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The Ocean Crust West and North of the Svalbard Archipelago: Synthesis and Review of New Results*

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Abstract: A large amount of new geophysical data have been collected in the deepwater areas around the Svalbard archipelago in the last half-decade. Within the area of permanent ice cover these data are primarily detailed aeromagnetic surveys, supplemented by a few bathymetric profiles collected by submarines. Areas open to surface ships have been investigated using 3.5 Kc bathymetry, single and multi-channel reflection profiling, sonobuoy and two-ship refraction, gravity, magnetic, heat flow, and other techniques. This paper summarizes these new geophysical data for the benefit of earth scientists investigating the Svalbard area.

The sea-floor spreading phase of the plate tectonic evolution of the Greenland-Norwegian Sea and Eurasia Basin began 57—58 m.y.b.p. during the reversed interval prior to anomaly 24. Svalbard and northeast Greenland slid past each other until about 36 m.y.b.p., when Greenland became attached to the North American plate. Subsequently, spreading from the Knipovich Ridge has been complex, including oblique spreading and probable eastward jumps of the accretion axis.

The "Yermak" hot spot has been postulated north of Svalbard to explain the Yermak and Morris Jesup Rise plateaus, Cenozoic volcanism in northeast Greenland and on Vestspitsbergen, and other effects.

Zusammenfassung: In der letzten halben Dekade ist eine große Zahl neuer geophysikalischer Daten in den Tiefwasserbereichen um den Svalbard-Archipel gesammelt worden. Innerhalb des dauernd eisbedeckten Gebietes bestehen diese Daten hauptsächlich aus detaillierten aeromagnetischen Aufnahmen, ergänzt durch einige von Unterseebooten aus aufgenommene bathymetrische Profile. Überwasserschiffen zugängliche Areale wurden unter Verwendung von Techniken wie 3,5 kc Bathymetrie, Ein- und Mehrkanal-Reflektion, Sono-Boje und Zwei-Schiff-Refraktion, Schwere, Magnetik, Wärmefluß usw. untersucht. Diese Arbeit faßt die neuen Daten für Geowissenschaftler zusammen, die im Raum Svalbard arbeiten.

Die „sea-floor spreading"-Phase der plattentektonischen Entwicklung der Grönland-Norwegischen See und des eurasiatischen Beckens begann vor 57—58 Mill. Jahren während der Revers-Intervalls vor der Anomalie 24. Svalbard und Grönland glitten aneinander vorbei bis vor etwa 36 Mill. Jahren, als Grönland Teil der nordamerikanischen Platte wurde. Die dann folgende Ausweitung vom Knipovich-Rücken aus komplizierte sich durch schrägen Verlauf und möglicherweise ostwärtiges Verspringen der Ausweitungs-Achse.

Der „Yermak"-Hot spot nördlich von Svalbard wurde postuliert zur Erklärung der Yermak- und Morris Jesup-Plateaus, des känozoischen Vulkanismus in Nordost-Grönland sowie auf Spitzbergen und anderer Effekte.

INTRODUCTION

Geophysical exploration of the oceanic regions north and west of the Svalbard Archipelago has intensified dramatically over the last half-decade. In this paper we draw together under a common roof the major data bodies and the present state of knowledge. Not the least of our objectives is to give the Svalbard researcher an idea of what publications exist or will exist in the near future. The parameters to be discussed are (1) bathymetry and morphology (Fig. 1); (2) 3.5 kilohertz reflection profiling; (3) single channel reflection (Fig. 2); (4) multi-channel reflection (Fig. 3); two-ship and sonobuoy wide-angle reflection and refraction and deep drilling (Fig. 4); (5) gravity (Fig. 5); (6) magnetics (Fig. 6, 7); (7) seismicity (Fig. 5); and (8) plate tectonic evolution. A schematic summary of the marine geophysical signatures west of Vestspitsbergen is given in Fig. 8.

1. SEA-FLOOR MORPHOLOGY

The most recent bathymetric charts of the Greenland-Norwegian Sea are those of PERRY

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et al. (1977) and GRØNLIE & TALWANI (1977). Both charts reflect the same data base except in the area north of 78° N, where the PERRY et al. chart is more accurate. Both publications also represent a significant improvement over the AMERICAN GEOGRAPHICAL SOCIETY (1975) chart which hypothesized numerous minor transform fracture zones that were not verified by subsequent bathymetric and aeromagnetic studies. A description of the PERRY et al. (1977) chart is in press (PERRY et al., 1979);

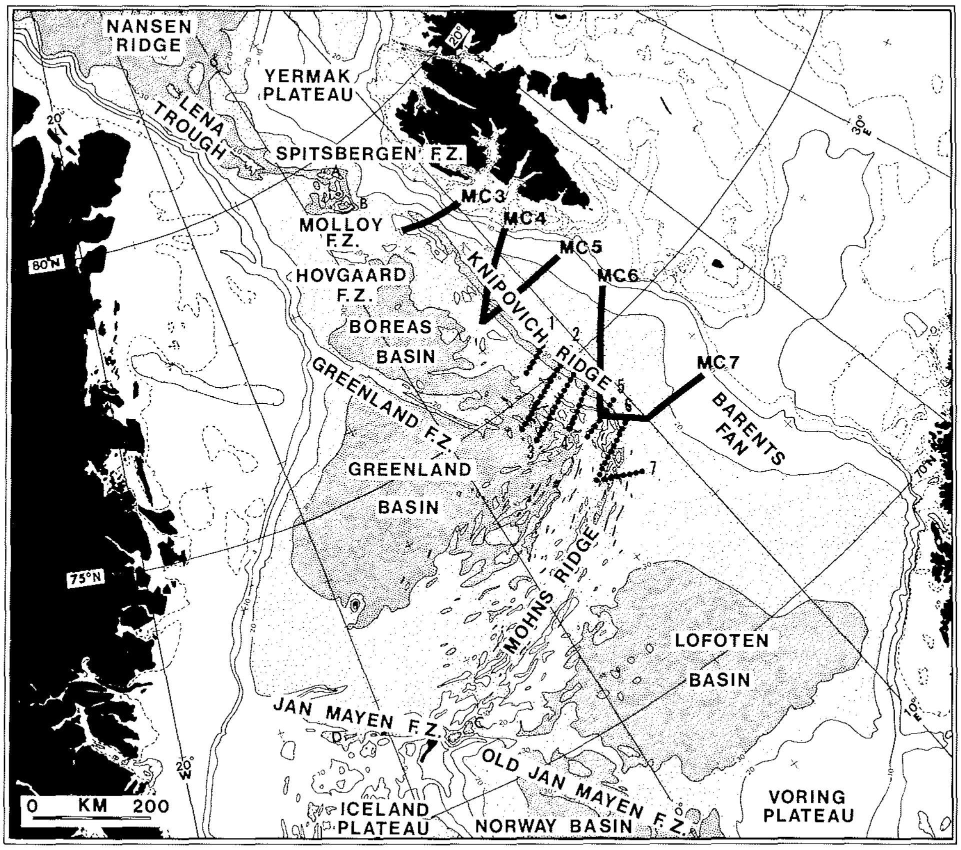

Fig. 1: Bathymetry of the Greenland-Norwegian Sea, derived from PERRY et al. (1977.) Contours in uncorrected meters. Horizontal chart edges approximately parallel the present direction of relative plate motion. Chart projection is polar stereographic. Locations of single-channel seismic reflection profiles 1 through 6 (Fig. 2) and multi-channel profiles MC—3 to MC—7 indicated by dotted and solid lines, respectively.

Abb. 1: Bathymetrie der Grönländisch-Norwegischen See, nach PERRY et al. (1977). Konturen in unkorrigierten Meter-Werten. Die horizontalen Kartenränder verlaufen etwa parallel zur heutigen Richtung der relativen Plattenbewegung. Stereographische Polar-Projektion. Lage der seismischen Einkanal-Reflexions-Profile 1—6 (Fig. 2) und der Mehrkanal-Profile MC—3 bis MC—7 durch punktierte und ausgezogene Linien angegeben.

a simplified version of that chart, for the area around the Svalbard Archipelago, is given in Fig. 1. The horizontal edges of this chart were chosen to approximate the present (post — 36 m. y. b. p.) direction of motion between the North American plate and the Eurasia plate (TALWANI & ELDHOLM, 1977).

