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# MULTI-CHANNEL SEISMIC REFLECTION MEASUREMENTS IN THE EURASIAN BASIN, ARCTIC OCEAN, FROM U.S. ICE STATION FRAM-IV *

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## ABSTRACT

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We present the first multi-channel seismic reflection data ever collected from the Eurasian Basin of the Arctic Ocean. The 200 km data set was acquired by a 20 channel sonobuoy array deployed at U.S. ice drift station FRAM-IV and operated for 34 days about 370 km north of Svalbard in April–May 1982. Cross array drift and ice floe rotation which may constitute the most serious obstacle to the advantage of multi-channel data acquisition did only occur to a minor degree during the experiment and render most of the data set suitable for processing using common mid-point binning.

A 0.7–1.4 s (two-way traveltime) thick sedimentary section has been deposited over oceanic crust of mid-Oligocene age below the Barents Abyssal Plain. In the deepest part, sediments are infilling topographic lows which indicate predominantly turbidite deposition. Erosional truncations are only locally present in the central part of the section. Conformable bedforms deposited over gentle basement highs indicate a relatively stable bottom current regime since mid-Oligocene time. Thus the establishment of a deep water connection between the Arctic Ocean and lower latitude water masses appear to have had only minor effect on Eurasian Basin bottom current circulation.

Extensive submarine slide scars on the north slope of Yermak Plateau show that mass waste have been a sediment source to the Barents Abyssal Plain.

## INTRODUCTION

Teleseismically recorded earthquakes contributed to recognition of the mid-ocean ridge system extending into the Arctic and mapping of magnetic anomalies identified the Eurasian part of the Arctic Ocean as an ocean basin which has evolved since the early Tertiary (Heezen and Ewing, 1961; Sykes, 1965; Johnson and Heezen,

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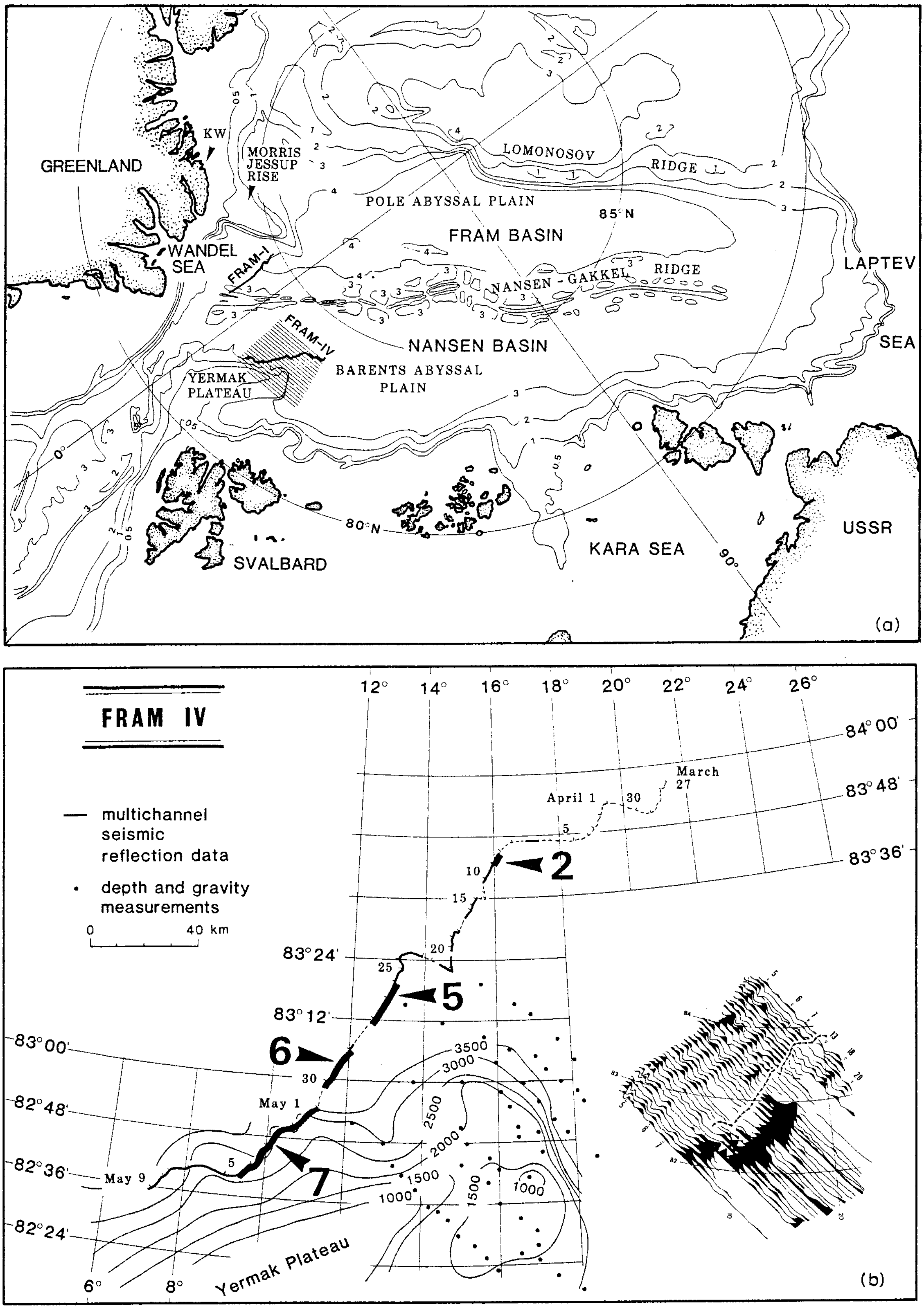


