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Drift of Greenland and Correlation of Tertiary Tectonic Events in the West Spitsbergen and Eurekan Fold-Thrust Belts.

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

Summary: In the Eurekan and Spitsbergen "orogens", the Tertiary tectonic development is similarly two-phase, including an earlier phase of transpression followed by a major phase of compression. The first event, which is likely Upper-Paleocene to Early Eocene in age, can be correlated with the northeasterly displacement of Greenland which took place just after chron 25. It corresponds to a regime of transpression with a significant coupling of the transcurrent and convergent components. The second event, which culminated around mid-Eocene, is compatible with the chron 24 to chron 21 and chron 13 northerly to northwesterly near-orthogonal convergent motion of Greenland relative to Ellesmere island. It agrees also with the oblique-slip motion which still prevailed for the same period of time between the Greenland - Spitsbergen paleotransform, but with a dominated component of convergence across the plate-boundary as a result of strain partitioning.

GEOLOGIC SETTING

The Eurekan "Orogen" (FORTIER 1963, THORSTEINSSON & TOZER 1970, DE PAOR et al. 1989, TRETTIN 1989, 1991, OKULITCH & TRETTIN 1991) in the northeastern Canadian Arctic Archipelago (Ellesmere and Axel Heiberg islands) and the West-Spitsbergen "Orogen" (HARLAND 1969, HARLAND & HORSFIELD 1974, BIRKENMAJER 1972, 1981, STEEL et al. 1985, DALLMANN et al. 1993) in the Norwegian Svalbard Archipelago, are Arctic belts, mainly formed, if not totally, during Tertiary (Paleogene) time. Both are genetically linked to the drift of Greenland with respect to North-America and Eurasia (Fig.1). The West Spitsbergen fold-thrust belt has been ascribed to dextral transpression (HARLAND 1965, 1969, LOWELL 1972) along the intracontinental paleotransform (De Geer-Hornsund Fault Zone) which formed during Paleocene-Eocene time and linked the coeval Norwegian-Greenland and Gakkel-Nansen (Eurasian) oceanic basins (TALWANI & ELDHOLM 1977, MYRHE & ELDHOLM 1988, ELDHOLM et al. 1987, 1990). The Canadian Eurekan fold-thrust belt and its extension in North-Greenland, is due to the general anticlockwise rotation (KERR 1967) and northerly motion of Greenland relative to the Canadian Arctic, as a consequence of the Labrador Sea and Baffin Bay opening, since the Late Cretaceous until the Eocene-Oligocene boundary (SRIVASTAVA, 1978 1985, SRIVASTAVA & TAPSCOTT 1986, ROEST & SRIVASTAVA 1989). In a more recent hypothesis (LYBERIS & MANBY 1993), it has been claimed that both the West Spitsbergen and the Eurekan belts did not form in a transpressional setting but were the result of a Greenland-Svalbard convergence in Late Cretaceous to Early Paleocene time.

Many attempts have been made, separately for each belt, to relate the tectonic evolution to the plate-tectonic framework. In the present paper, taking into account the timing of the tectonic events in the two areas, the deformational stage history and the sequence of stresses directions, deduced from kinematic analysis of Tertiary structures, are compared each other and correlated with the successive stages of the drift of Greenland relative to the North-America and Eurasia plates.