The present morphology of the basins south and west of Svalbard reflects the history of plate motions modified by the effects of sedimentation. Thus, the northeast Greenland and southwest Spitsbergen continental margin, the Greenland Fracture Zone (F. Z.)

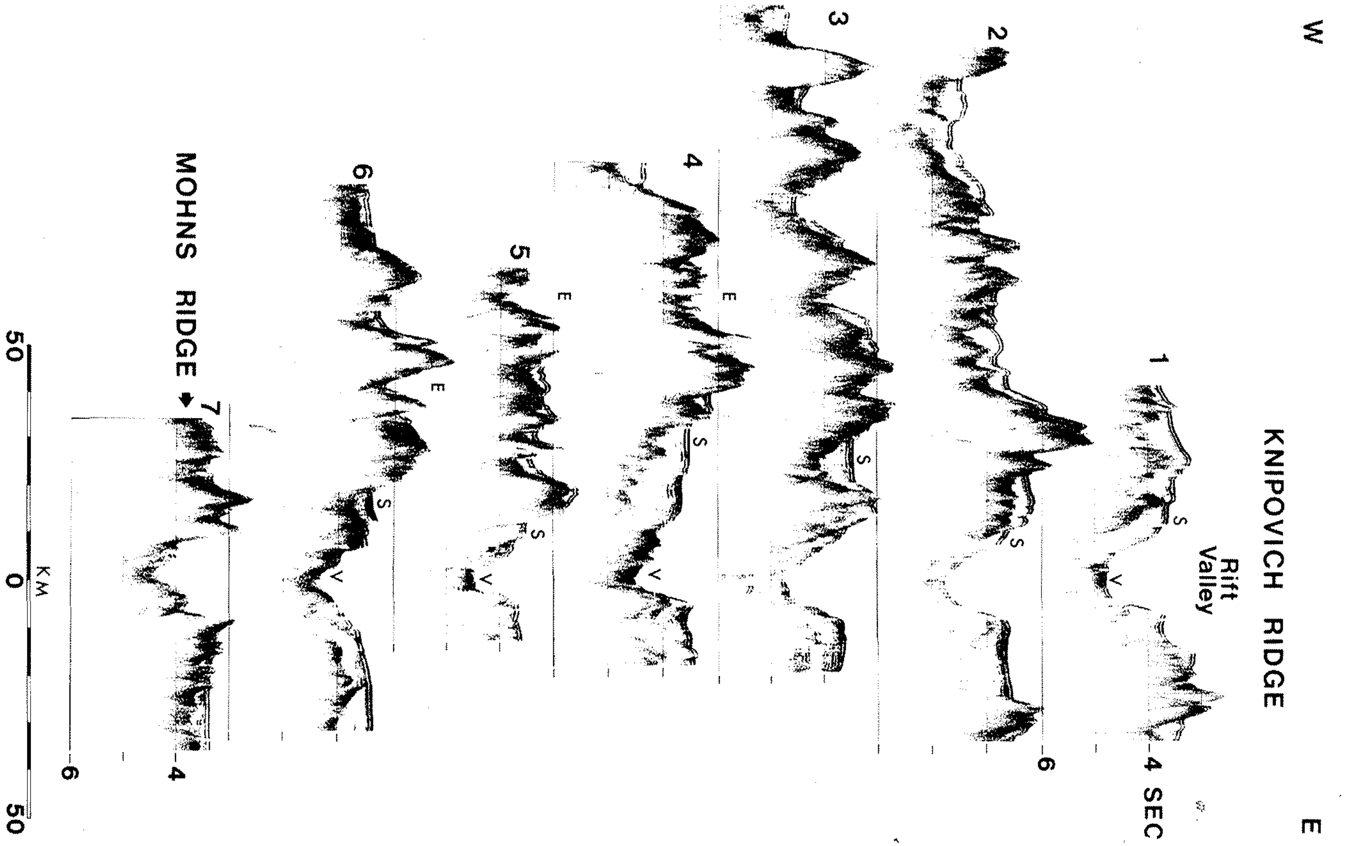

Fig. 2: Single-channel seismic reflection profiles 1—6 collected by U. S. Naval Research Laboratory across southern Knipovich Ridge. Horizontal scale is approximate: Profiles are plotted with respect to time. V denotes young volcanism on rift valley floor; S denotes thick sediment masses west of the Knipovich valley axis; and E denotes possible area of an extinct spreading axis.

Abb. 2: Seismische Einkanal-Reflexions-Profile 1—6, aufgenommen vom U. S. Naval Research Laboratory über dem südlichen Knipovich-Rücken. Horizontaler Maßstab angenähert. Die Profile sind im Zeit-Maßstab gezeichnet. V: junger Vulkanismus im Graben-Boden. S: mächtige Sedimentmassen westlich der Knipovich-Tal-Achse; E: möglicher Bereich einer früheren, jetzt inaktiven Ausweitungs-Achse.

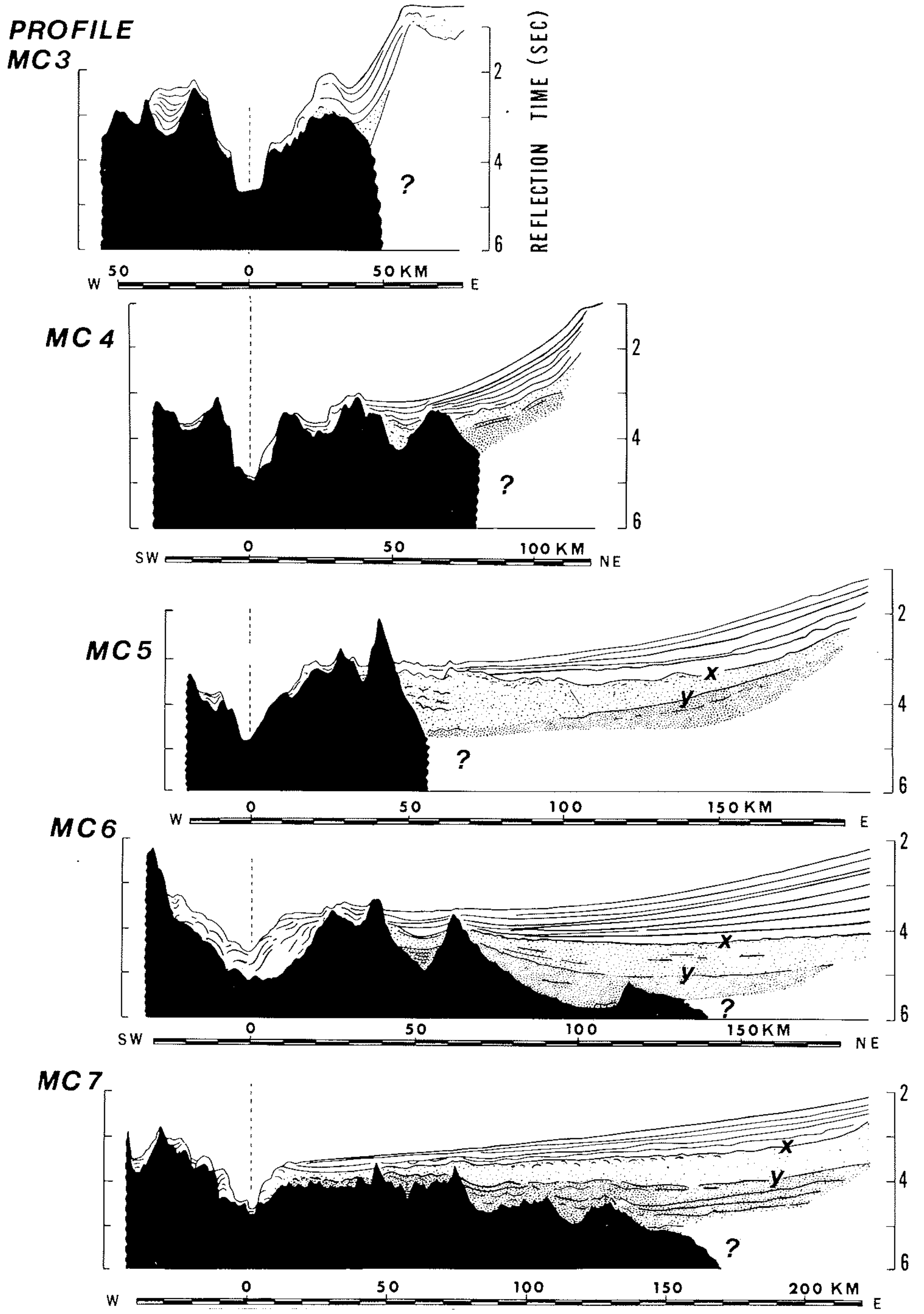

Fig. 3: Line-drawings of multi-channel reflection profiles MC—3 through MC—7, re-drafted after BRISEID & MASCLE (1975). Our interpretation of three sediment units (dense stippling, light stippling, and no stippling), separated by reflectors X and Y, is speculative. Oceanic basement is shown as dense black.

