THE TERTIARY STRIKE-SLIP BASINS AND OROGENIC BELT OF SPITSBERGEN

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ABSTRACT: The Svalbard margin evolved to its present rifted configuration through a complex strike-slip history of both transtension and transpression. Because the Paleogene plate boundary, the De Geer Line, lay just west of Spitsbergen, many of the details of this structural evolution are contained in a narrow fold and thrust belt, and within a series of sedimentary basins, on Spitsbergen. The early to mid-Paleocene Central Basin was of extensional (possibly transtensional) origin, and contains more than 800 m of clastic deposits. It evolved from a series of partly connected coal basins to a single, open-marine basin. The late Paleocene to early Eocene Central Basin, of transpressional origin, was infilled by more than 1.5 km of clastic sediments from deltas, which prograded out from the rising orogenic belt. The fold and thrust belt of western Spitsbergen, mainly of late Paleocene to Eocene age, was also a product of transpression. Forlandsundet Graben, infilled by as much as 5 km of alluvial and marine clastics, probably formed from late Eocene collapse of the crest of the orogenic belt, or from extension adjacent to a curved fault zone. Rift basins, up to 7 km deep, developed west of Svalbard as the continental margin changed, beginning in the early Oligocene, from a strike-slip to a rifted regime.

REGIONAL SETTING

The occurrence of sedimentary basins and an orogenic belt of Tertiary age in Spitsbergen (Figs. 1, 2) is well known. Details of the relation between Tertiary tectonics and sedimentation, and of the plate-tectonic causes of these events, have emerged over the years, beginning with papers by Harland (1965, 1969), who first suggested that the 'West Spitsbergen orogeny' was related to large-scale transcurrent movement between Greenland and Eurasia, during the opening of the Norwegian-Greenland Sea. It is therefore important to summarize our present knowledge of the Cenozoic history of the continental margin off northern Norway and Svalbard,[2] before discussing the Tertiary events on Spitsbergen.

A model for the Cenozoic tectonic history of the northeastern Atlantic region and the opening of the Norwegian-Greenland Sea, including a map of the sea-floor magnetic anomalies and the main structural elements, was proposed by Talwani and Eldholm (1977). The main feature of this model is that there were two distinct phases of tectonic development: the first, now generally recognized as beginning about the time of formation of magnetic anomaly 25/24 (58 Ma; Eldholm et al., 1984), involved north-northwesterly motion of Greenland from Eurasia; the second, dating from the time of magnetic anomaly 13 (37 Ma), involved a change in the pole of rotation and caused the relative plate movement to be west-northwesterly. These two tectonic phases thus produced a latest Paleocene to early Oligocene strike-slip regime and an early Oligocene to present rift regime, respectively, off western Svalbard (Fig. 1). The Paleogene transform boundary has been called the De Geer Line (Harland, 1969) or the De Geer-Hornsund Line (Crane et al., 1982), whereas the later plate boundary has been named Hornsund fault zone (Myhre et al., 1982).

New work has led to modification and refinement of the early tectonic model along the segment of the margin between Norway and Spitsbergen. The Hornsund fault zone was mapped in detail and is now thought to be located at or near the continent-ocean boundary (Myhre et al., 1982; Figs. 1, 2). A deep sedimentary basin (or series of basins) was identified and mapped between the Knipovich Ridge and the Hornsund fault zone (Schluter and Hinz, 1978), and was probably infilled largely during the post-early Oligocene rift phase of the margin's development (Myhre et al., 1982). In the more recent work summarizing the margin off Svalbard, Myhre et al. (1982) and Spencer et al. (1984) tentatively proposed a three-stage series of tectonic events (as shown in Fig. 1) involving: (1) sea-floor spreading south of the Senja Fracture Zone from about 58 Ma; (2) sea-floor spreading between the Senja Fracture Zone and the southern end of the Hornsund fault zone (anomaly 21; 48 Ma; mid-Eocene); and (3) sea-floor spreading opposite the Hornsund fault zone (anomaly 13; 37 Ma; early Oligocene). We emphasize the tentative nature of this scheme as no linear magnetic anomalies have been identified to date in the Greenland Sea.

The data outlined above imply a tectonic regime off Svalbard that evolved from several phases of strike slip to a phase of rifting, as new ocean floor was generated progressively farther north. This is clearly likely to constrain both the timing and the character of the Tertiary tectonic events on Spitsbergen.

The role of Svalbard's Tertiary fold and thrust belt in the development of the continental margin is not yet established in detail, but because the orogenic belt marks the approximate position of the early plate boundary, the De Geer Line (Fig. 1) and is of Paleogene age (Steel and Worsley, 1984), clearly it should be considered part of the framework of the Paleogene events described above (i.e., part of the pre-early Oligocene strike-slip system). This is consistent with the maps and observations of Lowell (1972) and

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[2]Svalbard includes the archipelago of islands in the area 74–81°N, 10–35°E; Spitsbergen is the largest of these islands.

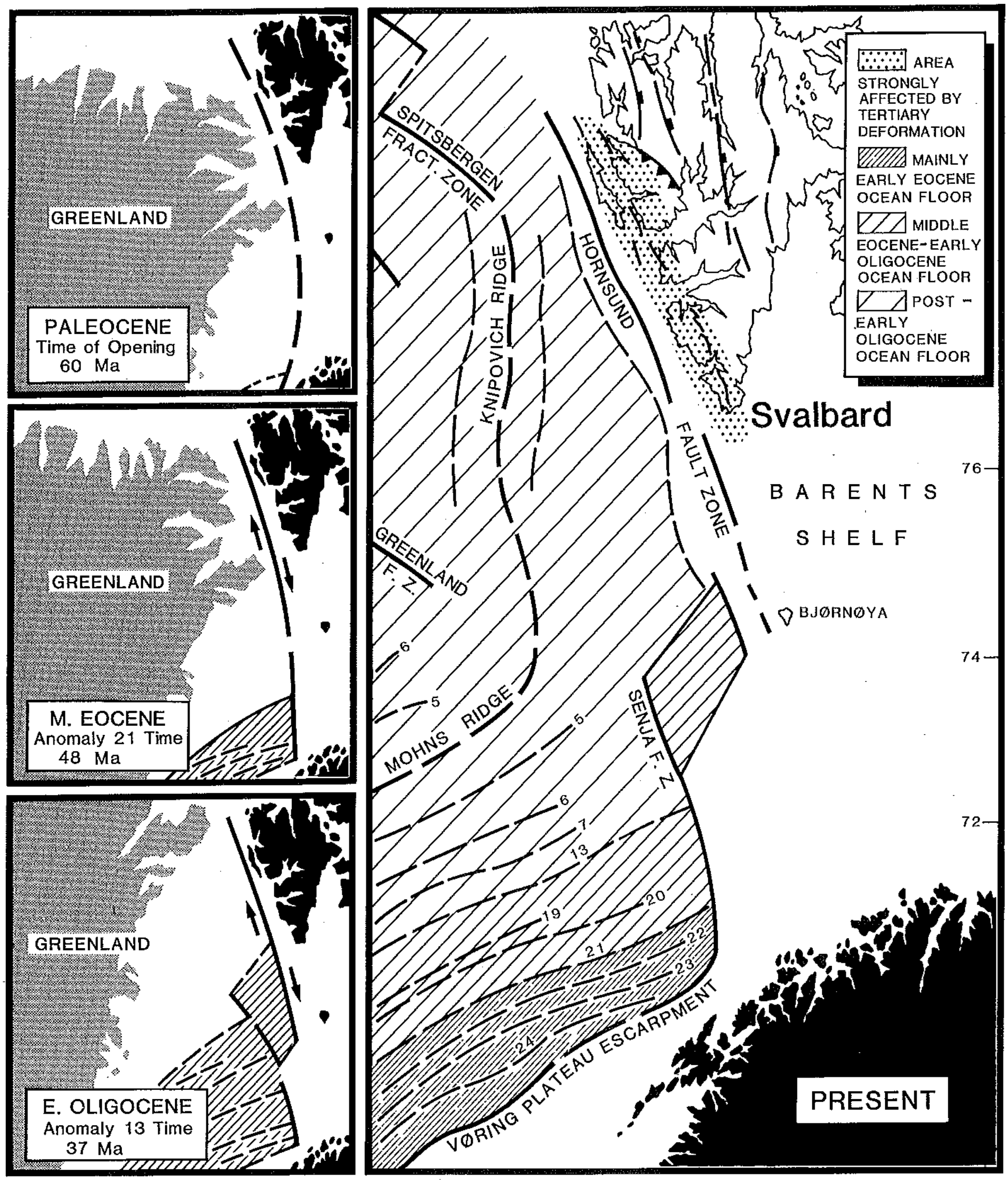

FIG. 1.—Present-day map of Svalbard margin together with an outline of the Tertiary displacement of Svalbard from Greenland during the opening of the Norwegian-Greenland Sea. Data from Grønlie and Talwani (1978), Myhre et al. (1982), Spencer et al. (1984).

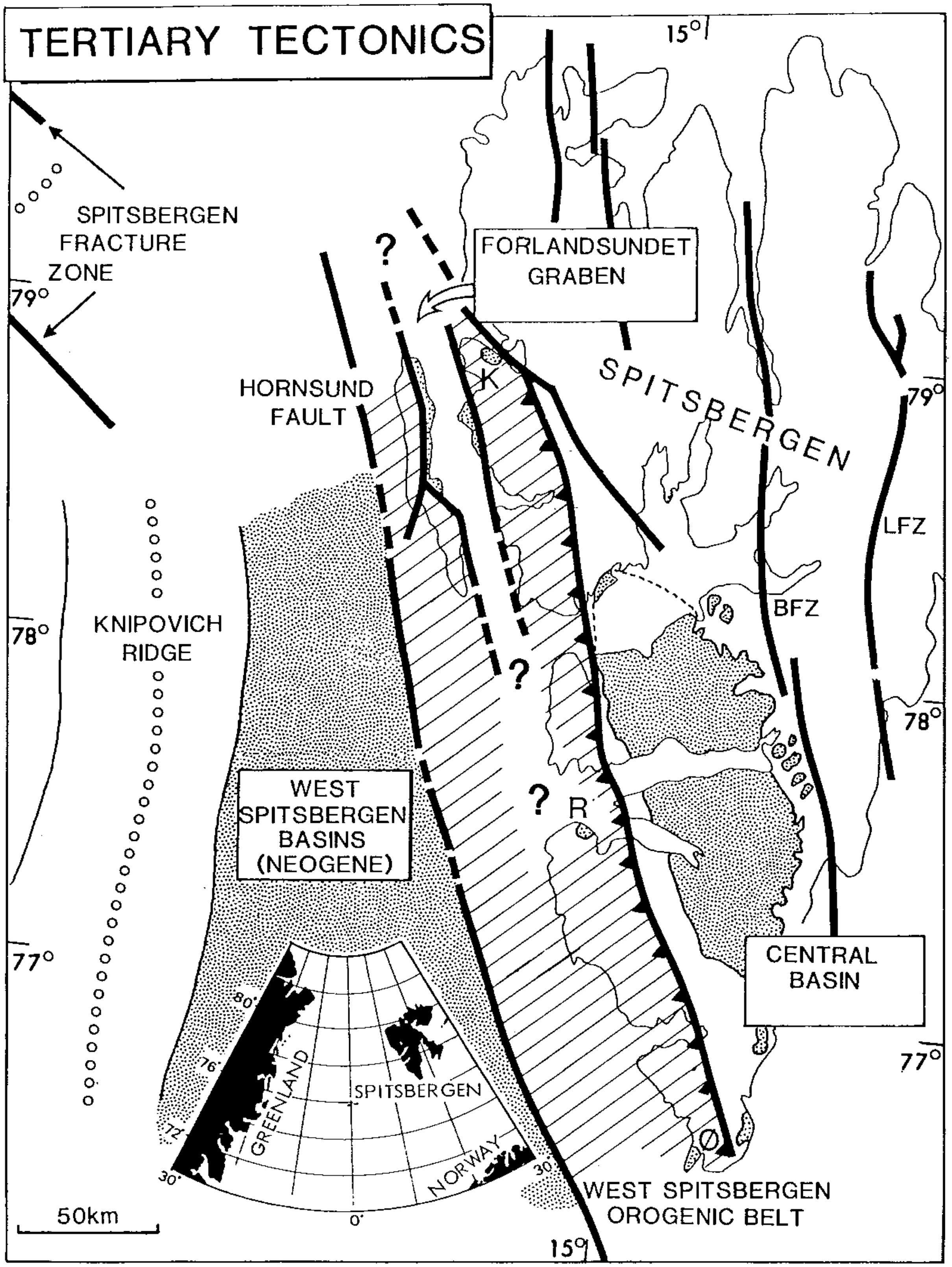

FIG. 2.—The Tertiary basins (stippled) and fold belt (lined) along the segment of the Svalbard margin discussed in text. Tertiary outliers at Kongsfjorden (K), Renardodden (R) and Øyrlandet (Ø) are still of uncertain age. BFZ, Billefjorden fault zone; LFZ, Lomfjorden fault zone.

of Kellogg (1975), which showed that some of the thrust faults steepen with depth and that some wrench faults can be traced laterally into overthrusts. Thus, it is likely that Svalbard's Tertiary orogenic belt is analogous to other major strike-slip fault systems (Lowell, 1972; see below). The timing of the earliest events, or at least of significant uplift along the fold and thrust belt, can be constrained more closely in relation to the infilling of the flanking Central Basin (Fig. 2). Major drainage reversal in the Central Basin, and accompanying influx of metamorphic rock fragments from the emerging orogenic belt, can be dated as late Paleocene (Steel et al., 1981). Thus there is evidence of major tectonic activity along the De Geer Line and adjacent areas somewhat earlier than the creation of the oldest dated ocean floor off northwest Norway. The climax of orogenic activity along western Spitsbergen is likely to have been about mid-Eocene, as judged by stratigraphic evidence from the Central Basin (Steel and Worsley, 1984), and we tentatively suggest that this climax corresponded with the migration of sea-floor spreading from the region south of the Senja Fracture Zone to the region between the Senja Fracture Zone and Bjørnøya (Fig. 1).