KINEMATIC STAGES AND PALEOSTRESS HISTORY IN THE EUREKAN AND SPITSBERGEN FOLD-AND-THRUST-BELTS

In Spitsbergen the fold-thrust belt (HARLAND 1969, HARLAND & HORSFIELD 1974, BIRKENMAJER 1981, DALLMANN et al. 1993), about 300 km long, strikes NNW-SSE, paralleling the western continental margin, except at the northern tip of the deformed zone, in Brøgger peninsula, where the structures shift to WNW-ESE. Equivalent but small-scale WNW-ESE structures, with an en échelon arrangement oblique to the general trend of the fold-thrust belt, have been recognized elsewhere, in Nordenskiöld Land (BRAATHEN & BERGH 1995). In the Eurekan orogen of the Canadian Arctic, several structural domains are distinguished (OKULITCH & TRETTIN 1991); the structural directions are not straight but arcuate turning from N-S in Axel Heiberg Island to NE-SW in north-central Ellesmere Island. In both cases bending is probably not a consequence of Tertiary shearing (BIRKENMAJER 1981, HUGON 1983) but is inherited and due to preexisting fabric in the basement. Deformation is superimposed with the same trend onto structures related to the Caledonian orogeny including the late Devonian Ellesmerian and Svalbardian events and causes the contractional reactivation and inversion of extensional structures related to the Late Paleozoic rifting episode (MAHER & WELBON 1992). The two fold-thrust belts are characterized by the involvement in deformation, at various degree, of the Carboniferous to Paleogene strata of the Sverdrup basin (including the Eureka Sound Group) and the equivalent sedimentary pile of Spitsbergen (including the Tertiary deposits).

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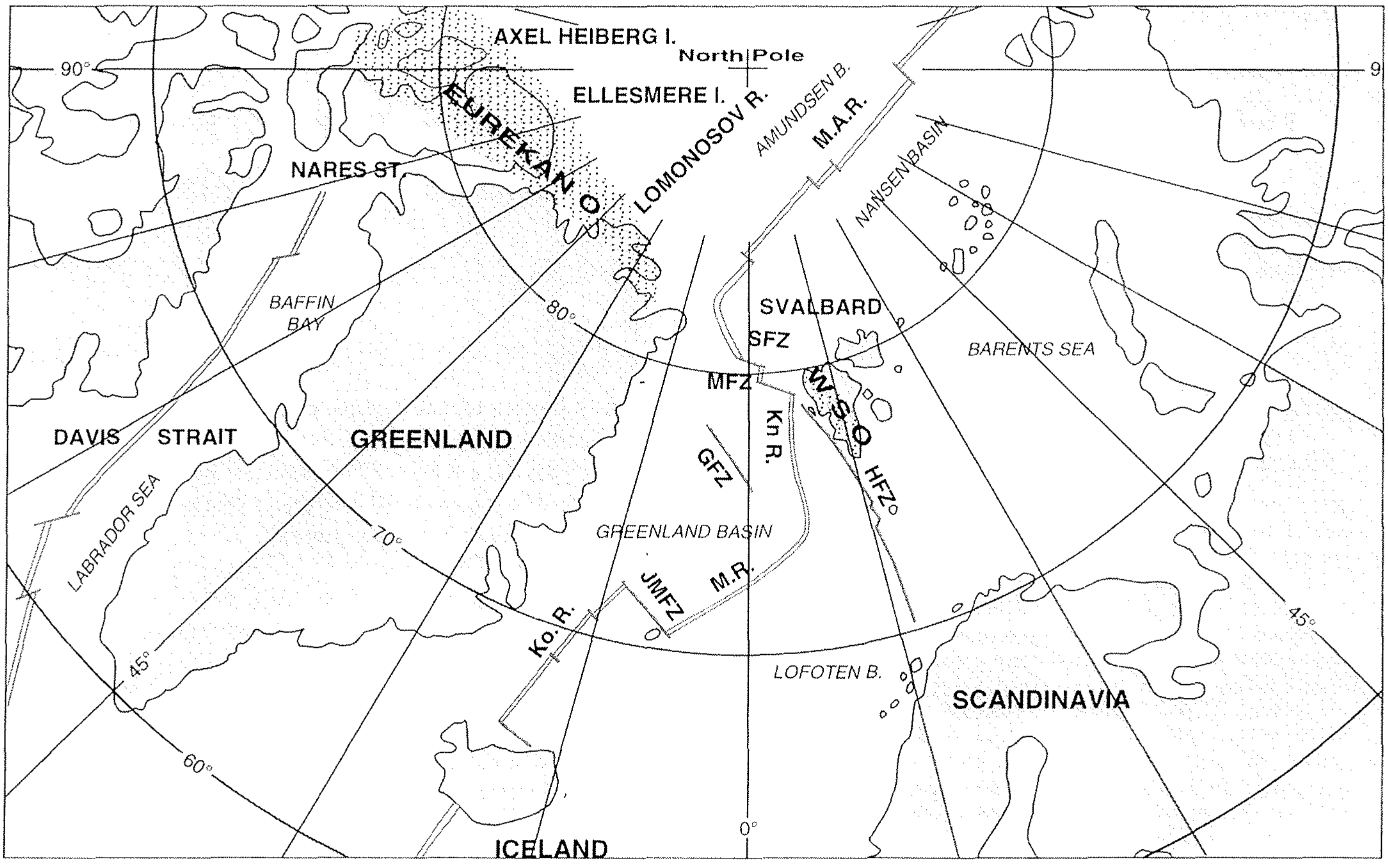

