

Breakthrough in Arctic Deep-Sea Research: The R/V *Polarstern* Expedition 1987

By the *Polarstern* Shipboard Scientific Party

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During summer 1987, the R/V *Polarstern* of the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Federal Republic of Germany (FRG), succeeded in penetrating the eastern Arctic ice pack as far north as the Nansen-Gakkel Ridge in the central eastern Arctic Basin. Our northernmost location, at 86°11'N (Figure 1), was further north than any surface vessel dedicated to marine research has attained previously, although Soviet nuclear-powered ice breakers have managed to penetrate to the North Pole. Prior to this cruise, most knowledge about the eastern Arctic Basin came from remote sensing techniques, Nansen's *Fram* expedition during 1893-1896 [Bøggild, 1906; Gran, 1904; Nansen, 1902, 1904, 1906], Russian ice camps [Gordienko and Laktionov, 1969], the U.S. ice island camps Fram I-Fram IV, 1979-1982 [Hunkins et al., 1979; Baggeroer and Dyer, 1982; Manley et al., 1982; Kristoffersen, 1982; Kristoffersen et al., 1982; Kristoffersen and Husebye, 1985], and explorations by submarines.

Our expedition (called ARK IV/3) began on July 4, 1987, in Tromsø, Norway, and ended on September 2, 1987, in Hamburg, FRG. A crew of 55 scientists and technicians from 19 institutions in seven European and North American countries joined forces to carry out a complex program of oceanographic, meteorologic, biologic, and geoscientific studies. Here we present a first preliminary report on scientific activities and shipboard results.

The eastern Arctic deep-sea basin between the Lomonosov Ridge and the Eurasian continental margin constitutes one of the world's least known and most unique oceans. Its shallow and deep water masses are exchanged with those of the Norwegian-Greenland Sea

and are linked to the formation of North Atlantic Deep Water, which ventilates the entire world ocean [e.g., Aagaard et al., 1985].

Through geologic time, its seasonally persistent ice cover is probably unstable. This ice cover seems to have existed, however, for at least 2.5 million years, with an important impact on the evolution, composition, and life cycles of Arctic fauna and flora, on sediment distribution, and on the climate of the northern hemisphere. The sediments of the ice cover should provide key data for solving the mystery of the initiation and variability of glacial ages during the Late Cenozoic. Broad features of its tectonic evolution are known from aeromagnetic investigations [see Vogt, 1986], which also show that the spreading rates there are the slowest in the entire world ocean.

Sea Ice Dynamics and Influence

The perennial sea ice cover (pack ice) is probably the most unique characteristic of the Arctic Ocean. Two major circulation patterns characterize Arctic sea ice drift. One is the so-called "Beaufort Gyre" in the Amerasian Basin. The other, called the "Transpolar Drift," extends over the entire Eurasian Basin (Figure 2). During ARK IV/3, we crossed from the basin marginal zone north of the Barents Sea into the Siberian branch of the Transpolar Drift. The basin marginal zone is the nearshore region east of the Yermak Plateau, north of Svalbard and Franz Josef Land up to 83°N. The main ice stream of the Siberian branch of the Transpolar Drift occurs at ~84-86°N (Figure 2).

Cover. R/V *Polarstern* in the ice of the central eastern Arctic Ocean. The *Polarstern*, the Federal Republic of Germany's modern polar research and supply vessel, is a double-hulled icebreaker that works in Antarctic and Arctic waters. The ship can pass through 1.5-m-thick ice with a speed of approximately 5.5 knots (~10 km/h) and can break ice up to several meters thick. The *Polarstern*'s expeditions are organized by the Alfred Wegener Institute for Polar and Marine Science in Bremerhaven, FRG.

Polarstern was used for the ARK IV/3 expedition into the central eastern Arctic basin during summer 1987. The ship car-

ried a crew of 47 and a scientific party of 55 on a 2-month-long voyage, collecting a wealth of scientific data and samples from an area that has rarely been visited by scientific expeditions. The northernmost position was close to 86°11'N, slightly further north than Fridtjof Nansen's famous *Fram* expedition nearly 100 years ago. For more information about the ARK IV/3 expedition and its investigations, see the article "Breakthrough in Arctic Deep-Sea Research: The R/V *Polarstern* Expedition 1987," p. 665. (Photograph by P. Schlosser, Institut für Umweltphysik, Heidelberg, FRG)

Investigations

Sea ice investigations during ARK IV/3 were primarily concerned with understanding sea ice dynamics/thermodynamics and the impact of ice on sedimentation and biologic productivity. The program was carried out as follows:

- deployment of an array of 12 satellite-tracked buoys for ice motion, ice temperatures, and meteorological observations;
- ice coring and surface snow and ice sampling for biologic, sedimentologic, ice crystallographic, and chemical analyses;
- helicopter observations and photography of ice characteristics; and
- measurements of light transmission through and below the ice.

