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The Eurasia Basin: An Update from a Decade of Geoscientific Research

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Invited Plenary Lecture

Summary: The pioneering geoscientific studies until 1990, from aircraft landings on sea ice, drifting ice stations and aeromagnetic surveys, have resulted in a set of working hypothesis for the first order geologic history of the Arctic Ocean Basin. After 1990, data acquisition from icebreakers, submarines and geopotential field studies from satellites and aircrafts present a new level of opportunities to test our models. The most significant results over the last decade are:

1) new insight into the seismic stratigraphic architecture of Lomonosov Ridge which supports the origin of the ridge as a continental fragment,
2) gravity evidence for thin crust Gakkel Ridge with its implication for a large role of tectonic extension at the spreading center, and
3) seismic reflection evidence for crustal scale detachments below the Laptev Sea Shelf.

Accumulating geological evidence and growing recognition of the importance of distributed deformation in the Canadian Arctic Archipelago to account for the Early Cenozoic relative motion between Greenland and North America, represent new insights into the behaviour of the lithosphere and resolves the Nares Strait enigma.

BACKGROUND

A Soviet basin-wide program of oceanographic measurements supported by aircraft landings on sea ice (High Latitude Air Expeditions) discovered the submarine transpolar ridge which extends from the margin north of the New Siberian Islands to Ellesmere Island and divides the polar ocean into the Eurasia and Amerasia basins (WEBER 1983). A major submarine feature had been postulated by HARRIS (1904) from the observed delay in the transpolar tide and was later supported by the work of FJELDSTAD (1936).The existence of Lomonosov Ridge became known in the west through publication of the first modern polar bathymetric map by the Russians in 1954, and came as a great surprise to western scientists (BURKHANOV 1957, WEBER 1983). Just before that, WORTHINGTON (1953) had concluded from differences in deep water temperatures north of Alaska compared with Nansen´s results that the water masses was most likely separated by a submarine transpolar ridge with a sill depth not greater than 2300 m.

Four decades of pioneering geophysical and geological studies from drifting ice stations after World War II combined with aeromagnetic surveys in late 1960s and 1970s have outlined the broad morphology and first order geologic history of the deep Eurasia Basin, its submarine ridges and maginal plateaus (GRAMBERG et al. 1991, JOHNSON 1983, VOGT et al. 1979, KARASIK 1968). We entered a new era in the history of geoscientific exploration of the Arctic Ocean when diesel driven icebreaking research vessels were able to penetrate beyond the North Pole in 1991 while collecting underway geophysical data such as bathymetry, gravity and seismic reflection measurements (FÜTTERER et al. 1992). As a result, the geophysical data base was almost doubled in a single expedition. The ultimate „quantum leap" in geophysical data acquisition capabilities in recent years has been access to US Navy nuclear submarines for collection of swath bathymetry, high resolution seismic profiling and gravity data under the SCICEX program (PYLE et al. 1997, COAKLEY & COCHRAN 1998). This highly efficient modus operandi will have a large scientific impact if its momentum can be maintained after 1999. Incidentally, the first attempt at Arctic oceanographic data collection from a submarine north of Svalbard in 1931 preceeded the first drifting ice station by five years (SVERDRUP 1931, PAPANIN 1939).

A large international effort to compile and integrate the circum-arctic magnetic total field data base has been completed (VERHOEF et al. 1996) and new updates are underway (GLEBOVSKY et al. 1998). Also an international initiative to update the Arctic Ocean bathymetry map is progressing (MCNAB & GRIKUROV 1997). Renewed aerosurveys of the magnetic field and gravity in the Eurasia Basin (KOVACS et al. 1998) and the margin north of Greenland and Ellesmere Island (FORSYTH et al. 1998) will provide improved tectonic constraints on the history of basin formation. The new exciting data are sharpening our arguments for future efforts to obtain more substantial geologic „ground truth" from the Arctic Ocean.

We review some of the advances over the last decade in our understanding of the geologic evolution of the Eurasia Basin as well as new insights into processes relevant to seafloor spreading at low opening rates.