Within the framework of these regional constraints we discuss below some of the details of the tectonic and sedimentary events in the Central Basin, in the fold and thrust belt, and in the Forlandsundet Graben (Fig. 2). We contend that it is possible to distinguish times of significant compression or extension superimposed on the regional strike-slip regime (transpression and transtension in the terminology of Harland, 1969). We also consider briefly the post-early Oligocene basins beneath the present continental shelf and slope because they record the important evolution of the plate margin from strike slip to rifting.

THE CENTRAL BASIN

The Tertiary Central Basin of Spitsbergen is 200 km long and 60 km wide (Fig. 2), and contains as much as 2.3 km of clastic deposits, referred to as the Van Mijenfjorden Group by Harland et al. (1976). According to the vitrinite reflection studies of Manum and Throndsen (1978a), an additional overburden of 1.7 km has been eroded since the Eocene. Despite a considerable amount of paleontological research, the precise ages of the various formations in the Tertiary succession are not well established. However, there is a consensus of opinion that the lower part of the succession (Firkanten, Basilika, and Grumantbyen Formations; Fig. 3) is of early to mid-Paleocene age, on the basis of mollusc and foraminifera evidence (Ravn, 1922; Vonderbank, 1970; Birkenmajer, 1972). The upper part of the successon (Hollendardalen, Gilsonryggen, Battfjellet, and Aspelintoppen Formations; Fig. 3) is likely to be late Paleocene and early Eocene in age, on the basis of a latest Paleocene palynological dating at the base of Gilsonryggen Formation (Manum and Throndsen, 1978b). This two-fold division of the succession is adopted below.

Early to Mid-Paleocene Development

Stratigraphy and Sedimentation.—The lower part of the Central Basin succession, which thickens from less than 300 m in the northeast to more than 800 m in the west, consists of four main sequences (Fig. 4): (1) a sequence of alternating coals, shales, and sandstones (Todalen Member of the Firkanten Formation), which are of mixed fluvial and marine origin, and are interpreted as shallow-water deltaic deposits (Steel et al., 1981; Nøttvedt, 1985); (2) a sequence of alternating marine siltstone and sandstone sheets (Endalen and Kolthoffberget Members of the Firkanten Formation), with abundant low-angle and hummocky cross-stratification, and interpreted as shoreline and inner-shelf deposits, which are in part transgressive (Nemec and Steel, 1985); (3) a sequence of marine siltstone and shale units (Basilika Formation), showing repeated upward-coarsening motifs in some areas, and interpreted as outer shelf deposits; and (4) gradationally developing upwards from the Basilika Formation, a sequence of well-bioturbated fine-grained marine sandstones with some siltstones (Grumantbyen Formation), interpreted as possible inner-shelf deposits.

Figure 5 documents grain-size data from 10 laterally equivalent profiles through the Todalen and Endalen/Kolthoffberget Members of the Firkanten Formation, and shows how the coal-bearing sequence appears to occur in sub-basins separated by a structurally high block. In contrast, the upper members are sheet-like, but become finer grained southward. Paleocurrent indicators in both of these sequences, together with the lateral facies changes evident in Figure 5, suggest that the early Paleocene basin was infilled mainly from the north, northeast, and east. The lower part of the succession also thickens toward the southwest and the Hornsund fault zone (Fig. 4). The upward change from coal-bearing deposits to marine sheet sandstones implies a relative rise of sea level. The Basilika and Grumantbyen Formations are less well understood than the underlying succession, but they appear to be in part correlative (Fig. 3), and to thicken significantly to the west. The basin continued to be filled from the northeast during the deposition of these two formations.

Tectonic Setting.—We suggest that the tectonic setting for the early to mid-Paleocene Central Basin was extensional for the following reasons: (1) the sedimentary succession is of considerable thickness and thickens towards the De Geer Line; (2) igneous activity is indicated by a number of volcanic ash layers in the Firkanten Formation (Major and Nagy, 1972); and (3) there is no evidence for uplift (compression) in the west at this time. Assuming a constant rate of sediment input and increasingly asymmetric basin subsidence (Fig. 4), the overall transgressive to regressive character of the Firkanten to Grumantbyen Formation succession can be explained by a eustatic rise in sea level followed by a eustatic fall. We tentatively propose that the sea-level fall corresponds to the mid-late Paleocene eustatic sea-level drop proposed by Vail et al. (1977) on the basis of global coastal onlap curves.

Two lines of evidence suggest that extension may have been accompanied by a component of strike slip. The early Paleocene Central Basin appears to have been partitioned into several, partly connected, coal sub-basins that become slightly younger toward the north (Figs. 5, 6). Although by no means diagnostic of strike-slip deformation, age variation of this sort is consistent with such an interpretation.

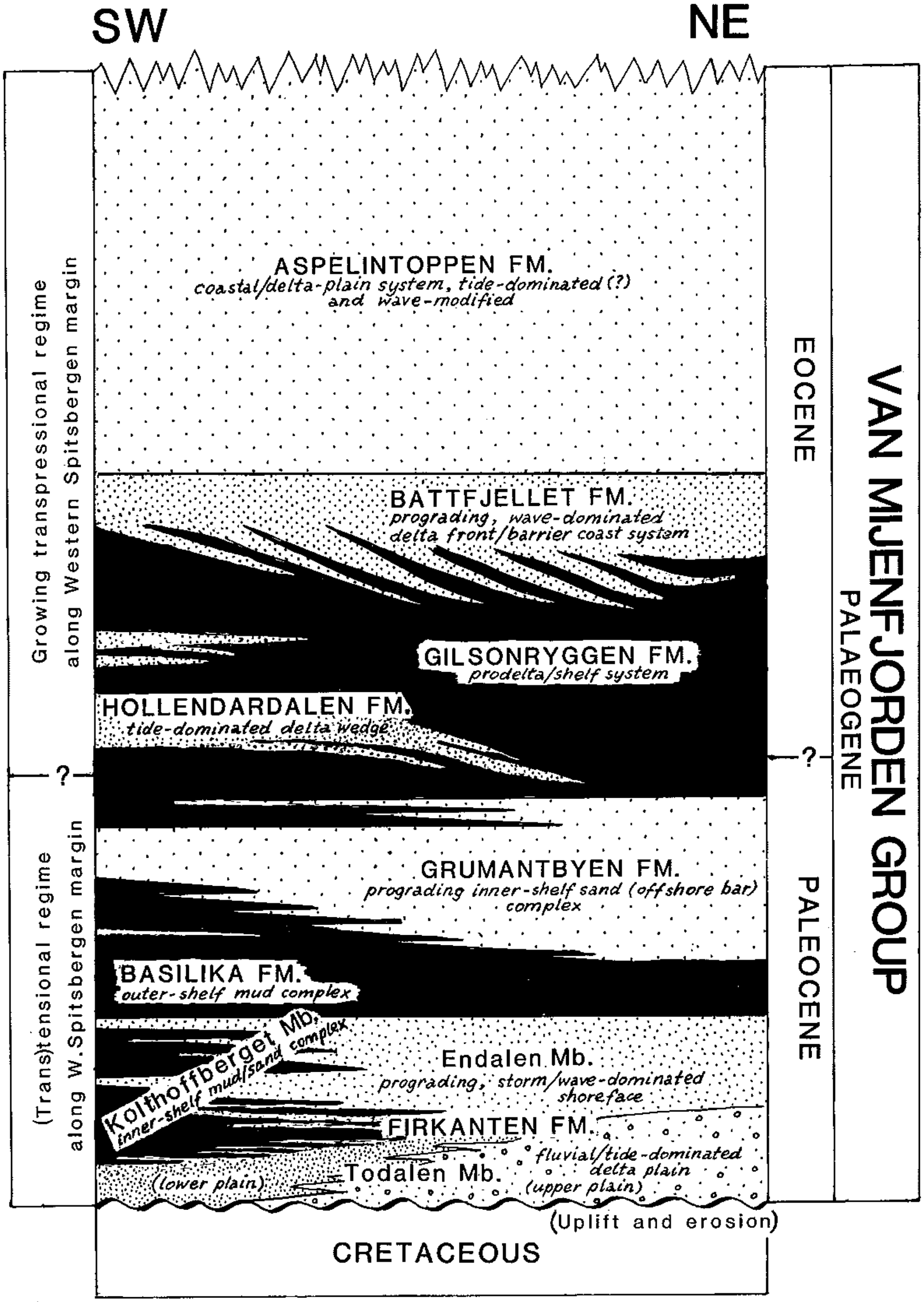

FIG. 3.—Summary of the stratigraphy of the Central Basin of Spitsbergen (Wojtek Nemec, personal commun., 1985). The geometry of the sandstone units is shown schematically.

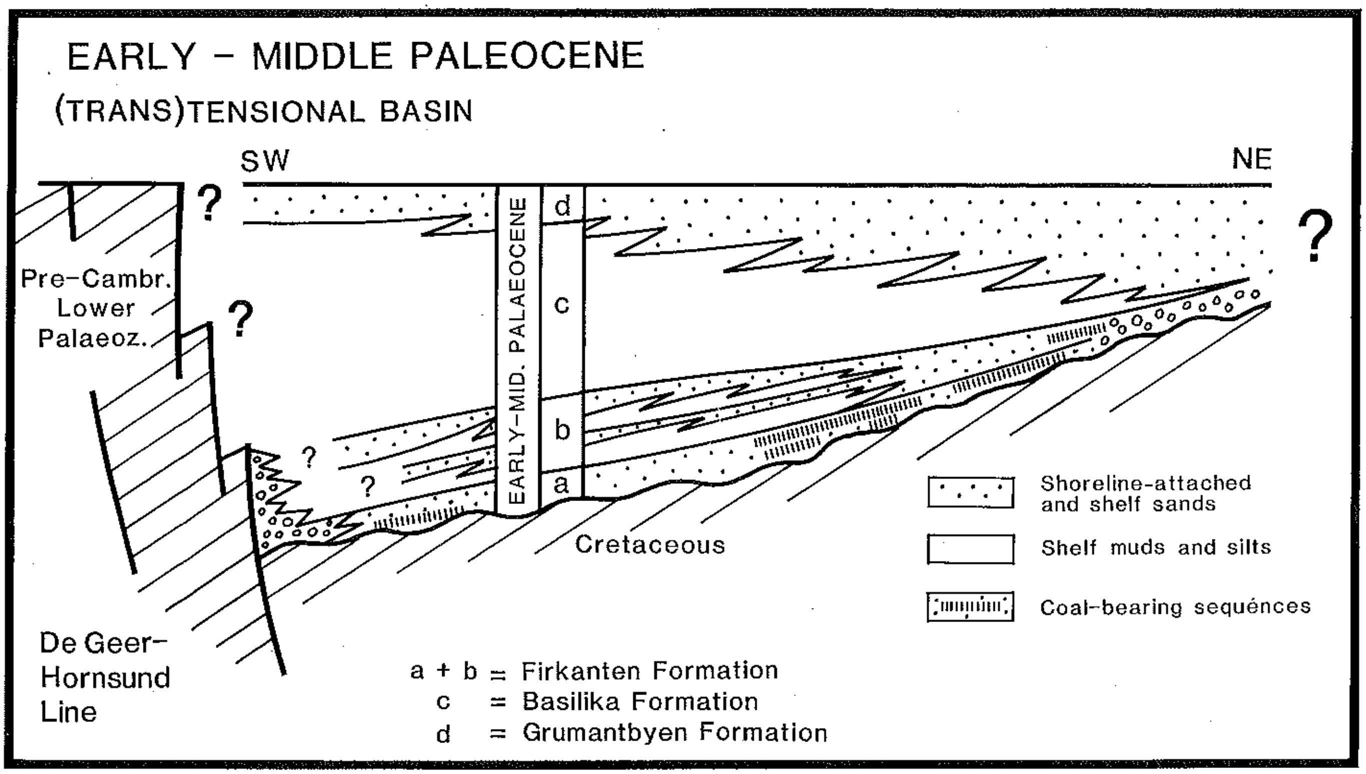

FIG. 4.—Schematic diagram of the main stratigraphic elements in the early to mid-Paleocene Central Basin, between Isfjorden and Van Mijenfjorden. Note that the asymmetry of the basin developed mainly after mid-Paleocene time, and that infilling was mainly from the east and northeast.