Abb. 3: Strichzeichnungen der Mehrkanal-Reflexions-Profile MC—3 bis MC—7, umgezeichnet nach BRISEID & MASCLE (1975). Unsere Deutung von drei Sediment-Einheiten (eng, weit, nicht punktiert), durch die Reflektoren X und Y getrennt, ist spekulativ. Ozeanisches Basement schwarz.

and the Old Jan Mayen F. Z. are transform fault trends displaying the early direction of plate motion (58—36 m. y. b. p.) between the Greenland and Eurasia plates (TALWANI & ELDHOLM, 1977). These shear-type plate boundaries only became rifted margins starting about 36 m. y. b. p. The Greenland continental margin between 77° N and 81° N, and the Barents margin south of Bear Island were initially margins of the rift type, albeit oblique to the direction of plate motion. This follows because the Greenland F. Z. — the trace of relative plate motion — does not parallel the margin to the northwest (PERRY et al., 1977). The Greenland continental margin south of the Greenland F. Z. and the Norwegian continental margin east of the Lofoten Basin typify the rifted margin type (ELDHOLM & SUNDVOR, 1979).

The present plate boundary is composed from south to north of (1) Kolbeinsey Ridge, an unusually shallow accretion (spreading) axis roughly normal to the present spreading direction; (2) the Jan Mayen F. Z., a classic transform fault formed subsequent to the separation of Norway from Greenland; (3) Mohns Ridge, a spreading axis more or less oblique (45—80°) to the present spreading direction, and exhibiting a prominent rift valley; (4) Knipovich Ridge, a more strongly oblique spreading axis (35°—75°); (5) the Molloy and Spitsbergen fracture zones, apparently classic transform faults paralleling the present direction of relative plate motion; (6) a short normal spreading axis — Molloy Ridge — located between these two fractures; (7) the poorly sounded Lena Trough, possibly a highly oblique spreading axis; (8) the poorly sounded Yermak F. Z. (not shown in Fig. 1); and (9) the Nansen Ridge, a long, relatively linear axis with a prominent, deep rift valley (3800 to 5300 m maximum depth).

Regionally the present spreading axis (Fig. 3) as well as the basement along older isochrons deepens more or less monotonically from Iceland to the Eurasia Basin. Local effects include the deeps commonly found where a spreading axis intersects a transform fault, such as points A, B, C, and D in Fig. 1. These deeps are thought to arise from a viscous head loss mechanism (SLEEP & BIEHLER, 1970). Another phenomenon of less certain origin is the tendency for highest rift mountain topography and shallowest basement to occur on the west side of the Mohns and Knipovich spreading axes. Although the depth of first-formed crust varies along the axis and from one flank to the other, subsequent subsidence appears to be a regular function of time, as elsewhere in the ocean basins (SCLATER et al., 1971; COCHRAN & TALWANI, 1978).

The Yermark, Vøring, and Iceland plateaus represent anomalously shallow oceanic crust, perhaps created by mantle hot spots (e. g. FEDEN et al., 1979). The Jan Mayen Ridge and inner Vøring plateau are presumed to be underlain by continental crust (TALWANI & ELDHOLM, 1977).

Although tectonic and magmatic activity is concentrated along plate boundaries — past and present — mid-plate seismicity is significant (HUSEBYE et al., 1975); probable off-axial volcanism is represented by Vesteris Bank in the Greenland Basin, Jan Mayen Island, plus several banks and other shoals south and west of Jan Mayen. These areas of "intra-plate" volcanism may be marine counterparts to the Miocene flood basalts and Quaternary central volcanoes in north-west Svalbard (PRESTVIK, 1977).

The morphology of the sea-floor around Svalbard also bears a pronounced imprint of sedimentary processes: deep-water areas have received thick sediment accumulations, while the shelves and fjords have suffered strong sub-glacial erosion. A prominent illustration is the Bear Island Trough, which has been deepened to over 500 m depth by an ice stream draining a large part of the Barents ice dome, with contributions from northern Norway (VOGT & PERRY, 1978). The Barents delta, cone and fan, as well as much of the Lofoten Basin, represents the accumulation region for this shelf-erosion. It is reasonable to deduce an outbuilding of at least 30 km from the original continental margin; however, until drilling is carried out we will not know how much of this prograding is of glacial origin (Plio-Pleistocene) and how much represents a pre-existing fluvial delta that may have existed when the Barents Platform was emergent.

2. 3.5 KILOHERTZ PROFILING

Echograms collected with 3,500 cps equipment provide information about shallow subbottom structure (~ 10 to 75 m penetration) in areas of unconsolidated or poorly-consolidated sediments. Regardless of sediment cover, 3.5 Kc, traditional 12 Kc, and 16 Kc (narrow-beam) echograms provide information on bottom morphology down to features of wavelength too small to be resolved for bathymetric purposes. DAMUTH (1978) has examined the 3.5 Kc echo character of the Greenland-Norwegian Sea, in combination with

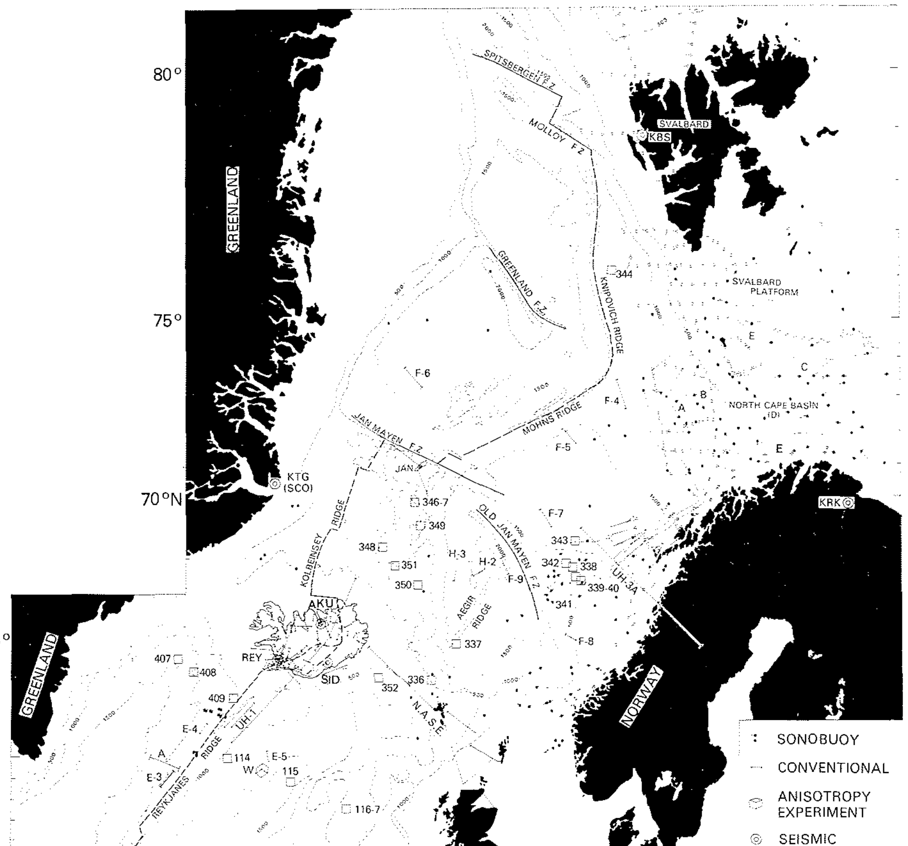

Fig. 4: Approximate locations of refraction and wide-angle refraction/reflection measurements, deep drilling (DSDP) sites, and teleseismic recording stations in the Greenland-Norwegian Sea excluding the British Isles-North Sea area. From VOGT et al. (1979 b).

