found: dextral transpressive regime; and N70-75 compressive regime, the later interpreted as coeval with climax of folding and thrusting in the deformed zone between the two basins; and finally extension (not well-defined in orientation) also correlated with the phase of rifting between Greenland and Spitsbergen. However, in addition, a new sinistral tectonic regime of Early Paleocene age has been recognized, the dextral transpressive considered to be of Late Cretaceous. In Forlandsundet, it is not impossible that dextral transpression was also established as early as Late Cretaceous period. In spite of the uncertainty as to the age of the sequence, this stress regime seems to have continued at least until Late Paleocene-Early Eocene. The sinistral regime, which is not recorded in the Forlandsundet area, could have been manifested only locally.

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