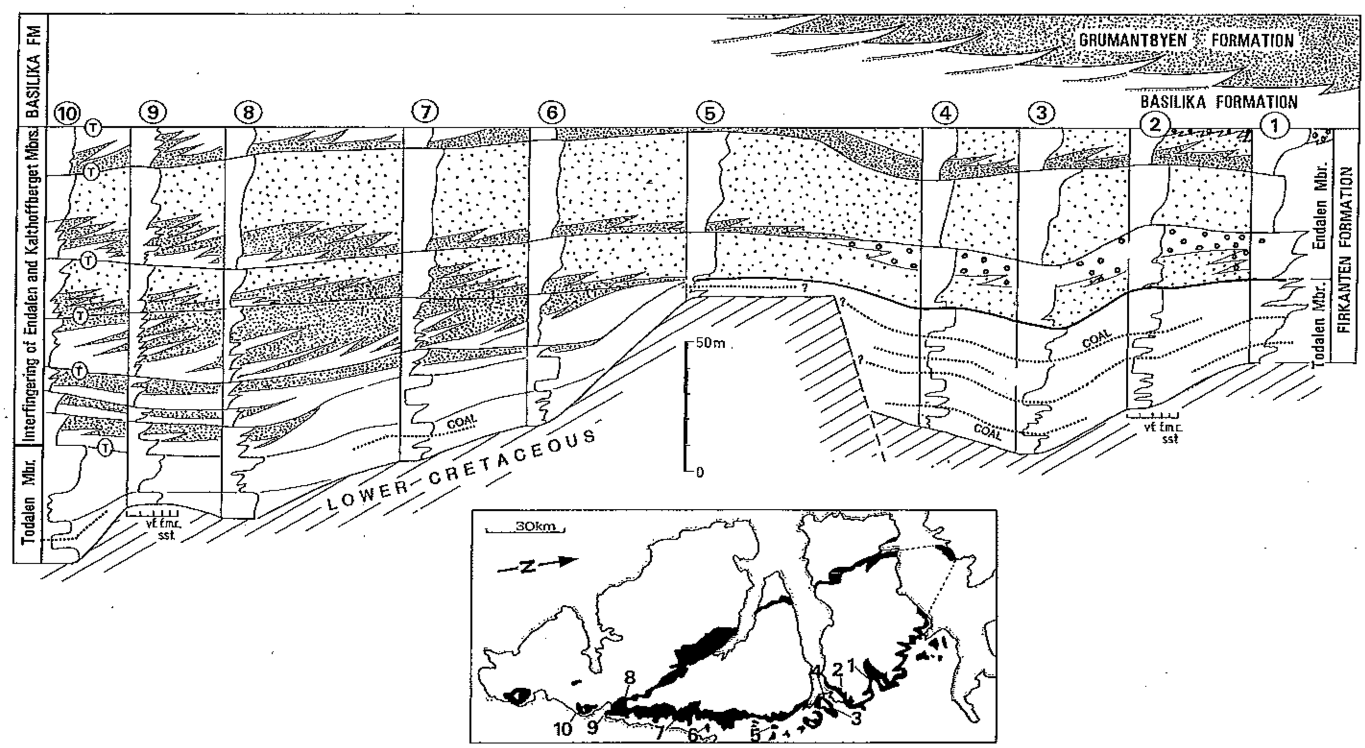

FIG. 5.—Ten correlated, measured sections across part of the Central Basin. The early coaly strata formed in several sub-basins whereas the later wave-generated sandstones (stippled) are sheet-like across the basin (the denser shading delineates more distal facies). The correlations suggest possible northwards younging of the coaly strata.

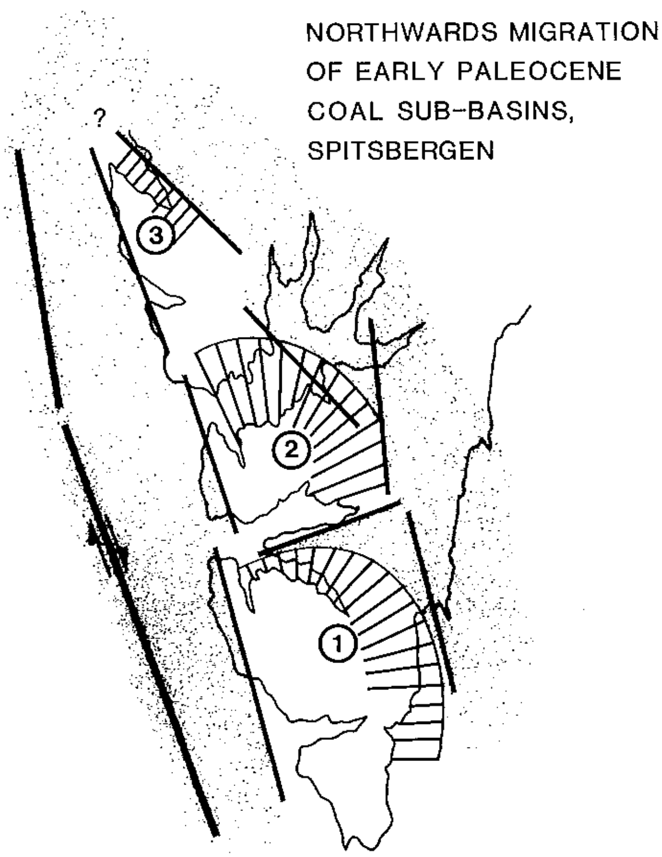

FIG. 6.—Speculative model of coal-basin development on Spitsbergen implying northwards migration and onlap of strata with time (1–3). The sub-basins are unshaded; the likely coal-forming areas are lined. The hinterland is shaded. Thick black lines show zones of faulting or flexure.

The other line of evidence consists of early Paleocene strike-slip structural features in the Wandel Sea Basin of northern Greenland (Hakansson and Schack Pederdsen, 1982). At that time, northern Greenland was adjacent to Svalbard, west of the De Geer Line.

Coal.—The importance of coal deposits (currently exploited by both Norwegian and Soviet communities) in the oldest part of the Paleocene succession is well known (e.g., Major and Nagy, 1972; Harland et al., 1976). Coal has a particular significance in the model outlined above. The coal-bearing strata formed during the earliest subsidence and extensional break-up along the eastern flank of the De Geer Line, and coal seams are best developed along the margins of the various sub-basins. Potential coal-forming conditions then disappeared in each sub-basin with relative sea-level rise, and the gradual 'drowning' of the early structural highs, and the onset of more open-marine conditions.

Late Paleocene–Early Eocene Development

Stratigraphy and Sedimentation.—The upper part of the succession in the axial region of the Central Basin is more than 1.5 km thick and consists of the Hollenderdalen, Gilsonryggen, Battfjellet, and Aspelintoggen Formations (Fig. 3). Palynological dating of the lowermost part of this succession (the lower part of the Gilsonryggen Formation) suggests a latest Paleocene age (Manum and Throndsen, 1978b).

The Hollenderdalen Formation consists of as much as 150 m of sandstone in the western part of the basin but thins toward the basin center. The sequence has been interpreted in terms of an eastward-prograding shallow-water deltaic system on account of paleocurrent indicators, wave and-tide-generated stratification, and occasional thin coals (Dalland, 1979).

Gilsonryggen Formation shales and the overlying Battfjellet Formation sandstones form a large-scale, coarsening-upward sequence which thins from more than 900 m in the west to less than 300 m in the eastern part of the Central Basin (Kellogg, 1975). Thin sandstone interbeds within the Gilsonryggen Formation appear to be turbidites (T_{abc} type) and tend to pinch out eastwards (Steel et al., 1981).

The Battfjellet Formation is 60 to 200 m thick and consists mainly of siltstones and sandstones, with abundant hummocky cross-strata and other wave-generated sedimentary structures. On account of such facies, the upward-coarsening nature of the sequence, and the presence of coalbearing deposits above, the Battfjellet Formation is interpreted as the product of a prograding deltaic and barrier coastline (Steel, 1977). An additional striking aspect of the formation is the presence, in the western part of the basin, of large-scale (200 m amplitude) clinoforms, which can be seen on mountainsides to cut obliquely through the formation and to continue into the underlying shales (Kellogg, 1975). This demonstrates both eastward-offlapping and the broad lateral time equivalence of upper Gilsonryggen, Battfjellet, and lowermost Aspelintoppen Formations. These features as well as a general eastward migration of the depocenter during late Paleocene and Eocene time, are illustrated in Figure 7.

The Aspelintoppen Formation is more than 1 km thick in places and consists of alternations of sandstones, siltstones, shales, and coals. Plant debris is abundant, as well as petrified tree fragments. Soft sediment deformation is common throughout the succession. The coal seams, lack of marine fauna, and presence of channelized sandstones and fining-upward sequences suggest a deltaic or coastal plain origin for the formation (Steel et al., 1981).

Tectonic Setting.—There was a significant change in the tectonic setting of the Central Basin during the late Paleocene. Sandstones of the Hollenderdalen and Battfjellet Formations were clearly derived from the western side of the basin, in contrast to the pre-late Paleocene deposits, which were transported into the Central Basin from the east and northeast. This drainage reversal, coupled with the evidence of increasingly abundant metamorphic rock fragments in the upper part of the succession, suggests pronounced uplift of the western margin of the Central Basin, associated with initiation of the fold and thrust belt of western Spitsbergen. Regional arguments suggest transpressional deformation (Myhre et al., 1982).