Abb. 4: Ungefähre Lage der Refraktions- und Weitwinkel-Refraktions-Reflexions-Messungen, Tiefbohrungen (DSDP) und teleseismischen Registrierstationen in der Grönländisch-Norwegischen See ohne das Gebiet „Britische Inseln — Nordsee". Nach VOGT et al. (1979 b).

piston coring, bottom photography, and bottom current measurements; the following conclusions are largely from his work.

Outcropping basement topography along Mohns and Knipovich ridges and the Greenland Fracture Zone is characterized by indistinct echoes composed of large irregular hyperbolae. In general, these are areas of outcropping basalt flows, basaltic rubble, etc., with a conformably draped or non-existent sediment cover.

The Svalbard-Barents continental rise and lower slope represents an alternation of five echo provinces: (a) sharp, continuous echoes with numerous parallel sub-bottoms; (b) sharp, continuous echoes with one or two unconformable wedging sub-bottoms; (c) semi-prolonged, indistinct echoes with intermittent, semi-prolonged parallel sub-bottoms; (d) very prolonged, indistinct echoes with no sub-bottoms, and (e) indistinct echoes comprising regular overlapping hyperbolae of varying vertex elevations. The same five province types also occur west of the Mohns-Knipovich ridges. Comparison with sediment cores indicates that types (a), (c), and (d) form a progression toward increasingly abundant coarse (silt, sand, and gravel) bedded sediment in the upper few meters of sea floor. Province (b) is associated with the Bear Island fan and probably represents glacial sediment deposited at the shelf edge and redeposited by localized gravity flows. Province (e) could also reflect some type of gravity-controlled mass flowage of bottom sediment, or also erosion and redeposition by bottom currents. All four types of echo-character are probably largely the result of glacial conditions. A veneer of Holocene marl probably nowhere exceeds 1 meter in thickness (KELLOGG, 1976).

Echoes returned by the Barents and Spitsbergen continental shelves and upper rises are sharp and continuous, with no sub-bottoms. Bottom morphology is flat to rolling, with some provinces of regular, intense hummocks generally less than 10 fm (22 m) in relief and several hundred meters in wavelength. DAMUTH suggests these hummocks are ground-moraine or ice-rafted till. Alternatively, the hummocks may represent glacial erosion and iceberg plow-marks.

Three important conclusions from the 3.5 Kc profiling data are (DAMUTH, 1978): (1) Bottom currents are and have been — during glacial times — comparatively weak; (2) the Barents shelf was probably covered by an ice dome during glacial maxima (see also HUGHES et al., 1977); and (3) ice-rafted sand and silt is very widespread in the Greenland-Norwegian Sea, reducing the penetration of 3.5 Kc sound pulses compared to more equatorial regions such as off Brazil.

3. SINGLE-CHANNEL REFLECTION SEISMOLOGY

Single-channel seismic reflection profiling, using air guns or sparkers as acoustic sources, has been carried out in the Greenland-Norwegian Sea primarily by Lamont-Doherty Geological Observatory and the U. S. Naval Research Laboratory (NRL). Results from the earlier Lamont cruises have been discussed by ELDHOLM & WINDISCH (1974). Additional data are found in GRØNLIE & TALWANI (1977). Both publications include isopach maps (Fig. 7). A combined analysis of NRL and Lamont seismic data north of 72° is in progress by the present authors. On the continental shelves and upper slopes, little sub-bottom structure can be resolved on single-channel records due to surface-bottom reverberations and the generally strongly reflective nature of the bottom. The igneous oceanic crust generally returns rough, well-defined sub-bottom echoes (Fig. 2). This oceanic "basement" reflector can be detected down to sub-bottom depths locally as great as 2 to 2.5 sec two-way reflection time (2 to 2.5 km at a nominal 2 km/sec sound speed in unconsolidated sediments). East of Knipovich Ridge, the basement is "lost" at only 1 to 1.5 sec sub-bottom depth, perhaps because of the relatively coarse continental rise sediments; increasingly abundant ice-rafted debris also explains a general northward decrease in maximum penetration, resembling what is observed on 3.5 Kc records (DAMUTH, 1978). The relatively high mean sediment thickness on oceanic crust (0.86 km in the entire Greenland-Norwegian Sea) is explained by proximity to continental sediment sources (ELDHOLM & WINDISCH, 1974).

On Knipovich and Mohns Ridges, pelagic sediments are ponded in basement depressions, suggesting locally active gravity flow and slumping from basement peaks (Fig. 2). A gradual increase of average thickness with crustal age on Mohns Ridge suggests a mean pelagic sedimentation rate of 2 cm/1000 yrs (ELDHOLM & WINDISCH, 1974). Knipovich Ridge is unusual in that the rift valley, particularly between 74° and 76° N, contains relatively thick (locally at least 1000 m) sediment masses presumably derived by down-slope transport from the adjacent Barents-Spitsbergen continental rise (Fig. 2, 3, and 8). The reflection profiles suggest that young volcanism ("V" in Fig. 2) has locally erupted on the valley floor, burying deeper sediments. Valley-floor sediments also appear to have been disturbed by normal faulting. The existence of relatively thick sediments ("S" in Fig. 2) immediately west of the Knipovich rift axis suggests the following: Either (1) there was a time in the last 10^6 years or less when sediments filled and transgressed westward across the spreading axis, or (2) the spreading axis has itself jumped eastward, developing within continental rise sediments. In the latter case, a relatively sediment-free extinct axis must exist to the west. Areas marked "E" in Fig. 2 might represent such an extinct axis. Magnetic lineations are difficult to interpret but do suggest a relatively recent (~ 1—2 m. y. b. p.) eastward jump of the spreading axis. A third explanation for the thick sediments (S) west of the axis — steady-state uplift and westward transport of valley floor sediments — is inconsistent with the smooth surface and relatively undisturbed appearance of the sediment masses (S) west of the axis.

4. MULTI-CHANNEL PROFILING, DEEP REFLECTION/REFRACTION STATIONS, AND DEEP DRILLING

In recent years, the techniques of multi-channel seismic profiling have spread from the petroleum industry to government and private institutions. The long towed arrays and extensive digital processing result in a high cost per data mile. Multi-channel profiles are especially valuable along continental margins where deep sediment structures can be charted and the oceanic basement traced further landward than with single-channel methods. Published results from the Greenland-Norwegian Sea suggest that penetration into a sedimentary sub-sea-floor is more than doubled with multi-channel techniques.

Multi-channel reflection profiling along the Vestspitsbergen-Barents continental margin has been carried out by SUNDVOR & ELDHOLM (1976), SUNDVOR et al. (1977), SUNDVOR & ELDHOLM (1979), HINZ & SCHLÜTER (1978), and BRISEID & MASCLE (1975) (Fig. 3). Sonobuoy and two-ship refraction/reflection stations (Fig. 4) provide complementary information on the variation of seismic velocity with depth (SUNDVOR & ELDHOLM, 1976, 1979; SUNDVOR et al., 1977; HOUTZ & WINDISCH, 1977; MYHRE, 1978).

Within the Knipovich Ridge axial zone, multi-channel data confirm the existence of locally thick (> 1 km) sediments within and to the west of the valley axis (Fig. 3). Up to five mid-sediment reflectors can be distinguished in some places, more intermittent and complex in the valley area than on either side. It is probable that these sediments correspond in age to the horizontally layered unit above reflector X on the Spitsbergen margin. This unit unconformably overlies an acoustically homogeneous unit (Fig. 3; See also SUNDVOR & ELDHOLM, 1976, 1979).