Fig. 1. a. Location of U.S. ice drift station FRAM-IV deployment area (hatched). The FRAM-I track is also shown. Bathymetry after Johnson et al. (1979). KW—Kap Washington. b. FRAM-IV drift track. Lower right: FRAM-IV drift track in relation to magnetic lineation pattern after Feden et al. (1979).

1965; Karasik, 1974; Vogt et al., 1979). The Arctic Ocean has at least throughout this period been a mediterranean sea where a deep passage to lower latitudes was established as a result of post-Oligocene relative plate motion in the North-Atlantic (Pitman and Talwani, 1972). Asymmetry in depth of the abyssal plains on either side of the Nansen–Gakkel Ridge has been attributed to greater sediment thickness in the Nansen Basin due to its proximity to a continental margin (Johnson, 1967; Vogt et al., 1979).

The dynamic ice cover of the Arctic Ocean, the major impediment to exploration, has required an approach which take advantage of the ice as a passively drifting platform for geophysical data acquisition (Sater, 1968; Johnson, 1983) and utilize the potential of airborne geophysical measurements (Feden et al., 1979; Kovacs and Vogt, 1982). In the years 1957–1970 more than 4000 km of single channel seismic data was recorded from drifting ice stations in the Amerasian part of the Arctic Ocean (Hunkins, 1961; Hall, 1973).

The first single channel seismic reflection data ever acquired by western scientists from the Eurasian Basin were recorded from U.S. ice drift stations ARLIS-II in 1964 (Ostenso and Wold, 1977) and later by FRAM-I and LOREX in 1979 (Weber, 1979; Jackson et al., 1982). Along the FRAM-I track (Fig. 1a), oceanic crust below the Pole Abyssal Plain is overlain by a 1 s (two-way traveltime) thick section of flat lying turbiditic sediments which abutt the northern flank of Nansen–Gakkel Ridge where only irregular patches of current deposited sediments cover volcanic basement.

This paper reports on the results of an experiment to acquire the first seismic multichannel reflection data from the Eurasian Basin during the drift of U.S. ice station FRAM-IV over the Barents Abyssal Plain. This experiment was part of an integrated geophysical survey (bathymetry, gravity and seismic refraction measurements) along a traverse from the Eurasian Basin onto the continental margin north of Svalbard (Kristoffersen, 1982; Duckworth and Baggeroer, 1985).

## DATA ACQUISITION AND PROCESSING

U.S. ice station FRAM-IV was deployed by aircraft on 2–3 m thick first year pack ice in the Arctic Ocean at 83°57′N 21°E in March 1982 about 370 km north of Svalbard (Fig. 1) and manned by about 20 scientists (Johnson, 1983). As part of the geophysical program a linear 2 km long seismic array of 20 telemetering sonobuoys was laid out on the pack ice to record the signal of a 120 cubic-inch airgun fired every 50 m the ice surface moved (Fig. 2). A total of 200 km seismic reflection data was recorded as the array drifted passively with the polar ice pack over a period of 34 days. Moderate cross array drift rendered a major part of the data set amendable to common midpoint processing (Fig. 1b). The data were demultiplexed, deconvolved and gathered in 50 m bins as a "crooked line case" using navigation and shot time information. Array feathering angles from cross array drift varied between 0 and 30 degrees, but generally less than 10 degrees. Stacking is based on velocities representative of a deep ocean environment (Hamilton, 1979; Houtz, 1981) due to the large water depth (3.8 km) compared to array aperture (2 km). The stacking fold is variable (5–10) due to operational problems and anomalous signal response of some channels in the low temperature environment. Details of the field experiment and processing are given by Kristoffersen and Husebye (1984) and Kristoffersen (1982).