Observations

In general, the sea ice conditions observed during the cruise in the Nansen Basin were characteristic of the melting season. Deep melt ponds and what appeared to be old snow covered much of the ice surface (see cover photograph). Ice in the Fram Strait was found to be unusually extensive for this time of the year (on the basis of comparison with the work of Vinje [1985]) and was often covered by fresh snow.

Distinct variations in ice characteristics were observed on the transect through the Nansen Basin. For example, ice in the basin-marginal region is probably formed either locally or in the Barents and Kara Seas. This is generally thin, 1-year ice. Most of the ice in the basin marginal zone will melt in the vicinity of the Yermak Plateau before reaching the Fram Strait. The thick, deformed multiyear ice floes of the Siberian branch of the Transpolar Drift stream, especially the oldest ones, probably originate on the Siberian shelves [Nansen, 1900, 1906; Sverdrup, 1929; Colony and Thorndike, 1985]. Much of this ice is exported out of the Arctic Ocean through the Fram Strait.

A surprising amount of sediment, composed of clay- to silt-sized mineral grains and biogenic material, was observed on the surface and within the sea ice. Sediment accumulations affect up to 10% of the ice surface south of 83°N, but usually the amount was less than 1%. Highest concentrations of "dirty" ice, where sediment accumulations locally affect more than half of the ice surface, occur north of ~83°30'N, in the region of the Transpolar Drift. Sediment accumulations were often aggregated, sometimes forming cohesive "mudballs" up to 3 cm in diameter, especially in the northernmost region over the Nansen-Gakkel Ridge.

On the basis of buoy drift trajectory observations obtained during the cruise, the mean drift of sea ice can be estimated at about 3 km/day in the southwest direction, characteristic of the Transpolar Drift [Nansen, 1900-1906; Gordienko and Laktionov, 1969]. The drift is extremely coherent, and motions are correlated over distances up to 1000 km. It is striking to note that one buoy drifted, with the same speed and direction, almost exactly over the 1895 path of the *Fram* [Nansen, 1902]. Most of the time, temporal variability of sea ice drift is caused by the winds, and dramatic changes in direction were observed in the trajectories of the buoy (and *Polar-*

