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# The Tertiary and Cretaceous of Spitsbergen and North Greenland: Its Alpine Signature

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THEME: 6: Eurekan Tectonics in Canada, North Greenland, Spitsbergen; Fold Belts adjacent to Extensional Ocean Basins

**Summary**: The results of the CASE-1 and CASE-2 expeditions permit the Alpine history of Spitsbergen to be compared with that of North Greenland. As far as sediments are concerned, the Tertiary basin sequences of the two regions have much in common, e.g., lithology, high sedimentary maturity, coal intercalations, and thin bentonite interlayers characterized by the presence of jarosite. However, the bimodal Cretaceous/early Tertiary volcanism of North Greenland has no equivalents on Spitsbergen, and the low-maturity, Tertiary graben sediments known on Spitsbergen are missing in North Greenland.

The tectonic history of the two regions shows some differences. On Spitsbergen only one Alpine tectonic event is clearly discernible, namely in the Eocene. In contrast, in North Greenland it is very likely that there were two events: 1) a Late Cretaceous/Early Palaeocene event affecting large areas adjacent to an old stable area on the northern to northeastern margin of the Greenland shield and 2) Tertiary deformation of the Kap Washington Group in northernmost Greenland. The two events are characterized by different fold vergences. The vergence of the older deformation was predominantly towards the stable area in the south and the younger deformation was to the north. The vergence of the younger event shows close analogies with that on Spitsbergen, which is towards the foreland ENE of the West Spitsbergen Fold-and-Thrust Belt. On Spitsbergen, the indistinct en-echelon arrangement of synclines and anticlines suggests a weak dextral strike-slip component during the dominant compression during the Alpine orogeny.

## INTRODUCTION

This paper presents the author's view of results of expeditions organized by BGR to Spitsbergen (CASE-1, 1992), and North Greenland (CASE-2, 1994). The study areas are located on opposite sides of the northern North Atlantic (Fig. 1). Cretaceous and Tertiary sequences in northernmost Greenland and on Spitsbergen will be discussed under sedimentological and structural aspects, particularly their Alpine structural features and Alpine tectonic history. Both the common features of the two regions and the differences will be mentioned.

## LITHOLOGICAL AND STRATIGRAPHIC CHARACTERIZATION OF THE TERTIARY AND CRETACEOUS SEQUENCES

On Spitsbergen, the Tertiary deposits (BIRKENMAJER 1972, HARLAND 1997) can be subdivided into two types: basin sediments and graben sediments (Fig. 2). The basin sediments (Van Mijenfjorden Group) of high sedimentary maturity accumulated in a broad depocenter, the Central Basin ENE of the West Spitsbergen Fold-and-Thrust Belt, stretching from Isfjorden to Bettybukta. There are isolated remnants in the Ny-Ålesund and Øyrlandet areas. The Van Mijenfjorden Group of the Central Basin is composed of sandstone-dominated sequences (details in Tab. 1) that alternate with siltstone-dominated sequences (Frisjaodden and Basilika Formations). Coal seams are present, particularly in the Firkanten and Aspelintoppen Formations. The base of the Tertiary consists of one or two conglomerate beds, each up to 1.6 m thick. The pebbles are mostly rounded and mainly 5 cm (max. 10 cm) in size. They comprise highly resistant rock types such as cherts from the Kapp Starostin Formation (Permian) and vein quartz. In general, the Tertiary Central Basin sequences above the conglomerate also display a high sedimentary maturity. Rare, yellowish bentonite interlayers (GRIPP 1927) up to 5 cm thick are present in the lower and middle parts of the Van Mijenfjorden Group (Tab. 1). They contain jarosite, which is responsible for the yellowish colour. In the Central Basin the Tertiary strata are underlain by Lower Cretaceous sediments. Upper Cretaceous strata, including Upper Albian, are missing. The total present thickness of the Tertiary attains almost 2 km in the northern part of the Central Basin. Judging from the coal rank data (mostly varying between 0.5-1 % vitrinite reflectance), the thickness of Tertiary rocks removed by erosion is estimated to be 1.7 km in the north and about 3 km in the south (PAECH & KOCH in press). Lithologically, Tertiary outcrops of the Ny-Ålesund area in the north and of the Øyrlandet area in the south are comparable with the sediments of the Central Basin. However, in the Ny-Ålesund area the Tertiary is underlain by Triassic and Permian sediments and in the Øyrlandet area the age of the underlying rocks is unclear.

In the Central Basin, Tertiary sedimentation began (Tab. 1) in the Palaeocene (e.g. ČEPEK, in press) and continued in the Eocene (MATTHIESSEN 1986, MANUM & THRONDSEN 1986). The presence of Oligocene sediments has not been confirmed biostratigraphically; however, it cannot be excluded.

On the other hand, sedimentologically immature Tertiary sediments with a large proportion of psephitic material accumulated in grabens, such as the Forlandsundet graben (RYE-LARSEN 1982, DALLMANN et al. 1995) and probably in equivalent grabens (EIKEN & AUSTEGARD 1987) to the SSE in offshore areas (Fig.2). The uppermost Tertiary formation is Late Eocene in age (ČEPEK, in press). Immature sediments also occur as erosion remnants at Renardodden (Calypsobyen; THIEDIG et al. 1979), where, they unconformably overlie the Caledonian basement.

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In North Greenland, lower Tertiary sediments are almost completely restricted to outcrops in the vicinity of the Danish Station „Nord" and the adjacent islands (Fig. 3). On the islands they comprise more than 200 m of psammites and intercalated pelites belonging to the Thyra Ø Formation; they have a high sedimentary maturity. Coal seams of low coal rank (about 0.55 % vitrinite reflectance) and very thin (less than 2 cm), yellowish bentonite interlayers containing jarosite are present. Judging from the coal rank data, the original Tertiary sequence was not as thick as in the Central Basin of Spitsbergen. No marine interlayers were found during the CASE-2 Expedition. Furthermore, in the Depotbugt area (Fig. 3) a local occurrence of Tertiary shales containing lignite fragments is known (CROXTON et al. 1980).