Fig. 1: Present-day location of the Eurekan and Spitsbergen orogenic system in the Arctic. NP = North Pole; M.A.R = Mid Arctic Ridge; SPZ = Spitsbergen Fracture Zone; MFZ = Molloy Fracture Zone; HFZ = Hornsund Fault Zone; GFZ = Greenland Fault Zone; JMFZ = Jan Mayen Fault Zone; Kn R = Knipovich Ridge; M.R. = Mohns Ridge; Ko. R. = Kolbeinsy R.

Spitsbergen fold-and-thrust belt

The prevailing structural features are those of an east-verging compressional near-orthogonal fold-and-thrust belt and cannot be considered as type example of a strike-slip belt, as previously assumed (LOWELL 1972). From the western hinterland to the foreland the tectonic style varies from thick-skinned (basement-involved) to thin-skinned (detachment-dominated) thrust tectonics, as a result of decollement horizons (Upper Paleozoic evaporites, Mesozoic shales) within the post-Devonian sequence (NØTTVEDT et al. 1988). A model of decoupling of the dextral transpressional motion between Greenland and Svalbard has been invoked in which the transcurrent component is supposed to be confined to the internal part of the fold belt, or even to an off-shore zone, (MAHER & CRADDOCK 1988, NØTTVEDT et al. 1988). In the Forlandsundet area, some structures parallel to the paleotransform show evidence of transcurrent movements. The en échelon arrangement of surface high magnetic-anomalies (KRASIL'SCIKOV et al. 1995), along the NW-trending eastern marginal fault of the Forlandsundet, is inferred to be the result of strike-slip faulting movement within an overall dextral regime of transpression (OHTA et al. 1995). Orogen-parallel motion have also been documented in the crystalline basement, at the SE margin of the Forlandsundet, along a major fault zone involving Carboniferous strata (LEPVRIER 1990, 1992, MAHER et al. 1997). Some structures in southern Spitsbergen also imply dextral strike-slip movements (DALLMANN 1992).

Kinematic analysis of fault populations conducted at different locations, in the post-Devonian strata and also in the Tertiary deposits, shows that the deformational history is polyphase.

A sequence of dextral transpression followed by compression and final transtension has been defined in the Brøgger and Forlandsundet areas (LEPVRIER & GEYSSANT 1985, LEPVRIER 1990, 1992). The major and widespread phase of pure contractional nature corresponds to an east-northeast-west-southwest (70-80 °N) direction of $\sigma 1$, orthogonal to the trace of the paleotransform. This event largely overprints the effects of a first episode characterized by a N-S to 10-20 direction of $\sigma 1$ and marked by dextral strike-slip movements along faults parallel to the paleotransform. In western Spitsbergen; the early development as pull-apart basins of the Forlandsundet graben (RYE-LARSEN 1982) and other comparable structures on the continental margin (EIKEN & AUSTEGARD 1987), as well as the northerly thrusting movements recognized in the Brøgger peninsula, are coevally attributed to this first episode, as far as these structures represent extensional and contractional relay zones of a dextral strike-slip system (LEPVRIER 1988). Along the Carboniferous slice of SE Forlandsundet the strike-slip movements, compatible with an overall dextral setting, are not attributed to this early stage but seem to postdate the compressional episode (MAHER et al. 1997).

A similar polyphase kinematic history is found in the Nordenskiöld Land (BRAATHEN & BERGH 1995); prior to the final extension, deformation is the result of two kinematic stages: successively NNE-SSW dextral transpression and WSW-ENE shortening.