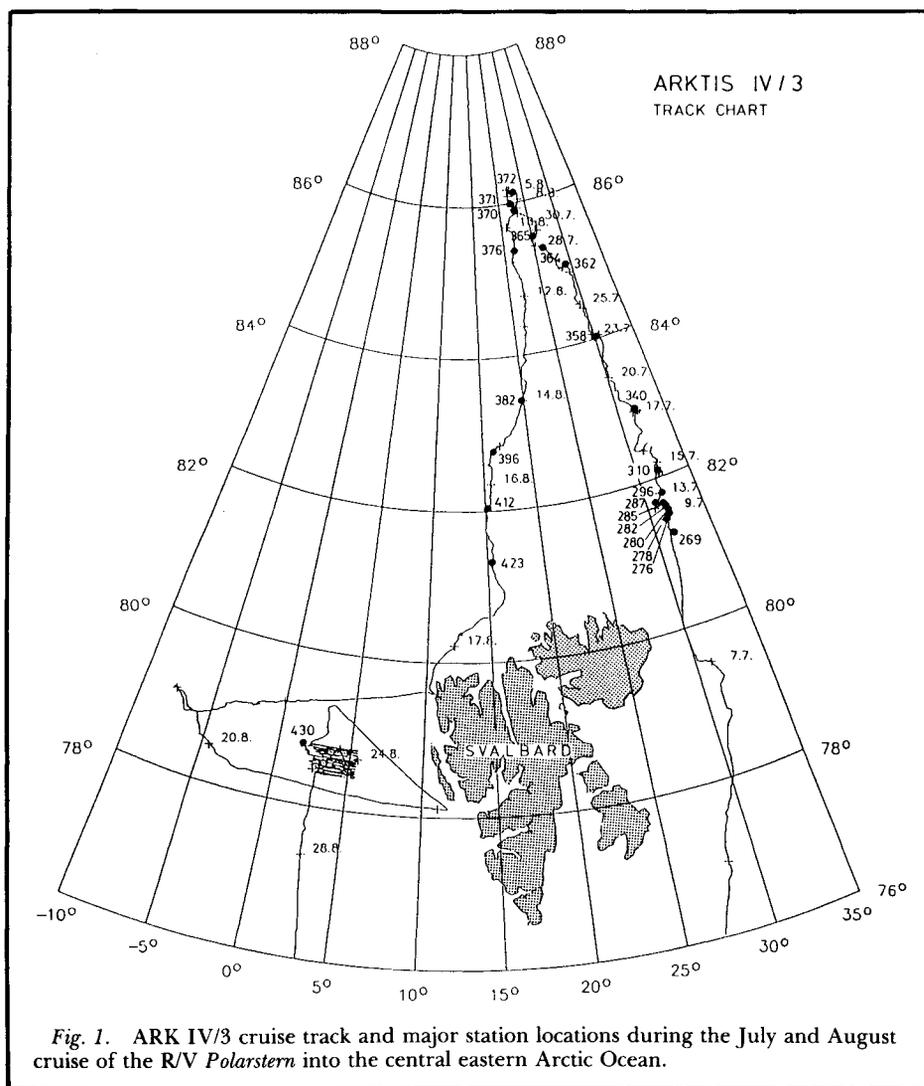


Fig. 1. ARK IV/3 cruise track and major station locations during the July and August cruise of the R/V *Polarstern* into the central eastern Arctic Ocean.

stern!) in response to changing wind direction. By comparing trajectories of northern and southern buoys, spatial variability of ice floe drift due to oceanic currents, in particular the Transpolar Drift, can be observed.

Oceanography of the Eurasian Basin Water Column

The extensive year-round ice cover over much of the Arctic Ocean forms a unique oceanographic environment [e.g., Aagaard *et al.*, 1985]. It inhibits heat exchange with the atmosphere and mixing by winds and, together with considerable freshwater runoff, results in a shallow mixed layer. Thus the Arctic Ocean is a low-energy regime in comparison to other oceans, with a stratified, stable surface region characterized by a pronounced halocline. Beneath the halocline, water of Atlantic origin is thought to be cooled by the surface layer. The Atlantic layer is underlain by cold water whose exact origin is not yet well determined but should constitute a major component of Norwegian Sea Deep Water.

ARK IV/3 gave us the opportunity to obtain the first comprehensive set of oceanographic

measurements in the Nansen Basin and the first oceanographic section ever made in the central Arctic Ocean. Our goals were to describe the main features of the halocline, intermediate, and deep circulation of the Nansen Basin with the intention of understanding the role of the basin in relation to the Barents Sea shelf, to the basins connected through Fram Strait to the south, and to the Amundsen Basin in the north. Sampling of natural and anthropogenic tracers was designed to describe the mixing history of the water masses tied into the full-depth circulation of the Nansen Basin.

Investigations

The oceanography program included

- continuous profiling of conductivity, temperature, pressure, and transmissivity;
- arctic environmental drifting buoy deployment (particle flux);
- small volume sampling: suspended sediments, nutrients, salinity, oxygen, total carbonate, total alkalinity, and calcium;
- trace elements;
- chlorofluoromethanes (Freons) and halocarbons;
- ^3H , ^3He , Ne, ^{18}O , accelerator mass spectrometry- ^{14}C ;
- nitrogen isotopes;

- large-volume sampling: ^{14}C , ^{85}Kr , ^{39}Ar , $^{226/228}\text{Ra}$, ^{90}Sr , and ^{137}Cs ;
- large-volume pumping for isotopes: Th, Pu, Am, and Cs;
- closely spaced measurements of temperature and velocity structure; and
- a SOFAR satellite acoustic ranging experiment.

Observations

These hydrographic, chemical, and tracer investigations produced a description of the mean circulation around 30°E across the Nansen Basin. Other important features were also revealed. For instance, along the northern slope of the Barents Sea, several well-defined cores of boundary currents or shelf plumes were found. These features are fed either from the shelf or through Fram Strait from the Norwegian/Greenland Sea.