In North Greenland, Upper Cretaceous sediments are present (HÅKANSSON & STEMMERIK 1989) in two areas along the Harder Fjord fault zone (Frigg Fjord area and east of Depotbugt), in Herluf Trolle Land in the Wandel Hav basin (HÅKANSSON & STEMMERIK 1989), and southeast of the Tertiary occurrences in the Kilen area (HÅKANSSON et al. 1981) (Fig. 3). The youngest marine Cretaceous sediments substantiated by marine fossils are Santonian (HÅKANSSON et al. 1981). As yet, no marine Campanian and Maastrichtian fauna has been found; only poorly preserved pollen are known from sedimentary intercalations in the Kap Washington Group (BATTEN 1982). The coal rank of the organic matter in Cretaceous sediments is high, mostly more than 1 % vitrinite reflection, locally attaining 3 %. In the Depotbugt area the high rank


**Fig. 1**: Location of the study areas on both sides of the northern North Atlantic.

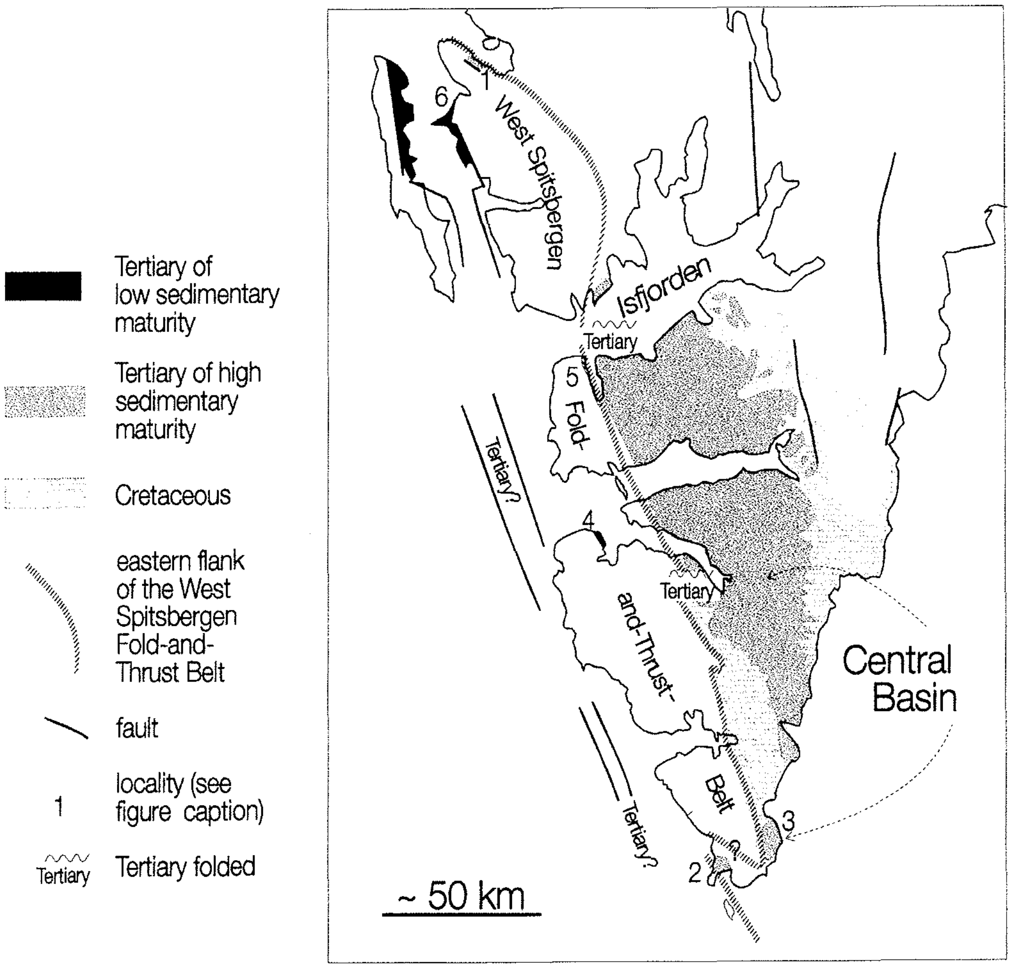



**Fig. 2:** Tertiary occurrences on Spitsbergen (1: Ny-Ålesund, 2: Øyrlandet, 3: Bettybukta, 4: Renardodden/Calypsobyen, 5: Grønfjorden, 6: Forlandsundet).

Cretaceous sediments probably are overlain by Tertiary shales of very low coal rank (lignite rank CROXTON et al. 1980, i.e., less than 0.5 % vitrinite reflection).

In the Frigg Fjord area, basaltic dykes intruded in the Upper Cretaceous and were affected by subsequent folding (ESTRADA 2000). Volcanic rocks occur in the region of Kap Washington (Fig. 3) in the northernmost part of North Greenland (Kap Washington Group, DAWES & SOPER 1970). They are composed of bimodal lavas and pyroclastic rocks of acid and basic composition and are inferred to be Cretaceous in age. However, radiometric data indicate an early Tertiary age (Rb-Sr 64 ±3 Ma, LARSEN 1982, ESTRADA et al. 2001). Most likely, basic magma was intruded prior to this subaerial volcanism.

## TECTONIC CHARACTERIZATION OF TERTIARY-CRETACEOUS SEQUENCES ON SPITSBERGEN

On Spitsbergen Palaeogene rocks onlap directly onto Lower Cretaceous strata (BIRKENMAJER 1972, NAGY 1970); they are separated by a gap of at least 30 Ma for which the sedimentary record is lacking. In the field, the two sequences show an apparently concordant relationship. However, a very low angular discordance of less than 1° between Tertiary and Cretaceous strata can be deduced by observing the southward younging of the Cretaceous subcrop strata below the overlying Tertiary sequences (BIRKENMAJER 1972, PAECH, in press) over a distance of more than 100 km. Thus, the absence of Upper Cretaceous sediments (including Upper Albian) is probably the result of weak upward tilting of the source area in the north and the adjacent part of the Central Basin, which underwent erosion. Therefore, the Ny-Ålesund Tertiary rests on older, i.e., Triassic to Permian, sediments than in the Central Basin. No compressive structures formed during this Late Cretaceous time gap could be identified with any degree of certainty (PAECH, in press).