From the analysis of striated fault-planes in the Tertiary stratigraphic units of the Central Basin, a comparable succession of stress tensors has been established (KLEINSPEHN et al. 1989, TEYSSIER et al. 1995) with two regionally significant tensors, successively oriented North-South and Northeast-Southwest. Short-lived and local faulting events including sinistral strike-slip movements occured in between.

Except for local variations of the paleostress field close to the plate boundary and the existence of local and short-lived events, the kinematic evolution established from different locations is therefore consistent at a regional scale and consistent with the major structures. Apart from the final extension, this history includes two main stages: a N-NNE-S-SSW transpression which allows dextral strike-slip movements on faults parallel to the paleotransform and an ENE-WSW compression subperpendicular to the paleotransform. However, using a similar analytical method of small-scaled structures, MANBY & LYBERIS (1995) consider the change in shortening direction (Brøgger peninsula, Nordenskiöld Land) as progressive and not representative of distinct kinematic phases; they define an opposite succession with an initial ENE-WSW compression and a later strike-slip regime, which appears to be invalid from field evidences.

Eurekan fold-and-thrust belt (Ellesmere and Axel Heiberg islands)

The Eurekan deformation concerns a wide zone characterized by eastwards to southeastwards thrusts (Stolz Thrust, Vesle Fjord Thrust, Lake Hazen thrust, Parrish Glacier thrust etc.) and overturned folds. Decollement horizons give rise to flat-ramp geometries (OKULITCH 1982, OSADETZ 1982). Tertiary sediments of the Eureka Sound group are fragmented in several foredeep subbasins within the belt and along Nares Strait (MAYR & DE VRIES 1982). Structural and kinematic analysis of faults have been performed in Central Ellesmere and Axel Heiberg Islands (DE PAOR et al. 1989, LEPVRIER et al. 1996). The major phase of deformation is characterized by a direction of $\sigma 1$ turning from WNW-ESE in eastern Axel Heiberg Island along the Stolz thrust to NNW-SSE in north-central Ellesmere Island (Blue Mountains, Lake Hazen thrusts), allowing there a moderate component of dextral motion (HIGGINS & SOPER 1983). Older structures expressed by tensional gashes and by rare reverse faults have been evidenced in the Blue Mountains area. The reconstructed direction of $\sigma 1$ is NE-SW oriented, allowing, as it has been suggested (MIALL 1985), left-lateral displacements before thrusting along the faults which run through Ellesmere Island slighty oblique to the Nares Strait. Along the Nares Strait itself, strike-slip faulting has been reported in Judge Daly Promontory (MAYR & DE VRIES 1982).

TIMING OF TECTONIC EVENTS

Age of the major deformational episode

In Spitsbergen as well in the Canadian Arctic, the major deformational episode (stage 2 structures) of contractional nature is Tertiary in age, as proved in particular by the clear involvement of Tertiary strata in the deformation. The recent hypothesis for a late Cretaceous-early Paleocene main tectonic development (LYBERIS & MANBY 1993, 1994) has been extensively discussed and rejected (LEPVRIER 1994, MAHER et al. 1995).

In the Canadian Arctic, deformation terminated by the end of Eocene with the deposition of the Eureka Sound Group (MIALL 1986, RICKETTS 1988) and only the Neogene Beaufort Formation is post-deformational. Thrust movements along Stolz and Lake Hazen Faults are dated by the synorogenic mid-Eocene conglomerates of the Buchanan Lake Formation, at the top of the Eureka Sound Group (RICKETTS & MCINTYRE 1986, MIALL 1988, RICKETTS 1988); upper(?) Paleocene sediments are similarly involved in the Parrish Glacier and other thrusts along Nares strait (MAYR & DE VRIES 1982). In North-Greenland the south-dipping Kap Cannon thrust, at the northern coast of Peary Land also moved during the Eocene (SOPER et al. 1982).

In Spitsbergen, in spite of stratigraphic uncertainties that still exist, a late Paleocene to Eocene age for the main episode of deformation is generally favored, on the basis of various observations (MAHER et al. 1995).