STRUCTURAL FRAMEWORK OF THE MARGINS OF THE EURASIA BASIN

Lomonosov Ridge

The asymmetric architecture of the Lomonosov Ridge expressed in its central part with alternating prograding and onlapping

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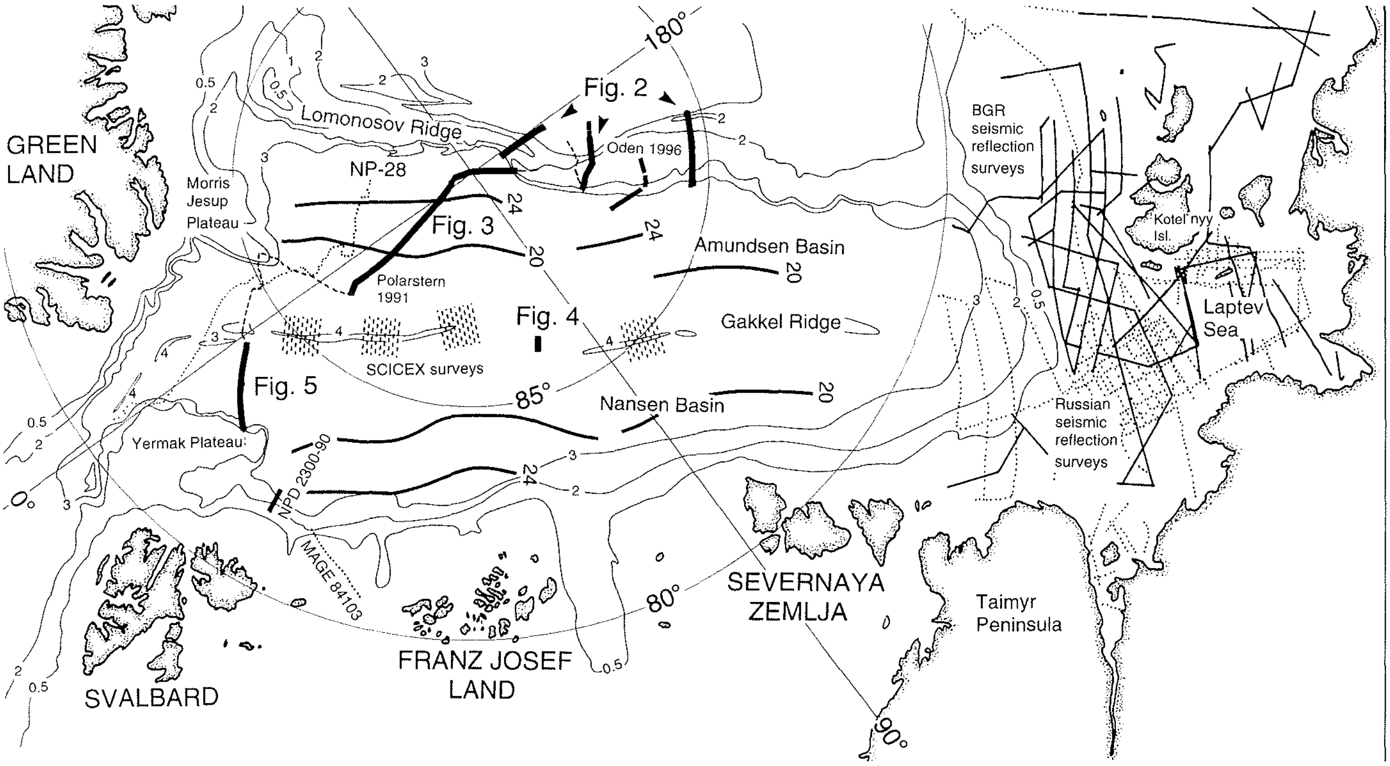

Fig. 1:Location of seismic reflection surveys acquired or available over the last decade in the Eurasia Basin and adjacent continental margins. Individual surveys are labelled in the figure. Magnetic isochrons after VOGT et al. (1979).

strata (v_p >4 km/s) dipping towards Makarov Basin present a strong case for the origin of the ridge as a fragment of a former continental margin (Figs. 1 and 2). The topsets have been eroded away and the units are unconformably overlain by a ~450 m thick sediment drape of velocity <2 km/s (JOKAT et al. 1992). In contrast, the Eurasia Basin side of the ridge is a steep terrace of narrow fault blocks which accomodate more than 4 km of vertical relief relative to basement underlying the Amundsen Basin (KRISTOFFERSEN 1997a, POSELOV et al. 1998, SOROKIN et al. 1998).