The structures in the Tertiary rocks have been described together with the Alpine West Spitsbergen Fold-and-Thrust Belt by DALLMANN (1992), DALLMANN et al. (1993) and summarized in HARLAND (1997). The Tertiary structures are also described by PAECH (in press) and summarized below.

The Tertiary strata adjacent to the fold-and-thrust belt (GOSEN et al. in press, PAECH in press) were involved in the folding, as is clearly recognizable on the west coast of the Grønfjorden (Fig. 4). In this area, the lowermost Tertiary occurs in the core of a small syncline which plunges gently to the north. This Tertiary core was affected by minor thrusts, some of which are along the bedding of ductile pelitic interlayers and coal seams. These bedding-parallel (within-sequence) thrusts played an important role in Cretaceous strata that underlie the Tertiary in the shallow southern part of the syncline core. Further south, the Cretaceous succession was tightly folded owing to the predominance of pelites. The structure is difficult to unravel

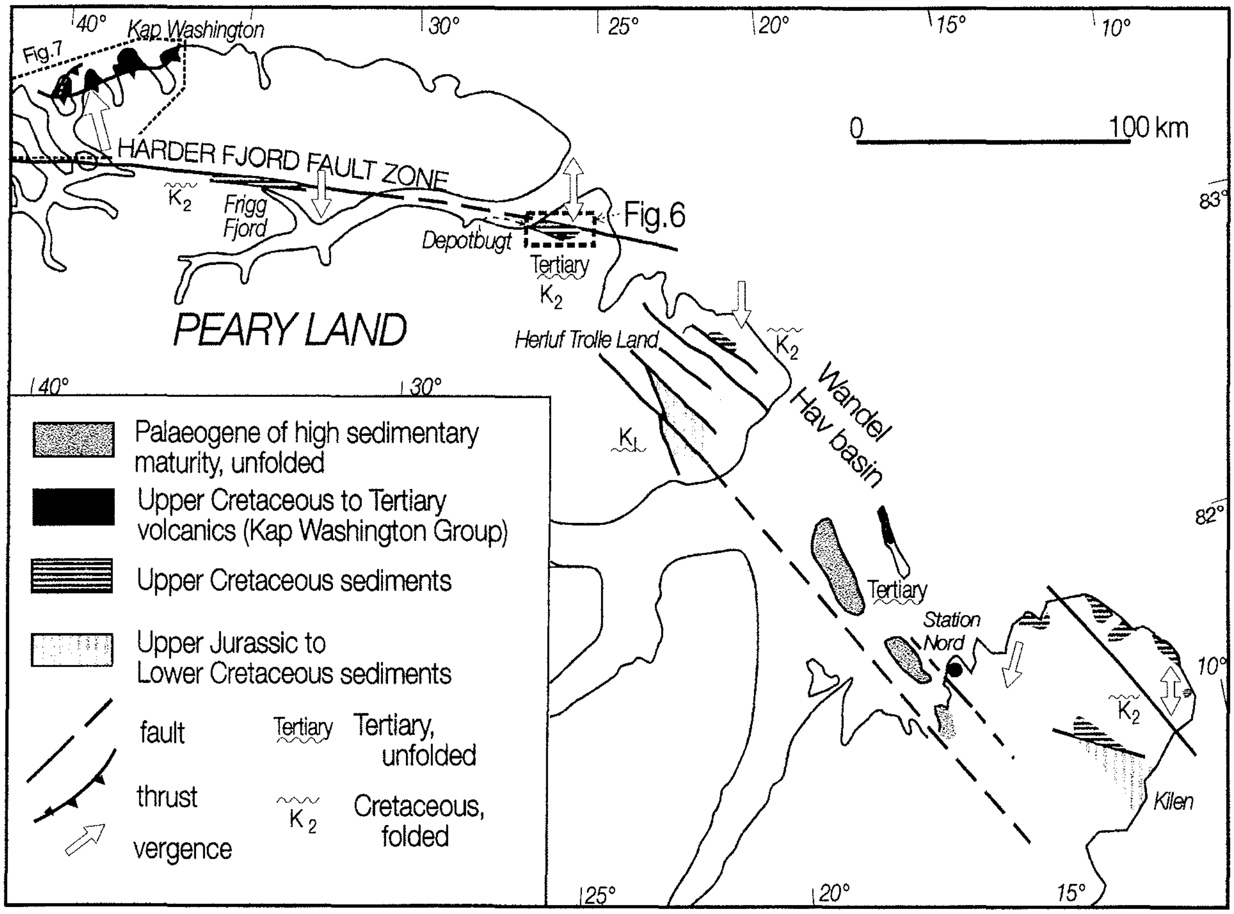



**Fig. 3:** Geological sketch map of the Mesozoic to Tertiary sequences in North Greenland (for location see Figure 1, Geology according to Geological Map of Greenland, Sheet 8, Peary Land, scale 1:500 000, GGU 1984).

