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Maps of the Arctic Basin Sea Floor: A History of Bathymetry and its Interpretation

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ABSTRACT. The history of oceanographic exploration of the Arctic Ocean basin from the beginning of this century to the present is summarized. Soviet, U.S. and Canadian contributions after World War II are described in some detail including sounding methods and navigational techniques. The major bathymetric charts of the Arctic Ocean basin from 1954 on are discussed. Comparison of the LOREX bathymetric map with other maps reveals that the Lomonosov Ridge is accurately positioned on early Soviet maps but is grossly in error on later U.S. and Canadian maps. It is shown that map makers relied too much on early U.S. submarine data (the only such data that were declassified) and that the latest General Bathymetric Map of the Oceans (GEBCO) is therefore suspect of being inaccurate in areas where publicly available sounding data are scant.

Key words: Arctic Ocean basin, bathymetry, Lomonosov Ridge, LOREX

RÉSUMÉ. Un résumé de l'historique de l'exploration du bassin océanique arctique depuis le début du siècle est présenté. Les contributions soviétiques, américaines et canadiennes depuis la deuxième guerre mondiale sont décrites avec quelques détails incluant des méthodes de sondage et des techniques de navigation. Les cartes bathymétriques principales du bassin océanique émises depuis 1954 sont discutées. La comparaison de la carte bathymétrique établie par LOREX avec d'autres cartes montre que l'emplacement de la dorsale de Lomonosov est exact sur les premières cartes établies par les Soviétiques, alors qu'il est erroné sur les cartes américaines et canadiennes plus récentes. Il est démontré que les cartographes se sont trop fiés sur les premières données sous-marines américaines (les seules données accessibles au public) et que, par conséquent, les données de la dernière édition de la carte bathymétrique générale des océans (GEBCO) peuvent être inexactes dans les régions où les résultats de sondages accessibles au public sont peu abondants.

Mots clés: bassin océanique arctique, mesures bathymétrique, la dorsale de Lomonosov, LOREX

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РЕЗЮМЕ. В работе подводится итог истории океанографических исследований бассейна Северного Ледовитого океана с начала столетия до настоящего времени. Подробно описываются вклады советских, американских и канадских ученых после Второй Мировой войны, включая описания методов эхолотных исследований и навигационной техники. Обсуждаются основные батиметрические карты бассейна Северного Ледовитого океана, составленные с 1954 года. Сравнение батиметрической карты LOREX с другими картами показало, что хребет Ломоносова точно указан на первых советских картах, но на более поздних американских и канадских картах допущены крупные ошибки. Указывается, что составители карт слишком полагались на первые данные Соединенных Штатов, полученные в результате исследований на подводных лодках, /только эти данные были рассекречены/ и что последняя "Общая батиметрическая карта океанов" (GEBCO) поэтому не может быть точной в районах, где отсутствует достаточное количество рассекреченных данных исследований рельефа морского дна.

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INTRODUCTION

For almost sixty years after the *Fram* drifted across the polar sea it was believed that the Arctic Ocean abyssal plain consisted of one deep basin. The highly successful Soviet airborne expedition to the Pole of Relative Inaccessibility in 1941 neither proved nor disproved the one-basin concept, but it did show that airplanes provided a practical and relatively inexpensive means of systematically exploring the Arctic Ocean basin. After World War II the Soviets initiated two programs of data collection in the Arctic Ocean: the High Latitude Airborne Expedition, which takes place every spring and was designated NORTH-series, and the more permanent NORTH POLE-series which is maintained for two to several years. Both programs are still in operation today. In 1948 Soviet scientists found the Lomonosov Ridge but kept the discovery secret until 1954. In the early 1950s the United States started a program of airborne expeditions and occupations of ice islands; from 1957 on these were complemented by submarine expeditions. Although the last ice island occupied by the U.S. was abandoned in 1974, springtime airborne operations are still being carried out. In 1958 the Canadian Government created the Polar Continental Shelf Project (PCSP), an imaginative and very effective organization with a broad mandate to coordinate and support field activities in the Canadian High Arctic, which catapulted Canada to the forefront of polar research. Long-range planning permitted the systematic bathymetric and gravity mapping of the Canadian Arctic continental shelf. PCSP supported two small-scale airborne expeditions to the North Pole in 1967 and 1969, the forerunners of the much larger multidisciplinary Lomonosov Ridge Experiment in 1979 (LOREX 79).

The first modern map that shows the ocean divided into two basins was published by the Soviets in 1954. With the exception of the chart compiled by the Canadian Defence Research Board in 1956 the early maps were all small-scale and appeared in scientific journals. Individual soundings were not

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printed and the contouring reflected, to some extent, the compiler's personal bias in favour of a particular theory of evolution of the ocean floor. By 1967 all the major physiological features had been discovered, and the first official chart was compiled by the Canadian Hydrographic Service in preparation for the first General Bathymetric Chart of the Oceans (GEBCO) published the following year. During the next decade a British, a U.S. and a second Canadian chart were produced, followed, in 1979, by the second GEBCO chart. The Soviets never produced any charts that were available to the public.

The major sea-floor features of the Arctic Ocean and place names mentioned in the text are shown in Figure 1. The names are those generally used today by Canadian geoscientists and correspond largely to the Beal *et al.* (1966) and Treshnikov *et al.* (1966) scheme of nomenclature which appears to be the only scheme in which most of the terms have been approved by the U.S. Board of Geographic Names and the International Hydrographic Bureau (Sweeney and Haines, 1978). Listed below are the names of submarine features used on U.S. maps that differ from the nomenclature used in this text.

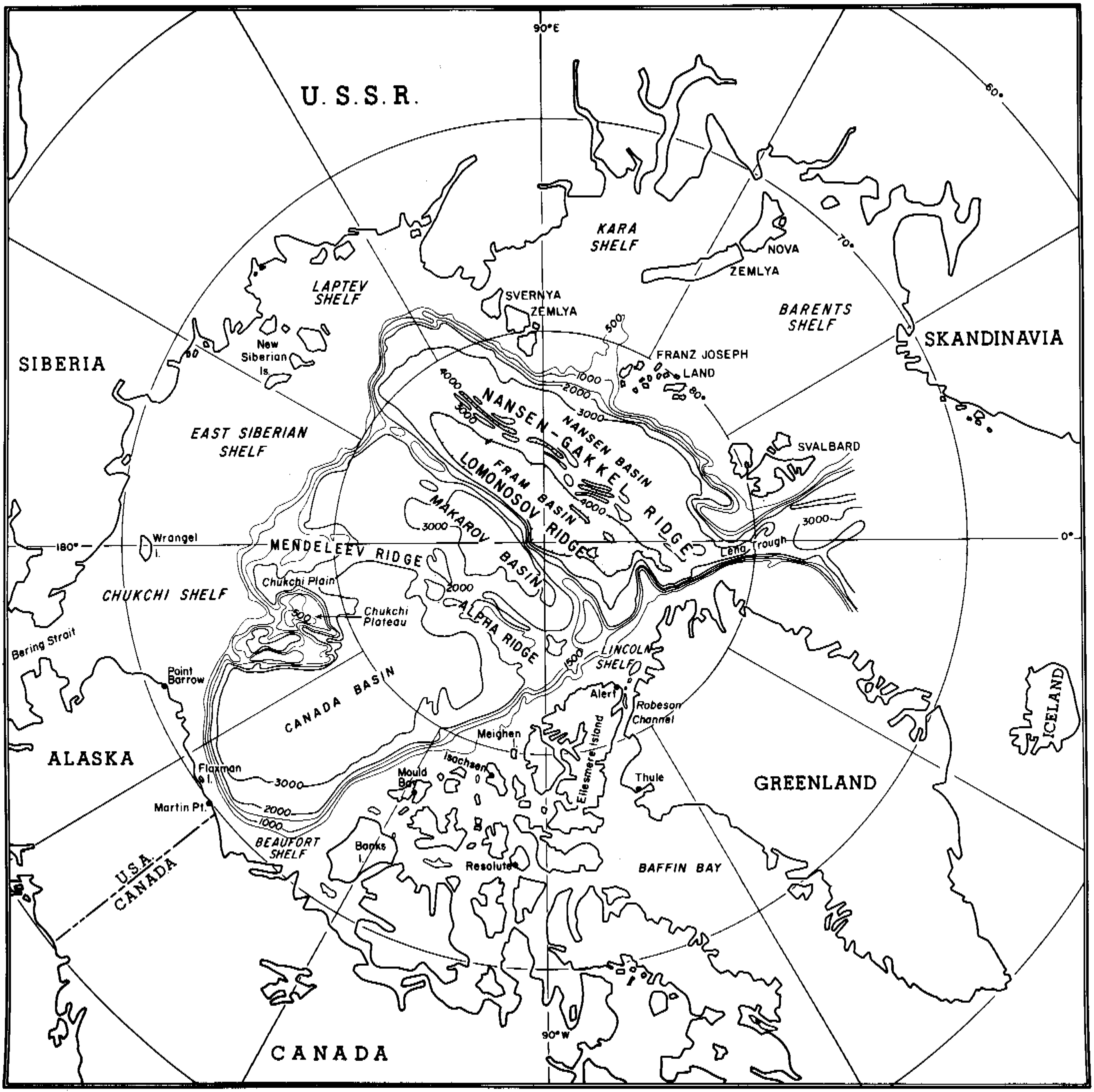


FIG. 1. Overview map of Arctic Ocean with names used in text. Nomenclature of sea floor features is that commonly used on Canadian maps and scientific papers.

Canadian nomenclature	*U.S. nomenclature*
Nansen-Gakkel Ridge	Arctic Mid Ocean Ridge Mid Arctic Ridge Nansen Ridge
Mendeleev Ridge	Mendeleyev Ridge
Fram Basin	Amundsen Basin
Makarov Basin	Fletcher Abyssal Plain
Nansen Basin	Barents Abyssal Plain

The methodology of early Soviet hydrographic surveys, a description of Soviet aircraft types mentioned in the text, and a list of acronyms have been included in the Appendices.

EARLY HYDROGRAPHIC EXPLORATIONS

From the Middle Ages until the end of the nineteenth century geographers believed that the North Pole was surrounded by land or by an archipelago of islands. This concept lost credibility after Nansen's ship *Fram* drifted with the arctic pack ice from the New Siberian Islands to Svalbard between 1893 and 1896 (Nansen, 1897). It was found that the ocean along the entire length of *Fram*'s drift path was more than 3000 m deep. This led many geographers to believe that the whole Arctic Ocean basin was a single oceanic deep, although, based on analysis of tidal data alone, Harris (1904) postulated that it was divided by a barrier or ridge into two basins with different periods of oscillation.

During the first decade of the twentieth century Bob Bartlett, supporting Peary's attempts on the North Pole, made a number of soundings off the northern coast of Ellesmere Island that outlined the general shape of part of its continental shelf.