The new bathymetric and seismic data show the main changes in trend of Lomonosov Ridge topography from the North Pole towards the Siberian margin to be related to the relative elevations of horsts in a series of en echelon horsts and grabens trending obliquely to the main ridge (Figs. 1 and 2). This oblique pattern was also noted in the aeromagnetic data by KARASIK (1974). The ridge structure changes character from a main block in the central part to a more broadly faulted area (JOKAT 1998) towards the Laptev Sea as well as the Greenland and Canadian margin (COAKLEY & COCHRAN 1998). The central narrow part of Lomonosov Ridge near the North Pole, exhibits a strong uneven reflection below ~600 m of sediments. The seismic event resembles the acoustic image of basalt flows (KRISTOFFERSEN 1998). Basalt flows have also been interpreted to cover basement on the margin north of Franz Josef Land and Kvitøya (BATURIN 1994). These indications together with the short wavelength character of the magnetic field over Lomonosov Ridge from the North Pole to Ellesmere Island (VERHOEF et al. 1996) may suggest a more or less continous basalt province between Franz Josef Land and Ellesmere Island during Cretaceous times (KRISTOFFERSEN 1998).

Present geologic information of pre-Cenozoic rocks from the Lomonosov Ridge is limited to piston core recovery of monolithic rubble of indurated siltstone clasts containing Devonian to Mississippian spores on the Eurasian flank of the ridge (88° 52.1" N) in 1520 m water depth (GRANTZ et al. 1998). Spore fragments of probable Devonian age along with more abundant Cretaceous spores and dinoflagellates were also recovered by gravity coring 100 km to the north along the flank during the Canadian LOREX expedition (BLASCO et al. 1979). GARD & CRUX (1994) have pointed out, based on the sediment cores recovered by RV „Polarstern“ during the ARCTIC-91 expedition, that reworked Jurassic-Neogene calcareous nannofossils are present in Quaternary sediments from the Lomonosov Ridge and the entire Eurasia Basin. The relative abundance of reworked micro fossils is highest in interglacial sediments and no specific distribution pattern can be detected.

The first attempt to recover sediments from Lomonosov Ridge by shallow drilling was carried out from RV „Oden“ in 1996 (KRISTOFFERSEN 1997). „Oden“ with 24.500 H.P. and a Thyssen-Waas bow design has the capability of maintianing position within 50 m while breaking 2-3 m sea ice drifting at several hundred meters pr. hour. A light riser was successfully set in 962 m. water depth, but problems developed when 250 m of drill string was out and the experiment had to be aborted.