The expedition also discovered a frontal transition at 83°N from the southern half of the basin, which has characteristics of Fram Strait and Barents Sea sources at most depths, to the northern half, which more resembles the central Arctic Ocean. An otherwise smooth transition from the boundary current regime to that of the abyssal plain is marked by strong horizontal gradients in this region.

Another important discovery is that the deep basin interior has no measurable chlorofluoromethanes (F-11, F-12, and methyl chloroform), but it does have detectable levels of carbon tetrachloride. Because carbon tetrachloride was produced and released earlier than the chlorofluoromethanes (early 1900s, compared to 1940s), these measurements indicate that the deep water masses in the Nansen Basin may be many decades old [Wallace and Krysell, 1987].

Total carbonate analyses show that the surface layer in the northern half of the section is clearly fed by input from Siberian rivers, while the source of the southern half is mainly sea ice meltwater. The absence of the shallow Arctic nutrient maximum found in the Canada Basin [Jones and Anderson, 1986] indicates that the Nansen Basin halocline is dominated by regional sources.

The Arctic Marine Ecosystem

Because of perennial ice cover, extreme seasonality, very low nutrients, and the existence of two benthic communities (attached to the bottom of the ice and to the seafloor), the Arctic deep sea is different from the rest of Earth's environments [e.g., Gray and Christiansen, 1985]. Highly specialized flora and fauna inhabit this remote region.

Investigations

The biologic sampling program included

- handnet (10- μm mesh) sampling of phytoplankton in the upper 30 m;
- multinet (0.25 m² opening, 63- and 300- μm mesh) sampling of planktonic foraminifers and other zooplankton in the upper 500 m;
- bongo net (300- and 500- μm mesh) sampling of herbivore calanoid copepods in the upper 80 m;
- membrane pump (20- and 41- μm mesh) sampling of phytoplankton, pollen, and spores in the upper 6 m;

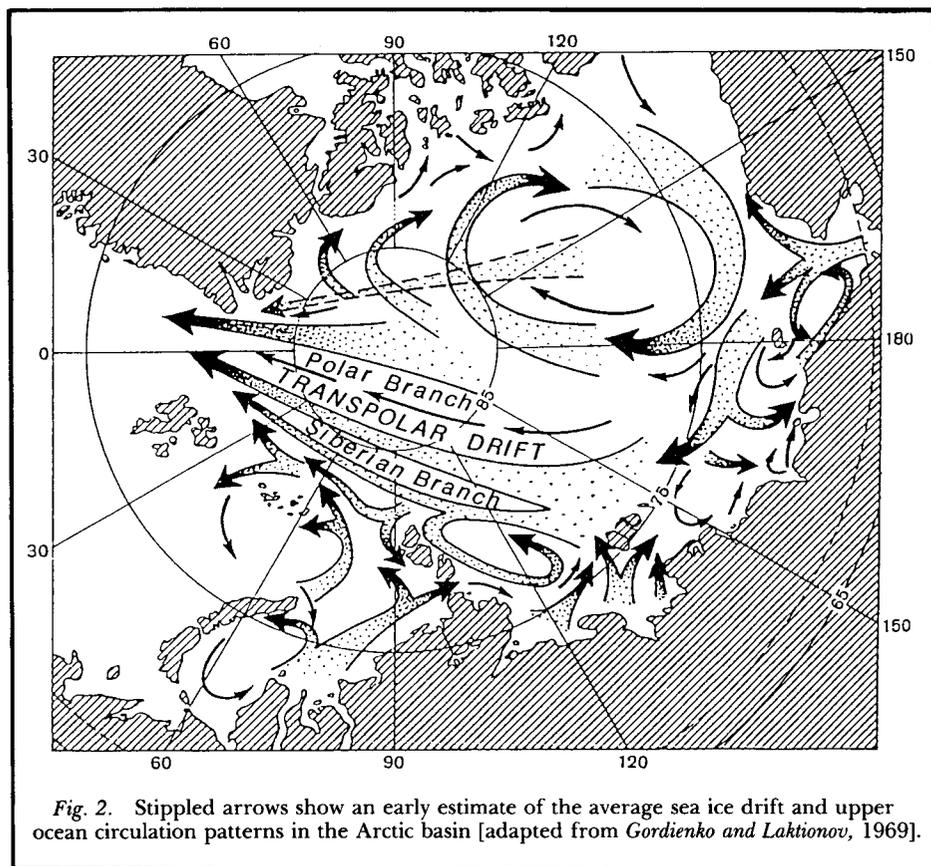


Fig. 2. Stippled arrows show an early estimate of the average sea ice drift and upper ocean circulation patterns in the Arctic basin [adapted from Gordienko and Laktionov, 1969].