One of the goals of the government-sponsored Canadian Arctic Expedition 1913-1918 under the command of Vilhjalmur Stefansson was to chart the waters of the Beaufort Sea north of Mackenzie Delta and Banks Island. Stefansson's ship, the *Karluk*, became beset in the pack ice near Flaxman Island, Alaska. For five months the *Karluk* drifted west until she was crushed near Wrangel Island on 10 January 1914; during that time the expedition's oceanographer, James Murray, indefatigably took soundings, dredged bottom sediments and collected biological and water samples (McKinlay, 1976). The soundings were recorded in the ship's log, but the samples sank with the *Karluk* and Murray's notes were lost with him when he attempted to reach the Siberian mainland on foot (McKinlay, pers. comm. 1980). Had the samples survived, the difference between Amerasian and Eurasian waters would have been discovered, and the existence of a dividing ridge predicted, some 30 years earlier.

In the spring of the same year Stefansson, with Storkerson and another companion, sledged over the ice of the Beaufort Sea from Martin Point, Alaska, beyond the continental shelf, to Norway Island near the west coast of Banks Island. He took soundings every 40 to 50 miles but unfortunately was limited to a maximum depth of 1386 m by the length of his sounding wire (Stefansson, 1921).

On 15 March 1918, starting from Flaxman Island, Storkerson sledged 280 km out into the Beaufort Sea where he established a station on the sea ice. From 8 April to 9 October he drifted with the pack ice between latitudes 72°45′ and 74°N and longitudes 145° to 150°W, taking numerous soundings (map compiled by Geodetic Survey of Canada, in Stefansson, 1921), keeping meteorological records and taking celestial positions. Storkerson had planned to occupy the station for a year, but he fell ill with asthma and was forced to return prematurely to Flaxman Island which he reached on 8 November. During the whole drifting period the party of 5 men and 17 dogs lived entirely "off the land", eating exclusively seal and bear meat and cooking and heating with seal blubber and bear fat. Storkerson had no doubt that they could survive on the ice indefinitely by hunting. There is every indication that their ice floe was, in fact, a tabular iceberg of the type which is now called an ice island. Storkerson mentions (Stefansson, 1921:699) that their floe could best be described as a large island, seven miles wide by at least 15 miles long and, judging from the freeboard near their camps, 50-60 feet thick. It moved at a different speed from the surrounding field of smaller floes, and apparently it never broke up during the entire six months they lived on it. He also comments on the appearance of the "land" which reminded him of certain stretches of prairie. Storkerson's was the prototype scientific drifting station, antedating the Russian explorer Papanin's North Pole drift by 19 years.

With Stefansson's expeditions the first phase of Canada's exploration of the Polar Sea came to an end. Robert Borden, prime minister of Canada during the First World War, was a staunch supporter of Stefansson. On his retirement in 1920 he was succeeded by Arthur Meighen who the following year was defeated by the Liberals under Mackenzie King. The King government had little interest in Canada's Arctic, and nearly forty years slipped away before the exploration of Canada's arctic coastal waters was seriously resumed.

In 1927 Sir Hubert Wilkins, flying from Alaska, landed his aircraft on the ice some 1300 km north of Bering Strait. By setting off an explosive charge and using a stop watch to measure the time it took for the echo to return from the ocean floor, he obtained a depth of 5440 m (Wilkins, 1928). This sounding later turned out to be erroneous (he may have heard a multiple echo), but for the next twenty years it was much quoted in support of the opinion of a single deep Arctic Ocean basin. The opinion was seemingly confirmed by 38 depth soundings made in 1937 between the North Pole and the East Greenland coast, along the nine-month drift path of the Soviet research station now known as North Pole 1 (Papanin, 1946). Further support came from the Soviet icebreaker *Sedov*, which made 46 soundings while drifting in the Eurasia Basin, following *Fram*'s path, between 1937 and 1940 (Armstrong, 1958).

Somewhat earlier Vilhjalmur Stefansson (1921) had introduced the concept of the "Pole of Relative Inaccessibility", i.e., the point in the Arctic which would be most difficult for an explorer to reach. Soviet pilots engaged in ice reconnaissance along the Northern Sea Route suggested an airborne expedition to the area of the Pole of Relative Inaccessibility. During April 1941 personnel from the Soviet All-Union Arctic Institute (VAI), in three successive flights in a ski-equipped four-engine N-169 aircraft based at Wrangel Island, established three stations in the regions of the Wrangel and Mendeleev abyssal plains between latitudes 78° and 81°N and between longitudes 175°E and 170°W. They stayed four to five days at each station, taking soundings, measuring temperature and salinity, sampling the water colum and the seabed, and taking meteorological, gravitational and magnetic observations. To take soundings the Soviets used a motor-driven wire winch, an improvement over the hand-operated winches used on the *Fram, Sedov* and North Pole 1 expeditions. Their depth measurements of 2427 m, 1856 m and 3370 m showed large variations but neither confirmed nor disproved the depth determined by Wilkins (Treshnikov, 1966).

The Soviet airborne expeditions were highly successful. They demonstrated the advantages of using aircraft over letting a ship freeze into the ice or occupying an ice station for a long period of time. Aircraft provided choice of location, simplified the logistics and, in some cases, decreased the cost. The importance of choice of location for bathymetric surveys will be discussed later. Reliance on aircraft was a turning point in arctic exploration for which the Soviets deserve every credit.

HYDROGRAPHIC SURVEYS AFTER WORLD WAR II
THE SOVIET CONTRIBUTION

The NORTH-Series Expeditions

The war interrupted arctic scientific explorations, but in 1948 VAI started a program of systematic exploration of the whole of the Arctic Ocean which they called "High-Latitude Air Expeditions" (HLAE). Several aircraft were used to land parties at a series of points on the floating ice on the Arctic Ocean during a period of approximately six weeks in spring. Lightweight, portable equipment was developed specially for the job. The routine of making oceanographic, magnetic, gravimetric (using a pendulum gravimeter) and meteorological observations was carefully worked out so that only a few hours were required at each stopping place. There are no detailed accounts of the early HLAE, but many landings were made (Armstrong, 1958).

During the 1948, 1949 and 1950 HLAE, groups of scientists were landed to carry out short-term observations, each lasting from a few hours to a few days, at 87 points distributed over the Arctic Ocean (Somov, 1955). Discoveries included the basic features of relief of the ocean floor and information on the scale and limits of the distribution of the Atlantic water layer. The surveys revealed that, far from being a flat abyssal plain, the Arctic Basin has a very complicated structure with both depressions and submarine ridges and elevations. The most significant discovery was made on 17 April 1948, at 86°26′ N, 145°E, where a relatively shallow depth of 1290 m was recorded. Further soundings at smaller intervals, the same year and again the following year, revealed the outline of a massive submarine mountain range, rising 3000 m above the sea floor and extending 1800 km from Ellesmere Island to the New Siberian Islands. It was named after M.V. Lomonosov, the eighteenth-century Russian scientist, grammarian and poet.

The HLAE took place every year from 1948 to the present, with the possible exception of the seasons 1951-1953. The aircraft landing sites from 1937 to 1957 are illustrated in Figure 2 (Laktionov and Shamont'ev, 1957).

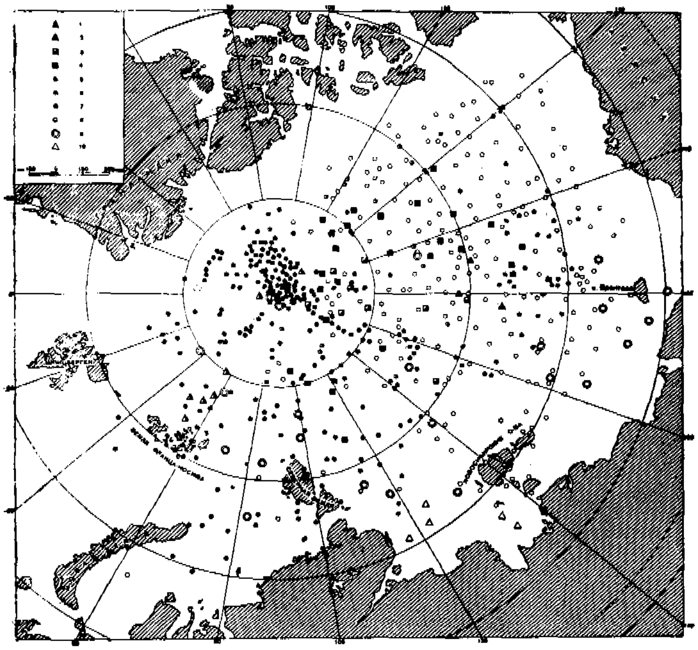


FIG. 2. Landing sites of Soviet aircraft on ice: (1) - 1937; (2) - 1941; (3) - 1948; (4) - 1949; (5) - 1950; (6) - 1954; (7) - 1955; (8) - 1956; (9) - 1957. On water: (10) - 1950.

These annual springtime High-Latitude Air Expeditions were renamed NORTH-series. Since the late 1950s the scope of these operations has increased tremendously, although few details are known outside the Soviet Union. On 29 April 1967, enroute to Ice Island T-3, one of the aircraft from the Arctic Research Laboratory at Point Barrow landed at the Soviet station NORTH-67. Brewer (1967) reported that the station consisted of 70 Jamesway-type buildings and that the operation involved some 300 people, 100 of whom were pilots. A 1500-m runway allowed aircraft of the Hercules C-130 type to land. The station was serviced by an average of six flights a day from the mainland, which required the presence of an air traffic controller. At the time of their two-hour visit, nine Polish-built Antonov AN-2s, one LI-2, one Ilyushin IL-14, and one helicopter were parked on the ice, and a second helicopter was flying. The scientific studies being carried out included gravity, seismology, oceanography and meteorology.

The NORTH POLE-Series of Drifting Stations

In April 1950 a 16-man party and 60 tons of equipment and supplies were landed some 1200 km north of Bering Strait, where a camp was established on a large floe of multi-year ice. Although the camp was meant to be evacuated in October, the work of collecting scientific data was so successful that the occupation of the station was extended to April 1951. To enable the station to be re-supplied for the winter, a 900-m runway was built on the old ice in the fall; the surface was smoothed by chopping away hummocks and flooding depressions with sea water. Scientific studies included meteorology, physical and chemical oceanography, microbiology, collection of bottom sediments, magnetic and gravity observations, and study of the properties of sea ice. Using a motor-driven winch with a 7-strand steel cable 5000 m long and 1.2 mm diameter, and a 10-kg sounding lead, the scientists took 285 soundings (Somov, 1955).

This was the first time a scientific drifting ice station had operated all year round. The occupants had little experience in coping with the intense cold of the polar night and with the flood of meltwater on the floe during the summer. They lived in double-walled tents, black on the outside with a white inner lining, which were enclosed in the winter in an igloo-like shell of snow blocks and which were difficult to heat and ventilate adequately. In the summer the tents soaked up the meltwater like wicks. Three times the camp had to be moved by sled dogs and a jeep, because of ice breakup. That they managed to keep up an uninterrupted full-fledged scientific program is a tribute to Russian ingenuity and perseverance. Some of the scientific results, including the 285 depth soundings (but not gravity observations, which appear to be a highly classified subject) were released as a Soviet contribution to the International Geophysical Year (Somov, 1955).