## SEISMIC STRATIGRAPHY

The sediments of the Nansen Basin attain a maximum thickness of 1.4 s two-way travel time along the drift track and are characterized by a monotonous section

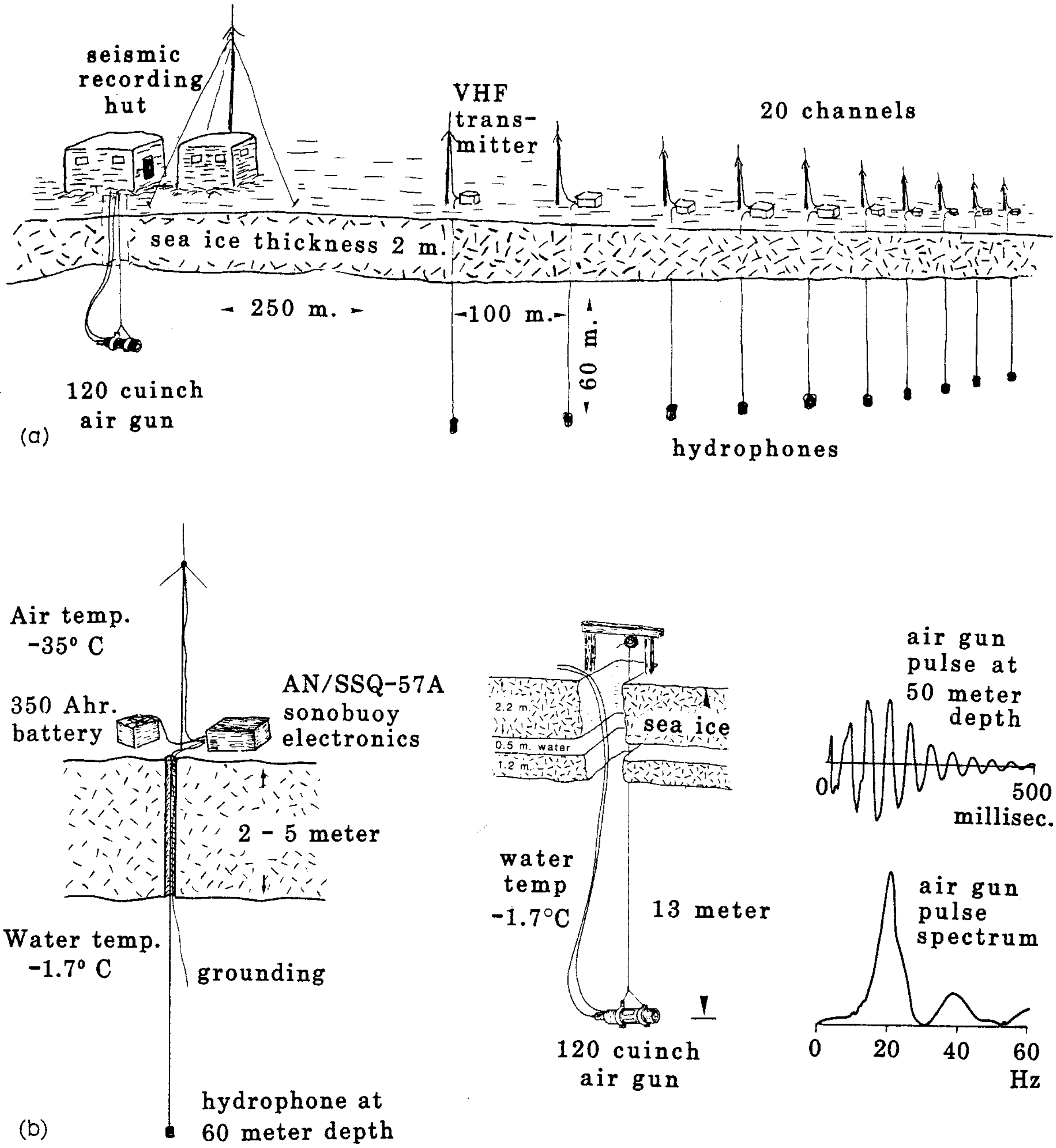


Fig. 2. a. Lay-out of seismic reflection experiment on ice station FRAM-IV. b. Diagram of sensor and source arrangement with signal characteristics.