One of the SUNDVOR-ELDHOLM (1976) profiles crosses Deep Sea Drilling Project Site 344, located just east of the Knipovich Ridge crestal mountains. This is the only drill site in the Greenland-Norwegian Sea north of 70° N (Fig. 4). The drilling revealed 377 meters of entirely glacial marine sediments above a basaltic basement (TALWANI & UDINTSEV, 1976). The age of the basal sediments could not be accurately determined but is probably Upper Miocene or Pliocene. According to SUNDVOR & ELDHOLM (1976) the sampled section may include their reflector E (probably the same one labelled "X" in Fig. 3). If so, the entire stratified sequence above the reflector E X is probably

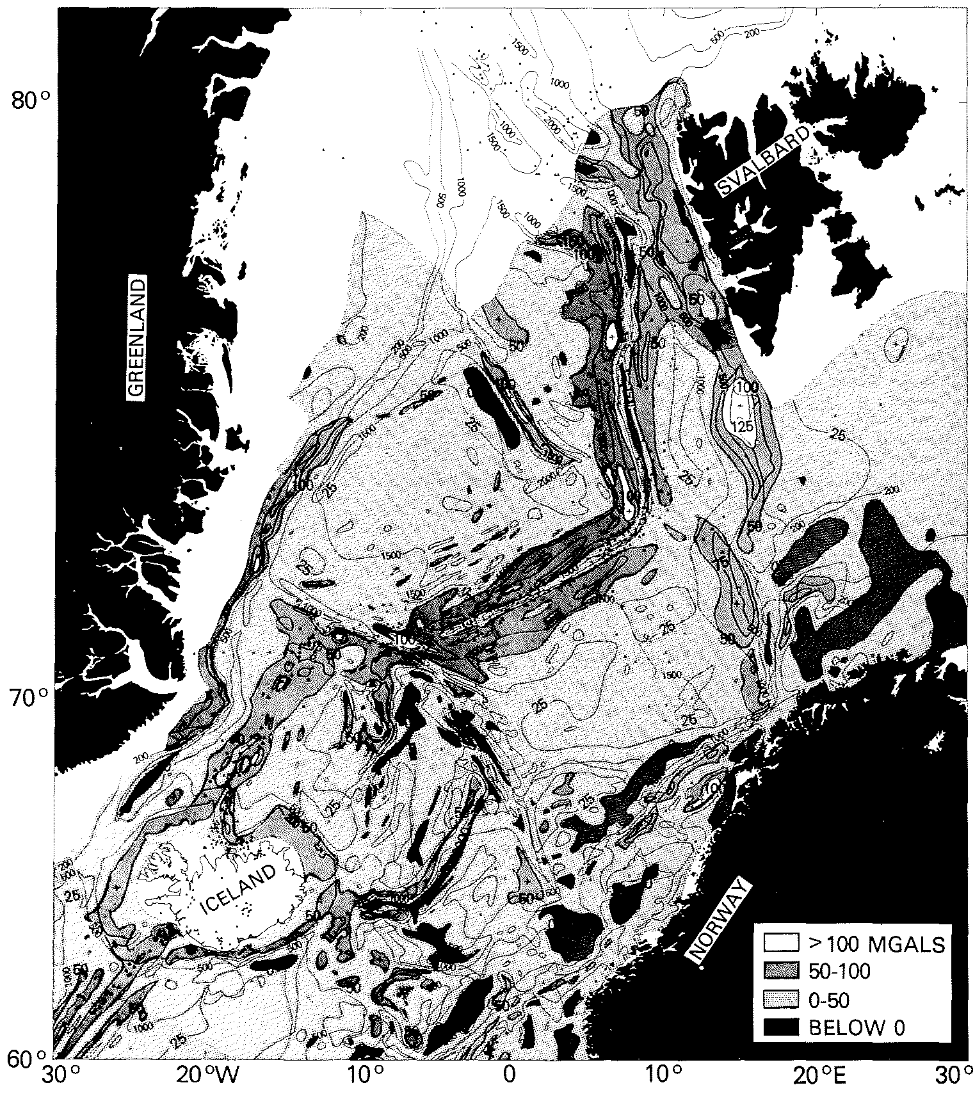

Fig. 5: Free-air gravity anomalies in the Greenland-Norwegian Sea, redrawn after GRØNLIE & TALWANI (1976). Fine contours are bathymetry, in uncorrected fathoms (GRØNLIE & TALWANI, 1976). Small triangles show earthquake epicenters through 1977.

Abb. 5: Freiluft-Schwere-Anomalien in der Grönländisch-Norwegischen See, umgezeichnet nach GRØNLIE & TALWANI (1976). Feine Konturen sind Tiefenangaben in unkorrigierten Faden-Werten (GRØNLIE & TALWANI, 1976). Die kleinen Dreiecke bezeichnen Erdbeben-Epizentren im Verlauf des Jahres 1977.

Plio-Pleistocene in age and may speculatively be equated with the period of continental-scale glaciation starting around 3 m. y. b. p..

A buried east-dipping escarpment about 35 km east of the rift valley may mark the eastern limit of oceanic crust formed at the present Knipovich Ridge spreading axis; the implied eastward jump of the axis would have occurred about 5—6 m. y. b. p. (SUNDVOR & ELDHOLM, 1979). Alternatively the escarpment simply marks the eastern edge of the "rift mountain" province commonly seen along the Mid-Atlantic Ridge.

Multi-channel profiles show what appears to be oceanic basement continuing landward beyond the escarpment (Fig. 3, 8). Basement returns are lost at sub-bottom depths of 2 to 4 sec. (Fig. 3; see also SUNDVOR & ELDHOLM, 1976, 1979; SUNDVOR et al., 1977; HINZ & SCHLÜTER, 1978). In general, maximum penetration decreases northward, as with single-channel data. This probably reflects the increasing northward proximity to coarse terrestrial sediment sources, as well as increasing ice-rafted sediment components and increasing slope gradients.

Greatest penetration is shown by BRISEID & MASCLE (1975) on profiles MC-6 and MC-7 which cross the continental rise south of Bear Island (Fig. 1, 3). In this area, a semi-continuous reflector (Indicated by us as "Y" in Fig. 3) is seen below the homogeneous unit. The sediments below Y are acoustically stratified in the southernmost profile (MC-7). Reflector Y has not been dated by drilling. However, it appears to extend seaward to within 100 km and perhaps within 50 km of the present spreading axis (Fig. 3). No reflector that is not diachronous can be older than the youngest oceanic crust on which it can be identified. This principle is shown schematically in Fig. 8, where T_X and T_Y are crustal ages giving upper limits to the ages of reflectors X and Y. Assuming the Knipovich axis has not jumped eastward, or at least not more than a few tens of kilometers, one can use reasonable spreading rates to conclude that T_Y is probably less than 10 m. y. b. p..

The exact location and nature of the continent-ocean crustal boundary west of Svalbard is uncertain. The boundary certainly lies east of the Knipovich escarpment (SUNDVOR & ELDHOLM, 1979) and probably landward of the easternmost basement returns on multi-channel profiles. A seaward limit of the crustal transition is provided by the „Hornsund Fault" (SUNDVOR et al., 1977; SUNDVOR & ELDHOLM, 1976, 1979). Detected by close-spaced sonobuoys, this feature is a westward dipping escarpment trending north-south under the outer continental shelf from Bear Island to northwest Vestspitsbergen (Fig. 1). Landward of the Hornsund escarpment is a layered sedimentary sequence with sea floor velocities generally between 3.8 and 4.2 km/sec. These sediments are almost certainly pre-rifting in age and underlain by continental crust (SUNDVOR & ELDHOLM, 1979).

Thick low-velocity sediments (sea-floor velocity 1.7—1.8 km/sec) west of the Hornsund escarpment may or may not be underlain by oceanic crust. Refractors with velocities characteristic of ocean crust are first encountered at sub-bottom depths as great as 7 km below the continental slope between Bear Island and southern Vestspitsbergen (SUNDVOR & ELDHOLM, 1976). This depth gives an upper limit to the thickness of post-rift sediments along this continental margin.

If the original continental margin — the crustal transition — lies near the Hornsund escarpment, post-rifting prograding of 20 to 50 km is implied. When the present plate boundary is rotated eastward by an angle equal 1/2 the total opening of the Lofoten-Greenland and Eurasia Basins, the rotated boundary overlaps the Barents-Spitsbergen continental shelf (TALWANI & ELDHOLM, 1977). Since the rotated boundary does not