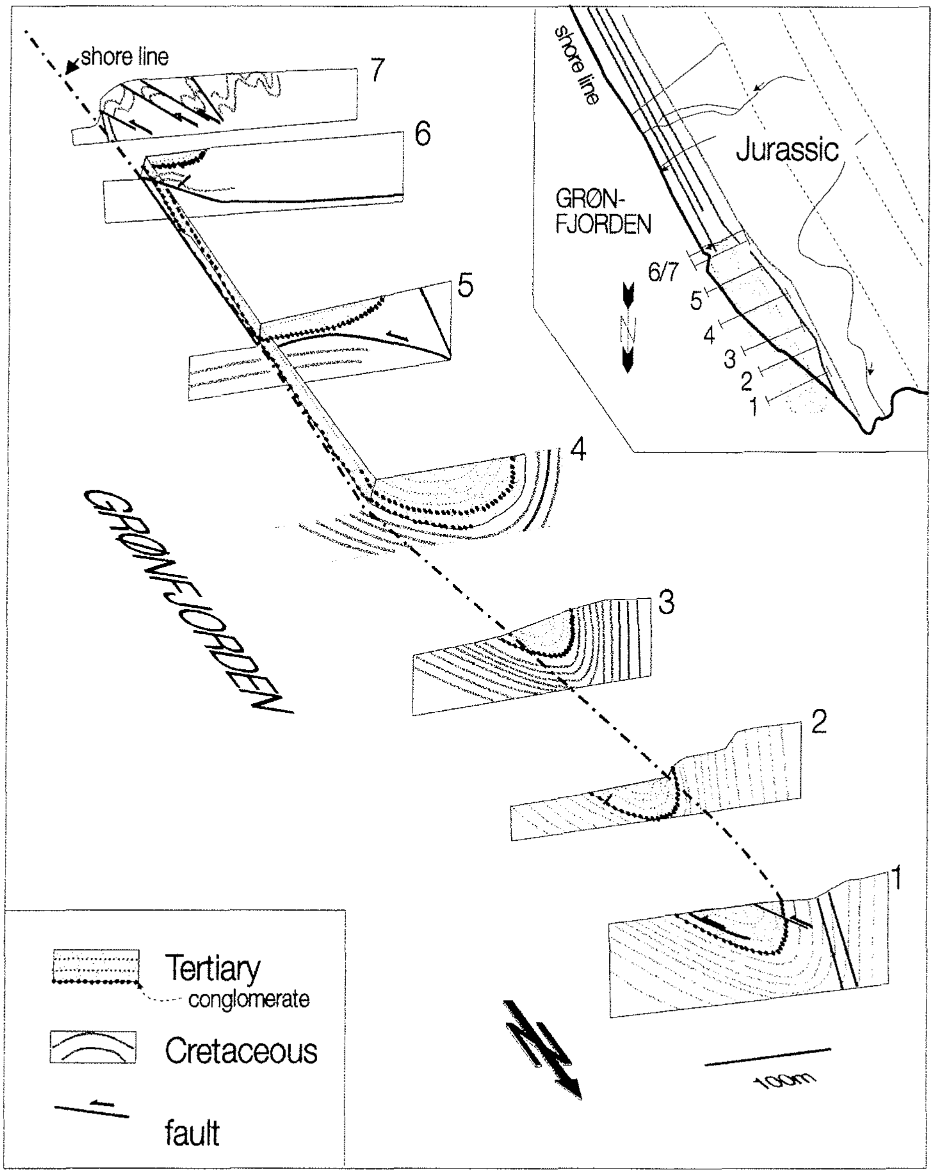



**Fig. 4:** Geological fence diagram along the west coast of the Grønfjorden (for location, see Fig. 2, site 5).

due to the poorly defined lithostratigraphic boundary between Cretaceous and Tertiary sediments. On the west side of Grønfjorden, the base of the Tertiary cannot be defined only by the occurrence of the thin Tertiary conglomerate interlayers as usual, because in the Grønfjorden area (Fig. 4) at least two impersistent, locally overlapping conglomerate layers occur within an arenaceous succession.

The pelitic Tertiary strata in the Central Basin, including those far from the fold-and-thrust belt often show cleavage. The entire Tertiary succession is folded into a syncline up to 50 km wide, known as the Central Syncline, east of the West Spitsbergen Fold-and-Thrust Belt. It contains smaller synclines and anticlines and gentle undulations (Fig. 5). Thus, the Tertiary sequence was more ore less entirely involved in the Alpine compression (PAECH, in press). The axes of these folds show an indistinct en-echelon pattern oblique to the West Spitsbergen Fold-and-Thrust Belt. Two subordinate synclines in the Central Syncline also display an en-echelon arrangement. (Fig. 4). Moreover, the Tertiary occurrences that form gentle synclines near Bettybukta (Betty Bay) are arranged en-echelon along the western margin of the Central Syncline. This en-echelon arrangement is also seen in the trend of individual folds running at an acute angle off the West Spitsbergen Fold-and-Thrust Belt into the Central Syncline where they shallow and finally die out (Fig. 5). The main deformation of the West Spitsbergen Fold-and-Thrust Belt is inferred to have taken place in Tertiary time.

The Ny-Ålesund Tertiary is overthrust by Permian and older sequences and is thus weakly, but clearly involved in the Alpine compression (ORVIN 1934, PIEPJOHN et al., in press). In contrast, the Tertiary in the Øyrlandet region is only weakly deformed, possibly not by compression. A local Late Cretaceous deformation prior to the accumulation of Tertiary sediments cannot be completely excluded in Øyrlandet.

The Forlandsundet Tertiary is intensely deformed (GABRIELSEN et al. 1992, GOSEN & PAECH, in press) and the Alpine compression does not seem to be younger than late Eocene in age.