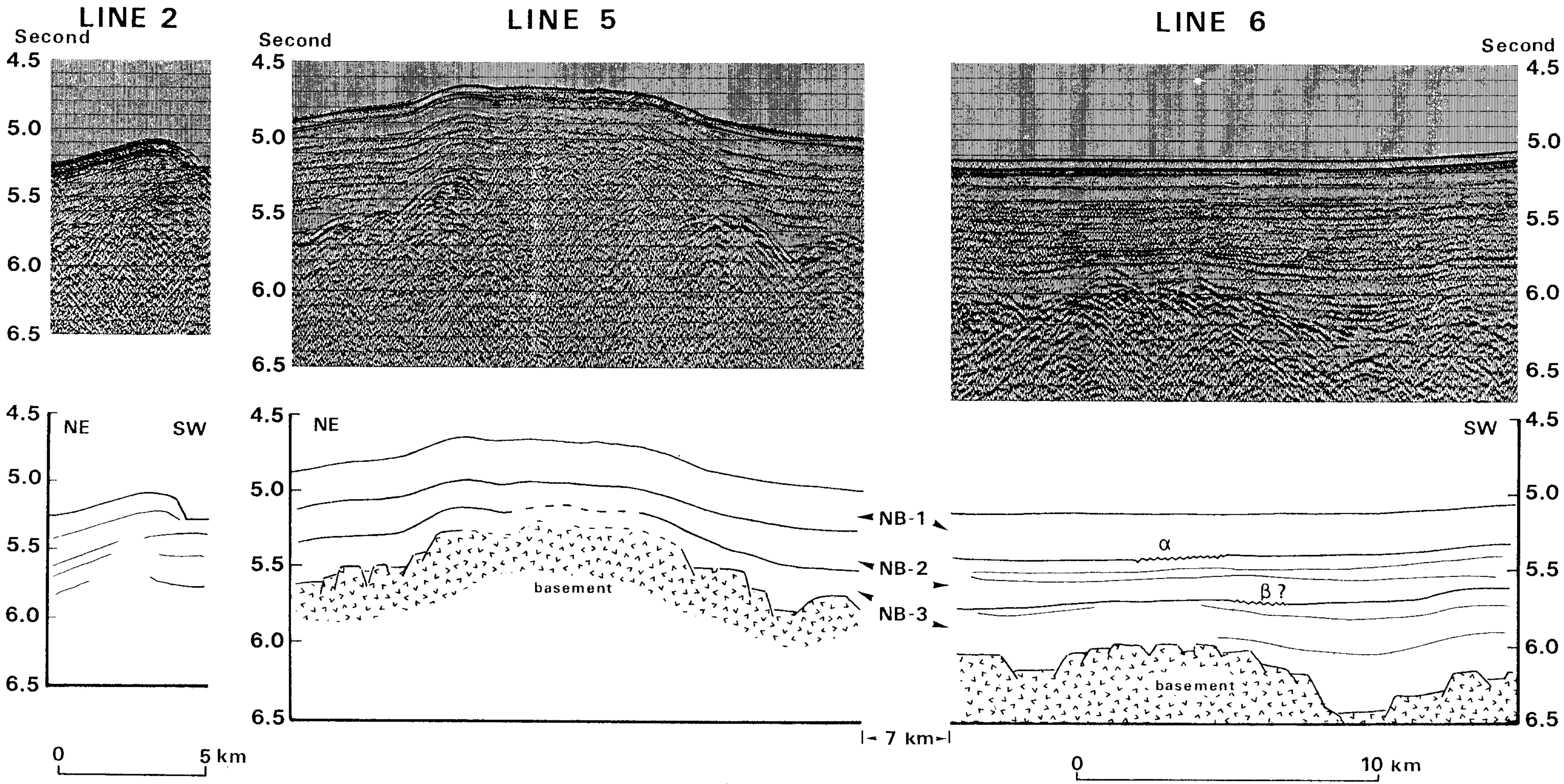


Fig. 3. Processed seismic sections and interpreted seismic sequences in the Nansen Basin. Processing include deconvolution before stack, stacking and timevarying filtering. Location of sections in Fig. 1.

which is acoustically transparent in its upper, reflective in its middle and semi-transparent in its lower part (Fig. 3). We recognize three seismic sequences:

*Sequence NB-1*: A minor erosional unconformity and its correlative conformity (reflector $\alpha$ on line 6) forms the base of an upper acoustically transparent seismic sequence (NB-1) in the Nansen Basin. Weak internal reflectors are generally conformable and the sequence show uniform thickness below the abyssal plain (line 6) and over the high ground (line 5), but strong lateral variations at other locations (line 2).

*Sequence NB-2*: This reflective seismic sequence bounded by reflectors $\alpha$ and $\beta$ is characterized by strong internal lateral variation from interfingering and truncated individual reflectors below the abyssal plain (line 6) with better continuity over higher areas (line 5). The record on line 5 (central part) is partly obscured by interference with out of line diffracted energy.

*Sequence NB-3*: This basal seismic sequence onlaps acoustic basement in its lower part and has an acoustically transparent character in its middle part (line 6).