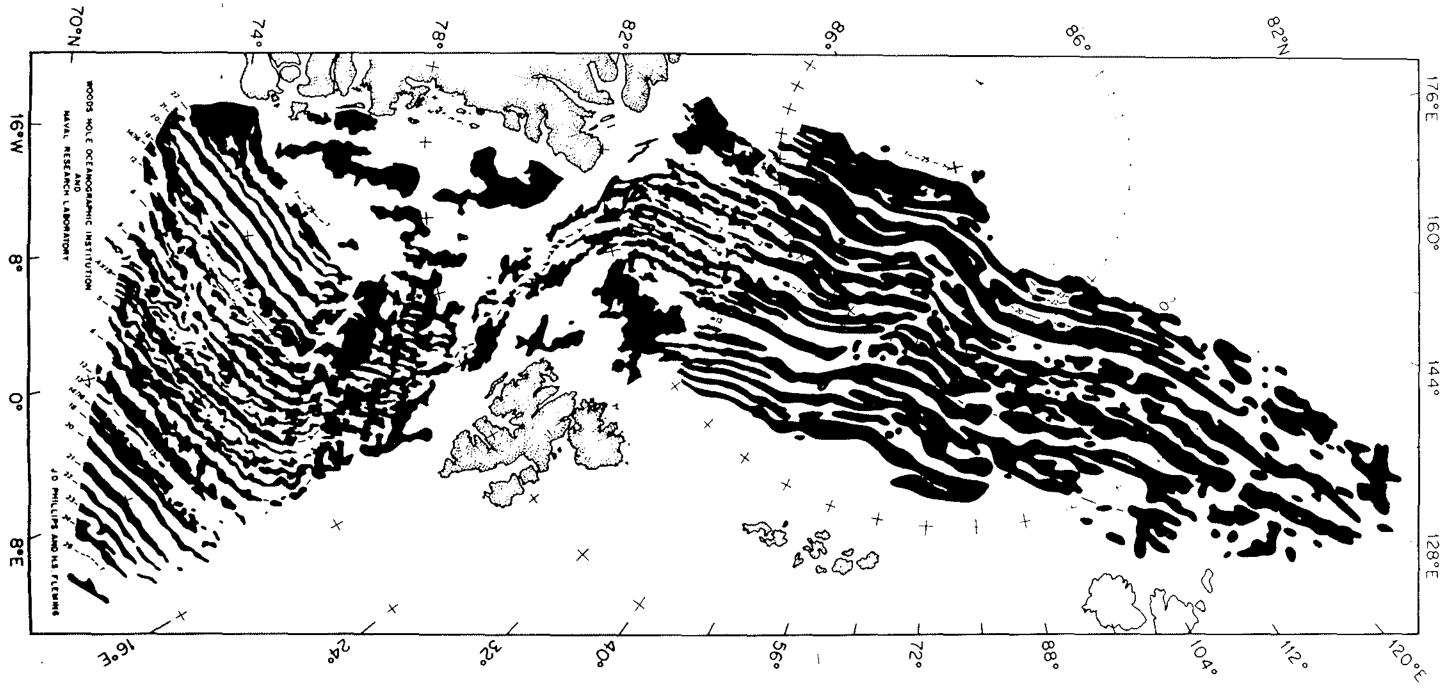

Fig. 6: "Zebra-stripe" chart of magnetic anomalies in Greenland-Norwegian Sea and Eurasia Basin. Black areas are positive anomalies, and anomaly identification follows the convention of HEIRTZLER et al. (1968). Based on aeromagnetic data collected by Naval Research Laboratory (south and west of arrow) and Soviet data (KARASIK, 1974) to the north and east.

Abb. 6: „Zebra-Streifen"-Karte der magnetischen Anomalien in der Grönländisch-Norwegischen See und dem Eurasiatischen Becken. Schwarze Areale sind positive Anomalien; die Bestimmung der Anomalien entspricht der Übereinkunft von HEIRTZLER et al. (1968). Nach aeromagnetischen Daten des Naval Research Laboratory (südlich und westlich des Pfeiles) und sowjetischen Quellen (KARASIK 1974) im Norden und Osten.

overlap the Hornsund escarpment except north of 78° N, no eastward migration of the spreading axis has to be postulated south of 78° N if the Hornsund escarpment marks the crustal boundary. However, SUNDVOR & ELDHOLM (1979) believe the boundary lies seaward of the escarpment.

Preliminary interpretation of sonobuoy and multi-channel data north of Svalbard (SUNDVOR et al., 1977; SUNDVOR & ELDHOLM, 1979) suggests that the southeastern Yermak Plateau is underlain at sub-bottom depths of 0.7 to 1.5 km by a smooth opaque basement reflector corresponding to a refracted velocity about 4—4.5 km/sec. This type of basement has been discovered elsewhere on thickened oceanic crust and aseismic ridges, for example, the outer Vøring Plateau.

5. GRAVITY

A free-air (F. A.) gravity anomaly contour chart of the Greenland-Norwegian Sea and adjacent Barents-Svalbard margin (Fig. 5) was published by GRØNLIE & TALWANI (1976). COCHRAN & TALWANI (1978) published charts of 1° X 2° and 5° X 10° average gravity anomaly. Since the gravity features of this area are discussed by G. Grønlie elsewhere in this volume, we present only a very brief summary here.

On the average, the deep-water areas of the Greenland-Norwegian Sea are part of a vast regional F. A. high centered on Iceland. The oceanic crust over Mohns and Knipovich Ridges and adjoining basins exhibit average anomalies of the order + 10 to + 25 mgals; the regional gravity high and associated depth anomaly is attributed in part to lithosphere compensation and in part to a positive temperature (hence reduced density) anomaly of the order 75° C in the asthenosphere (COCHRAN & TALWANI, 1978). Superimposed on this regional anomaly is a decrease of free-air anomaly with crustal age (+ 20 mgals for zero-age crust decreasing to zero by 40 m. y.). More local sea-floor and basement topography is not locally compensated and is therefore mirrored by the F. A. gravity field. Adjacent continental shelf crust exhibits anomalies of either sign, and averaging near zero. There is some correlation with topography, for example lows over the Bear Island Trough and Svalbard fjords. Other features undoubtedly reflect deep structures (e. g. ELDHOLM & TALWANI, 1977). Free-air highs tend to occur over the shelf edges, particularly in areas where the morphology suggests progradation (VOGT & PERRY, 1978). Examples are found at the mouths of Storfjord and Bear Island Troughs. The gravity highs may then represent uncompensated (SOBCZAK, 1975) or regionally compensated (WALCOTT, 1972) sediment masses of primarily Plio-Pleistocene age. Alternatively, the somewhat elongate high southwest of the Bear Island Trough could reflect a deep crustal structure, the "Senja Fracture Zone" of TALWANI & ELDHOLM (1977). In addition, free-air anomalies over shelf edges would be expected as continent/ocean edges effects, provided the actual crustal boundary indeed lies near the shelf edge. Unfortunately, this is not easily proven by seismic reflection and refraction methods (e. g., HOUTZ & WINDISCH, 1977).

6. MAGNETIC ANOMALIES

Detailed aeromagnetic surveys by the U. S. Naval Research Laboratory and U. S. Naval Oceanographic Office now extend from the Jan Mayen fracture zone northwards into the Eurasia Basin (VOGT et al., 1979a; PERRY et al., 1977; PHILLIPS et al., 1979) where they overlap Soviet surveys (Fig. 6). Even more detailed, petroleum-oriented surveys over the Norwegian and southern Barents continental margins have not been released in their entirety (ÅM, 1975). North of Bear Island, including the entire Svalbard archipelago and surrounding continental margins, only randomly oriented, widely spaced profiles exist (ÅM, 1973).