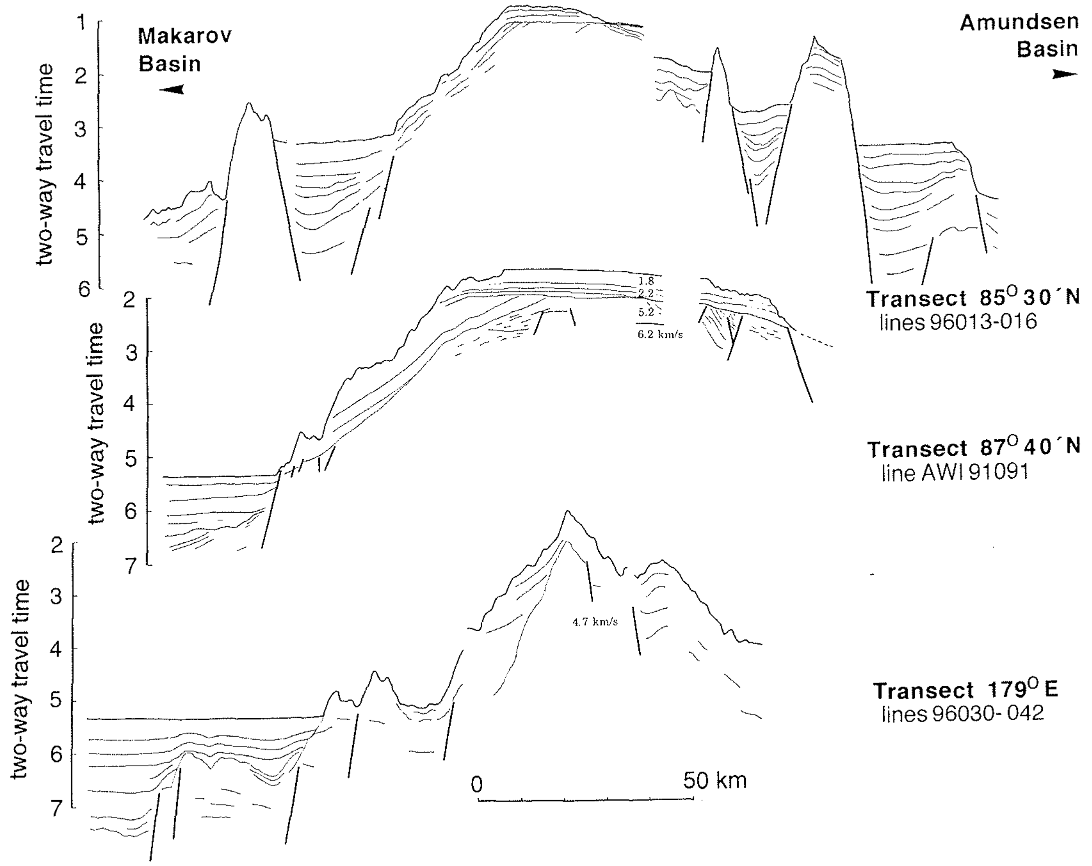

Fig. 2: Line drawing of multichannel seismic sections across Lomonosov Ridge acquired by RV „Polarstern" in 1991 (FÜTTERER 1992) and RV „Oden" in 1996 (KRISTOFFERSEN 1997a).

Svalbard - Severnaya Zemlja margin

During the last decade, more seismic data have become available over the Lomonosov Ridge than from the conjugate and more accessible continental margin between Svalbard and Severnaya Zemlja. Two lines, less than 200 km apart (Fig. 1), show considerable lateral changes with a single steep boundary fault north of Nordaustlandet (RIIS 1994) and farther east more gradual deepening of continental basement, attenuated by a series of rotated fault blocks (BATURIN 1987, BATURIN et al. 1994). VERBA et al. (1989) have integrated gravity, magnetic and seismic refraction results along a transect across the Barents Shelf, Franz Josef Land to Alpha Ridge. They suggest a 5 km thick section below the Franz Josef Land margin with average velocity of 3.7 km/s of Upper Paleozoic(?) to Cretaceous sediments. The overlaying Late Cretacous and younger sediments (v_p >1.85 km/s) are more than 1 km thick.

The Laptev Sea extensional margin

Current extension (CHAPMAN & SOLOMON 1976, FUJITA et al. 1990a) as well as the rate and magnitude (~300 km) of Cenozoic extension in the Laptev Sea is considered to be well constrained from plate tectonic considerations, yet geological manifestations of a cumulative extension of this magnitude have been difficult to recognize. The extension of the Gakkel Ridge into the Laptev Sea margin was argued by WILSON (1963) and GRACEV et al. (1971), and the gravity expression of the ridge is well defined in the satellite gravity field to the position of the 2 km isobath (LAXON & MCADOO 1998). Horst and graben structures defined by potential field and seismic refraction data (e.g. VINOGRADOV 1984) and also seismic reflection data (e.g. IVANOVA et al. 1990) generally emphasize vertical displacements due to insufficient definition of kinematic indicators such as listric fault systems and their association with crustal scale detachments. FUJITA et al. (1990b) have suggested that current tectonic activity and surface geology of the area are consistent with an asymmetric, simple shear extensional system. New seismic reflection data clearly suggest that crustal extension is at least in part accomodated by simple crustal scale shear (HINZ et al. 1998, ROESER et al. 1995). One example is the western boundary fault of the Laptev Horst penetrating most of the crust with a westward dip flattening out on the top of a reflective lower crustal unit below the Ust'Lena Basin.