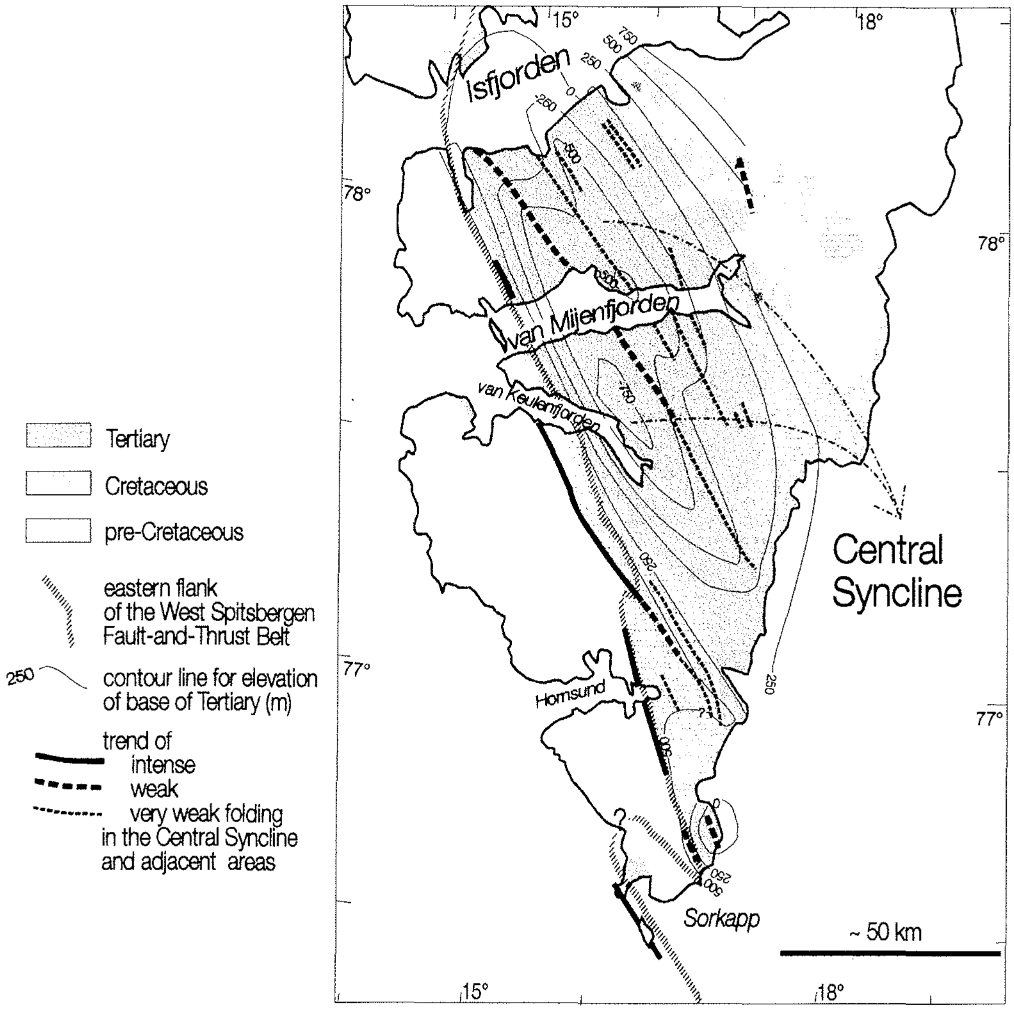



**Fig. 5**: Tectonic sketch map of the Central Syncline in Spitsbergen, WSFB: West Spitsbergen Fold-and-Thrust Belt, (contour lines of Tertiary base modified according to DALLMANN et al. 1993).

## TECTONIC CHARACTERIZATION OF THE TERTIARY-CRETACEOUS STRATA IN NORTH GREENLAND

The Palaeocene sediments that occuroccurring near the station „Nord" in North Greenland (Fig. 3) are not folded. They are mostly gently tilted (about 10°), and only locally do they show a dip of up to 50° owing to drag along a fault.

In contrast, the Upper Cretaceous strata were intensely folded or at least steeply tilted in Alpine time. Near the station Nord the vergence of open folding in Mesozoic rocks is to the south. Further south, in the Kilen area, upright folds are present in Cretaceous strata. In central Herluf Trolle Land, the Upper Cretaceous Herlufholm Strand Formation also shows folds and overthrusts with southern vergence.

The Upper Cretaceous strata in the Depotbugt and Frigg Fjord areas, as well as along the Harder Fjord fault zone, show upright, southward-younging strata and a south-facing fold. The influence of the Harder Fjord fault zone is evident. Near Depotbugt the Cretaceous rocks have been tilted vertically along the fault zone (Fig. 6). With increasing distance from the fault zone, the vertical attitude changes to a steep, southerly dip, which decreases southwards. In the southern part of the easternmost stream in the Cretaceous outcrops, the southern limb of a syncline with a very slight vergence to the south can be seen. In contrast, northward thrusting was also observed on the northern limb of the syncline in the Depotbugt area, i.e., along the Harder Fjord fault zone (PIEPJOHN & GOSEN, in press). Tertiary shales containing lignite (Fig. 6) probably overlie the Upper Cretaceous occurrences (CROXTON et al. 1980). This lignite (less than 0.5 % vitrinite reflectance) is of considerably lower rank than that of the coal (vitrinite reflectance around 2 %) in the Depotbugt Cretaceous, which is folded. This suggests that there is an unconformity between the Tertiary and Cretaceous sediments. However, due to the poor outcrop conditions, the unconformity is not exposed.

In the northernmost part of Greenland, the volcanic rocks of the Kap Washington Group (partly Tertiary in age) were involved in the Alpine compression (Fig. 7). They were overthrust by the Ellesmerian basement and they themselves were overthrust onto older sequences. Moreover, they show folding and bedding-parallel thrusting. Locally, they are cleaved. The vergence is clearly to the northnorthwest. Apart from the Cretaceous to Tertiary volcanics of the Kap Washington Group, the Ellesmerian basement was also involved in the compressive Alpine deformation. Adjacent to the roof thrust on top of the Kap Washington Group, the Ellesmerian basement was pervasively deformed under medium-grade metamorphic conditions. This is evidenced by the metamorphosed remnants of a dyke swarm, which is probably of Cretaceous