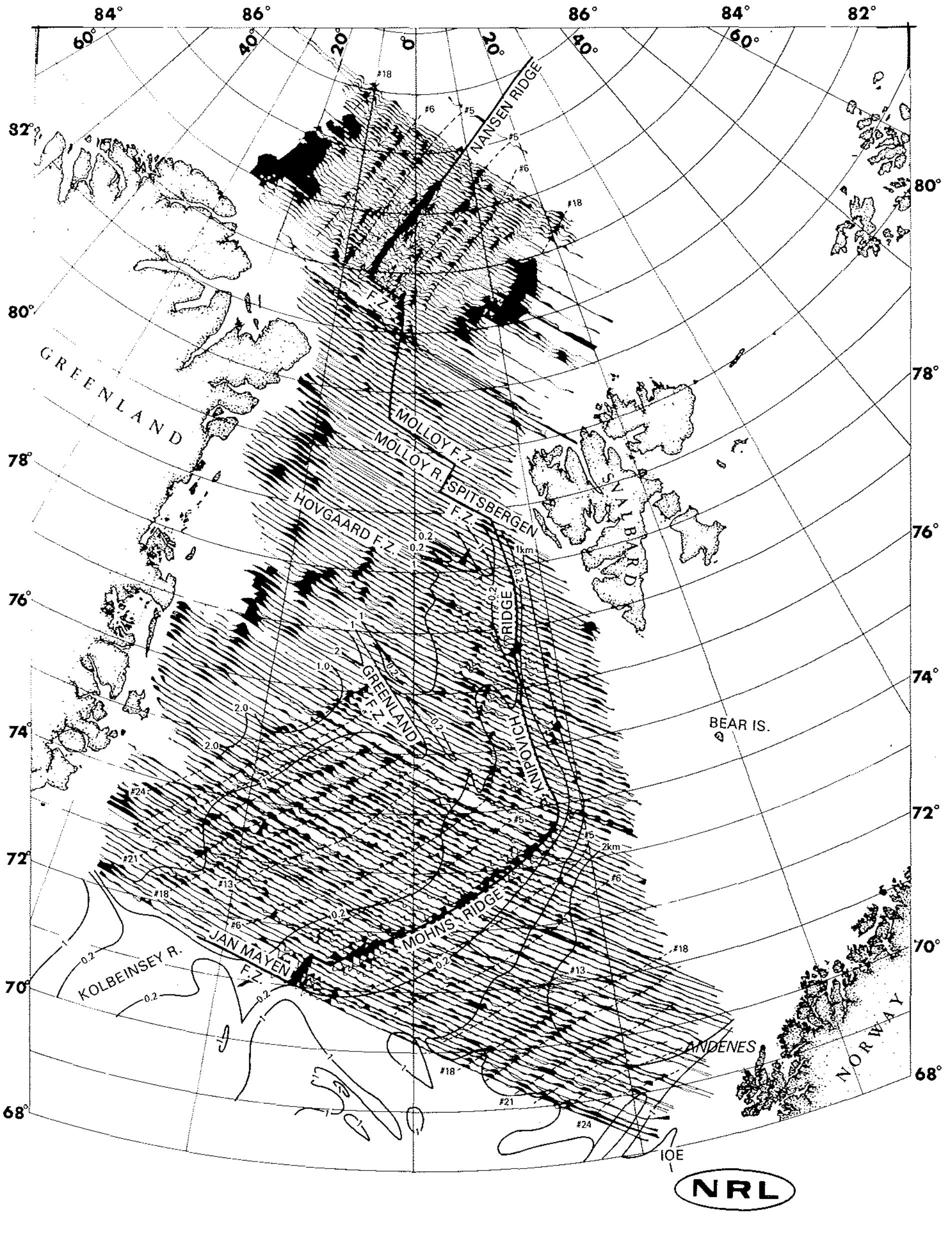

Fig. 7: Residual magnetic anomalies plotted along flinght tracks (PHILLIPS et al., 1979). Northernmost group of 7 tracks from VOGT et al., (1979 a). Sediment isopachs (in km) after ELDHOLM & WINDISCH (1974).

Abb. 7: Residuen der magnetischen Anomalien entlang aufgezeichneter Flugbahnen (PHILLIPS et al. 1979). Nördlichste der 7 Profillinien aus VOGT et al. (1979 a). Sediment-Isopachen (in km) nach ELDHOLM & WINDISCH (1974).

Linear anomalies due to sea-floor spreading and geomagnetic reversals (LABRECQUE et al., 1977) are well developed over Mohns Ridge and adjacent basins (Fig. 7). The principal indentifiable lineations are numbers 1, 2, 5, 6, 12, 13, 18 and 21—24 (PHILLIPS et al., 1979). Spreading rates (TALWANI & ELDHOLM, 1977) were highest in the early (1.25 cm/yr) and late Tertiary (0.91) and lowest in middle Tertiary time (0.5 cm/yr).

Between the Greenland F. Z. and the Yermak-Morris Jesup plateaus (Fig. 1, 7), the evolution of the basins by spreading is poorly known despite detailed aeromagnetic data. The central anomaly over the Knipovich Ridge rift valley is generally very low in amplitude, possibly due to the continental rise sediments being poured into the rift valley (Fig. 2, 3), or to slow, oblique spreading. Such processes might also explain the magnetically smooth regions surrounding Knipovich Ridge (Fig. 7).

PHILLIPS et al. (1979) have locally — and tentatively — identified anomalies 5, 6, 12, 13, 18, and 20—22 west of Knipovich Ridge, and 5 and 6 on the east. The existence of anomalies older than 13 (36 m. y. b. p.) conflicts with TALWANI & ELDHOLM (1977) who inferred only shear motion — with no spreading — between the Svalbard-Barents and northeast Greenland margins prior to 36 m. y. b. The present Knipovich spreading axis is closer to the Svalbard then to the east Greenland margin, particularly north of 78° N (Fig. 1). As previously discussed, this implies asymmetric spreading or eastward axis jumps. However, unambiguous magnetic evidence for an extinct axis west of Knipovich Ridge remains lacking. Clear from the magnetic anomaly patterns is the change in orientation of southern Knipovich Ridge in the last 1—2 m. y.. The present axis runs north-south whereas young flank lineations trend northeast (Fig. 7).

The short "Molloy" spreading axis, located between the Molloy and Spitsbergen fracture zones (Fig. 1) is associated with a weak positive anomaly. Anomaly 5 may be present on either side of the axis, but the over-all anomaly pattern is unclear (Fig. 7). No magnetic evidence for an extinct axis to the west has been found.

Magnetic lineations are again well-developed in the Eurasia Basin (PHILLIPS et al., 1979; VOGT et al., 1979a; KARASIK, 1974), particularly the southeasternmost section of Nansen Ridge where amplitudes of anomalies 5 and younger are exceptionally high (Fig. 6, 7). A pair of massive basement ridges — the Yermak and Morris Jesup plateaus — was apparently generated by this section of the Nansen Ridge between anomaly 12 and 18 time (PHILLIPS et al., 1979; FEDEN et al., 1979). These aseismic ridges are associated with complex, high-amplitude (400 to 1500 nT) anomalies. The high amplitudes of the post-5 lineations, the existence of the two plateaus, and other factors suggest the existence of a previously unknown hot spot (FEDEN et al., 1979). The high magnetic amplitudes are thought to reflect highly fractionated, FeTi-rich basalts such as found in the vicinity of other hot spots.

Excessive, partly explosive volcanism associated with the Yermak hot spot might explain the occurrence of lower Paleocene windblown tuffs in southwest Vestspitsbergen (DYPVIK & NAGY, 1978), the Miocene flood basalts and Recent volcanoes in northwestern Vestspitsbergen (PRESTVIK, 1977), and the early Tertiary (63±2 m. y. b. p.) Kap Washington Group volcanics exposed along the north coast of Greenland (LARSEN et al., 1978).

It appears probable that the Morris Jesup and Yermak plateaus formed a single Iceland-like, subaerial mass until about 36 m. y. b. p. when a deep rift opened between them (FEDEN et al., 1979). Until that time the plateaus thus formed another land bridge for faunal migration (e. g. WEST, 1978) and blocked the interchange of Arctic and Greenland Sea water.

Anomalies 19—24 have not been identified with certainty between the northeast trending segment of the Yermak Plateau and the Svalbard continental margin, or between the Morris Jesup Rise and the Lomonosov Ridge. However, since these anomalies occur farther northeast in the Eurasia Basin (Fig. 6, VOGT et al., 1979a) as well as in the Greenland and Lofoten basins (Fig. 7), plate reconstructions strongly suggest the existence of oceanic crust of anomaly 19—24 age (possibly as old as 31: see PHILLIPS et al., 1979 and SRIVASTAVA, 1978) just to the north of northern Svalbard (including the southeastern segment of the Yermak Plateau). The available seismic data are not inconsistent with such an interpretation (SUNDVOR et al., 1977; SUNDVOR & ELDHOLM, 1979).

Magnetic data from the Svalbard and Greenland continental margins have not revealed any systematic "marginal" anomaly. Long-wavelength features on the wide east Greenland margin are oblique to the younger spreading lineations (Fig. 7). These broad shelf anomalies probably reflect Caledonian or pre-Cambrian continental crystalline or metamorphic rocks buried beneath ~ 10 km of Permian and younger sediments (see also TALWANI & ELDHOLM, 1977).