THE OCEAN CRUST

New seismic reflection measurements across the Eurasia Basin

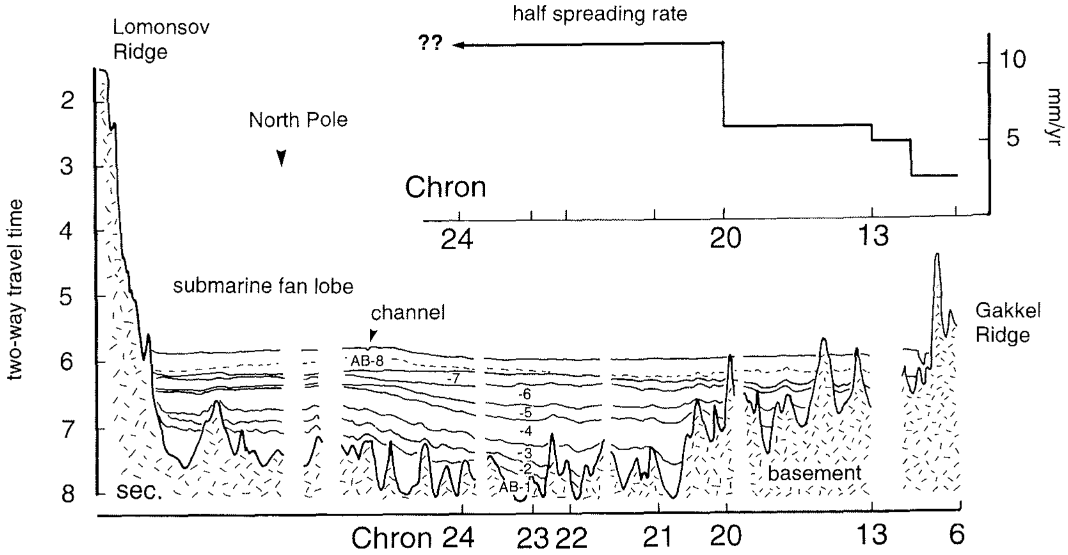

Fig. 3: Line drawing of seismic line across Amundsen Basin. Definition of seismic sequences after Jokat et al. (1995a), and spreading rates from Vogt et al. (1979).

(Jokat et al. 1995a, Sorokin et al. 1998) reveal the rough basement morphology formed at the slow spreading Gakkel Ridge (Fig. 3). There appear to be three distinct provinces with rough and relatively shallow basement on crust younger than Chron 21-20, less rough and deeper basement between Chrons 21 and 24, and deep basement pre-Chron 24. Variation in basement roughness with spreading rate is well documented (Small 1994), but may be more complex than a linear (Hayes & Kane 1991) or a power law dependence (Malinverno 1991). Basement roughness may arise from abyssal hill topography and ridge axis segmentation. Abyssal hills may form by mechanical failure of the lithosphere in the axial region, and in this case the topographic irregularity reflects a critical state of a temporally and spatially varying local stress field (Buck & Poliakov 1998). Spreading rates in the Eurasia Basin decreased by a factor of two after Chron 21 and have remained low since Chron 13 with a slight increase from the Micocene (Vogt et al. 1979). We suggest that the observed basement morphology reflects this decrease in opening rate at Chron 21-20 (Fig. 3), but note that the change in basement elevation may also be an early manifestation of the „Yermak Hot Spot“ extending east along Gakkel Ridge from the Greenland margin (Feden et al. 1979) or possibly a variation in subsidence rate related to variation in rigde crest elevation (Marty & Cazenave 1989). A conjugate basement step should also be present in the Nansen Basin extending east from the northeastern tip of Yermak Plateau.

The first bathymetric swath mapping of the Gakkel Ridge was carried out on a 25 km long segment at 84 °N, 0 °E and show a 12 km wide axial rift in water depths of 4000-4300 m with asymmetric elevation differences up to 500 m within the rift valley floor (Jokat et al. 1995a). Farther east along the ridge (10° -100 °E), four detailed grid surveys with bathymetry and gravity have been executed as part of the 1996 Scientific Ice Excercise program (SCICEX) using submarines (Coakley & Cochran 1998a) and augmented by swath mapped grids in 1998 (Coakley pers. comm.). The depth of the rift valley range from about 4000 m at the Grenwich meridian to 4600-4800 m at 50 °E. East of 60 °E where the rift valley abruptly changes strike it becomes almost completely filled with sediments (Perry et al. 1986, Jokat et al. 1998). Sediment thickness within the rift valley at 75 °E is more than 2.5 km (Fig. 4).The large amplitude gravity signature associated with Gakkel Ridge has profound implications since viable models imply either a thick high density crust or very thin crust (<4 km) of average density (less than 2.9 g/cm^3) getting thinner towards the Laptev margin (Coakley & Cochran 1998b). Available crustal thickness measurements by seismic refraction experiments are broadly in agreement with such a model. New measurements of crustal thickness in the Eurasia Basin have not been carried out or reported for more than a decade. Useful ranges of sonobuoy signals have been less than 15 km (Jokat et al. 1995a) and also the seismic source level have been insufficient for crustal thickness determination.

The low degree of melt implied by thin crust indicates that deformational processes with emplacement of mantle rocks at the seafloor (Mutter & Karson 1992, Cannat 1993) progressively become more important in crustal extension along Gakkel Ridge. The presence of a larger percentage of ultramafic rocks should be detectable as high seafloor velocities provided their dimensions are comparable to seismic wavelengths (greater than 500 m). Kiselev reports seismic velocities of the upper oceanic crust in the range 4.4-6.0 km/s (ref. in Verba et al. 1989).