In the Central Basin, the onset of transpression is documented by the reversal of the source supply in the latest Paleocene as a response to upthrusting of the western zone; this episode marks its evolution as a foreland piggy-back basin with an eastward migration of the depocenter (KELLOGG 1975, STEEL et al. 1981, NØTTVEDT et al. 1988, HELLAND-HANSEN 1990). Within the overall regime of dextral transpression, MÜLLER & SPIELHAGEN (1990) separate a dominantly compressive phase restricted to the late Paleocene - early Eocene and a strike-slip-dominated dextral transpression in early to middle Eocene. The stress tensor recorded in the Central basin and related to the phase of orthogonal compression, is similarly attributed to the late Paleocene-Eocene period of time (KLEINSPEHN et al. 1989, TEYSSIER et al. 1995).

In the Forlandsundet basin, the age of the youngest strata is early Oligocene (FEYLING-HANSEN & ULLEBERG 1984) or most probably restricted to the Eocene (MANUM & THRONDSEN 1986). The entire sequence suffered ENE-directed compression by the late Eocene-early Oligocene, before the tectonic regime changed into extension (LEPVRIER & GEYSSANT 1985, LEPVRIER 1990, GABRIELSEN et al. 1992, KLEINSPEHN & TEYSSIER 1992). LYBERIS & MANBY (1993) fail to recognize the existence of the ENE-WSW to EW compression in the Tertiary rocks of Forlandsundet basin which would be only affected by the late dextral transtension and NW-SE extension.