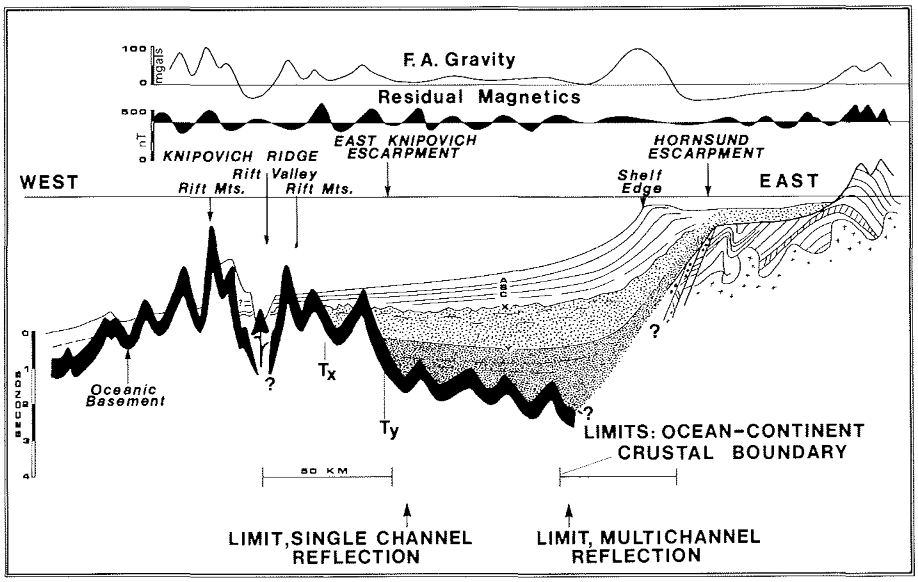

Fig. 8: Schematic interpretive system of major geophysical features encountered along a representative profile westward from Spitsbergen to the east flank of Knipovich Ridge. Although based on Figs. 1 through 7, this profile does not represent any actual profile.

Abb. 8: Deutungsschema wesentlicher geophysikalischer Erscheinungen längs eines repräsentativen Profils vom Westen Spitzbergens bis zur östlichen Flanke des Knipovich-Rückens. Dieses abstrahierte Profil basiert auf den Abb. 1—7.

7. SEISMICITY

Earthquakes of teleseismic magnitude occur frequently along the world's active plate boundaries. Thus, accurately located events (1963—1977) serve to trace the complex path of the America-Eurasia plate boundary from the Reykjanes Ridge northward into the Arctic Basin (Fig. 5). Some of the events have been strong enough to yield fault plane solutions (See, for example, HORSFIELD & MATON (1970), HUSEBYE et al. (1975) and BUNGUM & HUSEBYE (1977)). Teleseismic activity along the Mid-Oceanic Ridge appears more reduced within 900 km of central Iceland than, for example, along the more typical Mohns Ridge (VOGT, 1978). The reduced seismicity around Iceland may reflect high mantle temperatures associated with the Iceland hot spot. Earthquake epicenters along Knipovich Ridge are geographically more scattered compared to neighboring Mohns Ridge; the tectonic significance of this difference is uncertain.

Intra-plate (or "mid-plate") seismicity is comparatively high in several parts of the Greenland-Norwegian Sea, for example, in the Lofoten Basin, the Barents-Vestspitsbergen continental margin, parts of Svalbard, and the northeast Greenland Shelf. There is no consensus on the cause of such earthquakes (HUSEBYE et al., 1975). Regional effects of the Iceland hot spot (VOGT, 1978), deglaciation, and reactivated basement structures are among the proposed factors.

8. PLATE TECTONIC EVOLUTION AND REMAINING PROBLEMS

In very general terms the plate tectonic history of the oceanic regions around Svalbard can be considered understood (PHILIPPS et al., 1979; FEDEN et al., 1979; PHILLIPS & TAPSCOTT, 1979; TALWANI & ELDHOLM, 1977; KARASIK, 1974). This is true even though the precise age of the oceanic crust bounding Vestspitsbergen on the north and west cannot be determined from available magnetic data (Fig. 7). However, many details in the evolution remain conjectural.

The plate tectonic history can be divided into three stages: (1) prior to 57—58 m. y. b. p., i. e., the reversed period just before anomaly 24, (2) from this point to about anomaly 13; and (3) from anomaly 13 time to the present.

(1) Pre-anomaly 24 history. Most recent plate tectonic syntheses (e. g. SRIVASTAVA, 1978; KRISTOFFERSEN & TALWANI, 1977) agree that the Eurasia, Baffin, Labrador and Lofoten-Greenland basins were closed at anomaly 31—32 time. The southwestern Lomonosov Ridge lay adjacent to northern Svalbard. Beyond, to the north and northeast, lay an earlier oceanic basin, the Amerasia Basin, whose age and origin is still conjectural (VOGT et al., 1979a).

Anomalies between 24 and 31/32 have not been positively identified in the northeast Atlantic north of 52° N, in the Eurasia Basin, or in Davis Strait-Baffin Bay. However, a number of authors have inferred that plate motion was already in progress during this interval (e. g., KARASIK, 1974; SRIVASTAVA, 1978; PHILLIPS et al., 1979). Others have found no evidence that spreading began at anomaly 25 time or earlier (VOGT et al., 1979a; ELDHOLM & SUNDVOR, 1979; TALWANI & ELDHOLM, 1977).

Although $\sim$ 50 km wide strips of relatively deep water (continental rise and slope) in many areas lie between anomaly 24 and the shelf edge, the nature of this marginal crust remains uncertain. If pre-anomaly 24 oceanic crust exists, a mechanism must be found to explain (1) the absence of identifiable lineations; and (2) the lack of parallelism between anomaly 24 and the shelf edge in the Greenland and Lofoten basins (Fig. 6, 7).

(2) Between anomaly 24 and 13 time, plate motion was complex in the Svalbard area (PHILLIPS et al., 1979). Plate reconstructions using anomaly trend superposition techniques suggest at least four active plates with triple junctions both north and south of Greenland and compression in both the American Arctic basin (Alpha Ridge?) and the Canadian Arctic Islands (Eurekan Orogeny). Regardless of any motion for Greenland or the complexities in the Svalbard area, the plate rotation poles for anomalies 24—13 are different for the North Atlantic and Eurasia basins. This demands non-rigid behavior or additional plate boundaries within the present North America and Eurasia plates. The Yermak and Morris Jesup plateaus were apparently produced between anomaly 24 and 12—13 time, particularly towards the end of the interval. The origin of these aseismic ridges has been ascribed to triple junction effects (PHILLIPS et al., 1979) or to a "Yermak hot spot" (FEDEN et al., 1979).

During the anomaly 24—13 period, motion between Greenland and the Barents-Svalbard margin was primarily shear. However, TALWANI & ELDHOLM'S (1977) conclusion that there was no opening north of the Greenland-Senja fracture zone before 36 m. y. b. p. is inconsistent with the claimed discovery of anomalies as old as 22 in the Boreas Basin north of the Greenland F. Z. (PHILLIPS et al., 1979). The early to middle Tertiary "Spitsbergen orogeny" is thought to reflect compressional components as Greenland and Svalbard slid past each other (LOWELL, 1972).

(3) Since anomaly 12—13 time all plate motion has been restricted to opening the Mid-Atlantic-Mohns-Knipovich-Nansen Ridge about a single pole of opening (PHILLIPS et al., 1979). That is, the Baffin-Labrador and other possible plate boundaries became extinct at about anomaly 12—13 time. However, the occurrence of Miocene as well as Recent volcanism on Svalbard (PRESTVIK, 1977) and a relatively high level of mid-plate seismicity (HUSEBYE et al., 1975; VOGT, 1978) suggests some continuing mid-plate deformation.

After Greenland became attached to the North American plate, motion between Greenland and Svalbard became more east-west, thereby developing a deepwater rift in the region between Eurasia Basin and the Greenland-Lofoten basins. Simultaneously with this change in spreading direction, a deep rift also developed between the Morris Jesup and Yermak plateaus. The connection between these two coeval events is not well understood, however.

The kinematic change at anomaly 12—13 time turned Mohns Ridge into an oblique spreading axis, a configuration it has maintained to this day. This is surprising since most spreading centers are thought to prefer a "zed" geometry (transform faults and orthogonal spreading centers) to oblique spreading. By contrast, Knipovich Ridge — at least in the south — appears to have acquired its oblique configuration from an earlier "zed" geometry in the last few m. y.. Meanwhile, Molloy Ridge (Fig. 1) resembles a "classic" orthogonal spreading center. Too little is known about the dynamics of accreting plate boundaries to justify trying to explain these different features.

Finally, we should stress that perhaps the major unsolved problem concerns the location and nature of the continent-ocean crustal boundary north and west of Svalbard (Fig. 8). Until the total amount of extension represented by this marginal crust can be estimated, we cannot apply plate tectonic methods to predict the amount and sense of deformation that occurred on land — for example — during the lower Tertiary Spitsbergen Orogeny.

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