THE SEDIMENTS

The bathymetry of the abyssal areas of the Eurasia Basin reflects the proximity to terrigenous sediment sources. Gravity driven sediment input into Amundsen Basin has been restricted to both ends of the basin after Lomonosov Ridge subsided below sea level whereas the Nansen Basin adjacent to the Svalbard-Severnaya Zemlja margin source area is 300-700 m shallower than the Amundsen Basin. The most recent compilation of sediment thicknesses in the Nansen Basin suggests that the Paleocene-Miocene section along the continental margin is 1-2 km thick and overlain by a Plio-Pleistocene section of similar thickness (Rasmussen & Fjeldskaar 1996), see also Kristoffersen (1990). The two seismic sections from the continental slope published so far (Fig. 1) support this estimate (Baturin 1994, Riis 1994). No seismic data are available from the deep basin east of Yermak Plateau (Fig. 1). The abyssal plain north of Yermak Plateau is only about 50 km wide and underlain by 1.5 km of turbidite fill (Jokat et al. 1995a, Kristoffersen & Husebye 1985). This area is proximal to the Fram Strait gateway and features of current controlled sediment deposition include a consistently thicker sediment cover on the northfacing slopes on seamounts of the Gakkel Ridge south flank, and a sediment drift where total thickness reach 2 km along the foot of the Yermak Plateau north slope (Fig. 5).

The sediment thicknesses in Amundsen Basin are locally more than 2 km (Jokat et al. 1995a, Sorokin et al. 1998; Poselov et al. 1998). The three published seismic profiles across the central part of the basin all show the deep sequences onlapping the