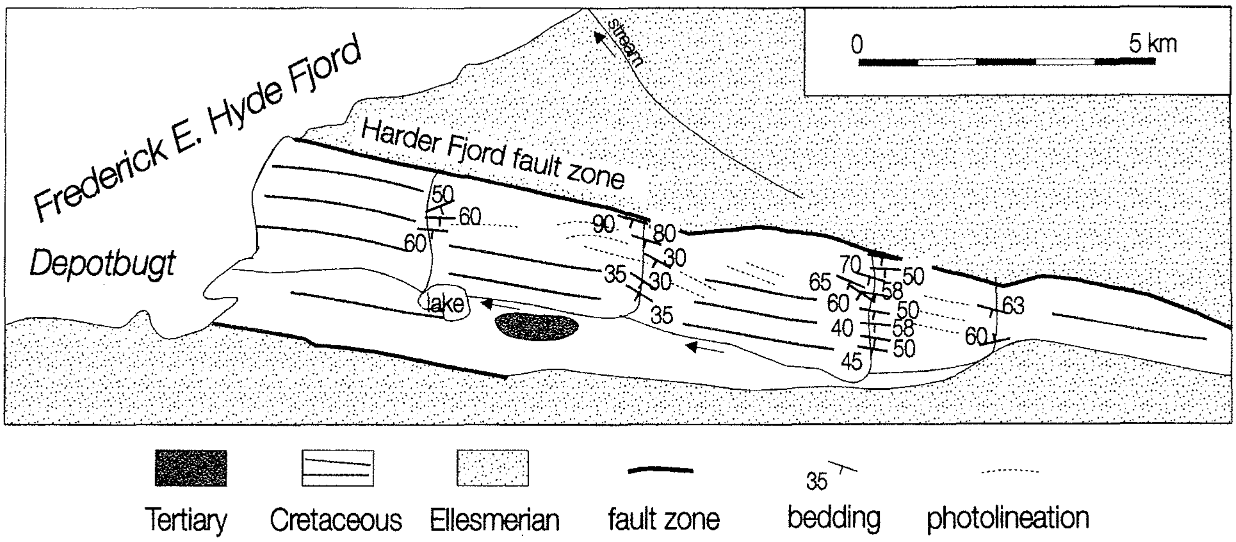



**Fig. 6:** Geological sketch map of the Depotbugt are (Topographic base is the aerial photograph Kort- og Matrikelstyrelsen taken 1994, No. 8874E 1093; Geology according to Geological Map of Greenland, Sheet 8, Peary Land, scale 1:500 000, GGU 1984).

age (ESTRADA 2000). Near the thrust the dykes are intensely deformed to thrust-parallel lense-like bodies ranging in length between 10 cm and 20 m. However, the compressive deformation is not restricted to the area near the thrust zone, since Cretaceous dykes more than 20 km to the south of the thrust zone show widespread weak, but distinct compressive deformation in the form of Riedel shear planes with slickensides (Fig. 8). The direction of compression is N–S to NW–SE. Moreover, small sills are folded. The deformation age of the Kap Washington Group is weakly constrained by the Ar-Ar age of amphibole separates of 37.7 ±0.3 Ma (ESTRADA et al. 2001).

## DISCUSSION AND CONCLUSIONS

Lithologically, the Tertiary basin sediments in Spitsbergen have much in common with those of North Greenland. This