This operation, under the leadership of M.M. Somov from VAI, was the beginning of the NORTH POLE-series of drifting stations, and was later designated NP2 (Papanin's drifting station from 1937-1938 was renamed NP1).

In 1954, NP3 and NP4 were established under the leadership of Treshnikov (later director of the Arctic and Antarctic Research Institute in Leningrad), Tolstikov, Gordienko and Dralkin. They were followed by NP5 (1955), NP6 (1956), NP7 (1957), NP8 (1959), and NP9 (1960). The experiences gained from NP2 enabled the researchers to equip these stations much more comfortably and efficiently. Besides meteorological, oceanographic and geophysical laboratories, their inventory included a bulldozer for preparing runways and pulling loads, and a piano for entertainment. Fixed-wing and rotary-wing aircraft were permanently stationed at the camp (Gordienko and Laktionov, 1960; Treshnikov, 1960).

The Soviets did not confine their survey activities to international waters. There is evidence that during the early 1950s they extended their soundings to the inter-island channels of the Canadian Queen Elizabeth Islands.

To date 25 stations have been established. They remain occupied from one to several years until they either "exit" via the Greenland Current into the Atlantic or otherwise lose their usefulness. Currently (December 1982) NP25 is located over the Alpha-Mendeleev Ridge at 170°W.

THE AMERICAN CONTRIBUTION

Airborne Expeditions and Drifting Ice Islands

It was not until April 1951 that U.S. scientists joined in the exploration of the Arctic Ocean by mounting two airborne expeditions to the Beaufort Sea. Supported by the U.S. Air Force Cambridge Research Centre and using a C-47 aircraft, they established six stations north of Martin Point, Alaska, between latitudes 73° and 76° N. The observations consisted of seismic soundings, gravity measurements and determination of the ice drift (Crary *et al.*, 1952). Concurrently, sponsored by the U.S. Office of Naval Research (ONR), Project Skijump was inaugurated. Twelve landings on the ice north of Point Barrow were made by a Navy R-4D aircraft. Salinity, temperature and depth (STD) measurements were made at three sites using winch and Nansen bottles. The following year, refuelling the R-4D on the ice from a Navy P-2V aircraft, scientists established five more hydrographic stations and reached 82°22′N. The operation ended prematurely when the port landing gear of the R-4D collapsed and the aircraft had to be abandoned. The observations showed that water temperature and salinity values differed significantly from those obtained by Nansen on the *Fram*, and that a large anticyclonic (clockwise) gyral exists north of Alaska. From these observations Worthington (1953:550-551) concluded that "there is a submarine ridge, running roughly from Ellesmere to the New Siberian Islands, which separates the deepest water of the Beaufort Sea from the remainder of the basin", and that "the sill depth of the ridge should not exceed 2300 m." Ironically, the Americans were unaware of the Soviet NORTH and NORTH POLE-series operations and did not know that the existence of the Lomonosov Ridge had in fact been confirmed five years earlier.

The brief-landing type of airborne survey was replaced in 1952 by year-round occupation of drifting ice islands. Unlike ice floes, which consist of frozen sea water, are on the average 3 m thick, and can break up at any time, ice islands originate mainly from the Ellesmere Island Ice Shelf, consist of freshwater ice up to 60 m thick, may extend over an area of many square kilometres, and have, as long as they remain in the Arctic Ocean, a life expectancy of decades. The best known of these ice islands, Fletcher's Ice Island T-3, has been occupied at intervals from 1952 to 1974 (Hunkins, 1977); it is presently (December 1982) located over the Nansen-Gakkel Ridge and is expected to be swept into the North Atlantic by the Transpolar Current within the next year. Other drifting ice islands that were occupied were Alpha (1957/58), Charlie (1959), and Arlis II (1961-1965). T-3 and Alpha served as U.S. stations during the International Geophysical Year.

Throughout its occupation, Alpha drifted over a ridge which was parallel to the Lomonosov Ridge. Although identified as a general feature on the 1954 Soviet chart, it was mapped in comparative detail for the first time from Station Alpha, from which it derives its name. Research on these ice islands embraced a broad range of oceanographic, geophysical, atmospheric and glaciological studies (Hunkins, 1960a, b, c, d; Hunkins *et al.*, 1962).

In 1960 the Americans resumed their airborne reconnaissance surveys under the sponsorship of ONR and the Geophysical and Polar Research Centre of the University of Wisconsin. Using Cessna 180 aircraft based along the north Alaskan coast and on drifting stations, they landed on the ice of the Beaufort Sea, Chukchi Shelf, and Canada Basin to take depth soundings and gravity measurements. This program continued every spring until 1969, by which time over 800 stations had been established (Wold, 1973).

Submarine Expeditions

Since 1957 the U.S. Navy has operated nuclear submarines in the Arctic Ocean. Echograms from the ocean floor obtained from the USS *Nautilus* (1957, 1958), *Skate* (1958, 1959, 1962), *Sargo* (1960) and *Seadragon* (1960, 1962) have been analyzed by Beal (1969). Figure 3 shows the cruise tracks of the four submarines. The accuracy of the depth profiles obtained from the echograms depends on knowing: 1) the submarine's position and motion (which includes speed and change of speed, depth and change of depth); 2) thickness of the ice; and 3) velocity of sound in sea water. Positioning of the submarines was obtained by dead reckoning, by the Ships Inertial Navigation System (SINS), and by celestial fixes whenever possible. The accuracy of SINS on submarines is classified, but an inference can be made from Beal's (1969:24) remark that "if a volcano is misplaced ten miles on a map of the ocean floor, this itself is not apt to lead to serious mistakes in interpretation of geological history". Echograms are annotated with submarine speeds and keel depths, but these data remain classified. The ships' echo sounders were calibrated at constant speed of sound of 1463 m·s^{-1}. No attempt has been made to correct for the variation of velocity with depth, so that basins appear approximately 100 m too shallow and the Lomonosov Ridge crest approximately 50 m too deep.

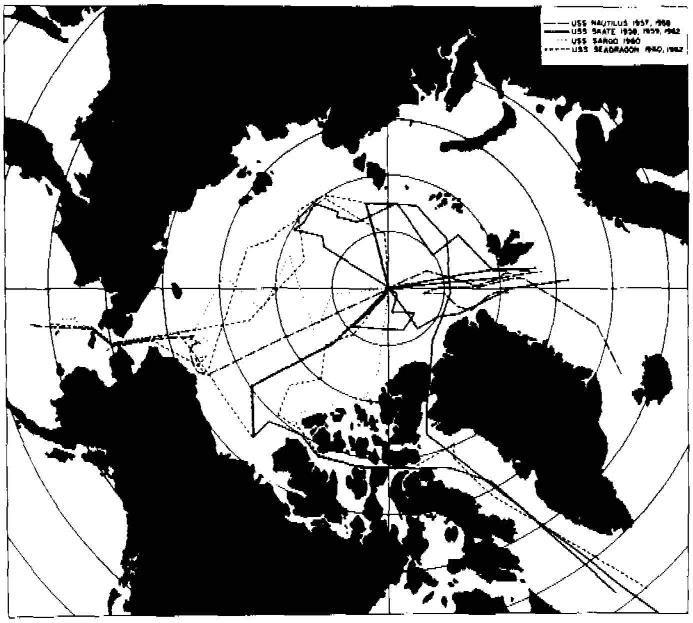


FIG. 3. U.S. nuclear submarine tracks in the Arctic Ocean 1958-1962. (Figure taken from *Polar Research*, 1970:51).

Beal prepared the depth profiles along the submarine tracks by digitizing the echograms once every 20 minutes. In his thesis the profiles are drawn at a horizontal scale of 1:5 000 000 and a vertical scale of 1:100 000. The geographical locations of the submarine tracks are drawn at a scale of about 1:33 000 000. The echograms and Beal's work sheets are classified, as are all post-1962 U.S. submarine depth data.

In 1975 and 1976 the British nuclear submarine *Sovereign* made a number of cruises into the Arctic Ocean. Although not an American contribution, it is mentioned in this context because some of its non-classified bathymetric data have been used in the compilation of the 1979 GEBCO map (Sobczak, pers. comm. 1980).

Surveys across the Alaskan Polar Continental Shelf

In 1951 the icebreaker USS *Burton Island* and in 1957 the icebreakers USS *Staten Island* and USCGC *Northwind* carried out continuous echo soundings across the continental slope into the Beaufort Sea north of Point Barrow (Fisher *et al.*, 1958).

In the course of conducting seismic reflection surveys across the continental shelf into the Beaufort Sea, bathymetric data were acquired by the U.S. Geological Survey between 1972 and 1978, and by the Geophysical Corporation of Alaska in 1973 (Greenberg *et al.*, 1981).

Based on all the data available, including Canadian soundings east of longitude 141°W, Greenberg *et al.* (1981) published a bathymetric map of the continental shelf, slope, and rise of the Beaufort Sea north of Alaska at a scale of 1:5 000 000.

The East Arctic Operations

In 1979 ONR initiated the East Arctic Operations, a continuing program of exploration of the Eurasia Basin. The initial operations, the FRAM expeditions, were conducted each spring from 1979 to 1982. Up to 20 people were airlifted from station Nord in Greenland onto camps on the ice pack to undertake 10-12 weeks of bathymetric, physical and chemical oceanographic, marine geophysical, atmospheric, biological and underwater acoustic studies. The expedition staff were from U.S., Canadian, Norwegian, and Danish universities and institutions. Financial support was provided by ONR, the National Science Foundation and Polar Continental Shelf Project.

In the spring of 1981 soundings were also taken in the western part of the Eurasia Basin by a temperature-salinity mapping program code-named EUBEX for Eurasia Basin Experiment. Flying in tandem in two Twin Otter aircraft, and landing on the ice at approximately 50-km intervals, scientists from the University of Washington carried out STD measurements.

The FRAM series expeditions have been superseded by the MIZEX-series (Marginal Ice Zone Experiment). Studies in physical oceanography along the southern edge of the permanent ice cover are scheduled to take place every spring beginning in 1983.

THE CANADIAN CONTRIBUTION

Geological Survey of Canada

Canadian investigations of the Arctic Ocean basin resumed, after a lapse of 37 years, with a series of airborne magnetometer and scintillometer surveys by the Geological Survey of Canada. In spring 1955 a party led by L.W. Morley, using a Canso long-range amphibious aircraft, made a number of flights to measure the total magnetic field and gamma field background throughout the Canadian Arctic Archipelago and adjacent ocean (Gregory *et al.*, 1961). Two of the flights extended over the ocean some 200 km beyond the Sverdrup Islands. Over much of the offshore area, the magnetic and radiometric readings were found to be relatively uniform, but at the northwest end of one of the flights, at the limit of aircraft range, there was an unmistakable change in magnetic character. This was clear evidence of a dramatic change in bedrock topography or offshore geology in the area hitherto known only from Stefansson's soundings. That same year, a large party from the Geological Survey, known as Operation Franklin (Fortier *et al.*, 1963) was engaged in studying the geology of the archipelago, and E.F. Roots, who was responsible for structural and geomorphological interpretation on that operation, attempted to reconcile the magnetic results with the evolving knowledge of the geology of the area. He became convinced of the scientific value and operational feasibility of a concerted and systematic investigation of the geology, geophysics, oceanography and bathymetry of the area, and began to seek support for a continuing study. The continental shelf area, unknown except for that single offshore magnetic "teaser", was the logical place to begin.