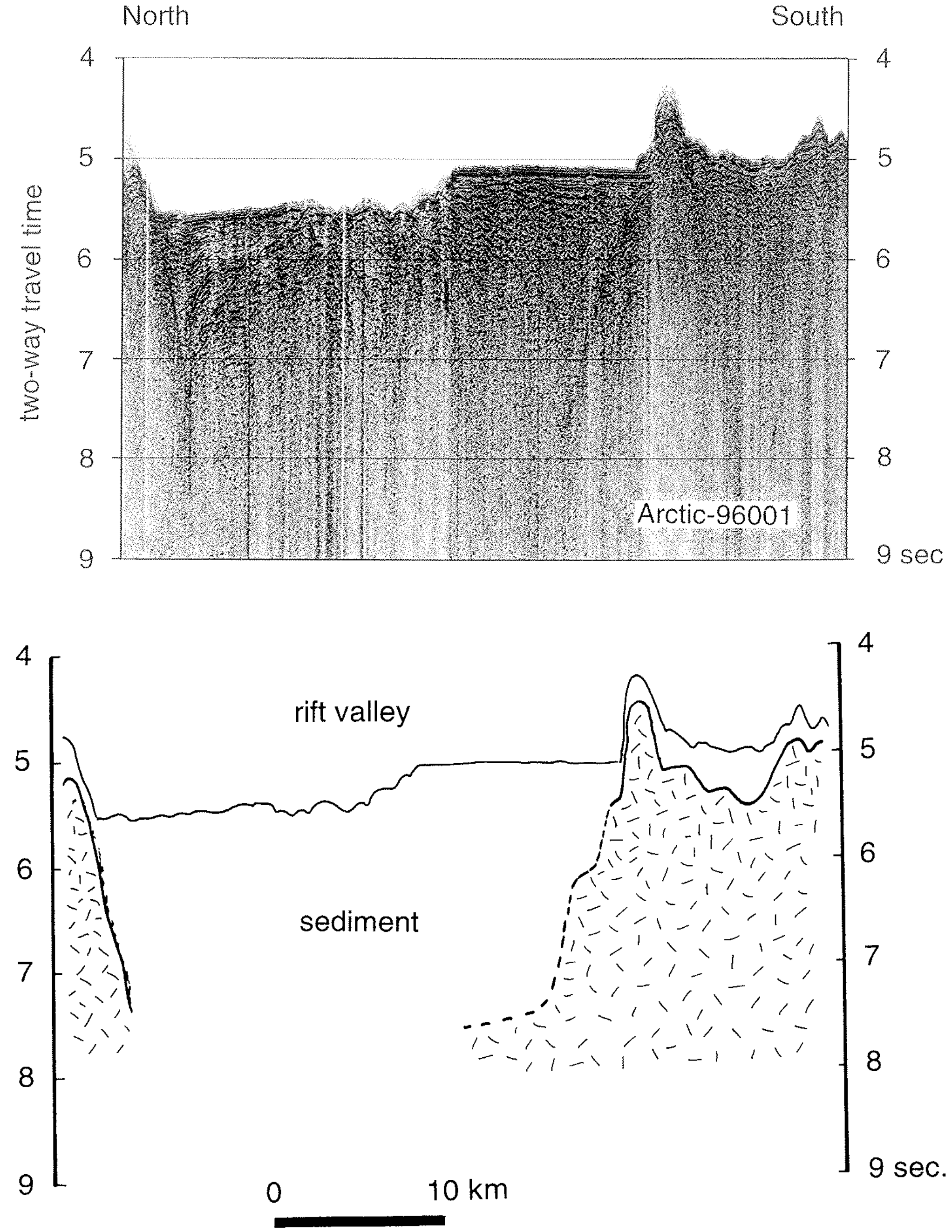

Fig. 4: Seismic reflection profile across Gakkel Ridge at 75 °E obtained by RV "Oden" in 1996.

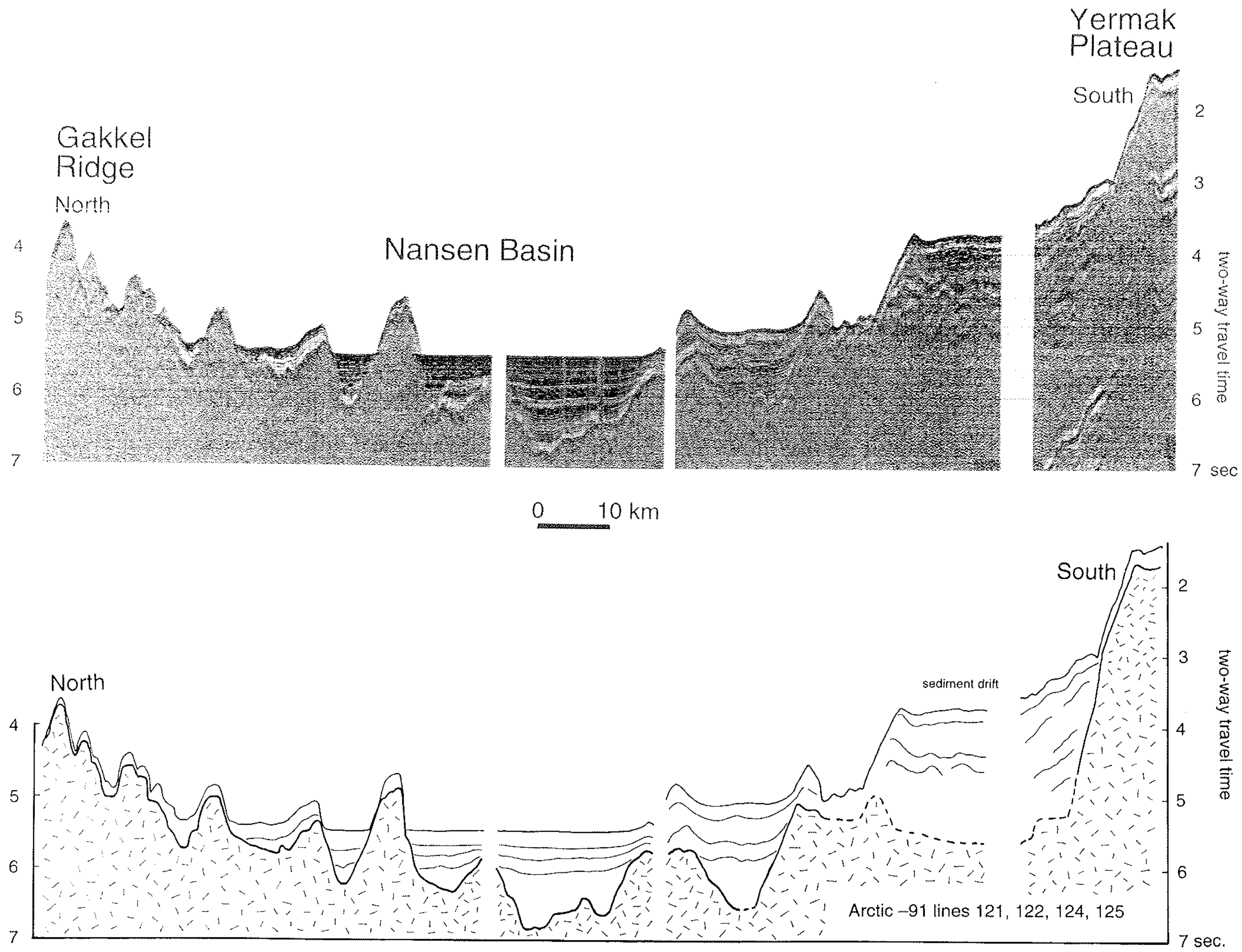

Fig. 5: Seismic reflection profile across western end of Nansen Basin obtained by RV "Polarstern" in 1991. Modified from Jokat et al.(1995b)