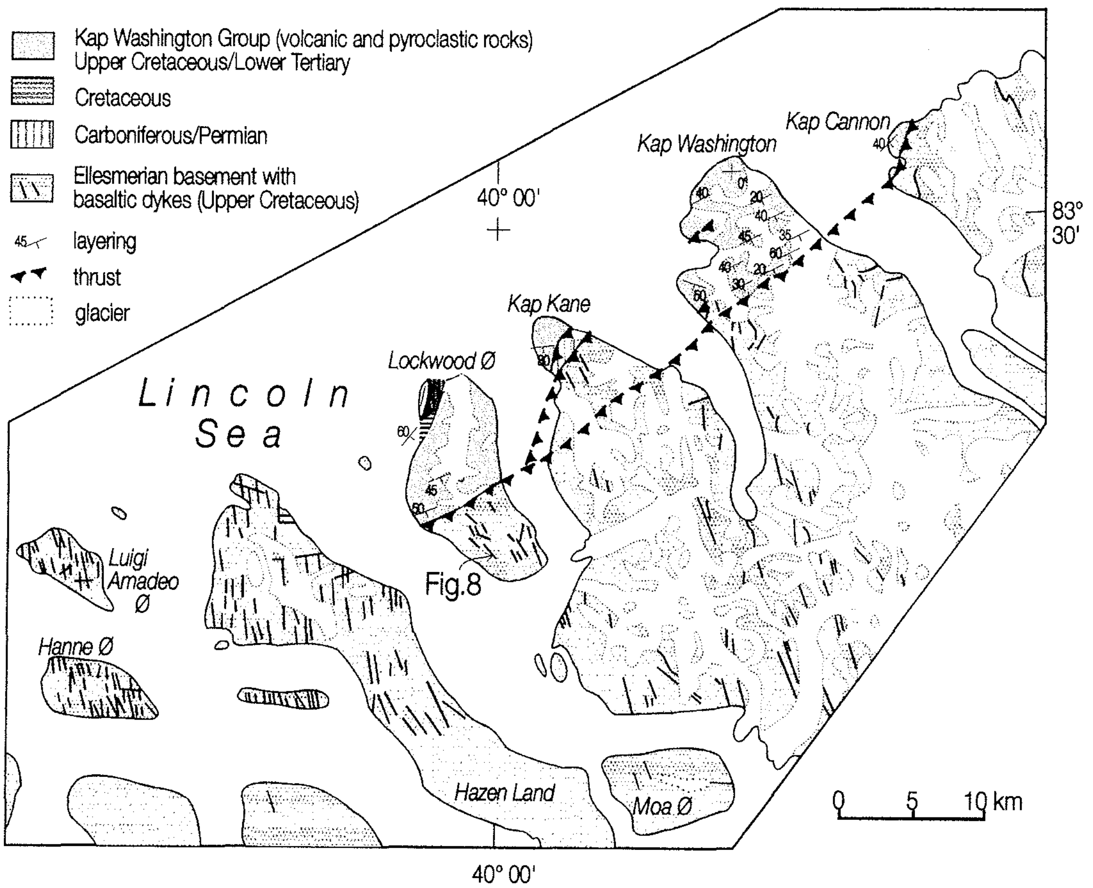



**Fig. 7:** Geological sketch map of the Kap Washington area, North Greenland (Geology according to HIGGINS 1985).

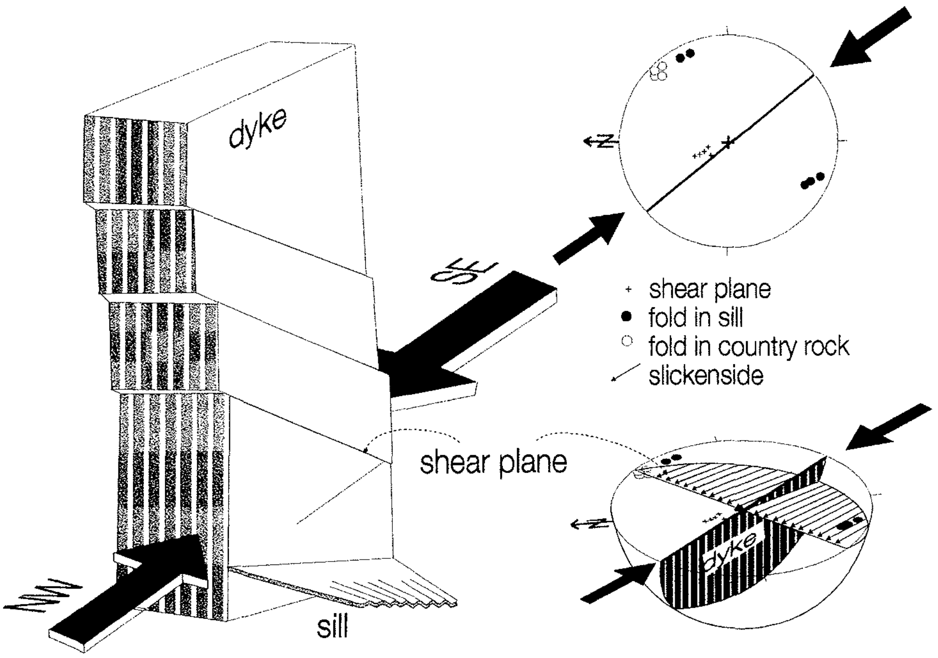



**Fig. 8:** Block diagram of a compressively deformed dyke (about 2 m thick) in the Cretaceous dyke swarm in northernmost Greenland (Lockwood Island) (for location see Fig. 7).

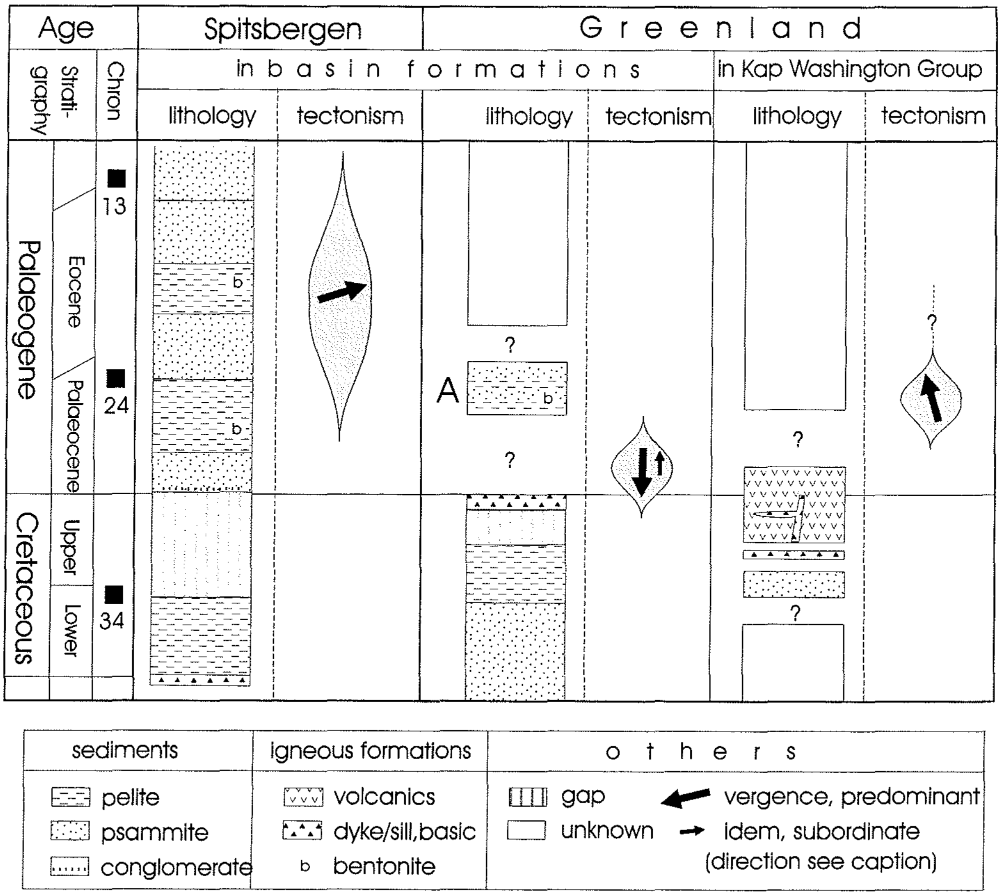
lithological resemblance, reflected in the high sedimentary maturity, is underlined by findings of thin bentonite interlayers containing jarosite in Spitsbergen and in North Greenland (recently discovered). Despite these striking similarities, clear differences exist between the two areas with respect to the conditions of accumulation during the Tertiary. Thus, the sedimentologically immature Tertiary in grabens on Spitsbergen has no equivalent in North Greenland. Moreover, the volcanic rocks of North Greenland (Kap Washington Group) have no counterparts on Spitsbergen.