### *Sediments on the Yermak Plateau north slope*

The thickness and seismic character of the sediments along the slope of Yermak Plateau show considerable lateral variation (Fig. 4). On some high areas or mounds, internal reflectors appear truncated at the sea floor and reflective sediments partly infill the intervening depressions. Truncations may be due to part of the section being removed by downslope gravity sliding and the profile thus essentially traversing a series of slide scars. Sediment thickness is generally 0.5 s. The seismic section contain abundant side swipe from seafloor diffractors along the higher slopes. Within a narrow cone of angles with the seismic line, diffracted energy may actually be enhanced by the CMP stack (Newman, 1983). Deeper reflectors or acoustic basement (?) can only be discerned for some distances (Fig. 4).

## INTERPRETATION AND DATING

The general appearance of seismic reflectors and in particular the gentle wavy conformable bed forms present clearly demonstrate a relatively stable depositional environment throughout the time spanned by the sedimentary section in the Nansen Basin (Fig. 3).

The uniform thickness of sequence NB-1 over the high ground on line 5 (Fig. 3) as well as its monotonous internal seismic reflection character indicate a depositional environment where sediment draping have been important. The intervening Barents Abyssal Plain isolates the high ground from sediments transported by various forms of gravity controlled flows. The sediment drape is therefore likely to be hemipelagic clays with more dominant contributions of pelagic sediment in the pre-Glacial section as observed at Norwegian Sea DSDP sites (337 and 350) in a similar setting

(Talwani and Udintsev et al., 1976). Current controlled deposition is locally important at abyssal depths in the Nansen Basin (line 2, Fig. 3). On the Nansen–Gakkel Ridge northflank bottom currents control sedimentation from the ridge crest down to depths where the abyssal plain abutts the ridge (Jackson et al., 1982). Thus the relatively sluggish bottom circulation requires topographically induced local turbulence to significantly alter the depositional pattern. The apparent non-transgressive character of the current deposits indicate a relatively stable current regime (line 2, Fig. 3).