The Central Basin, from late Paleocene time, was thus analogous to a foreland basin, depressed by flexural loading of the thrust sheets. Differential compaction of the thick shale succession, which is thickest in the west, may have

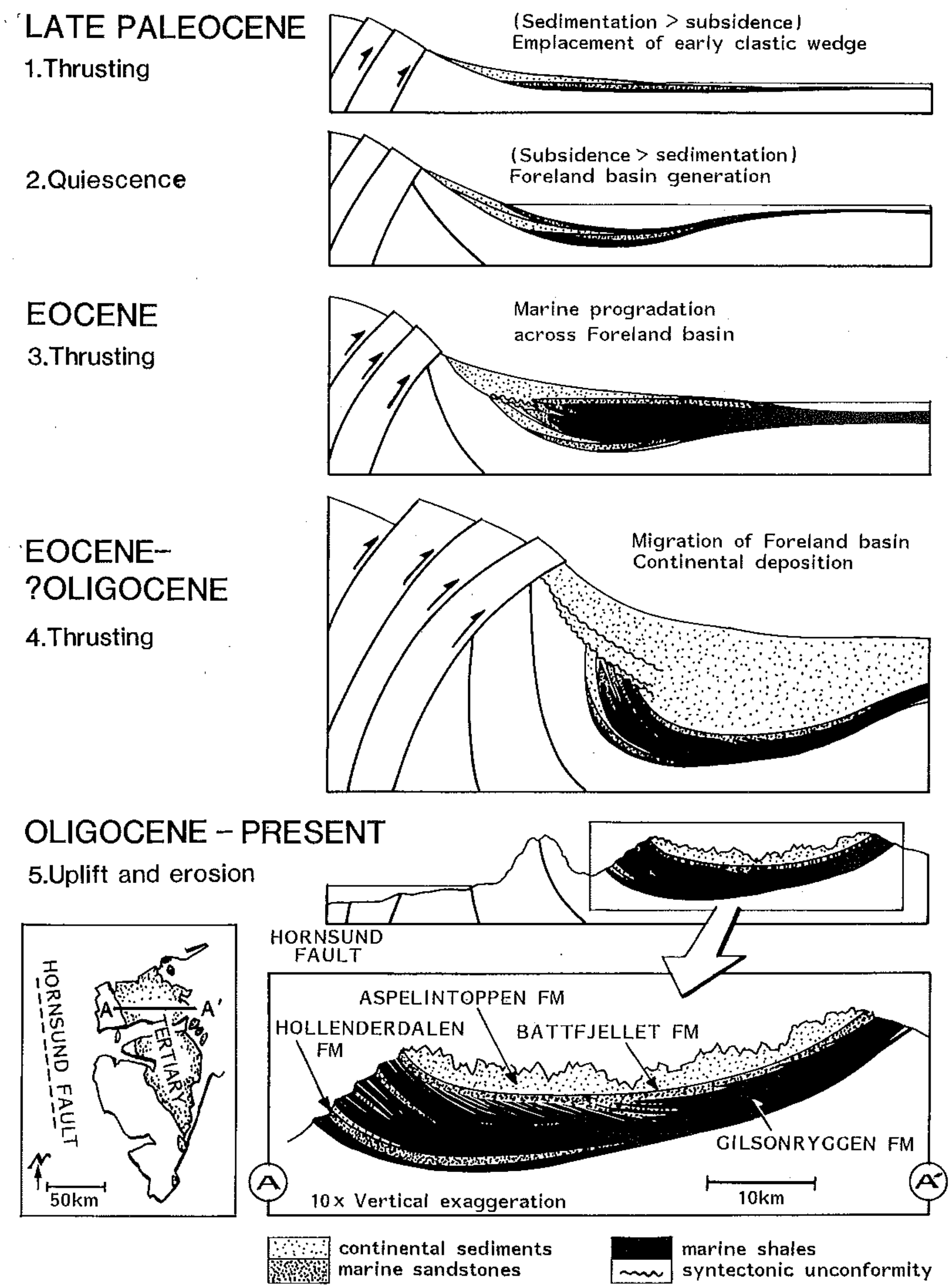

FIG. 7.—Series of diagrams showing the suggested relationship of the late Paleocene–?Oligocene development of the Central Basin and tectonic movements in the fold and thrust belt of western Spitsbergen. Note the large-scale clinoforms in the Battfjellet Formation, one of the more striking responses to hinterland uplift and thrusting. There is an eastward migration of the depocenter with time of at least 20 km.

permitted additional accumulation of sand. There is also evidence of eastward migration of the basin's depocenter during continued eastward movement of the thrust sheets. The eastward shift is on the order of 20 km, as inferred from a comparison of the position of the eastern margin of the latest Paleocene depocenter and the position of the present basin margin (Fig. 7). Manum and Throndsen (1978a) reached a similar conclusion from vitrinite studies.

THE FOLD AND THRUST BELT OF SPITSBERGEN

The fold and thrust belt of western Spitsbergen is some 300 km long and less than 50 km wide (Fig. 2), and is characterized by wrench faults, thrust faults, and asymmetric folds. The fold belt terminates somewhere north of Bjørnøya (Fig. 1) where only extensional, post-Paleozoic tectonism has been recorded (Horn and Orvin, 1928; Gjelberg, 1981). Figure 8 illustrates the present-day fault pattern on Spitsbergen. Most of the faults of western Spitsbergen are of Tertiary age or were reactivated in Tertiary time. The cross sections of Figure 9 illustrate the internal character of the fold belt in the vicinity of Hornsund. The severe deformation along the fold belt has been a subject of study for a long time (Nordenskiold, 1866; Orvin, 1940), but the first clear suggestions that it was related to the opening of the Norwegian-Greenland Sea were made by Harland (1965, 1969), who interpreted the deformation in terms of compression generated by the northward movement of Greenland against Spitsbergen. Lowell (1972) emphasized the strike-slip regime of this orogenic belt and concluded that such belts differ from those related to subduction "in having a discrete pattern of *en echelon* folds, in having a narrow zone of deformed sedimentary cover with a much greater degree of basement involvement, in having presumably different cross-sectional profiles of thrusts, upthrust versus downward flattening, in being shorter in length, and probably in lacking alpine ophiolites and lacking metamorphism." Kellogg (1975) noted that the fold belt consists of three zones that have reacted somewhat differently to stress (Fig. 8): a southern zone of thrusting (Sørkapp to Bellsund), a middle zone of folding (Bellsund to Isfjorden), and a northern zone of thrusting (Isfjorden to Kongsfjorden).

The southern zone (south of Bellsund) is dominated by gently to moderately dipping thrust faults (Fig. 9; CC′ in Fig. 10) and normal faults (generally orientated parallel with the coast). Thrusting was towards the northeast or east-northeast and involved rocks of Precambrian to Paleogene age (Birkenmajer, 1981). Some of the thrust surfaces can be mapped as becoming steeper at depth (Fig. 10). Normal faults (probably younger than the thrust faults) with down-to-the-west displacements are common in western Sørkapp Land (Fig. 8). Minor northeast-striking normal faults are also present in the same area, as well as farther east.

In the central zone (Nordenskiold Land), thrusts are generally absent (BB′ in Fig. 10), but steeply dipping, basement-involved reverse faults are probably responsible for a series of en echelon asymmetric folds developed along the steep, eastward-dipping western flank of the Central Basin. The only obvious thrust fault is located near Grumantbyen. It is, however, possible that the normal faults present in the Lower Paleozoic–Precambrian basement of western Nordenskiold Land were thrust faults during the main orogenic phase (most associated structures indicate so), but have later been reactivated as normal faults during post-orogenic extension. Northeast-striking normal faults are also present in the area.

In the northern zone (between Isfjorden and Brøggerhalvøya; AA′ in Fig. 10), the rocks are tightly folded about northwest-trending axes, with amplitudes and wavelengths of 0.5 to 1 km (Harland and Horsfield, 1974). Prominent faults, also striking to the northwest, have been observed, some of which are thrust faults (Fig. 8). North- and northeast or east-striking faults are present, mainly in the areas where pre-Caledonian rocks are exposed (Kellogg, 1975). On Brøggerhalvøya, west-northwest-striking thrust faults are associated with tight folds suggesting significant northerly movements (Challinor, 1967). The most prominent tectonic element in the area is the Forlandsundet Graben, located along north-northwest-striking faults. The sedimentary succession in the graben is slightly deformed, suggesting that it developed during or prior to the last deformation phase.

The thrusting in the fold belt was directed mainly toward the east or east-northeast (Birkenmajer, 1981), but in the Brøggerhalvøya area it was towards the northeast. West-directed thrusting has been recorded only from the St. Jonsfjorden and Bellsund area (Fig. 8), but magnitudes are relatively small (<1 km). The crustal shortening due to folding and thrusting has been estimated as about 10 km in the north and 15 km in the south (Birkenmajer, 1981). Birkenmajer also suggested that the entire west coast of Spitsbergen, between Kongsfjorden and Sørkapp has been translated to the north-northwest from a southerly location, possibly by some 30 km, and that at Kongsfjorden this zone collided with the rigid mass of northwest Spitsbergen, causing the anomalous orientation of the structural trends on Brøggerhalvøya.

The notion that thrusting along western Spitsbergen was a high-level expression of wrench-faulting along the De Geer Line was first implied by Lowell (1972). Later mapping has shown more clearly that some of the thrust faults steepen with depth and that some wrench faults can be traced laterally into thrusts (Kellogg, 1975). This hypothesis, that the thrusts are connected with wrench faults, for example, as part of a large flower structure along western Spitsbergen, is consistent with the results of the recent marine geophysical studies (Myhre et al., 1982) west and south of Spitsbergen. The presence of latest Paleocene and Eocene oceanic crust south of Spitsbergen implies contemporaneous, large-scale strike slip along western Spitsbergen. Furthermore, the climax of transpression in the orogenic belt, dated as Eocene from evidence discussed from the Central Basin, may be related to the mid-Eocene sea-floor events reported by Myhre et al. (1982), namely the northwestward migration of the new rift margin to the segment north of the Senja Fracture Zone (Fig. 1). However, we emphasize that the amount and large scale of the thrusting seen in western Spitsbergen primarly indicates that there was significant crustal shortening across parts of western

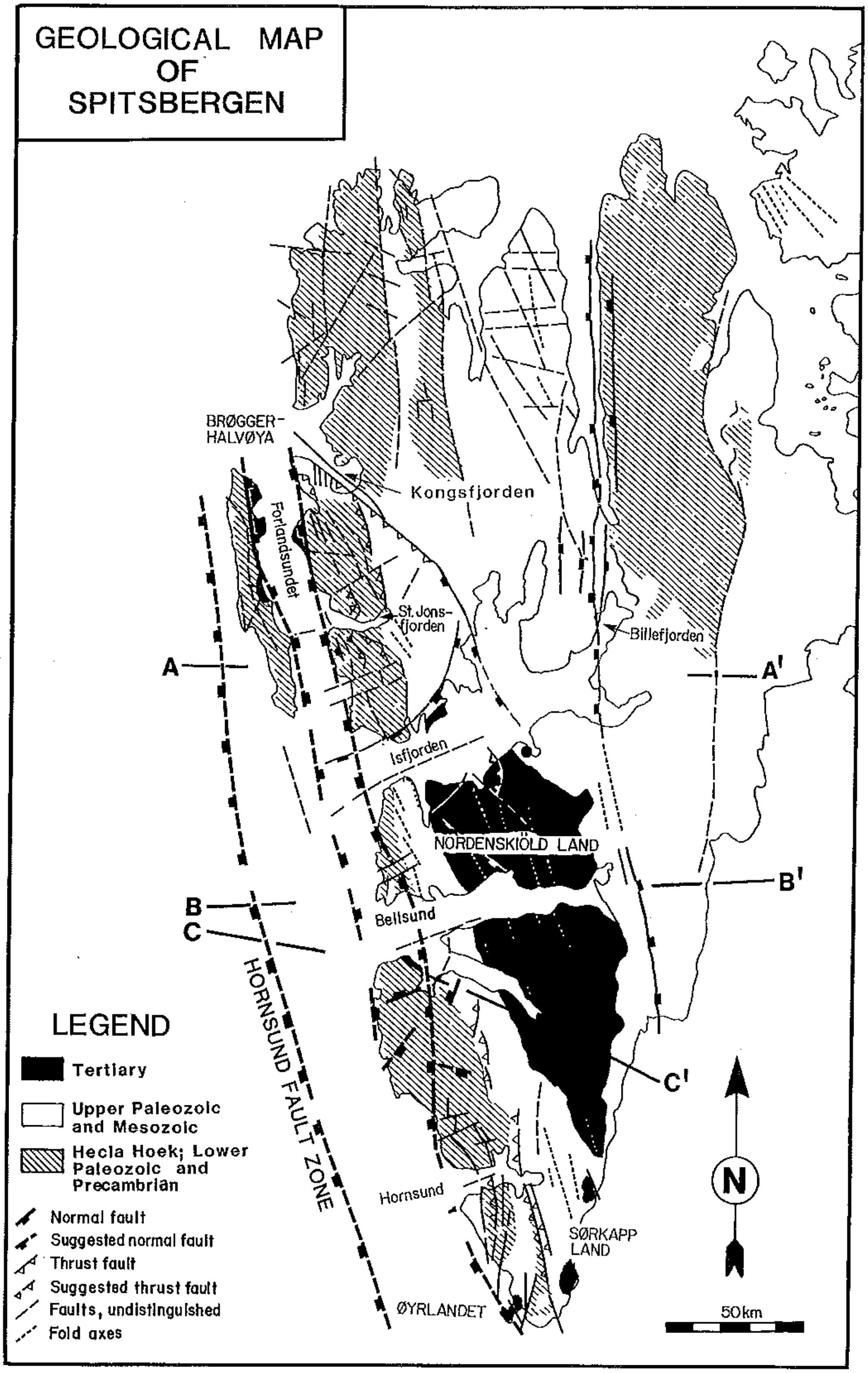

FIG. 8.—Simplified structural map of Spitsbergen. Lines AA′, BB′ and CC′ are the lines of section shown in Figure 10.