oldest oceanic crust in the direction of Gakkel Ridge. These sequences have progressively been tilted by relatively faster subsidence of the younger rigde flank and are overlain by sediments onlapping in the opposite direction i.e. towards the Lomonosov Ridge (Fig. 3). Jokat et al. (1995a) divided the basin sediments into eight sequences and estimated maximum ages from the age of the underlying oceanic crust dated by magnetic lineations referred to the geomagnetic polarity time scale (Berggren et al 1995). We may add a constraint by backtracking the tilt of the abyssal plain and divide the observed differential thickening of individual sequences with the theoretical tilt rate from cooling of unloaded oceanic crust. This will yield the minimum time required to create the differential accomodation space for each sequence. Evidence of well defined submarine channels suggest that Plio-Pleistocene input to the abyssal plain of the Amundsen Basin in the vicinity of the North Pole has been by several depositional lobes originating on the North-Greenland margin (Svendsen 1997)

RECONSTRUCTIONS

After Chron 13, a simple two-plate situation north of 45 °N in the North Atlantic is manifested by the quality of the isochron fit of matching conjugate plate boundaries from the Eurasia Basin to Kings Trough west of Spain using a single pole position (Srivastava & Tapscott 1986). However, plate reconstructions prior to Chron 13 when Greenland was a separate plate, present apparent problems with overlapping boundaries depending on what constraints are used. Magnetic isochrons and fracture trends along the plate boundary from south of Iceland (57 °N) through the Norwegian-Greenland Sea are in agreement with a position of Greenland relative to Europe at Chron 23 which gives no overlap between the present subareal land masses of Greenland and Svalbard (Talwani & Eldholm 1977). When the additional constraint from the triple-junction in the Labrador Sea is taken into account, the reconstructions show an overlap of more than 50 km (Kristoffersen & Talwani 1977), and also when known parts of the Eurasia Basin plate boundary are included along with the Labrador Sea boundary (Srivastava & Tapscott 1986, Srivastava 1985). Vink (1982) has explained the overlap as a consequence of continental extension during rift propagation prior to onset of seafloor spreading, i.e. rifting between Svalbard and Greenland following the strike-slip motion after Chron 20, assuming there are no yet unidentified microplates involved, and the identification of the magnetic isochrones are correct. This process is clearly important, but its applicability to this part of the plate boundary is particularly doubtful in light of several hundred published accounts of compressional tectonics on Spitsbergen (e.g. Dallmann et al. 1993), and absence of post-Palceocene tectonic events in Northeast-Greenland (Håkanson and Pedersen, 1982). Non-rigid plate behaviour may be localized or distributed over a wide area (e.g. Okulitch et al. 1998, Miall 1983, 1984). Alternatives such as pre-Chron 24 crustal extension in the Labrador Sea must be looked into as a more viable explanation for this problem, or an independent Rockall plate between chrons 20 to 24 as suggested in a widely referenced, but unpublished manuscript by Phillips & Tapscott (1981). Another issue is whether Lomonosov Ridge was part of the North American plate during the Paleogene as has been assumed by several workers (Pitman & Talwani 1972, Vink 1982, 1984, Srivastava 1985). The significance of a 50-100 km wide zone between Chron 24 and Lomonosov Ridge as noted by Vogt et al. (1979) entering into a more than 1500 m deep channel between the end of Lomonosov Ridge and Ellesmere Island (Argyle et al. 1994) is not known. Hopefully the new generation of aeromagnetics and gravity surveys will shed light on this issue (Forsyth et al. 1998).

SUMMARY

The last decade represents renewed activity and optimism in Arctic Ocean exploration with utilization of the latest of modern technology including access to submarines. New marine- and aerogeophysical data sets have been acquired and the large information potential of Russian geoscientific data is being realized and integrated in publications. Our understanding of plate interaction has advanced through the recognition of distributed deformation as a solution to the Nares Strait enigma.

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