The Polar Continental Shelf Project

In 1958 the International Conference on the Law of the Sea was held in Geneva. One of the resolutions adopted by the conference was that mineral and other resources underlying continental shelves should be considered to be the property of the country claiming the coastline adjacent to the shelf. As a signatory to this resolution, Canada found herself, in effect, claiming ownership to resources beneath a continental shelf that had never been delineated, and whose outline was inferred mainly from Soviet maps. In order to remedy this situation, early in 1958 the Canadian Cabinet approved a proposal to organize a project to "conduct surveys and scientific research in the continental shelf area of Arctic Canada". The organization was to be known as the Polar Continental Shelf Project (PCSP), and it was to come under the jurisdiction of the Department of Mines and Technical Surveys (now Energy, Mines and Resources) (Roots, 1968).

The project was authorized by Cabinet Directive on 5 April 1958, and was designed to conduct general mapping, oceanographic, hydrographic, geological, geophysical, geographical and related studies, to be undertaken on the Arctic Ocean continental shelf, on the islands of the Archipelago, and in the channels. It was to act as a logistic instrument for all divisions of the department in conducting research in the arctic regions of Canada. It was to supply logistic support and facilities to other agencies conducting research in the area. No fixed date was contemplated for the completion of the project. Its first director was Dr. E.F. Roots. He was succeeded in 1972 by Mr. George D. Hobson, who still holds the position.

The initial field headquarters was established in 1959 at Isachsen on Ellef Ringnes Island, where a permanent weather station was maintained. Experiments were carried out on the electromagnetic propagation characteristics of the area, with a view to designing and installing an electronic survey and positioning system to cover the major area of investigation. The initial program was supported by one Beaver and one Otter aircraft, both ski-wheel-equipped, which in the first year made nearly 500 landings on unprepared strips on both land and ice.

The full-scale research and survey program got underway in 1960. In the first year work was concentrated on the continental shelf to the northwest of Meighen, Ellef Ringnes and Borden islands in one area approximately 300 km long and extending some 400 km to sea. A low-frequency Decca Lambda hyperbolic position-fixing system was erected, with the master station on Ellef Ringnes Island and the slave stations on Meighen Island and Borden Island, to give immediate determination of positions to an accuracy of 200-800 m within an area 300 × 500 km (Sobczak and Weber, 1970).

Studies undertaken during the first year's operation included hydrographic soundings, STD measurements and water sampling at standard depths, current and tidal measurements, grab sampling and coring, gravity, seismic and magnetic measurements, and geological investigations of the sea floor sediments.

The results of the initial year indicated that increased air support and more suitable ground equipment were required to increase efficiency of data collection. This was accomplished in later years by the addition of helicopters, both small and large, replacement of the Beaver by more ski-wheel-equipped Otter aircraft, the addition of a twin-engine Beechcraft and other multi-engine specialized survey aircraft, and the acquisition of more suitable vehicles for travelling over snow, ice and frozen ground. The first year's work demonstrated that with a well-planned program and proper equipment it was feasible to conduct research under arctic conditions with reasonable comfort and considerable success.

The PCSP's basic plan of study has been maintained, although the scope of investigations has expanded year by year since 1959. At first, the project depended on the Isachsen Weather Station for accommodation and some facilities. In 1964 the main headquarters of the project was moved southwest to Mould Bay on Prince Patrick Island and six years later it was moved further southwest to Tuktoyaktuk on the Mackenzie River Delta.

In addition to the main camps, temporary camps are established in the Arctic Archipelago or on the ocean, as required. One such camp was established at Alert, Ellesmere Island, in 1967 and served as a base camp for a hydrographic and gravity survey in Robeson Channel and Lincoln Sea. On this particular survey a portable Decca Hi-Fix navigational system was used for positioning.

The purpose of the program has been to investigate, as thoroughly as possible, each area covered by the Decca Lambda electronic positioning system before moving the Decca transmitter stations to new positions. The plan has been to leap-frog the stations progressively to the southwest; by 1975 the most westerly slave station was located on Herschel Island near the Yukon-Alaska border. In 1976 the Decca chain was moved to Amundsen Gulf where it has been deployed in inter-island surveys. In the fall of 1982 it was moved to the Ellesmere Island coast in order to fill in, in 1983, most of the gap left on the continental shelf between Meighen Island and Lincoln Sea.

The initial bathymetric survey was carried out with the use of a wire line, and with regular marine echo sounders either mounted on snowmobiles travelling on the ice, or carried in aircraft and operated through open leads or through holes drilled through the sea ice at landing places. From the beginning, one of the priorities was the development of an echo-sounding system with a transducer that allowed soundings to be made through the ice, thus eliminating the need for drilling a hole or searching for open leads. Such equipment, incorporating transducers sufficiently powerful and directional to sound reliably to depths of 2000 m, has been in use with both analog and digital output since 1961. Equipment and techniques were also developed to obtain echo soundings through open leads and cracks, from both helicopters and air-cushion vehicles (hovercraft) towing echo-sounding equipment while in flight. Extensive areas in critical straits and near the coastline have been surveyed by these methods, which give continuous sounding profiles rather than spot readings. Bathymetric surveys on the ice, between the islands, and on the continental shelf to a depth of 360 m (200 fathoms) are carried out at a 6-km (or less) grid interval. On the continental shelf between the 360 m and 1000 m isobaths, the grid interval is 10 km. These operations resulted in bathymetric mapping at a scale of 1:500 000 and regular hydrographic surveys at scales of 1:100 000 and 1:50 000. The cost per square kilometer of such surveys is now comparable with that of ship-borne surveys.

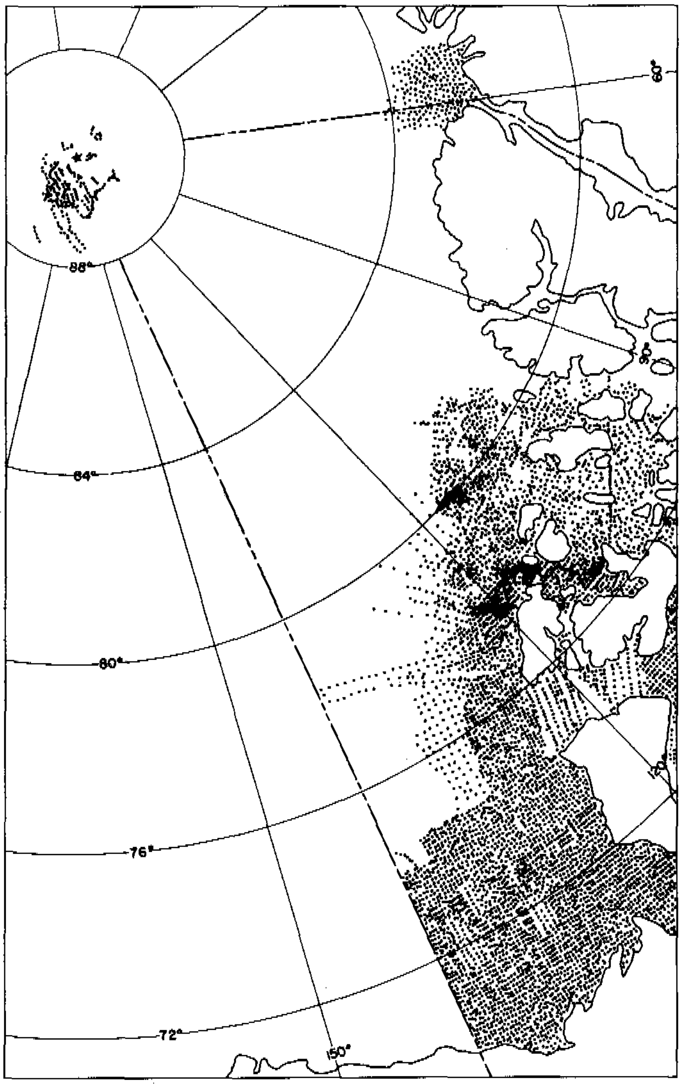


FIG. 4. Plot of Canadian bathymetric and gravity stations established on the Arctic Ocean and adjoining inter-island waters as of 1980.

Since 1961 the Gravity Division of the Earth Physics Branch and the Canadian Hydrographic Service have been undertaking joint bathymetric and gravity surveys as part of the PCSP activities. Usually two observers travel together in a helicopter, a hydrographer to operate the sounding equipment and a gravimetrist to read the gravimeter. By this method up to 26 stations can be established during a single 4-hr helicopter traverse. Figure 4 shows the locations of the gravity and bathymetric stations that have been established to date on the Arctic Ocean and adjoining inter-island waters. The bar chart in Figure 5 depicts the number of stations that were established on the polar continental shelf and beyond from 1960 to 1976. The count includes all stations on the ocean side of the Arctic Islands, the mainland coasts from Meighen Island to 141°W, and Lincoln Sea to 60°W; it excludes all inter-island surveys and the polar stations north of 85°.

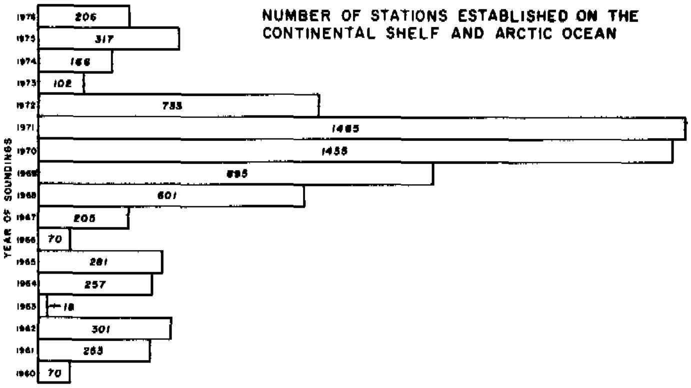


FIG. 5. Number of bathymetric and gravity stations established over the polar continental shelf, 1960-1976.

Polar Expeditions

The First Canadian North Pole Expedition. In 1967 the Dominion Observatory (now the Earth Physics Branch of the Department of Energy, Mines and Resources [EMR]) in cooperation with PCSP carried out a geophysical expedition to the vicinity of the North Pole. The main objectives of the expedition were to: 1) establish a line of gravity stations from

Alert to the North Pole, and obtain as many gravity observations as possible in the vicinity of the Pole and across the Lomonosov Ridge; 2) determine the deflection of the vertical at the North Pole (Lillestrand and Weber, 1974); and 3) develop and test new techniques for precise navigation in the polar region.