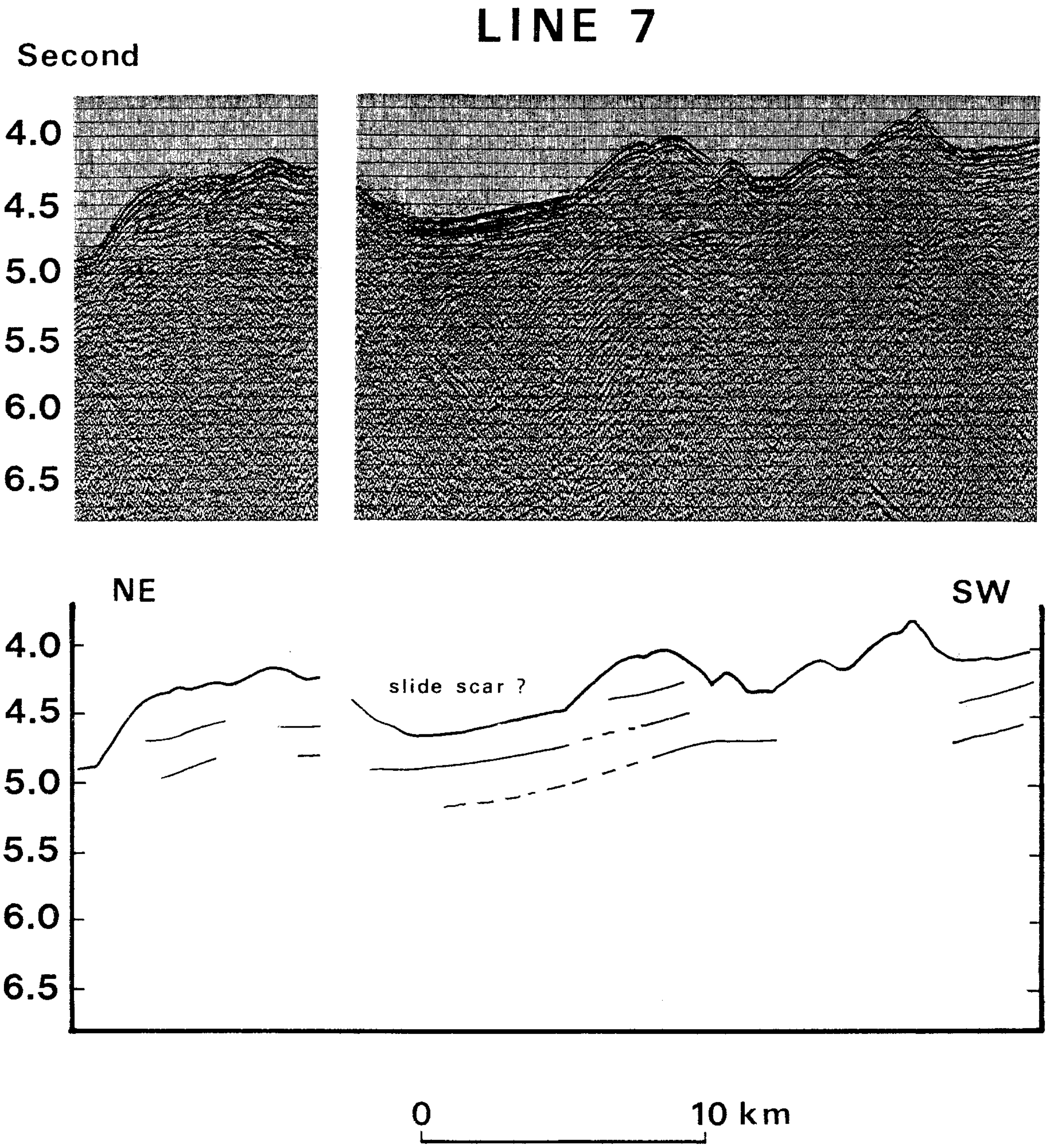


Fig. 4. Processed seismic section and interpreted line drawing from the slope of Yermak Plateau. Processing as in Fig. 3. Location of section in Fig. 1.

The reflective seismic sequence NB-2 below the abyssal plain shows numerous local pinch-outs, an environment which may be interpreted as the site of turbidite deposition fed by gravity controlled mass flows. The turbidites may originate from distant sources on the northern Barents Sea margin or from mass waste from the adjacent Yermak Plateau.

Below the Barents Abyssal Plain, sequence NB-3 smooth topographic lows of the acoustic basement and farther up in the section depressions caused by differential compaction of the sediments. The section is thickening towards the Yermak Plateau which may have been a major source area for the basal reflective sediments, probably volcanic detritus and later more fine-grained material brought in by turbidite currents. We note that the undulating bedform northeast of the basement high (line 5) was initially formed in the lower part of NB-3 and its amplitude afterwards maintained by conformable overlying sediments.

The minor erosional truncations associated with reflector $\alpha$ and $\beta$ (Fig. 3) appear to be confined to the deep basin with no dramatic evidence indicative of current scouring. These events may therefore in part be local erosional events generated by catastrophic turbidity currents entering the basin or erosion/non-deposition caused by moderate bottom currents. The appearance of the seismic reflection pattern seen in line 5 is evidence of remarkably uniform paleoceanographic conditions through time in this area.

The FRAM-IV track (Fig. 1) is located between magnetic anomalies 7 and 13 (Vogt et al., 1979) which imply a post mid-Oligocene age of the sedimentary sections and an average sedimentation rate of of 30 m/Ma. Assuming this value, a rough estimate of the NB-1/NB-2 sequence boundary would be 10 Ma.

Sedimentation rates based on magnetostratigraphy in the glaciated Arctic Ocean evaluated from some 500 sediment cores recovered from the Amerasian Basin (Clark et al., 1980) average 1 m/Ma for the last 5 Ma whereas recent oxygen isotope dating of cores from the Nansen Ridge yield Holocene rates an order of magnitude larger (Markussen et al., 1984). Thus the latter values ($\sim 10$ m/Ma) are not very different from the average sedimentation rate for the total section. DSDP results from the Norwegian–Greenland Sea show glacially influenced sediments that have been deposited on isolated topographic highs in the deep basins at a rate of 10–15 m/Ma and on the continental rise $> 20$ m/Ma assuming Northern Hemisphere glaciation was initiated 5 Ma ago (Talwani and Udintsev et al., 1976). Therefore the glacial part of the sedimentary section in the Nansen Basin may not be resolved by the seismic data presented here.

The apparent truncation of the reflection pattern observed along the Yermak north-slope is difficult to reconcile with any primary depositional regime and secondary processes unless partial mass removal is invoked. Partly infilling of slidescars and present water depth of the plateau indicate that the mass wasting probably is a relatively old event which took place sometime in the Miocene when the plateau was at or near sea level. Whether this was a local event or affected most of the north slope and tie-in with some of the complexities of sequence NB-2 remains an open question. It is likely, however, that mass waste from the Yermak Plateau has contributed as sediment source to the deep basin.

## ASPECTS OF PALEOCEANOGRAPHIC IMPLICATIONS AND OUTLINE OF THE TECTONIC EVOLUTION OF AN ARCTIC SEAWAY

The establishment of a deep water connection between the Arctic Ocean and the Norwegian Sea is likely to have been a significant paleoceanographic event. However, its timing and effect is presently unknown. The two principal paleoceanographic implications of the FRAM-IV seismic data (Fig. 3) are:

(1) Post late-Oligocene bottom current conditions appear to have remained remarkably uniform in the deep basin north of Yermak Plateau.