The conditions at the beginning of the Tertiary sedimentation differ in the two regions, too. On Spitsbergen, the early Tertiary palaeogeographic pattern is little different from that in Early Cretaceous time. In both periods the source areas were in the north. This is surprising since a time span of almost 30 Ma separated the accumulation of the two formations (Tabs. 1 and 2). In North Greenland the relationships between Tertiary and Cretaceous are more complicated. It is possible that this time span is represented by a hiatus, which may continue from late Santonian into earliest Palaeocene, i.e., it has a duration of more than 10 Ma. Little is known about the palaeogeography , although the Tertiary sedimentation does seem to differ from that of the Cretaceous. Cretaceous sedimentation took place predominantly during only part of the Late Cretaceous and the marine sedimentation probably ended in the Santonian, followed by a hiatus. During the Late Cretaceous, dykes and sills were intruded and possibly basalt lavas erupted along the

| | | Lithology | Lithostratigraphy: Group | Lithostratigraphy: Formations | Thickness in [m] | Tertiary biostratigraphic evidences: ČEPEK in press | MANUM & THRONDSEN 86 | MATHIESSEN 1986 | LIVŠIC 1974 |
|---|---|---|---|---|---|---|---|---|---|
| Palaeogene | Oligocene | coal | Van Mijenfjorden | Aspelintoppen | >1000 | | | | $Pg_3$ |
| | Eocene | | | Battfjellet | 60-300 | | | | $Pg_2$ |
| | | b | | Frysjaodden | 200-450 | | $Pg_{1-2}$ | $Pg_{1-2}$ | |
| | | | | Grumantbyen | 45-200 | | | | $Pg_2$ |
| | Palaeocene | b | | Basilika | 10-350 | | $Pg_1^{u}$ | $Pg_1^{u}$ | |
| | | coal | | Firkanten | 100-170 | $Pg_1$ | | | $Pg_1$ |
| Upper Cretaceous | | hiatus | | | | | | | |
| Lower Cretaceous | | | | | | | | | |

$Pg_3$ Oligocene ...... conglomerate
$Pg_2$ Eocene b bentonite
$Pg_1$ Palaeocene
$Pg_1^{u}$ Upper Palaeocene
pelite-dominated
psammite-dominated

**Tab. 1**: Lithostratigraphy and stratigraphy of the Tertiary Van Mijenfjorden Group according to the recommendations of the Committee on the Stratigraphy of Svalbard (HARLAND 1997), and underlying sequences on Spitsbergen (the biostratigraphy, shown in bold letters, was determined on the basis of marine fossils).




**Tab. 2:** Correlation of lithology and Alpine tectonism of Spitsbergen and North Greenland (upward arrow is vergence to north, right to east etc.; Tertiary chrons according HARLAND 1997, Fig. 20.4; A-Thyra Ø Formation)

Harder Fjord fault zone as well as north of it.

The Alpine tectonism in the two regions exhibits some differences. In Svalbard, Late Cretaceous compression has not been proven. The difference in the compressive structures in the Tertiary and Lower Cretaceous strata is due to the difference in the lithologies of these two units, resulting in different behaviour under stress. The lowermost Tertiary formation consists of a thick sandstone-dominated sequence, whereas the underlying Lower Cretaceous is often composed of pelitic rocks. Only in the Øyrlandet area is it impossible to completely exclude Late Cretaceous movement.

In contrast to Svalbard, there is some evidence in North Greenland of a twofold tectonic history. The earlier tectonic event is characterized by a predominance of southward vergence and the restriction of the deformation to Cretaceous and older sequences in the region from the Harder Fjord fault zone in the north to the Kilen Cretaceous in the south (Fig. 3). Orogenic movement took place after the intrusion of Cretaceous dykes and sills, but it did not affect the Tertiary sedimentary rocks. This is suggested by undeformed Tertiary shales most likely resting on folded Cretaceous strata in the Depotbugt area (Fig. 6). Further undeformed Tertiary strata are found near folded Upper Cretaceous rocks in the vicinity of the station „Nord". Predominantly (but not exclusively) south-facing folds and thrusts were formed during this folding event (Fig. 3). Thus, the foreland was to the south or southwest and consists of the Precambrian platform of central Greenland, which had been stable since the Palaeozoic. The presence of an Alpine tectonic event between Tertiary and Cretaceous is corroborated by a distinct difference in coal rank: The Tertiary sediments are characterized by a coal rank of about 0.55 % vitrinite reflectance and the Cretaceous sediments by about 1.8 % or more vitrinite reflection.

A later tectonic event probably affected the entire volcanic Kap Washington Group (Tab. 2). This event is characterized by a vergence opposite to that of the older folds of the Cretaceous strata further south. Here in northernmost North Greenland, the vergence is to the NNW, towards the foreland, which corresponds to that of the foreland-directed folding in the West Spitsbergen Fold-and-Thrust Belt. Moreover, the Kap Washington Group may include both Tertiary and Cretaceous rocks. Thus, Tertiary sequences are involved in the younger Alpine tectonism. The Ar-Ar age of an amphibole separate of 37 Ma (ESTRADA et al. 2001) is a further indication of the Tertiary age (Eocene?) of the younger tectonism. The deformation of these two areas of Spitsbergen and North Greenland was probably a single event. It may be coeval with the formation of the West Spitsbergen Fold-and-Thrust Belt.

In general, with respect to the tectonic history and tectonic pattern, the two areas show remarkable differences (Tab. 2) which do not fit with the idea of HARLAND (1969) and LOWELL (1972) of a common transpressive orogen formed during dextral displacement of Svalbard relative to North Greenland. The geological development was more complicated than this. On Spitsbergen, only one event, spanning the Late Palaeocene and most of the Eocene, gave rise to the West Spitsbergen Fold-and-Thrust Belt, which is characterized by vergence towards the foreland, i.e., to the ENE. This event was coeval with the opening of the North Atlantic between Chron 24 and Chron 13. The general compressive nature of the Palaeogene movements was complicated by a slight dextral strike-slip component, as indicated in the indistinct en-echelon arrangement of the folds oblique to the West Spitsbergen Fold-and-Thrust Belt (PAECH, in press).

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