In the days before satellite receivers became commercially available and before very low frequency radio navigation aids, such as the Omega system, became operational in the polar region, the only means of positioning was by celestial observations. However, because of the unknown drift rate and direction of the ice, and because of atmospheric refraction, the accuracy of position fixes obtained from conventional sun observations could not be determiend to better than a few kilometres. This was unacceptable for the type of geodetic measurements that were planned. The problem of precise navigation in the polar area during the polar day was solved using a technique developed for this purpose by Lillestrand *et al.* (1967) from Control Data Corporation in Minneapolis. It involved continuous viewing of a number of celestial targets and solving by computer for ice drift and atmospheric refraction. Since minicomputers sufficiently rugged for field operations in the arctic winter environment were not yet available, zenith angles of the sun and of stars observed with a Kern DKM-3 theodolite, and atmospheric pressure and temperature, were relayed by amateur radio operators in Alert and Ottawa to Control Data Corporation in Minneapolis where the data were processed on a computer. The computed positions, the rate and direction of the ice drift at the time of the last observation, and a prediction on the probable ice movement during the next few hours were then relayed back to the ice station via the radio communications link. The purpose of this procedure was to position the observers within a few hundred metres upstream of the geographic North Pole and let them

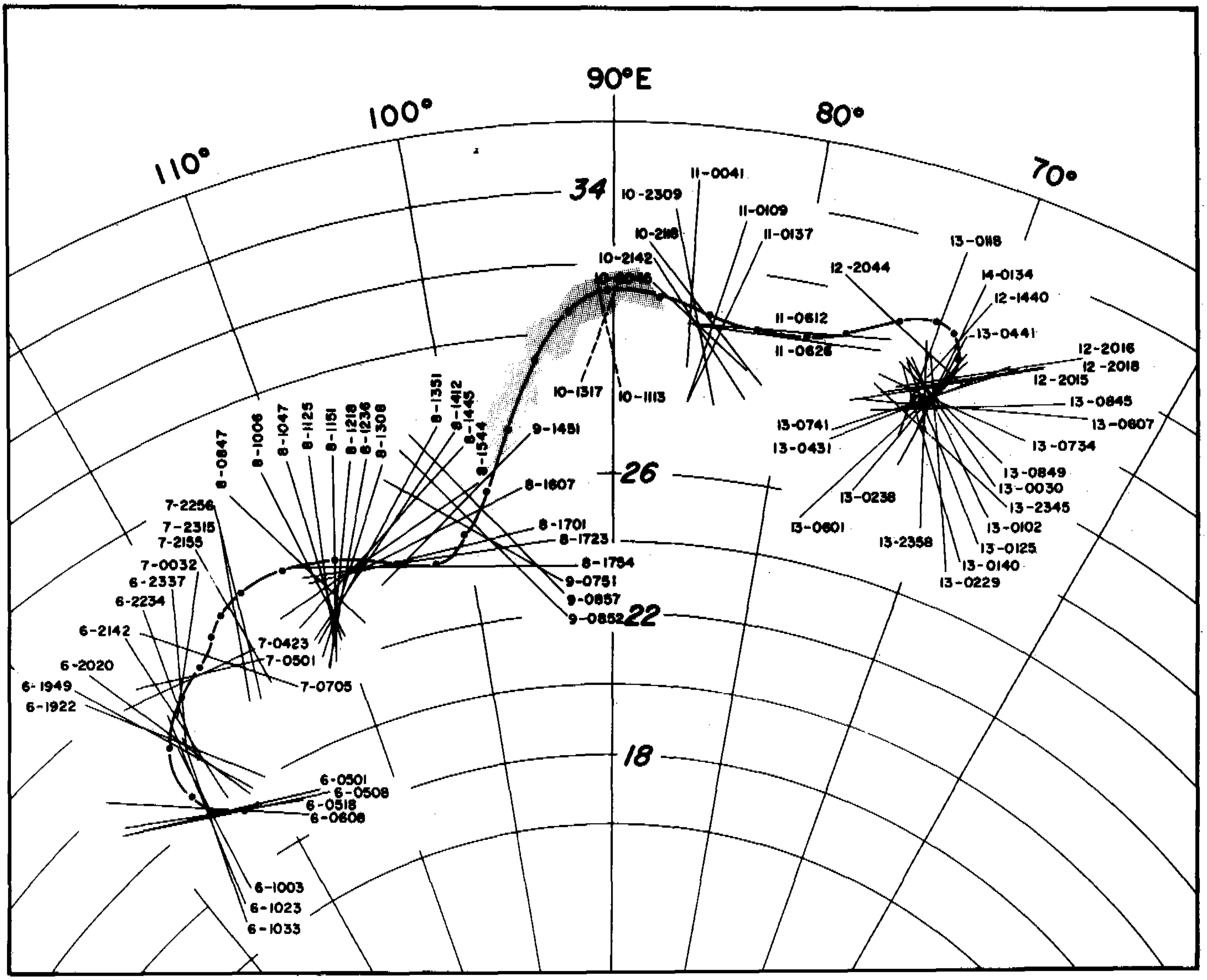


FIG. 6. Drift track of the 1967 Canadian North Pole station with lines of positions determined from sun observations. Time intervals between dots on the track are six hours. Numbers beside position lines represent day of May 1967, and universal time at which the sun was observed. Numbers along 90°E meridian represent co-latitude in minutes.

drift across the Pole while carrying out plumb line deflection and gravity measurements. As it turned out, because of difficulties with the two single-engine Otter aircraft sent out to assist the scientists and, eventually, evacuate the camp, 900 km from base, the full program was not carried out.

Viewing of stars in daylight requires an up-to-date star catalogue especially generated for the particular geographical area and time period. Figure 6 shows the lines of positions of celestial targets, mostly of the sun, starting on 6 May at 1003 h GMT, minutes after the Bristol Freighter aircraft had landed on the ice with the seven expedition members, until 14 May at 0134, just before the camp personnel were evacuated to Alert. The solid line represents the computed drift path with a dot every six hours. Except for a 28-hour period of overcast weather (shaded area in Fig. 6), the sun was visible most of the time, but because of the presence of crystal fog in the air the stars were visible only occasionally. During the first six days the drift speed ranged from 300 to 700 $m \cdot h^{-1}$. It is estimated that the drift path positions are accurate to ±200 m when only the sun is used as a target and to ±50 m when the targets also include stars and planets. Figure 6 illustrates the ambiguity of determining the drift path by conventional survey methods during periods of rapid drift, without modern computing aids on hand. Consider, for instance, the time period from 0847 to 1754 on 8 May during which 16 sun observations were taken. The only way an observer on the ice, equipped with theodolite, watch, paper, pencil and ruler, can determine his position is from successive position line intersections. The positions thus obtained are scattered several kilometres about the actual drift path positions.

Although the gravity survey from Alert to the Pole and across the Lomonosov Ridge, and the plumb line deflection experiment, had to be abandoned, the knowledge acquired about navigation in the polar area proved invaluable in planning the 1969 and LOREX 79 polar expeditions.

The Second Canadian North Pole Expedition. Two years later the expedition returned to the north polar area and occupied an ice floe from 12 April to 3 May 1969. Their equipment included a Magnavox transit satellite receiver (the first commercial satellite receiver to operate in Canada; its raw data were recorded on punch paper tape and processed in Ottawa after the expedition returned), a Kern DKM-3 and a Wild T-2 theodolite, and an acoustic bottom reference system. In addition, the Twin Otter aircraft used for spot gravity measurements and depth soundings had an experimental Omega receiver on board (the forerunner of the Global Navigational System, a very low frequency, world-wide navigational aid). Because of clearer weather and lower sun angle in April the stars were much more visible than in 1967. Except for a period

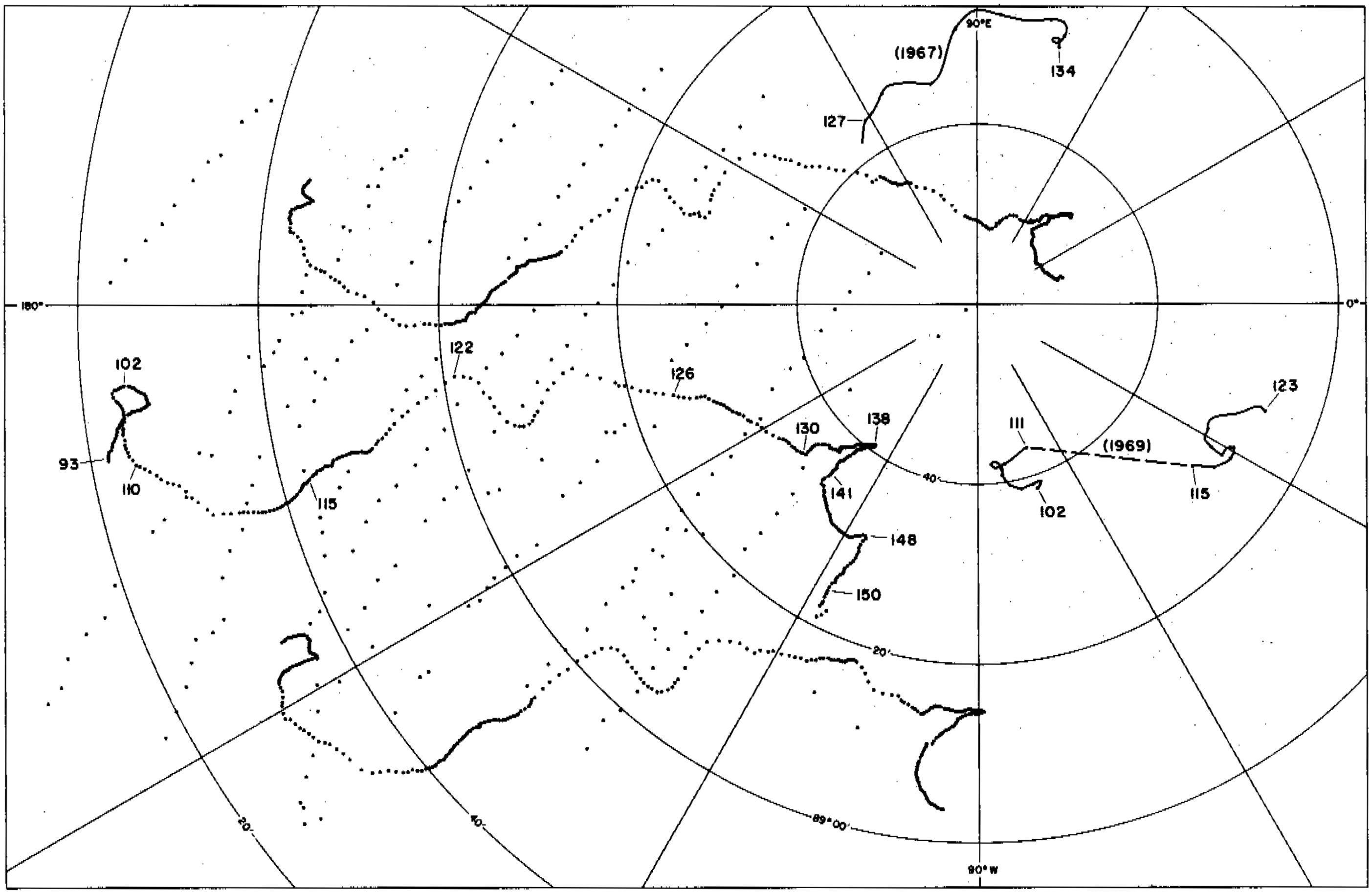


FIG. 7. Drift tracks of the 1967 and 1969 expeditions and of the three LOREX 79 camps. Numbers represent Julian days. Also shown are locations of spot soundings and gravity observations.

of four days, when a storm blew the ice station 40 km to the southeast while the satellite receiver was shut down, star and satellite position fixes were obtained continuously. By ranging once a minute from an acoustic transducer at the camp to two transponders on the sea bottom, the scientists obtained measurements of the fine structure of the ice drift relative to the ocean floor. By superimposing the acoustically-determined drift path on the path determined astronomically and by satellite receiver, they obtained the plumbline deflection along the drift path, and track positions, to an accuracy of better than ±40 m (Lillestrand and Weber, 1974).