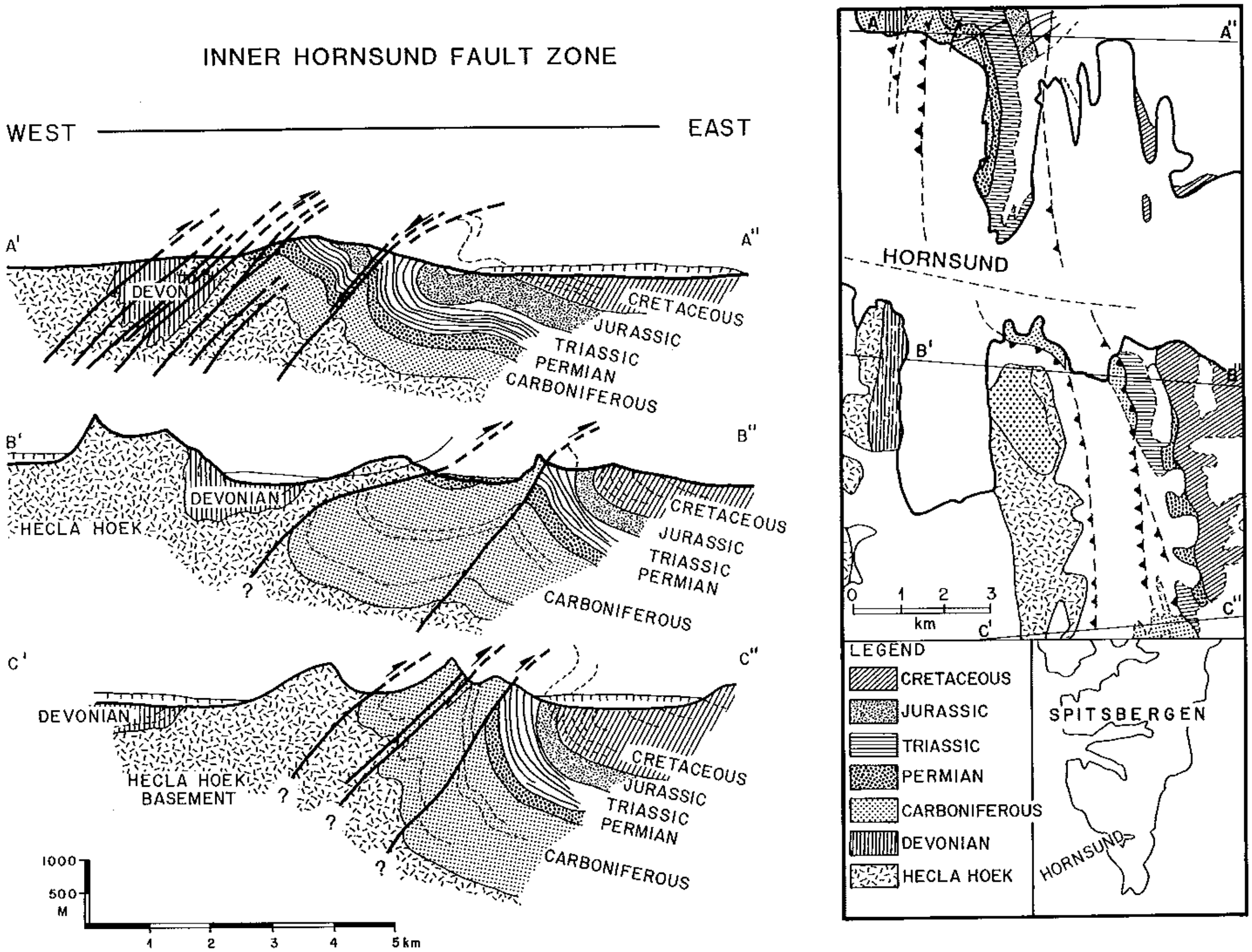

FIG. 9.—Map and representative cross sections of the fold belt in the inner Hornsund area of southern Spitsbergen.

Spitsbergen. This may have been caused by significant curvature along parts of the plate boundary between Greenland and Spitsbergen or by a non-orthogonal relationship between the De Geer Line and the bounding spreading ridges (Crane et al., 1982). There has been insufficient detailed mapping of the fold-and-thrust belt, as yet, to comment further on the likelihood of *most* of the thrusts being attached to wrench faults, or whether there is significant detachment at depth.

A STRIKE-SLIP BASIN WITHIN THE FOLD-AND-THRUST BELT

Tertiary rocks are exposed in three areas within the zone of pronounced Tertiary deformation in western Spitsbergen: Forlandsundet, Renardodden (R in Fig. 2), and Øyrlandet (Ø in Fig. 2). The largest and best exposed area, the fault-bounded Forlandsundet Graben (Atkinson, 1962), contrasts with the Central Basin both in the character of the contained sedimentary succession and in its structural style.

Stratigraphy and Sedimentation

Forlandsundet Graben is some 80 km in length and 25 km wide, but shows only scattered exposures along both margins (Fig. 11). Despite the fragmentary nature of the stratigraphic evidence, a composite succession with an apparent thickness of as much as 5 km has been established (Rye-Larsen, 1982). Along the eastern and southwestern margins of the basin, alluvial-fan deposits, characterized by poorly sorted, unstratified conglomerate beds of debris-flow origin, and finer-grained, flat-stratified and cross-stratified conglomerates, originating from streamflow, have been documented. In the southwestern area, the fan deposits appear to grade laterally (basinwards) into sequences of black shales, siltstones, and cross-stratified/ripple-laminated sandstones, which have been interpreted as fan-delta and nearshore deposits on account of their structures and facies motifs (Rye-Larsen, 1982). In the more than 3-km-thick succession in the northwestern region, there are black shales with associated turbidite and conglomerate beds, inter-

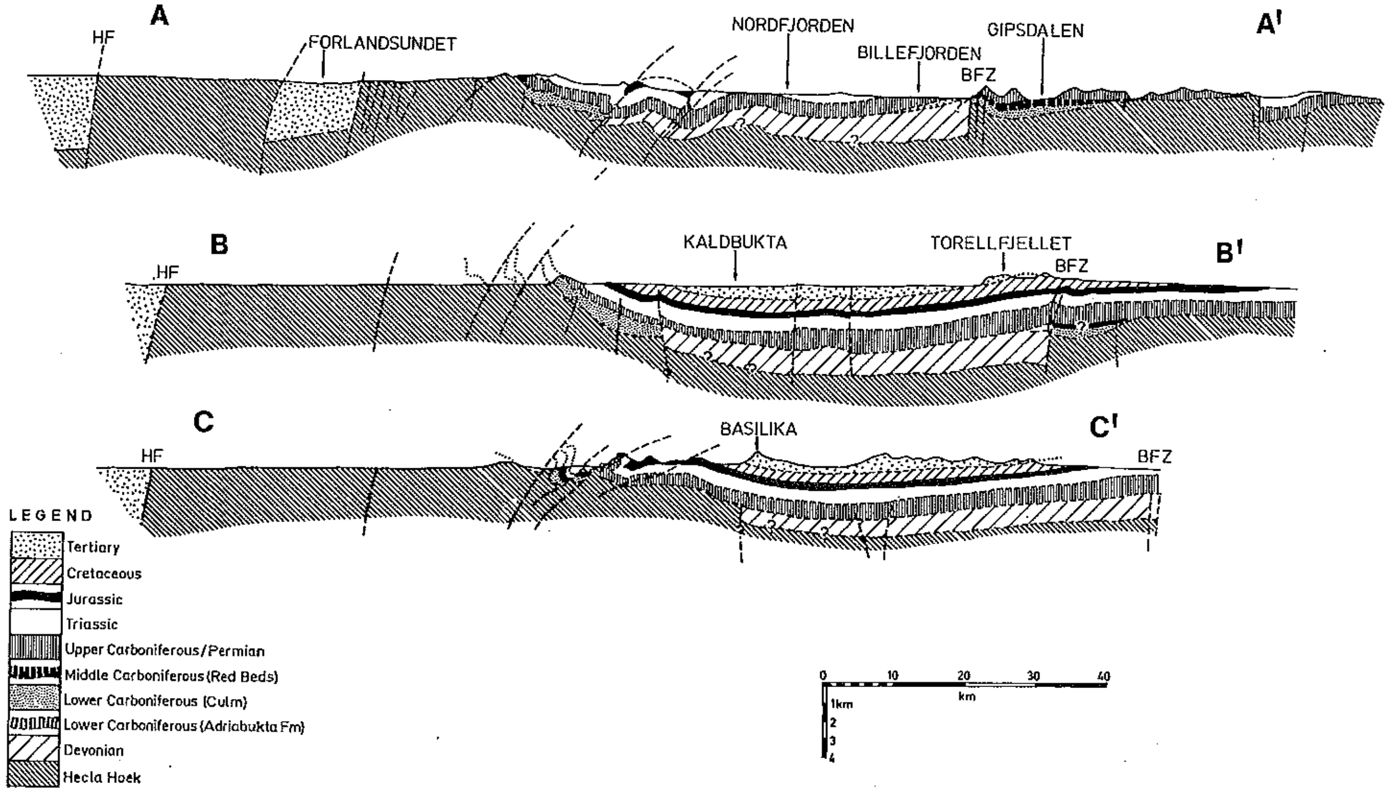

FIG. 10.—Large-scale cross sections across Spitsbergen along the lines shown in Figure 8.

preted as a submarine-fan association. The marginal alluvial-fan sequences (Selvagen, Sarsbukta, and Sarstangen Formations) are laterally equivalent to the nearshore and shallow-marine deposits (Sesshøgda, Reinhardpyten, Krokodillen, and Marchaise Lagune Formations) and to the submarine-fan succession (Aberdeenflya Formation; Fig. 17 below).

Dating of the Forlandsundet Group by Manum (1962) and Livshits (1965; 1974) has suggested Eocene to early Oligocene ages. Recent palynological dating on samples from the eastern margin of the graben, from the Sarstangen Formation, indicates an age not younger than Eocene. This is based mostly on the occurrence of the dinoflagellate *Svalbardella Cooksonia* (W. Morgan, personal commun., 1984). Additional recent dating using foraminifera (Feyling-Hansen and Ulleberg, 1984) suggests an Oligocene age for Sarsbukta Formation.

Origin of Forlandsundet Graben

Available dating suggests that the Forlandsundet Graben developed partly during and partly after the main interval of deformation. However, as in most other ancient strike-slip basins, it is relatively easy to demonstrate syn-depositional, dip-slip faulting, but difficult to find evidence of the strike-slip component of movement. Active subsidence during sedimentation is reflected both in the great thickness and coarseness of this small basin's succession. Lateral facies changes are abrupt adjacent to the bounding faults. The most persuasive evidence for strike slip is the regional tectonic setting, less than 20 km from the strike-slip De Geer Line. Although the local evidence is inconclusive, the following features also suggest strike slip along the margins of the graben:

(1) Metaconglomerate clasts in Selvagen Formation are offset by at least 3 km from their source area (Rye-Larsen, 1982).
(2) The measured stratigraphic thickness of the succession within the graben is at least three times the maximum vertical stratal thickness inferred from marine geophysical surveys along the basin axis (Guterch et al., 1978). This is a feature typical of other strike-slip basins. Because of depocenter migration in strike-slip basins, and progressive basement onlap of strata, stratigraphic thicknesses are commonly many times greater than true vertical thicknesses (Crowell, 1974; Steel and Gloppen, 1980).
(3) Horizontal slickenside striae are abundant along faults cutting the Forlandsundet Group. Paleostress azimuths have been calculated from micro-structural data in the southwestern part of the basin. These suggest a principal direction of extension of N60°W, which is consistent with right-lateral transpression on north-northwest-striking faults.