- fishing and fish traps for polar cod (unsuccessful);
- biorosette (6 × 30 liters) sampling of biologic productivity;
- fluorometer;
- Secchi disc;
- underwater quantum meter for measuring light attenuation under changing ice conditions;
- large box grab (50 × 50 × 60 cm) for sampling benthic foraminifers and macrofauna; and
- examination of sea ice samples.

Observations

In general, productivity and standing stocks of plankton and benthos were higher than expected. The scientific crew observed various interesting features about the region. For example, arctic food chains are based on production of single-celled algae that grow only during part of the short Arctic summer. Both plankton tows and skeletal material in surface sediments seem to indicate that phytoplankton is a qualitatively important but quantitatively rare element of the Arctic pelagic biota. Measured production rates of phytoplankton range from 1 to 30 mg organic carbon/m³/day. In contrast, the maximal production of algae recovered from sea ice, both surface and the underside, was much higher. However, true light conditions under the ice must be considered in comparing these measurements.

The researchers observed a faunal boundary between 83 and 84°N, coinciding with the oceanographic front described above. It is surprising that large faunal changes were observed in a region of perennial ice cover. Hy-

drographic conditions seem to control main faunal patterns of planktonic and benthic communities from the Svalbard slope to the Nansen Basin. The inflow of warm water of Atlantic origin through Fram Strait influences the water column from the Svalbard slope up to 83°N, permitting establishment of subpolar Atlantic assemblages of calanoid copepods, dinoflagellates, planktonic foraminifers, and benthic micro- and macrofauna. Only north of 83–84°N do typical Arctic species appear.

Geoscientific Investigations of the Eurasian Basin and Fram Strait

The sparse geologic and geophysical data available prior to this expedition permitted only an outline of the major geologic features in the eastern Arctic Basin. The primary objectives of the *Polarstern* geoscientific party were to understand the tectonic and paleoclimatic-oceanographic evolution of the eastern Arctic Basin.

Investigations

Because very heavy ice conditions prevailed on most of the ship's track, towed equipment was not used. The sampling program included a variety of geologic and geophysical approaches:

- Sea Beam;
- continuous profiling with 20- and 3.5-kHz echo sounders;
- sediment sampling with a large box grab (50 × 50 × 60 cm), a long box corer (30 ×

30 cm), and gravity and piston cores (12 cm diameter);

- in situ measurements of the thermal gradient in upper sedimentary layers; and
- continuous marine gravimeter recording system with additional measurements at 26 stations on ice floes, using a land gravimeter.

Observations

Close coordination of geological studies with oceanography, meteorology, and marine biology permitted correlation of recent patterns of sediment production and distribution to environmental parameters. Among preliminary findings are bathymetric (SEABEAM) and subbottom (3.5 kHz) profiles that show that the continental slope and foot north of Svalbard grade into the extraordinarily flat, ~4000-m-deep Barents Abyssal Plain (this is slightly deeper than was reported by Perry *et al.* [1986]). Strongly reflecting layered sediments in the abyssal plain proved impossible to core. Whatever might be hidden below the upper few decimeters of soft terrigenous muds recovered in large box grabs remains unknown. To the north, the abyssal plain is limited by the flanks of the Nansen-Gakkel Ridge. The midocean ridge is known to be anomalously deep compared to other midocean ridges [Vogt, 1986]. On our transect, we found the ridge crest to have a deeply incised, block-faulted midocean ridge valley that was more than 5300 m deep, and the northern rim of the valley was considerably deeper than its southern counterpart. The return transect, across the northeastern flank of the Yermak Plateau, showed that this plateau was an unusual bathymetric feature, forming an almost vertical wall rising abruptly from the abyssal plain.