Spot gravity and depth measurements between Alert and the Pole and across the Lomonosov Ridge were carried out using Twin Otter aircraft. Positions were obtained from sun observations of at least two hours using the T-2 theodolite with a Roelofs prism. Precise positions were later determined by computer, taking drift and atmospheric refraction into account, and are estimated to have on the average an accuracy of ±500 m. The drift paths of the 1967 and 1969 expedition are shown in Figure 7. The dots on the tracks, spaced at one-day intervals, illustrate the speed at which the stations drifted; the numbers refer to Julian days.

The LOREX 79 Expedition. In spring 1979 EMR undertook a large-scale, multidisciplinary project to study the nature and origin of the Lomonosov Ridge. The scientific program was planned and coördinated by the Earth Physics Branch, and logistic support was provided by the PCSP. Scientists from other branches of EMR, from the Department of Fisheries and Oceans and from a number of universities in Canada and the U.S.A. took part in the project which was code-named LOREX 79 (Weber, 1979, 1980; MacInnes and Weber, 1980).

Positioning of the LOREX 79 main camp, and the two satellite camps ~60 km from the main camp, was based on satellite Doppler observations of the Navy Navigation Satellite System. Real-time navigation fixes were computed from the on-line satellite receiver at the main camp approximately every hour (Wells and Grant, 1977). The two satellite camp receivers recorded raw data on cassettes which were collected every few days and flown to the main camp for off-line processing. In this way, ice camp positions were continuously updated with precisions of about ±250 m, which provided reference for the aircraft Global Navigational System (GNS) and useful information on ice speed and direction during the expedition. This represented a considerable improvement over the 1969 expedition when ice velocity information became available only months later, after the data had been processed in Ottawa.

A new software package has been developed for geodetic positioning of slowly moving platforms from satellite Doppler tracking (Popelar *et al.*, 1983). The three-dimensional data reduction model uses consecutive satellite passes for a sequential adjustment of the station coordinates and evaluation of mean linear velocities over pre-determined time intervals. The LOREX satellite Doppler data set has been reprocessed, using the new software and post-fitted precise satellite orbits providing mean station positions for 3-hr intervals with a horizontal precision of ±24 m and a vertical uncertainty of ±0.4 m. Drift velocities of up to 1200 $\text{m}\cdot\text{h}^{-1}$ were recorded.

During the month of April star observations were also taken using a Wild T-4 theodolite. The astronomical positions yielded about the same accuracy as the Transit Satellite fixes and were used to determine the plumbline deflections.

The drift paths of the LOREX 79 main and satellite camps, as they drifted across the Lomonosov Ridge with the Transpolar Current, are illustrated in Figure 7 as dots spaced at 3-hr intervals. The numbers 93 to 150 along the main camp drift track represent Julian days.

Some 270 spot soundings were carried out by helicopter and Twin Otter aircraft equipped with a GNS. Although no accuracy tests of the GNS seem to have been conducted in the polar region, we estimate from repeated comparisons with the main camp positions that the accuracy achieved on this operation is of the order of ±1000 m.

All soundings of the earlier expeditions, as well as all spot soundings on the LOREX 79 helicopter traverses, were taken by the seismic method using two geophones placed on the ice and dynamite charges ranging from 0.1 to 0.5 kg. Explosives were either drilled into the ice or, when feasible, detonated in the water. Spots for underwater detonation were chosen based on either the presence of cracks and/or open leads or the presence of thin ice that could be quickly pierced with an ice chisel or drilled with a hand auger. Soundings along the 1967 and 1969 drift paths were obtained at least twice a day. Depths at the LOREX 79 satellite camps were recorded on 3.5 kHz echo sounders, and at the main camp soundings were obtained from the 3 kHz sub-bottom profiler and from a 164-cm^3 shallow seismic air gun. Figure 7 shows the locations of most of the spot soundings that were established by helicopter and fixed-wing aircraft, as well as the drift tracks along which depth soundings were recorded.

Based on all the depth soundings that were taken on the three polar expeditions (over 300 spot soundings and 650 line kilometres of continuous echo and shallow seismic soundings), a 100-m contour map of the sea floor of the area around the North Pole was compiled. The map (Fig. 8) was prepared at a scale of 1:250 000 and extends from the Makarov Basin across the Lomonosov Ridge to the North Pole in the Fram Basin. The shallowest and deepest depths recorded were 955 m on the Lomonosov Ridge, and 4309 m in the Fram Basin, respectively.

JOINT CONTRIBUTIONS

The Arctic Ice Dynamics Joint Experiment

In 1970 the Arctic Ice Dynamics Joint Experiment (AIDJEX) was established for the purpose of studying the large-scale interaction between hydrosphere and atmosphere in the Arctic Ocean. This highly successful multidisciplinary, multiagency project included U.S. and Canadian scientists and was supported by the National Science Foundation and PCSP. Pilot studies in spring 1970, 1971 and 1972 were followed in 1975

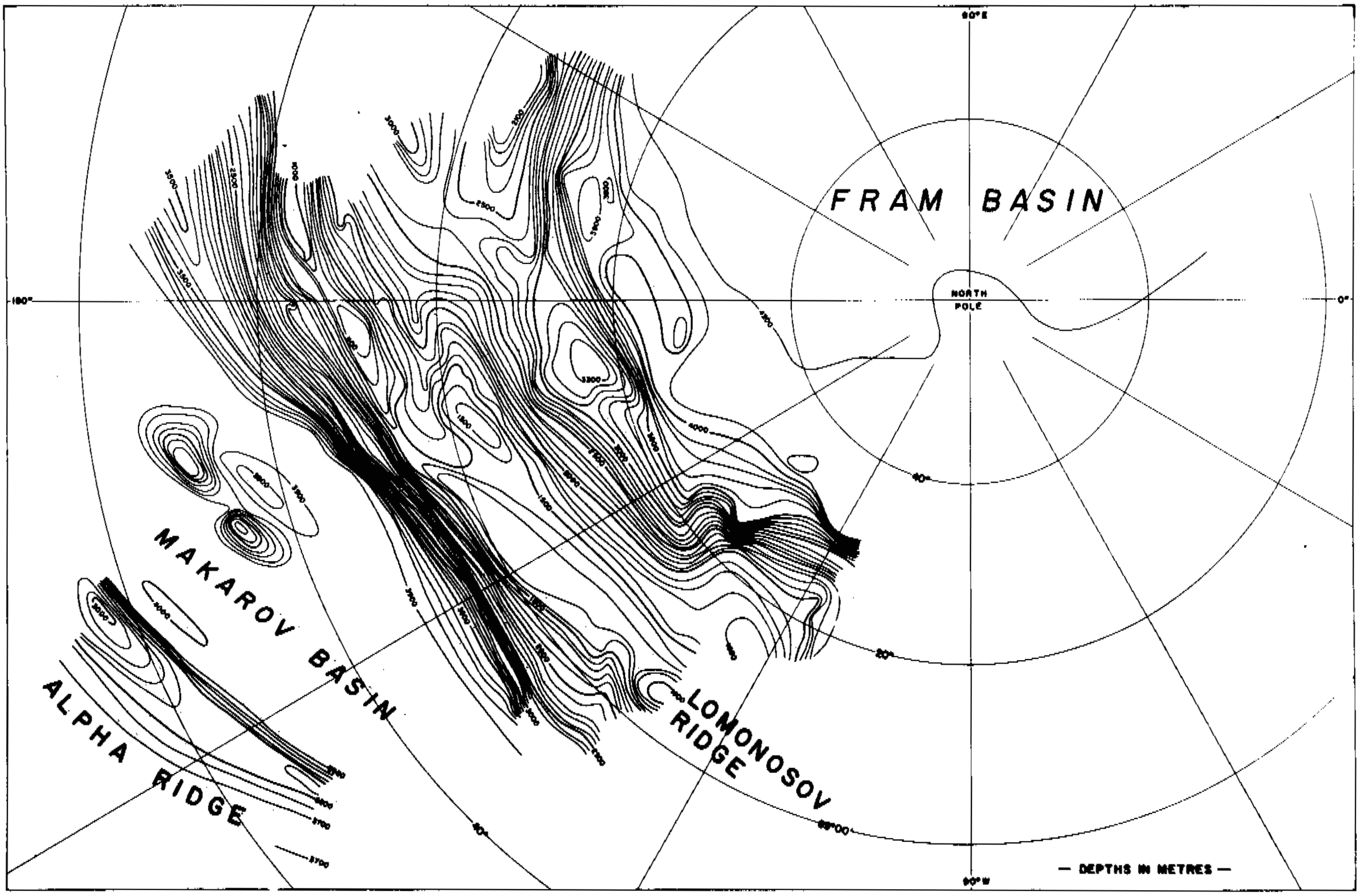


FIG. 8. LOREX 79 bathymetric map. Contour interval 100 m.

by the main experiment, during which four manned stations drifted for 15 months in the Beaufort Sea. This was the largest scientific operation of its kind ever to be undertaken in the Arctic Ocean. Continuous depth and gravity measurements and a seismic refraction survey were carried out by the Earth Physics Branch during the main experiment; these results added to the bathymetric and morphological knowledge of the Canada Basin.

THE MAPS AND CHARTS OF THE ARCTIC OCEAN BASIN

The 1954 Soviet Map

By 1954 the Soviets had established over 2000 soundings resulting in the compilation of a map of the arctic sea floor (Fig. 9) which, for the first time, revealed the existence of the Lomonosov Ridge (Burkhanov, 1956). Ya. Ya. Gakkel was the best known of the Russian hydrographers of that period and much of the credit for compiling the map goes to him. He had compiled a map showing part of the Lomonosov Ridge in 1949 but it was kept secret at the time. In recognition of Gakkel's contribution, the Arctic mid-oceanic ridge in the Eurasia Basin was named after him. Others who contributed significantly were Ostreikin, Tolstikov, Gordienko, Somov, Burkhanov and Treshnikov (Lloyd, pers. comm. 1980). Understandably, the map caused a sensation among arctic experts outside the Soviet Union, who until 1954 had been unaware of the scope and magnitude of Soviet exploration.