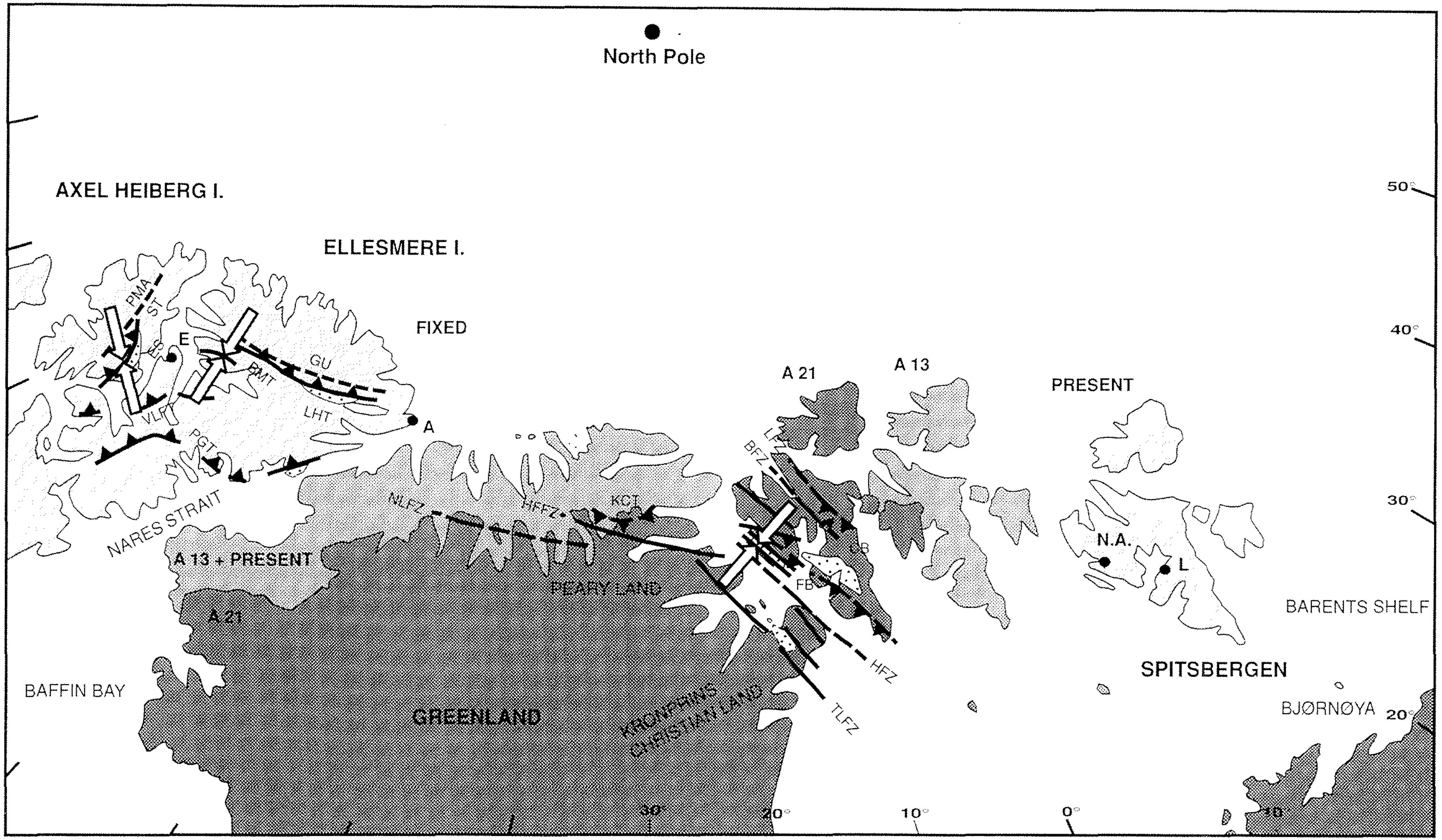

Fig. 2: Restored paleopositions, at chron 21 and chron 13, of Greenland and Spitsbergen-Barents sea blocks with respect to Canadian Arctic Islands. The plate-tectonic model of Srivastava & Tapscott (1986) is used in this reconstruction. Ellesmere and Axel Heiberg are maintained fixed in their present day position (Polar projection with present-day grid). The different landmasses are represented with their modern coastlines. The main structures (faults and thrusts) active during the major phase of deformation (mid to late Eocene) are reported on the chron 21 situation, together with the corresponding directions of compression (arrows) and the main areas of Paleogene deposits.
Abbreviations are as follows: ST = Stolz Thrust, VFT = Vesle Fjord Thrust, BMT = Blue Mountains = Thrust, PGT = Parrish Glacier Thrust, LHT = Lake Hazen Thrust, NLFZ = Nyeboe Land Fault Zone, HFFZ = Harder Fjord Fault Zone, KCT = Kap Canon Thrust, TLFZ = Trolle Land Fault Zone, HFZ = Hornsund Fault Zone, BFZ = Billefjorden Fault Zone, LFZ = Lomfjorden Fault Zone; PMA = Princess Margaret Arch, GU = Grantland Uplift; CB = Central Basin, FB = Forlandsundet Basin, ES = Eureka Sound. E = Eureka, A = Alert, NA = Ny Alesund, L = Longyearbyen.

Age of earlier movements

The onset of deformation for the earlier structures (stage 1) and for strike-slip movements is more difficult to constrain. In Ellesmere Island, they are tentatively attributed to the early to middle Eocene (MIALL 1985). Recent apatite fission track data (ARNE et al. 1998), from the Vesle Fjord Thrust, indicate an initiation of fault movement during the Paleocene.

In Spitsbergen, the WNW-ESE stage 1 structures related to the N-NNE-S-SSW direction of shortening may have been formed only in the Late Paleocene-earliest Eocene just prior to the main compressional event, a short period separating the two events (BRAATHEN et al. 1995). The early development of the Forlandsundet basin as a transtensional relay zone within a dextral transpressional setting is probably synchronous with these stage 1 structures (STEEL et al. 1985, LEPVRIER 1988, GABRIELSEN et al. 1992). However, an earlier formation of these stage 1 structures cannot be excluded. An early Paleocene and possibly a Late Cretaceous age is suggested (BRAATHEN & BERGH 1995). According to the paleostress record in the Central Basin, the oldest north-south stress tensor was established as soon as the Late Cretaceous-earliest Paleocene, followed until the Late Paleocene by short-lived faulting events (KLEINSPEHN et al. 1989, TEYSSIER et al. 1995). Fission track analyses tend to indicate an initial 70-50 Ma cooling period due to uplift (BLYTE & KLEINSPEHN 1997) but only minor structures can be attributed to the Late Cretaceous to early Paleocene time interval (MAHER et al. 1997). However, in the Kronprins Christian Land of NE Greenland, dextral transpression has been argued as Late Cretaceous (HÅKANSSON & PEDERSEN 1982).