Regional and local evidence for strike slip combined with

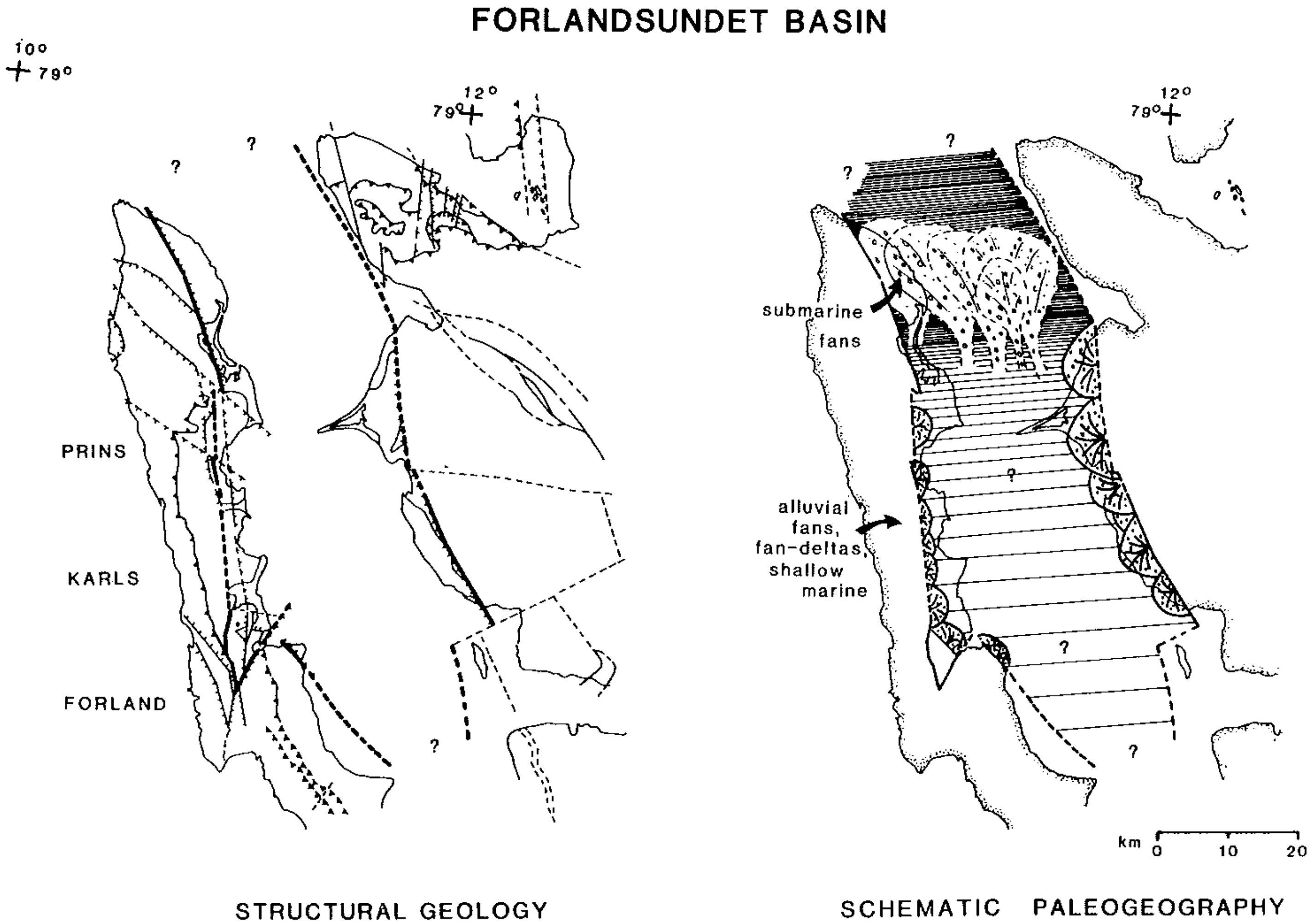

FIG. 11.—Maps of the Forlandsundet Graben showing structure and schematic paleogeography. Bold lines are the major faults: fine lines are minor faults. Thrust faults indicated by sawteeth in upper plate. The more densely spaced lines in the graben's axial region schematically indicate deeper water.

available age control thus suggests that Forlandsundet Graben originated and developed in a transpressional strike-slip regime (Steel et al., 1981). This conclusion is at odds with earlier opinion (e.g., Harland and Horsfield, 1974), which assumed that Forlandsundet Graben was entirely post-orogenic, because it appears to cut the orogenic belt.

The co-existence of compressional and extensional features along strike-slip zones is well known (e.g., Crowell, 1974). However, the development of the Forlandsundet Graben in a transpressional regime is still difficult to explain, especially considering the size of the graben (>25 km wide and several kilometers deep).

There are two possible hypotheses for the early development of the Forlandsundet Graben within the setting of the orogenic belt: (1) The graben is related to extension adjacent to a curved strike-slip fault zone (Fig. 12A). This hypothesis is based on plaster cast modelling carried out in cooperation with John Sales at the Dallas Research Division of Mobil Oil Company. It shows that deep and narrow elongated grabens may develop behind bends in the strike-slip system owing to stress release, whereas overthrusting and folding occur around the bends. (2) The graben originated as a collapse graben in the central part of the uplifted and arched orogenic belt (Fig. 12B).

Later extension and deepening of the graben probably took place during the extensional phase from earliest Oligocene time as suggested by Harland and Horsfield (1974). This is, however, difficult to document as only the marginal parts of the graben are exposed today. The proposed sequence of events in the fold belt is summarized in Figure 13.

The other small areas on western Spitsbergen with Tertiary strata, Renardodden and Øyrlandet (Fig. 2), may also be fragments of strike-slip basins or they may be related to post-early Oligocene rifting on the Svalbard margin. The former setting is likely for Renardodden strata, as suggested by recent dating of the strata as Paleocene (Theidig et al., 1980) and late Eocene to early Oligocene (Head, 1984).

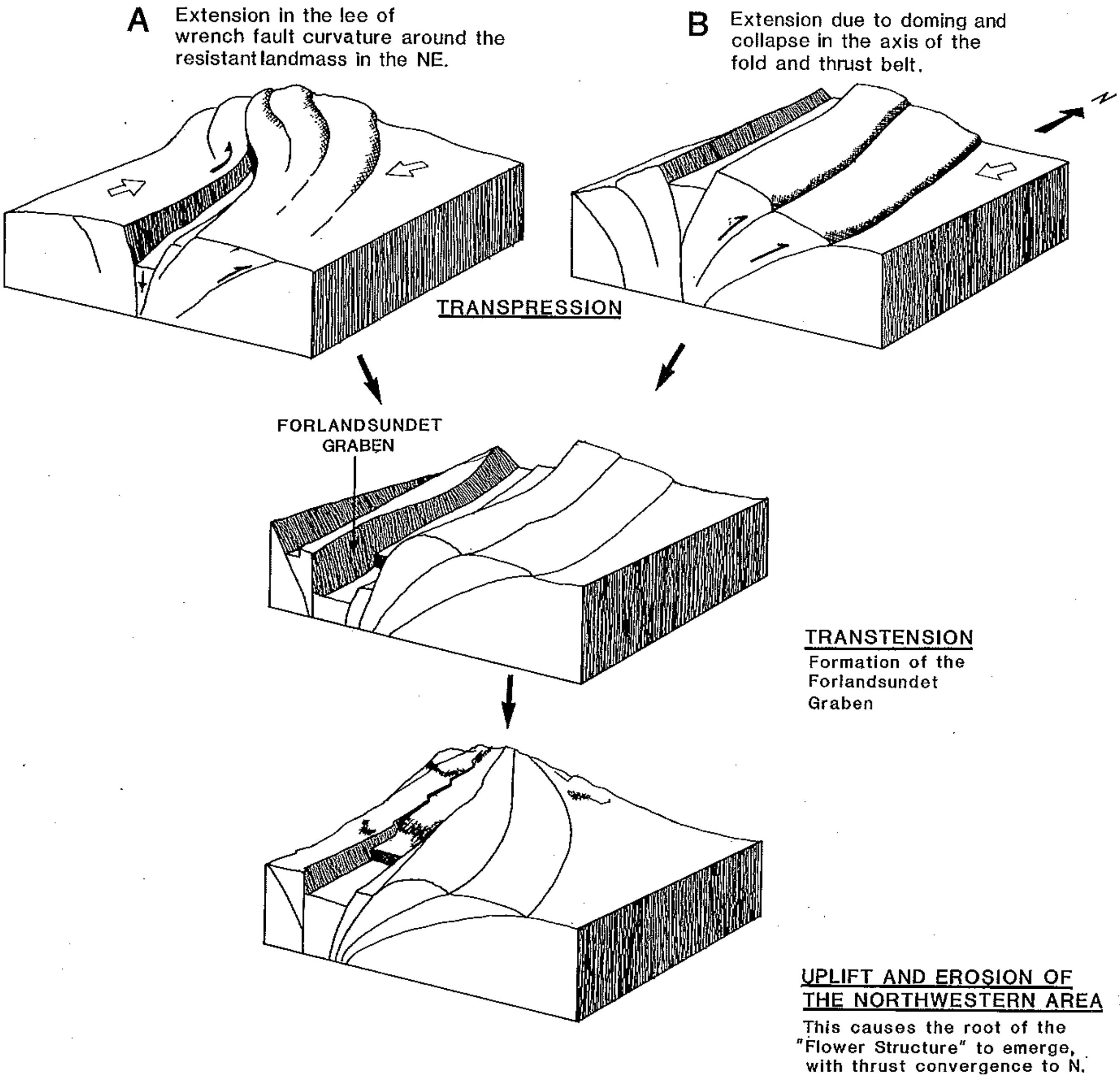

FIG. 12.—Schematic block diagrams showing the possible structural development of the Forlandsundet Graben in relation to the fold and thrust belt of western Spitsbergen. Hypothesis A suggests the graben developed from stress release in relation to fault-zone curvature and to a rigid northwest Spitsbergen landmass. Hypothesis B suggests that the graben may be a collapse feature in the fold belt.

THE BASINS OF THE RIFT MARGIN

The evolution of the continental margin of Svalbard from an oblique-slip to a dip-slip regime, took place in a diachronous manner. The southernmost segment of the margin was subject to rifting by latest Paleocene time, but this did not happen in the north until the early to mid-Oligocene (see Myhre et al., 1982; Eldholm et al., 1984). The post-early Oligocene rifting off Svalbard produced a characteristic suite of sedimentary basins, which partly cut and partly overlap the western edge of the older oblique-slip basins and the orogenic belt of western Spitsbergen. These sedimentary basins, locally up to 7 km deep, have long been recognized to cover an extensive area of the present continental shelf and slope (Eldholm and Ewing, 1971; Sundvor, 1974; Eldholm and Talwani, 1977; Sundvor et al., 1977; Schülter and Hinz, 1978). This region of young Tertiary deposits is bounded by the Knipovich Ridge to the west and the Hornsund fault zone to the east (Figs. 2, 14), and is floored predominantly by oceanic crust. The continuity of the basement reflection suggests that the continent-ocean boundary is located at or near the Hornsund fault zone (Myhre et al., 1982).