The DRB Chart

In 1956 the Defence Research Board of Canada (DRB) compiled a map of its own (Fig. 10). I have tried unsuccessfully to track down how and by whom the map was compiled; Surveys and Mapping Branch of Energy, Mines and Resources Canada, where the map was prepared, has no records (Falconer, pers. comm. 1981). It appears to have been compiled by using the Soviet map as a base and adding U.S. airborne and T-3 data, and by re-contouring Somov's NP2 soundings. Here, for the first time, the Alpha-Mendeleev Ridge is outlined as separating the Makarov Basin from the Canada Basin. For many years the DRB map remained the best bathymetric chart of the Arctic available to the public outside the Soviet Union. It is rumoured that the U.S. Navy used it to navigate the *Nautilus* to the North Pole in 1957.

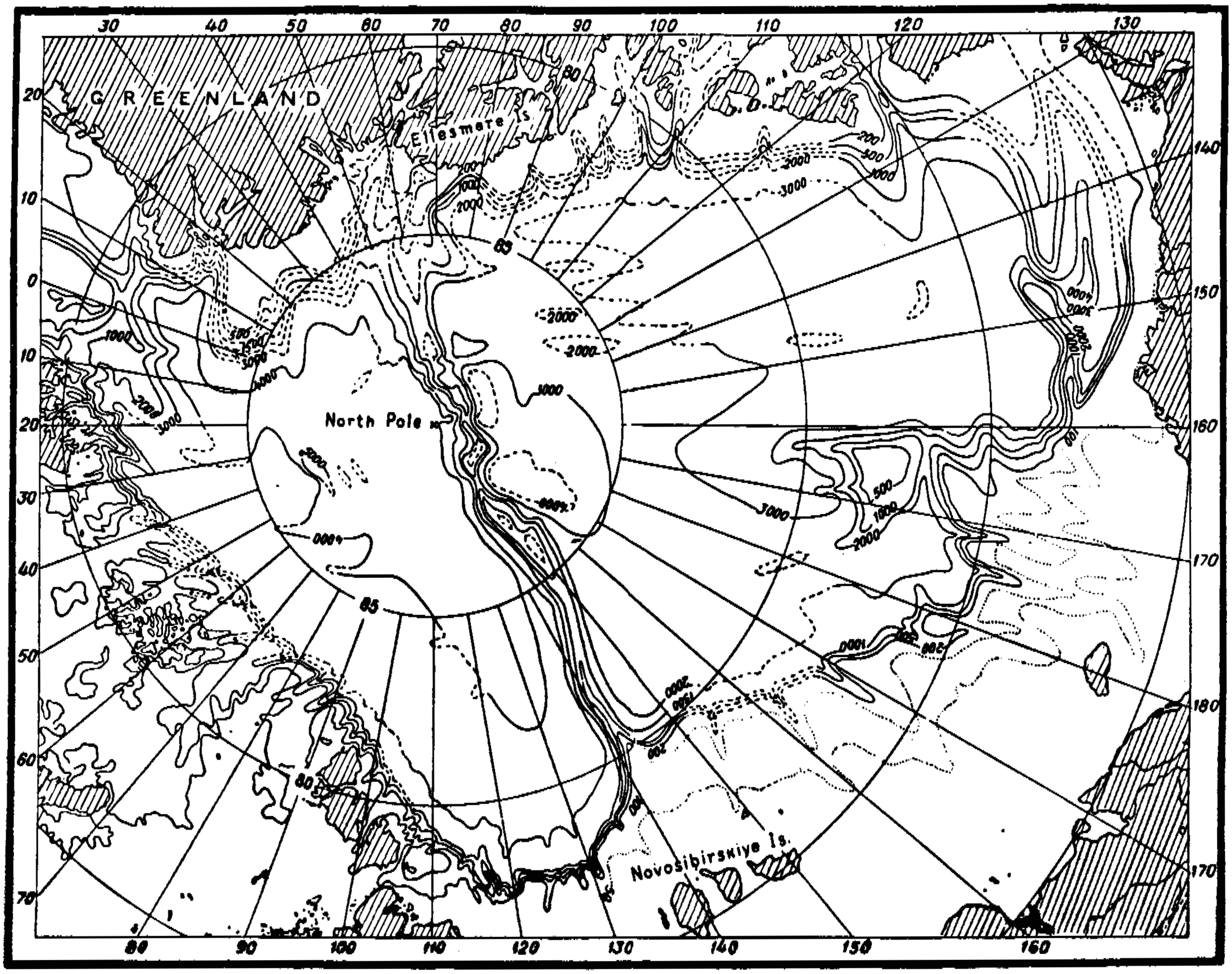


FIG. 9. 1954 Soviet bathymetric map of the Arctic Ocean.

The 1960 Soviet Map

By 1960, 900 deep-water oceanographic STD (salinity, temperature, depth) stations, 100 24-hr oceanographic stations, 300 hydrobiological stations and over 20 000 soundings had been established. These data resulted in the publication of a second Russian map (Fig. 11; Gordienko, 1960), which utilized data to 1 March 1959. Although generalized because of its small scale and because depth soundings are highly classified in the Soviet Union, it clearly delineates the Canada Basin, the Alpha-Mendeleev Ridge and the Makarov Basin, but the Nansen-Gakkel Ridge is not yet clearly defined. No Russian maps have since been published that show significantly more detail.

Heezen and Ewing

In Nansen Strait, between Spitzbergen and Greenland, the Norwegian Sea narrows to about 300 km from shelf to shelf. In 1912 Nansen postulated that a shallow east-west submarine ridge connects the two shelves, effectively separating the Arctic from the North Atlantic water. The existence of Nansen's Sill, as this hypothetical ridge became known, remained unchallenged until 1958 after the Russians had conducted a detailed bathymetric survey from three icebreakers. It was found that the ridge did not exist but rather that the relatively shallow strait was bisected by a narrow north-south trough over 4000 m deep (Laktionov, 1959), now known as Lena Trough (compare, e.g., Figs. 10 and 13). It has long been known (Linden, 1959) that the mid-oceanic seismic belt continues through the Arctic Ocean and that earthquake epicentres follow a line from Jan Mayen Island through Nansen Strait across the Eurasia Basin to the Laptev Sea. Heezen and Ewing (1961) speculated that this seismic belt signifies the continuation of the Mid-Atlantic Ridge and that the Lena Trough is a rift feature of the ridge. They re-examined the *Fram* and *Sedov* water depths and re-evaluated the Soviet data; i.e. by superimposing the Soviet drift tracks and landing sites of the High Latitude Air Expeditions (Fig. 2) over the bathymetric charts (Figs. 9 and 11) they re-established the locations and values of Soviet soundings. Based on these data they revised the chart of the Eurasia Basin (Fig. 12), which shows the mid-oceanic ridge extending from the Lena Trough to the Laptev Shelf and bisecting the Eurasia Basin roughly halfway between the edge of the Barents Continental Shelf and the Lomonosov Ridge. It should be noted that, at this stage, the Nansen-Gakkel Ridge, as the Arctic mid-oceanic ridge later was named, was only a hypothesis of Heezen and Ewing's, the existence of which was not contradicted by known or inferred soundings. The bathymetric data were far too scarce and too scattered to delineate the ridge to more than a purely schematic representation. Although the Soviets had far more data available than did Heezen and Ewing, they apparently did not see the ridge because they were not looking for it, believing, at that time, that the Arctic Ocean was formed by subsidence of continental platforms (Saks *et al.*, 1955; Hakkel, 1958). Heezen and Ewing saw it because, as adherents of the then-emerging theory of plate tectonics, they were expecting it. The existence of the Nansen-Gakkel Ridge was not unequivocally confirmed until 1969 with the publication by Beal of the U.S. submarine bathymetry. Virtually no new unclassified depth data from the Eurasia Basin have become available until the last two years when detailed soundings were made near the Atlantic end of the ridge during the FRAM I and FRAM II expeditions. This leaves most of the Nansen-Gakkel Ridge still poorly mapped.

Ostenso's Bathymetric Map

In 1961 N. Ostenso compiled a new map of the Arctic Ocean sea floor based on all available unclassified material (Ostenso, 1962, 1963). The map (Fig. 13) is contoured at 200, (500), 1000, 2000, 3000, (3800), 4000 and 5000 m and as published is plotted at a scale of about 1:18 000 000. The data were weighted according to their indicated degree of control. Necessary interpretation and interpolations were made conser-

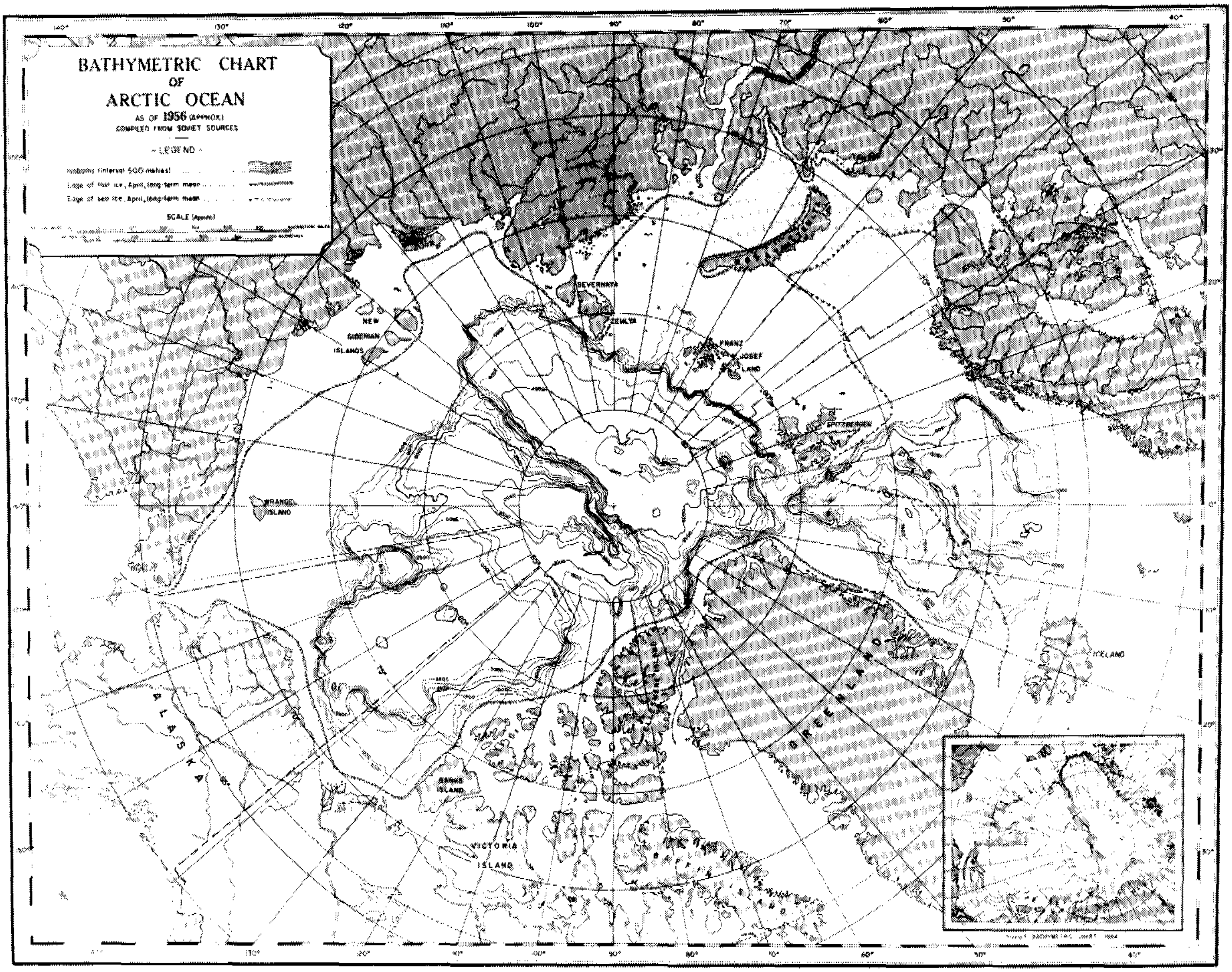


FIG. 10. 1956 Defence Research Board bathymetric chart of the Arctic Ocean.