Sediment deposits covering the continental slope and foot north of Svalbard consist of strongly stratified, carbonate-poor, terrigenous sandy-clayey silts, at least partly deposited by downslope mass transport. Both carbonate content and preservation of calcareous fossils improve with increasing distance from the shelf region [Markussen, 1986]. Well-preserved planktonic foraminiferal fauna is found in sediments from the central midocean ridge valley of the Nansen-Gakkel Ridge, despite its great water depth (more than 5 km). Comparison of ARK IV/3 samples with published results from western Arctic Ocean samples appear to show that coccolith [e.g., Worsley and Herman, 1980] and dinocyst abundances [Mudie, 1985] are much higher in surface sediments of the eastern Arctic than on the Alpha and Lomonosov ridges, while the opposite may be true for foraminifers [Aksu *et al.*, 1988]. Pteropods are absent in most of the eastern Arctic sediments, although they are always present in the youngest sediments (those less than 0.4 Ma old) in the western Arctic Ocean [Aksu *et al.*, 1988; MacNeil and Mudie, 1987]. These observations suggest that primary productivity is higher in the eastern Arctic, while the water/sediment chemistry appears to be less favorable for aragonite preservation.

Coarse ice-rafted terrigenous debris was virtually missing in surface sediments as well as downcore in sediment cores from the survey area northeast of Svalbard. As noted by Bøggild [1906] for samples obtained on the *Fram* expedition, it is obvious that sea ice and