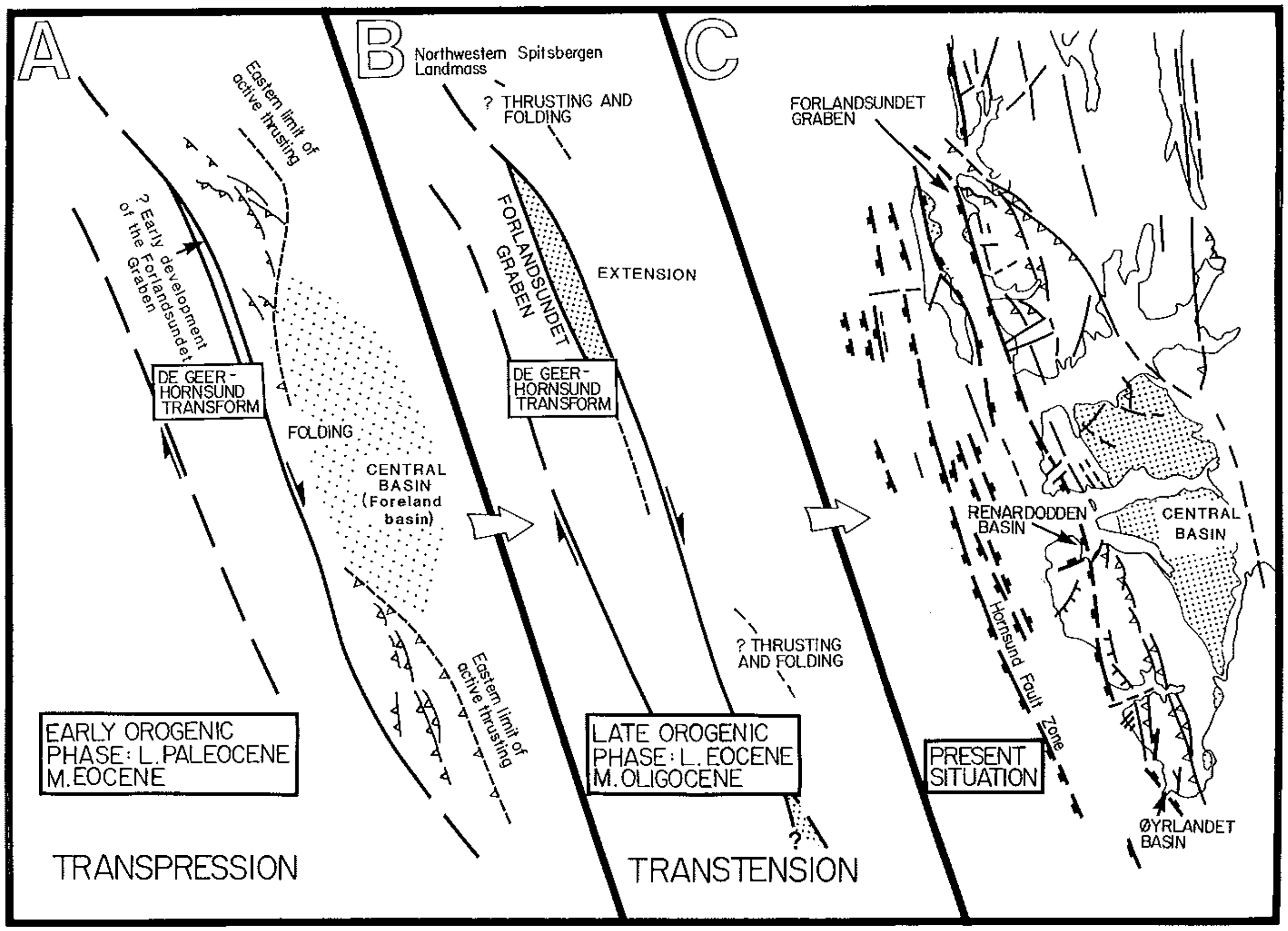

FIG. 13.—Maps showing the main sequence of Tertiary events along the fold belt of western Spitsbergen and a map of the major present-day structural features. A) Late Paleocene to mid-Eocene, B) late Eocene to mid-Oligocene, C) present.

The Stratigraphic Sequences

The sedimentary succession in the rifted region has been divided into three main sequences (SPI 1–3 in Figs. 14, 15), separated by two regional unconformities (U1, U2; Schlüter and Hinz, 1978). An upper low-velocity sequence, SPI 1 (1.7–2.8 km/sec), forms a prograding wedge beneath the outer shelf and slope. It is thickest in the south (2–2.5 km), where it is characterized by sloping, sub-parallel high-continuity reflections (Figs. 14, 15). Northward it becomes thinner (1–1.3 km) and increasingly complex, showing evidence of faulting and erosion (Fig. 15, line A). In general, sequence SPI 1 terminates westward against the Knipovich Ridge (Fig. 14), but in the narrow, northernmost part of the basin, the sediments have overflowed into the present rift valley (Eldholm et al., 1984).

An unconformity, U1, separates sequence SPI 1 from the underlying SPI 2, which is characterized by medium-range velocites (2.4–3.1 km/sec) and an irregular, discontinuous to chaotic reflection pattern. The sequence thickens seaward from the shelf edge, with the maximum development in the southern part of the basin (0.6–0.8 km).

The lowermost sequence SPI 3 is separated from sequence SPI 2 by an unconformity, U2. Sequence SPI-3 is a high-velocity unit (2.9–4.8 km/sec), and although it is masked by multiples to a large extent, it shows a sub-parallel reflection pattern and evidence of onlap against both the Knipovich Ridge and the Hornsund fault zone (Fig. 15, line A).

Discussion

From correlation by reflection tracing from the DSDP site 344 (Fig. 14; Talwani and Udintsev, 1976) the upper sequence SPI 1 has been dated as Pleistocene-Pliocene. The DSDP site 344 cores show sequence SPI 1 to consist of terrigenous muds, silty and sandy muds, and some muddy sandstones of inferred gravity-transported (lower part) and glacial marine (upper part) origin.

The seismic signature of SPI 1 is that of a typical progradational shelf-slope sequence, deposited in response to a changing glacial regime, and with little evidence of major tectonic influence. Some normal faulting can be seen on line A, however, which clearly extends up into sequence

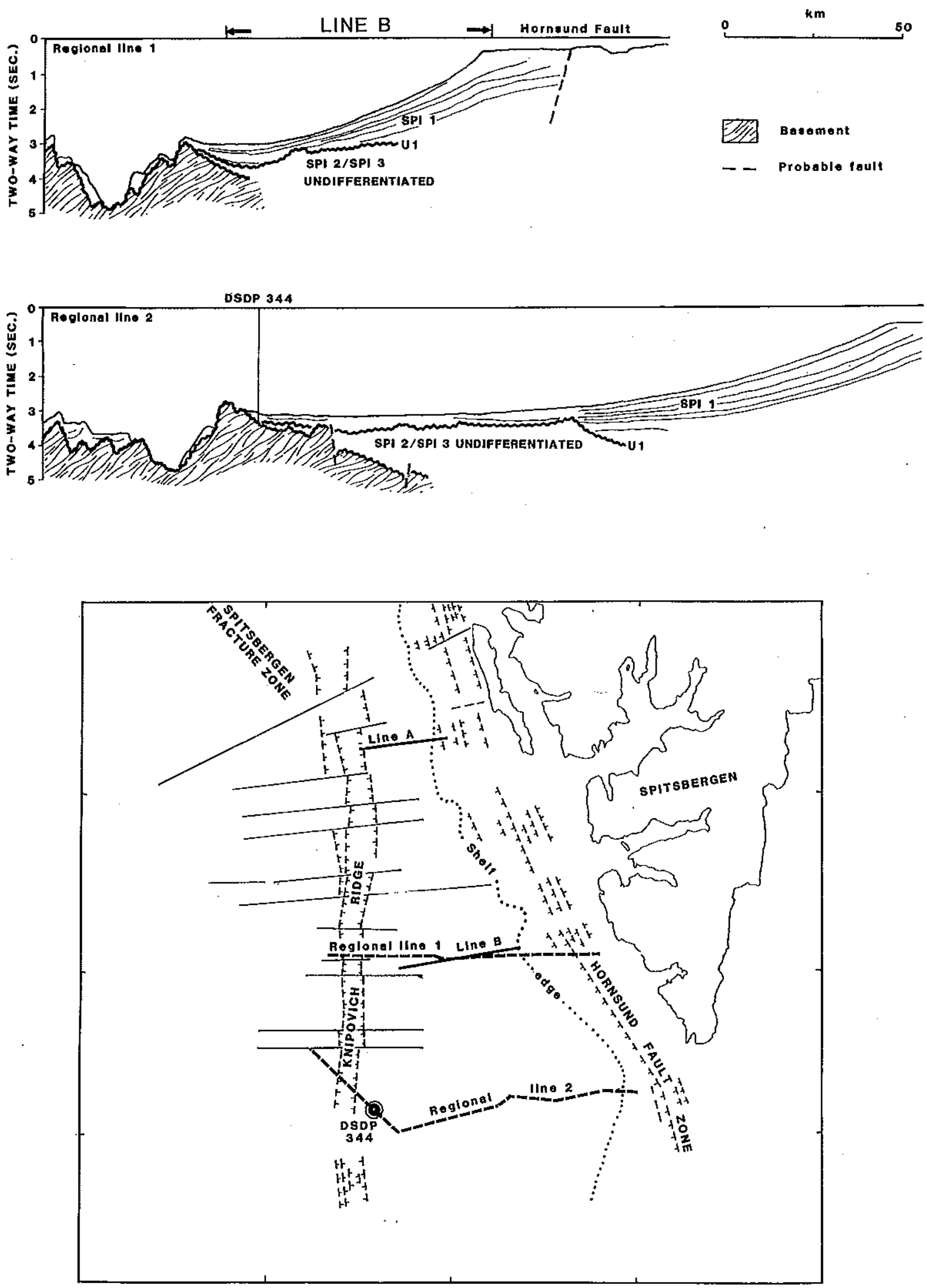

FIG. 14.—Two regional cross sections of the Svalbard margin off Spitsbergen. Data from Schlüter and Hinz (1978). The map shows the location of the regional lines and lines A and B shown in Fig. 15.

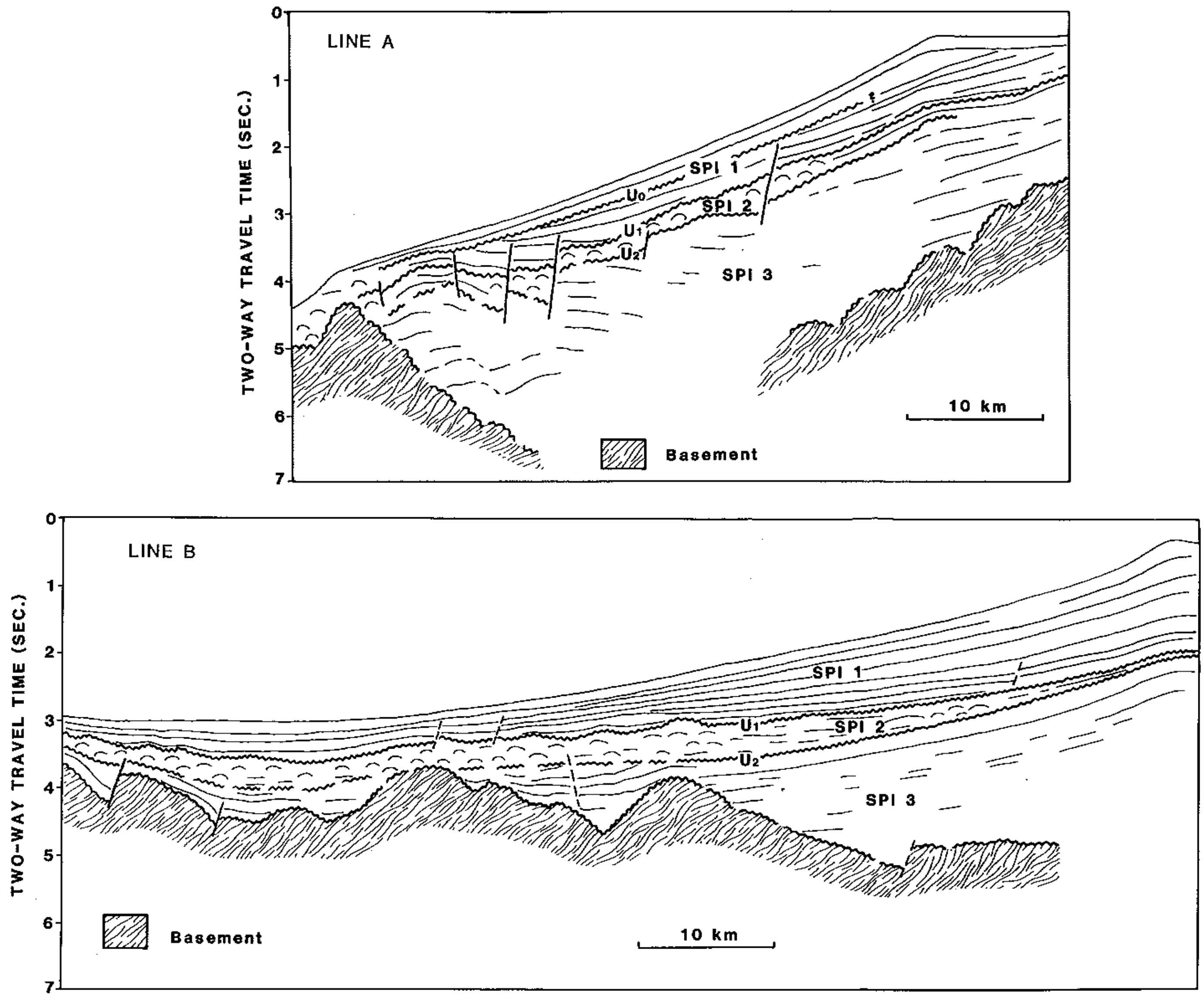

FIG. 15.—Details of seismic sequences SPI-1, 2, and 3 on the Svalbard margin, along lines A and B shown on Figure 14. Data from Schluter and Hinz (1978). See text for discussion.

SPI 1, but terminates against a local unconformity within the sequence.