(2) Evidence of a change in environment at reflector $\alpha$ with a transition from predominantly turbiditic sediments of seismic sequences NB-3 and -2 to the hemipelagic drape of the overlying sequence NB-1.

The depositional event at reflector $\alpha$ may have been significant for the entire Eurasian Basin as stratigraphic similarities are apparent with seismic data recorded over the Fram Basin on the opposite side of the Nansen Ridge from ice station FRAM-I (Jackson et al., 1982). This suggest intrusion of warm Atlantic water or alternatively a relative increase in productivity of Arctic Ocean surface water at this time. The event may be of middle/late Miocene age or older assuming sedimentation rates to be higher than average during the early history of the basin. By this time Atlantic water penetrated into the Norwegian Sea over the subsiding Greenland–Faeroes Ridge (Talwani and Udintsev et al., 1976). Marine microfossils from DSDP sites in the North Atlantic suggest isolation of the Arctic and the Norwegian–Greenland Sea until at least Miocene time (Schrader et al., 1976). Oxygen isotope measurements show that formation of North Atlantic Deep Water towards which Norwegian Sea Overflow Water is a major component had started at the end of middle Miocene (Blanc et al., 1980).

The most significant factors in determining the late Cenozoic onset of a deep water exchange between the Arctic Ocean and the Norwegian-Greenland Sea are:

(1) the relative plate motion between Europe and North America;
(2) the geologic history of the southwestern part of the Yermak Plateau;
(3) the subsidence history of the plateau; and
(4) the rate of progradation of the Wandel Sea shelf.

During the Paleocene–Eocene the relative motion between Greenland and Svalbard was strike-slip (Talwani and Eldholm, 1977). In northeast Greenland the early Tertiary Kap Washington volcanics were overridden by highly deformed Paleozoic metasediments during this period (Soper et al., 1982). In central west Spitsbergen, a western sediment source area was effective from mid-Eocene into the Oligocene and a southern zone of upthrusting, a middle zone of folding and a northern zone of overthrusting can be recognized along the west coast of Spitsbergen (Kellogg, 1975). Thus during Paleocene to early Oligocene there was no deep seaway between Svalbard and Greenland or east of Svalbard. Subsequent reorientation of the relative motion between the Eurasian and North American plate at magnetic anomaly 13 (base Oligocene) changed the motion between Svalbard and Greenland from strike-slip to oblique spreading (Talwani and Eldholm, 1977) with concommittant block faulting and infilling of grabens off west Spitsbergen (Harland, 1969; Birkenmajer, 1972) and in the Wandel Sea (Håkanson, 1979). At this point the Yermak Plateau has become a crucial structure controlling the proto-Fram Strait seaway.

Prominent associated magnetic anomalies in conjugate position with respect to the Nansen Ridge suggest that at least the northeastern part of Yermak Plateau and Morris Jessup Rise are volcanic structures formed between anomalies 18 and 13 (Vogt et al., 1979; Feden et al., 1979) in the late Eocene (Lowrie and Alvarez, 1981). Low-amplitude magnetic anomalies over the southern part of Yermak Plateau and dredged gneiss boulders of uncertain provenance has been interpreted as evidence of continental crust (Sundvor et al., 1982). However, the few high heat-flow values along the southwestern plateau margin suggest a young thermal episode where post