CORRELATIONS OF TECTONIC EVENTS WITH THE DRIFT OF GREENLAND

From magnetic anomalies recorded in the Labrador Sea, Baffin Bay (SRIVASTAVA 1978, SRIVASTAVA & TAPSCOTT 1986, ROEST & SRIVASTAVA 1989) and Norwegian-Greenland Sea (TALWANI & ELDHOLM 1977, MYRHE & ELDHOLM 1988, ELDHOLM et al. 1990, VÅGNES et al. 1988, FALEIDE et al. 1993, SKILBREI & SRIVASTAVA 1993), it has been demonstrated that Greenland was an independant plate with respect to the North America and Eurasia plates between chrons 25-24 and 13. Prior to the existence of this three-plates system, Greenland was linked to Eurasia; but since chron 33 (80 Ma) it moved away from America in a east-northeast direction. A major anticlockwise change to the north-northeast occured during the chrons 25-24 interval (59-56 Ma), which marked the beginning of sea-floor spreading in the coeval Norwegian-Greenland and Eurasian Oceanic Basins. Then Greenland moved northeastwards and finally from chron 21 (49 Ma) until chron 13 (36 Ma) moved north-northwestwards. After chron 13 it became attached to America but continued to separate from Eurasia in a WNW direction. According to the reinterpretation of previous data, sea-floor spreading in the Labrador Sea is thought to have started only from chron 27 in the Paleocene and not in the Late Cretaceous (CHALMERS & LAURSEN 1995).

This plate tectonic evolution, from the late Cretaceous or the early Paleocene to the Oligocene, implies a period of orthogonal convergence between Greenland and North America along Nares Strait (Wegener fault), preceeded by a first and significant episode of left-lateral motion. Although the amount of sinistral displacement has been considerably reduced in a more recent model (ROEST & SRIVASTAVA 1989), this question has been a matter of controversy (KERR 1980, DAWES & KERR 1982, HIGGINS & SOPER 1989). The model of SRIVASTAVA & TAPSCOTT (1986) used in our reconstruction Fig.2 and the amount of sinistral displacement along Nares Strait are not discussed in this paper. Sinistral strike-slip faulting are known in Judge Daly Basin at the northeastern part of the Strait (MAYR & DE VRIES 1982) but it has been suggested that the movement was distributed throughout the foldbelt itself, forming a diffuse plate boundary (MIALL 1983, HUGON 1983).

The direction of $\sigma1$ for the major compressional phase (stage 2 structures) fits well with the north to northwestwards movement of convergence between Greenland and Ellesmere Island. The preceeding oblique-slip regime of deformation (sinistral transpression) can be related to the northeastwards displacement of Greenland. A mechanism of coupling could have existed during this phase but some of the ENE to NE faults of northern Ellesmere could have been successively the site of strike-slip faulting and thrusting as suggested by MIALL (1985). The arcuate distribution of $\sigma1$ during the second event is better explained by the influence of basement acting as an indenter (LEPVRIER et al. 1996) than by the effect of pivotal tectonism (PIERCE 1982, DE PAOR et al. 1989). On the other hand, the WNW to NW direction of compression observed on Axel Heiberg Island could be slightly younger than the thrusts on Ellesmere Island and could coincide with the latest WNW drift of Greenland.

Along the intracontinental paleotransform between Greenland and Svalbard, the plate tectonic model implies dextral motion, with successively strike-slip, compression-dominated transpression (chrons 25-24), strike-slip-dominated transpression (chrons 24-21) and then strike-slip followed by transtension after chron 13 (MÜLLER & SPIELHAGEN 1995). A short-lived period of sinistral motion could have existed (SKILBREI & SRIVASTAVA 1994).