The unconformity U1 clearly cuts the sequence SPI-2, but shows no evidence of major erosion. Schlüter and Hinz (1978) interpreted sequence SPI-2 as an "allochthonous wedge of gravity-driven masses" on the basis of the chaotic reflection patterns (Fig. 15). We agree with this interpretation but emphasize that the sequence most likely consists of an alternation of all types of gravity-transported deposits, and not a continuous package of slump deposits alone. Furthermore, the distinct character of this sequence, together with the evidence of syn-sedimentary normal fault activity within the sequence in some areas (there is stratal thickening on the downthrown sides of the faults in Line A, Fig. 15), suggests that sequence SPI-2 may reflect a period of significant, tectonic activity on the margin, compared to the intervals represented by the underlying and overlying sequences. We suggest that this tectonic activity may have been related to the eastward shift of the Hornsund transform to the Spitsbergen transform and the incipient development of the Knipovich Ridge in this area, at about 16-10 Ma (Crane et al., 1982).

Sequence SPI-3 has been interpreted from velocity analysis as highly consolidated interbedded sandstones and shales (Schlüter and Hinz, 1978). The lack of large-scale deformation suggests that it post-dates the main transpressional tectonic phase along western Spitsbergen. This is consistent with the suggestion of Myhre et al. (1982) that sequence SPI 3, in front of the Hornsund fault, was deposited beginning in mid-Oligocene time (from 37 Ma) in response to a prominent change in plate motion, the onset of rifting and the early opening of the northern Greenland Sea.

The presence of only a single age determination from the seismic sequences remains an outstanding problem in our understanding of the rift basins, and has been the cause of some debate (compare Schlüter and Hinz, 1978, with Myhre et al., 1982). However, the argument that the rifting was initiated by the major plate-tectonic change at 37 Ma, is persuasive. Based on this hypothesis, the two lower seismic sequences span mid-Oligocene to late Miocene time, and the rift basins were sourced from the post-mid-Oligocene, rising Spitsbergen landmass. Figure 16 summarizes the possible stratigraphic relationships between the rift basin succession and the earlier Tertiary sequences on Svalbard.

CONCLUSIONS

The Paleogene plate boundary between northeastern Greenland and Svalbard, the De Geer Line, lay just west of western Spitsbergen. Sea-floor data indicate strike slip along this fault zone from latest Paleocene time, whereas data from the Central Basin on Spitsbergen suggest major fault activity with a possible strike-slip component, from early Paleocene time. Data from the Central Basin and from the fold and thrust belt on Spitsbergen suggest a transpressive regime beginning in late Paleocene time. Marine geophysical data indicate an early to mid-Oligocene change in the relative plate motion and a shift from a strike-slip to a rift regime along the margin.

The early to mid-Paleocene Central Basin on Spitsbergen evolved from a series of partially connected coal basins to a single, open marine basin in an extensional, possibly transtensional, regime to the east of the De Geer Line. Subsidence was increasingly asymmetric, and greatest (>800 m) towards the De Geer Line during this phase of basin development (Fig. 17I).

The late Paleocene–Eocene development of the Central Basin was characterized by a reversal of drainage direction and an influx of metamorphic rock fragments. The region along and east of the De Geer Line was uplifted and became the main sediment source for the Central Basin (Fig. 17II). The sedimentary sequence which accumulated in this phase was more than 1.5 km thick and of overall regressive character. Shelf sediments pass upwards through deltaic and shoreline deposits to continental deposits.

The fold and thrust belt of western Spitsbergen developed through late Paleocene–Eocene time and was partly contemporaneous with the late phase of infillng of the Central Basin. Extensive east-directed thrusting and folding suggests crustal shortening of 10 to 15 km in places. Al-

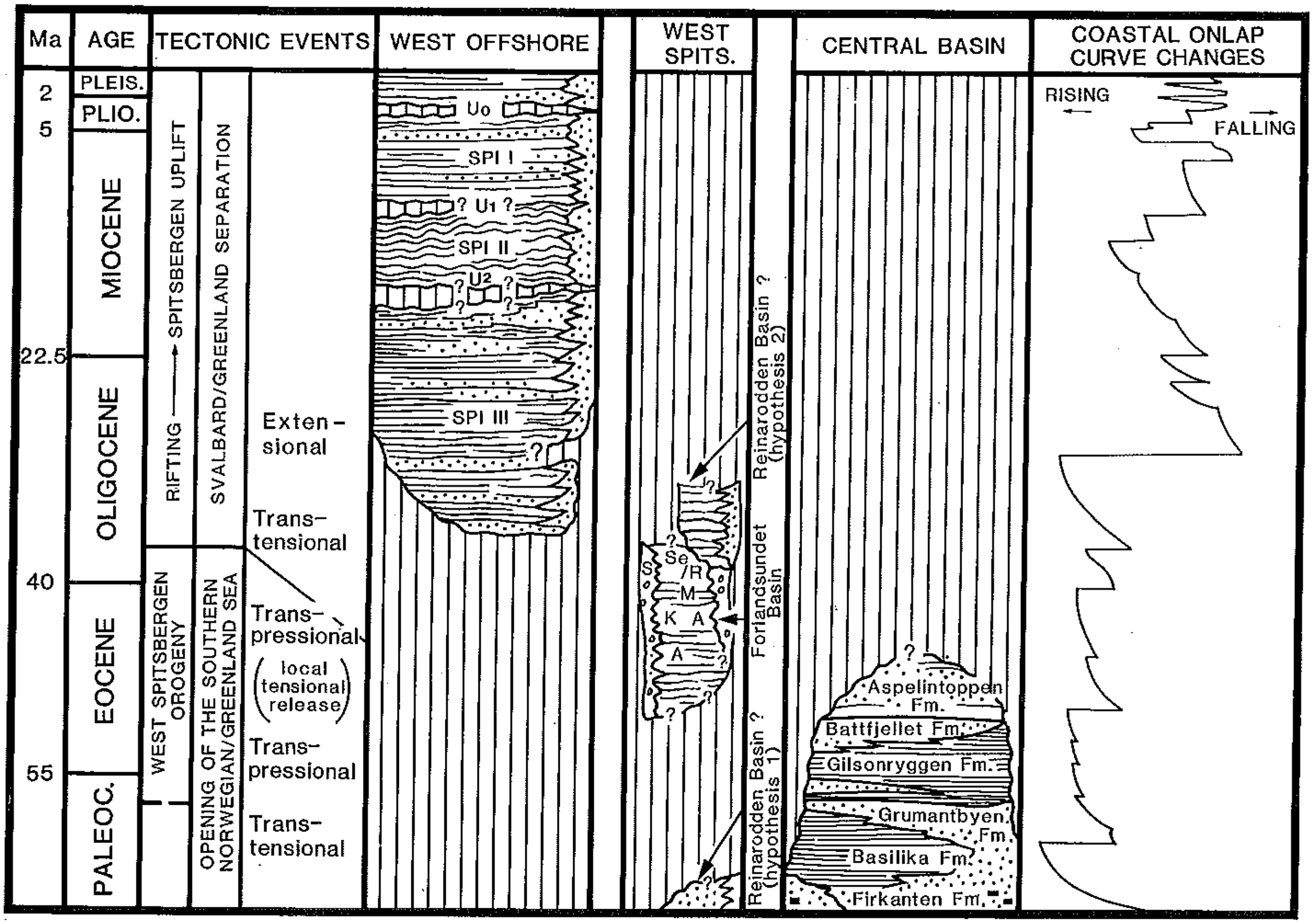

FIG. 16.—Summary of the stratigraphy of the Tertiary basins of Svalbard in relation to the proposed tectonic setting and a curve of global coastal onlap (from Vail et al., 1977).

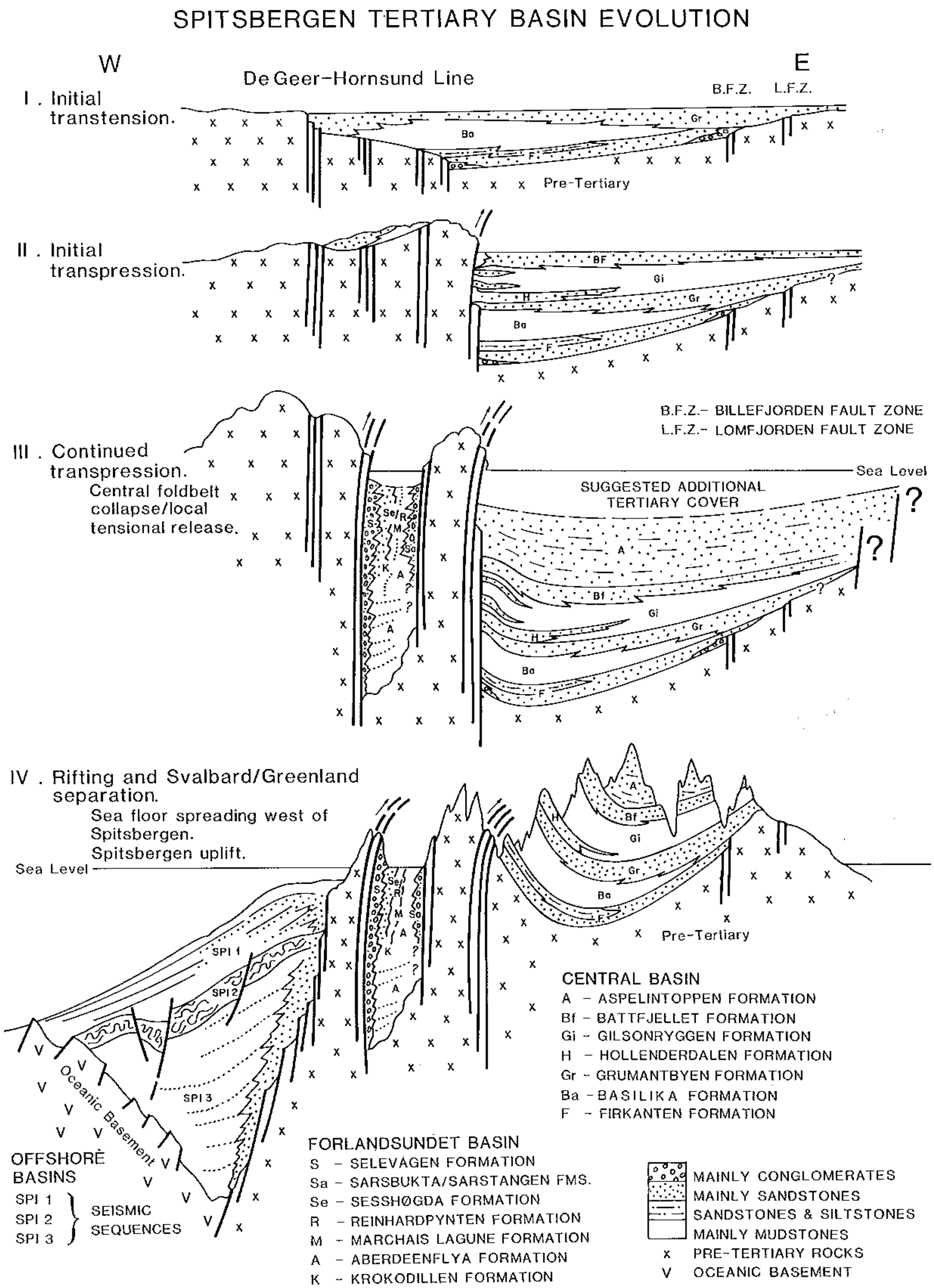

FIG. 17.—Schematic summary of basin development in relation to tectonic evolution of the Svalbard margin. Large vertical exaggeration has been necessary to illustrate stratigraphical details in the basins. See text for discussion.

though some of the wrench faults and thrust are clearly related, there has not been enough detailed structural mapping to confirm the suggestion that most of the thrust faults steepen with depth, and are therefore part of a giant flower structure. The extent of the thrusting suggests major compression, and implies significant curvature along parts of the De Geer Line or a temporal change in the relative plate motion.

The Forlandsundet Graben, located within the fold and thrust belt, developed mainly in Eocene to early Oligocene time, and contains a thick succession of alluvial, shallow-marine and deeper-marine strata (Fig. 17III). Regional evidence suggests that this graben developed in transpressive and later transtensional regimes. Local evidence within the graben is not conclusive as regards strike slip along the boundary faults, but pebble mismatches, some small-scale structural data, and the anomalous stratigraphic thickness of the succession (suggesting depocenter migration) support the notion.

From early Oligocene time, the Svalbard margin was rifted and basins up to 7 km deep developed (Fig. 17IV).

The combination of marine geophysical data with data from the sedimentary basins and fold and thrust belt of Spitsbergen thus suggest that the Svalbard margin off Spitsbergen evolved through regimes of transtension, transpression, and transtension during its strike-slip history, before being rifted beginning at 37 Ma.

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