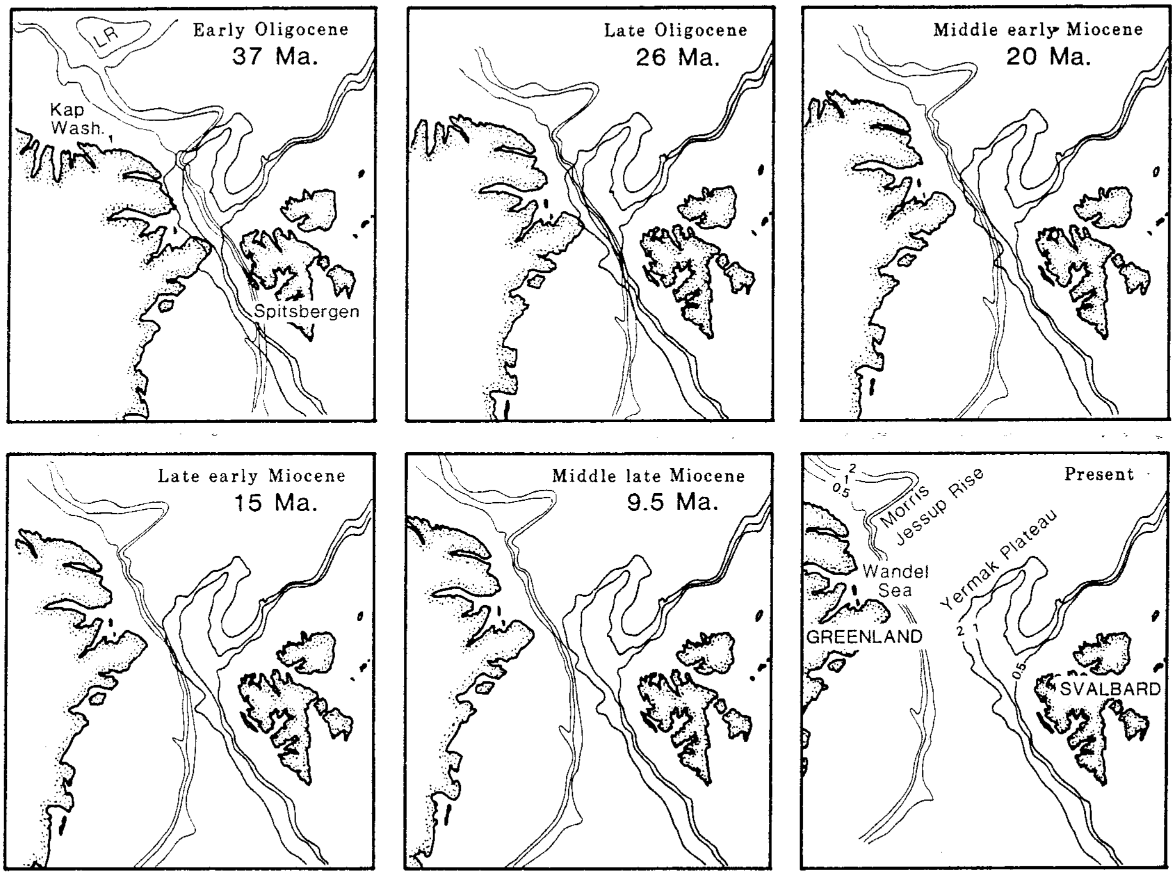


Fig. 5. Reconstructions of the late Tertiary relative position of the North American plate with respect to Europe (fixed) in the Svalbard area using poles of rotation for magnetic anomaly 5 and 13 from Talwani and Eldholm (1977) with interpolations for intermediate times.

mid-Miocene volcanic activity may have formed this part of the plateau in response to deviatoric stresses across an oblique ridge-transform configuration in the area (Crane et al., 1982). Following the empirical world-wide depth–age relationship of Sclater et al. (1971), the Yermak Plateau subsided below sea level at 10 Ma or 20 Ma B.P. depending on the assumption of local Airy compensation or regional isostasy with rigid coupling to the sediment loaded cooling oceanic crust on either side, respectively. If the southwestern margin of the plateau is oceanic crust or intruded continental crust, the maximum age of the event is 13 Ma or 18 Ma B.P., respectively and its effect was to offset the crustal subsidence (Crane et al., 1982).

Post Early Miocene out-building of the Wandel Sea margin may have partly contributed to the overlap seen in the pre-Middle Miocene reconstructions (Fig. 5). The Oligocene–Early Miocene control of this arctic seaway exerted by the depth of submergence of Yermak Plateau was gradually taken over by the widening proto Fram Strait. By the end of Mid-Miocene, this passage must have extended down to water depths of 2000 m.

Thus, broadly speaking there is general agreement between the timing of changes in the arctic depositional environment derived by crude interpolation from average sedimentation rates and the establishment of a Fram Strait seaway from plate tectonic considerations. However, the establishment of a deep water connection between the Arctic Ocean and lower latitude water masses appears to have had little effect on Eurasian Basin bottom current circulation.

## CONCLUSIONS

200 km of 20 channel seismic reflection data was collected in the Arctic Ocean over the Barents Abyssal Plain north of Svalbard during the U.S. FRAM-IV Expedition in a pilot project for multichannel seismic data acquisition. A major part of the data set is suitable for common-mid-point processing and the principal findings are:

(1) Post mid-Oligocene bottom currents have been remarkably stable over the Barents Abyssal Plain and the sluggish bottom circulation had no significant effect on sediment deposition except for local topographically induced turbulence.

(2) A regional reflector 0.35 sub-bottom marks the change from earlier predominantly turbidite deposits to overlying hemipelagic sheet drape. The event is tentatively assigned a middle/late Miocene age using an average sedimentation rate for the whole section and may relate to the establishment of an arctic seaway between Greenland and Svalbard.

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