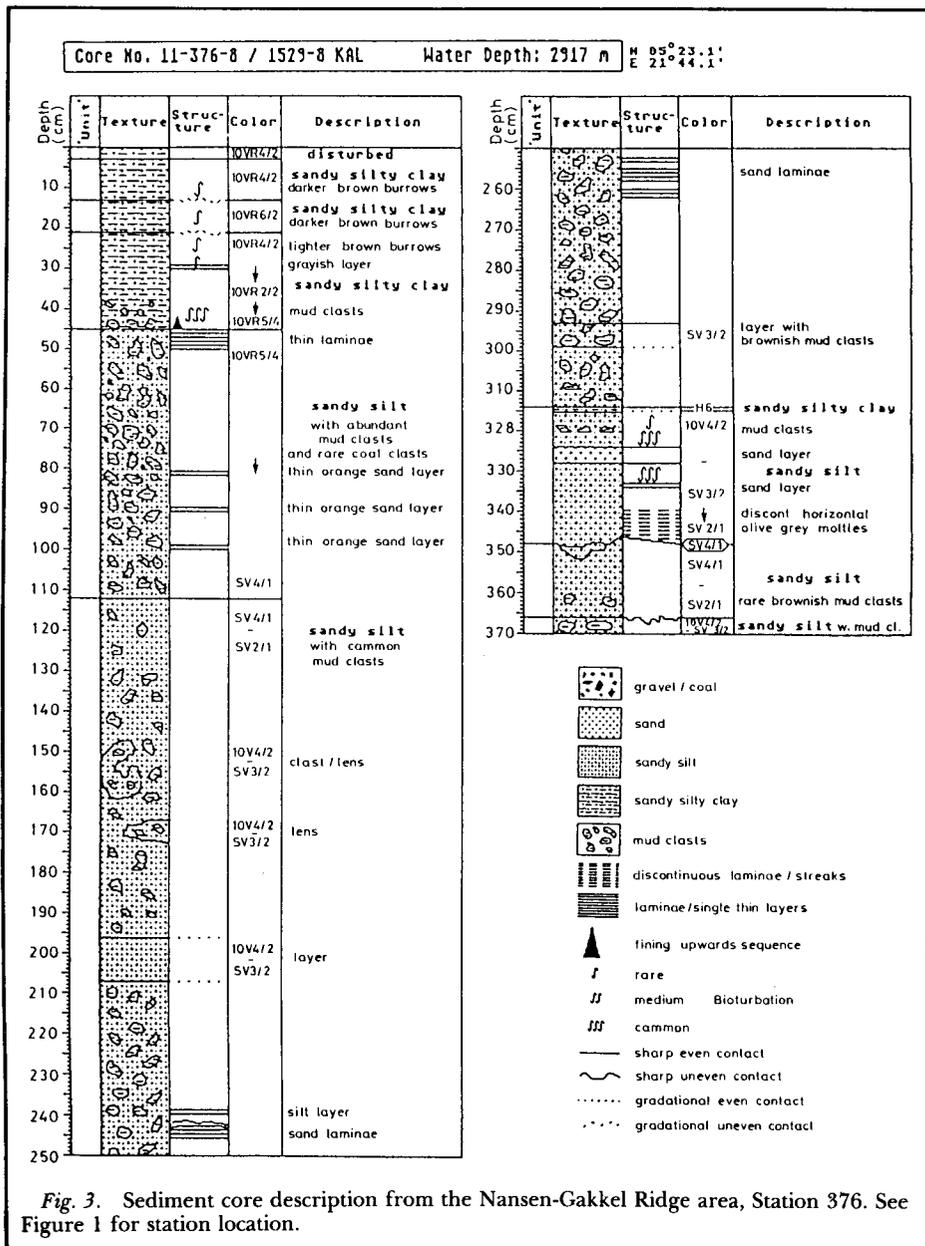


Fig. 3. Sediment core description from the Nansen-Gakkkel Ridge area, Station 376. See Figure 1 for station location.

icebergs in the Nansen Basin rarely contain or deposit coarse material. The dominant share of ice-rafted sediment input appears to have consisted of fine-grained sediment, much like the clays and silts found in the modern pack ice. There is some evidence that the cohesive "mudballs" found today in sea ice in the vicinity of the Nansen-Gakkkel Ridge may sink intact to the seafloor. Entire sections of the stratigraphic record in some seafloor sediment cores from the Nansen-Gakkkel Ridge consist of apparently similar mud clasts (Figure 3).

Evidence for reworking and lateral transport of fossil assemblages and sediments by bottom currents is observed along the continental margin north of Svalbard and the Nansen-Gakkkel Ridge in the vicinity of deep boundary currents inferred from oceanographic observations.

Sediment samples from the Nansen-Gakkkel Ridge had several interesting features. In one core from the Nansen-Gakkkel Ridge valley, hydrothermally altered and tectonized basal-

tic rock rubble (up to 15 cm in diameter) was recovered. This is the first sample of well-preserved basement rocks from the entire Arctic Ocean, although highly weathered basalts had previously been recovered from the flanks of Alpha Ridge during the Canadian Expedition to Study the Alpha Ridge (CESAR) [Van Wagoner and Robinson, 1985]. Sediment cores from the ridge area contain hydrothermal sediments (mostly iron oxides), volcanic glass, and coccoliths. Concentrations of magnetite in sediment, inferred from magnetic susceptibility measurements, show a general trend of decreasing concentration with increasing distance from the ridge crest. In addition, a downcore sequence of amplitude variations found in the core logs of magnetic susceptibility and remanent magnetic intensity can be traced over a wide area in the vicinity of the Nansen-Gakkkel Ridge axis. These variations point to temporal changes in ridge processes that generate magnetite and appear to correlate with the downcore thermal conductivity pattern and lithostratigraphy.

Two heat flow measurements in the Nansen-Gakkkel rift valley indicate an extreme temperature regime. Observed heat flow values are two to three times higher than values reported from the Knipovich Ridge [Sundvor, 1987]. Such high heat flow is characteristic for active magmatism, possibly explaining the common hydrothermal features encountered in the sediments and the volcanic rocks retrieved from the Nansen-Gakkkel rift valley.

Preliminary magneto- and biostratigraphic data seem to suggest that most of the cores have been deposited at rates of a few centimeters per 1000 years, offering much better possibilities for high stratigraphic resolution than central Arctic cores [Clark et al., 1980; Aksu and Mudie, 1985; Zahn et al., 1985].

Future Prospects

Data obtained on the *Polarstern* expedition ARK IV/3 will substantially advance our understanding of the Arctic Ocean and its linkage to the climate and oceanography of the northern hemisphere. The success of this cruise showed that even in a year of worse than average ice, a properly equipped research vessel can penetrate the Arctic pack ice to within 230 nautical miles (428 km) of the North Pole. We only spent ~40 days north of 81°N, including ice breaking and station time. We are confident now that it is possible to address the many questions that are still open with a second interdisciplinary expedition deep into the central Arctic Ocean. The focus of this proposed expedition (provisionally scheduled for 1991) is already well-defined: investigation of the contribution of the Siberian continental shelves to the ice, oceanography, and sedimentology of the Arctic interior (including the Amundsen and Makarov basins). We have named our future expedition TRAPOLEX: the Transpolar Expedition.

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