The sedimentary development of the Tertiary Central Basin is consistent with the motion between the Greenland and Eurasia plates and particularly with the onset of transpression in late Paleocene (MÜLLER & SPIELHAGEN 1990). The kinematic history and paleostress evolution established from fault-slip analysis (LEPVRIER & GEYSSANT 1985, KLEINSPEHN et al. 1989, BRAATHEN & BERGH 1995, GABRIELSEN et al. 1992, LEPVRIER 1992, TEYSSIER et al. 1995) are also in accordance with dextral transpression. However, there is an apparent discrepancy between the compressional nature of the main tectonic episode, with a 70-80 °N direction of shortening, subperpendicular to the trace of the paleotransform and the plate setting. This situation, which is not surprising for a regime of transpression (HARLAND 1997), can be explained by decoupling of the two components of transcurrence and convergence (MAHER & CRADDOCK 1988). A coupled to decoupled succession has been proposed to account for the stage 1 and stage 2 structures (LEPVRIER 1992, BRAATHEN et al. 1995, TEYSSIER et al. 1995). Coupling was prevailing during the formation of the stage 1 structures when Greenland and Spitsbergen starts to slide past each other. Conversevely, stage 2 structures are related to decoupling. The orogen parallel motion observed in the hinterland of the fold-thrust-belt is coeval with the orogen-perpendicular transport to the ENE in the foreland (MAHER et al. 1997). The chron 25 to chron 24 interval, marked by the drastic counterclockwise rotation of Greenland could correspond to the change from coupling to decoupling. Short-lived intervals of decoupling could exist during this period. A correlation diagram of Tertiary regional tectonic events and plate-tectonic stages is given in Table 1.

synchronous ENE-vergent stuctures which developed in Spitsbergen as a result of decoupled transpression. The stage 1 structures are consistent with the northeastward displacement of Greenland which took place after chron 25; they correspond respectively in the two areas to oblique sinistral and dextral regime of transpression, with coupling of the components of transcurrence and convergence. The earlier period of sea-floor spreading in the Labrador Sea, from the late Cretaceous or the early Paleocene to the late Paleocene, is only responsible of uplift, without significant contractional deformation.

The sequence of tectonic events in Spitsbergen and in Canadian Arctic shows a good accordance and fits rather well with the plate tectonic setting. However, the correlation established in

chronostratigraphic age			chronometric age (Ma)	magnetic anomalies	plate tectonic framework: sea-floor spreading			age of tectonic events	
					Labrador sea	Norw-Greenl.	motion of Greenland	Spitsbergen	Ellesmere Island Axel Heiberg Island
OLIGOCENE							WNW	transtension-extension	
			36	13					
EOCENE	upper	Priabonian							
EOCENE	upper	Bartonian							
EOCENE	mid	Lutetian					NW	transpression (with decoupling): ENE-WSW orthogonal compression (foreland) dextral strike-slip (hinterland)	WNW-ESE (Axel Heiberg Island) NNW-SSE (Ellesmere Island) orthogonal compression
			49	21			N		
EOCENE	lower	Ypresian					NE		
			56	24					
PALEOCENE	upper	Thanetian	59	25			sinistral rotation	N-S to NNE-SSW dextral transpression (with coupling)	ENE-WSW to NE-SW sinistral transpression (coupling ?)
			60.5	26					
PALEOCENE	lower	Danian					ENE	transtension with dextral strike-slip	
			65	29	CHALMERS & LARSEN (1995)				
LATE CRETAC.		Maestrichtian							
LATE CRETAC.		Campanian	80	33	ROEST & SRIVASTAVA (1989)			uplift	uplift

Tab. 1: Correlation diagram of regional tectonic events (Spitsbergen and Ellesmere-Axel Heiberg islands) and plate-tectonic stages. The time scale is from KENT GRADSTEIN (1986).

CONCLUSIONS

A two-stage tectonic development characterizes the Eurekan fold-thrust belt of the Canadian Arctic and the Spitsbergen fold-thrust belt, with a climax of deformation around mid-Eocene. The sequence of tectonic events is fully compatible with the motion of Greenland with respect to Eurasian and North American plates (Tab. 1). The northerly to northwesterly motion which took place from chron 24 to chron 13, through chron 21, (Fig. 2) coincides with the stage 2 structures observed on Ellesmere and Axel Heiberg islands. It accounts also for the this paper needs to be confirmed, because of the remaining uncertainties on the stratigraphic age of the Tertiary Formations involved in the deformation. Furthermore, this correlation needs to be corroborated by additional data from North and Northeast Greenland.

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