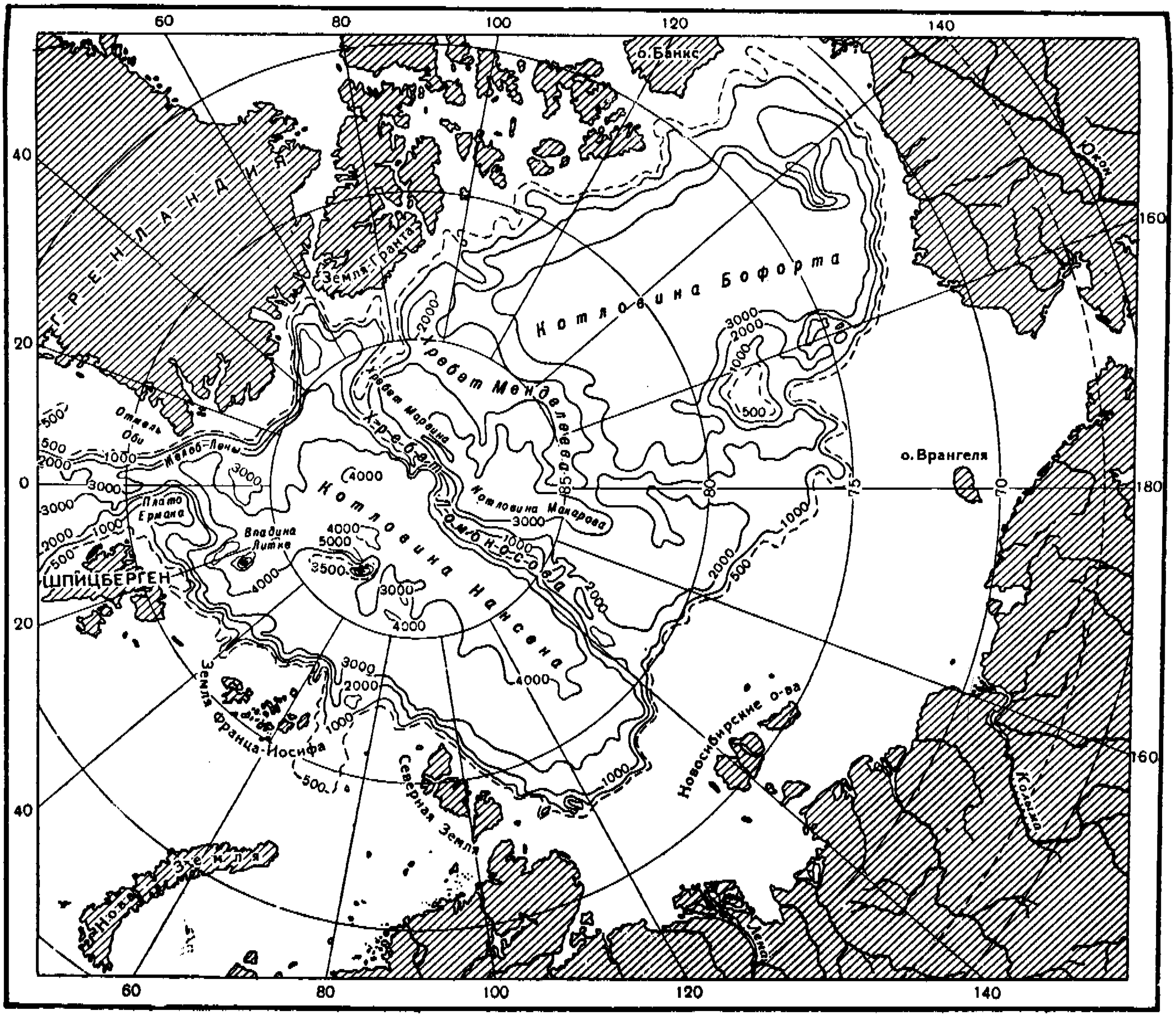


FIG. 11. 1959 Soviet bathymetric map of the Arctic Ocean.

vatively and detailed flexures of isobaths were made only when sufficient and reliable data warranted. This is apparent for the Eurasia Basin when compared with Heezen and Ewing's contouring.

Except for the Lena Trough region, the contours in the central part of the Arctic, in the region north of 80°, do not differ significantly from those on the DRB chart (Fig. 10).

Canadian Bathymetric Chart of 1967

In 1967 the Canadian Hydrographic Service published two charts of the Arctic Ocean north of 72° from longitude 0° to 90°W (map sheet 896) and from 90°W to 180° (map sheet 897). The map was compiled by De Leeuw (1967) from some 12 000 soundings of which about 6000 were from inside the Canadian Archipelago and Greenland inter-channel waters. Beyond the 200 m isobath the chart is contoured at 500-m intervals; the scale is 1:2 000 000. The bathymetry is colour-coded with six colour ranges and land masses are left blank. Except for the continental shelf of the Queen Elizabeth Islands, which had been charted by PCSP, and the Chukchi Rise, Alpha Ridge and Canada Basin, where the University of Wisconsin had been carrying out sounding operations, the chart does not differ significantly from Ostenso's.

The GEBCO Map of 1968

The Canadian Bathymetric Chart of 1967 served as the basis for the General Bathymetric Chart of the Oceans (GEBCO), 3rd edition, sheets CI and CII, which were published in Paris in 1968 by the Institute Géographique National at a scale of 1:3 100 000. The land topography is contoured at 1000-m in-

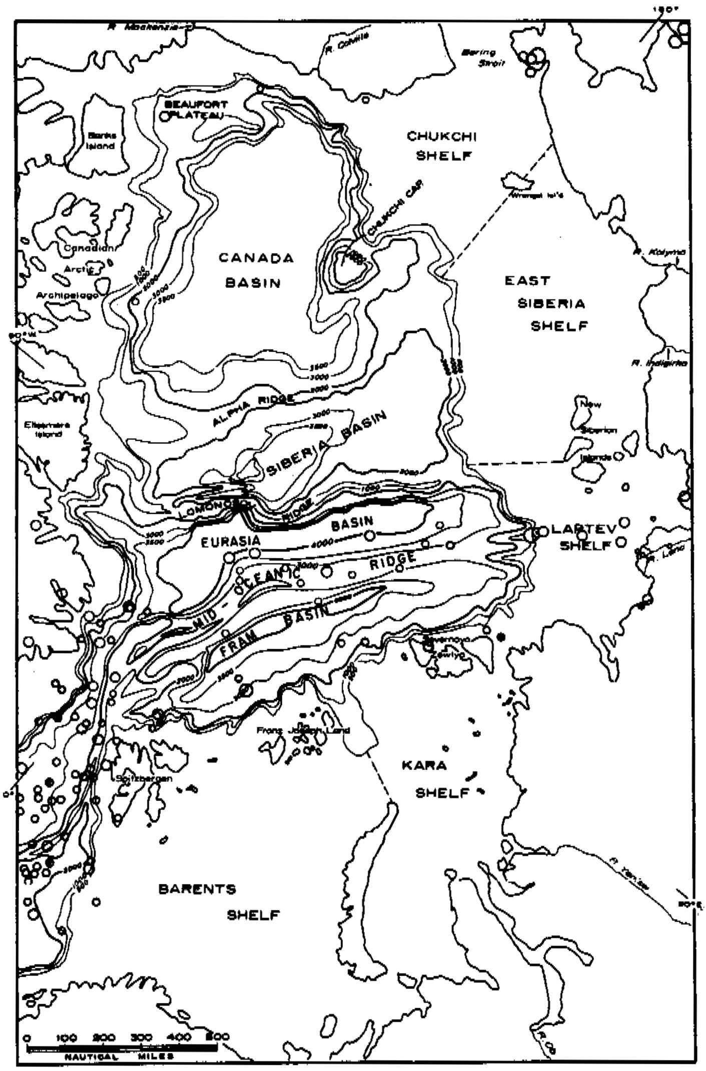


FIG. 12. Heezen and Ewing's 1961 bathymetry of the Arctic Ocean. Circles represent earthquake epicentres.

tervals and colour-coded. Other than the scale, and the fact that the GEBCO bathymetry shows more soundings, it is identical to Canadian Charts 896 and 897.

The British Admiralty North Polar Chart

In 1969 The United Kingdom Hydrographic Department published the North Polar Chart, Admiralty Chart No. 4006. It was compiled by Ritchie (1969) at an approximate scale of 1:7 500 000. Beyond the 100-fathom isobath the depth is contoured at 500-fathom intervals. The chart does not present any new information, and the contouring of the western half of the Arctic north of 72° is essentially an interpolation, in the old depth units, of the Canadian Hydrographic Charts 896 and 897. The balance of the Admiralty chart does not differ significantly from Ostenso's chart.

Heezen and Tharp's Map of the Arctic Region

In 1975 the American Geographical Society published "Map of the Arctic Region", sheet 14 of "The World Series". This is the most ambitious topographic-bathymetric map of the Arctic ever to have been produced. The coloured map, scale 1:5 000 000, measures approximately 120 × 150 cm; 18 colour steps cover an elevation range from a depth of 8000 m in the Aleutian Trench to a height of over 5000 m in the St. Elias Range. It was compiled by Bruce C. Heezen and Marie Tharp of the Lamont-Doherty Geological Observatory, based on all available unclassified soundings and on extensive use of Beal's (1969) submarine depth profiles. Topographic elevations are contoured at 1000-m intervals whereas the bathymetric contour intervals range from 500 m over steep slopes and over the Nansen-Gakkel Ridge to as little as 10 m over the abyssal plains. The ocean floor is depicted in great detail everywhere, without regard to how much or how little data are available. A portion of Heezen and Tharp's map with some of the isobaths removed is illustrated in Figure 14 (from Sobczak, 1977); the original has 100-m intervals over the abyssal plains and 200-m intervals over the Lomonosov Ridge. The Nansen-Gakkel Ridge is shown with numerous transform faults and flat-topped rectangular structures, illustrating the compilers' view on what the bottom topogaphy of an active spreading ridge might look like; however, the scant sounding data available for this region provide no evidence for such features (Sobczak, 1977). In their detailed aeromagnetic investigation of the Arctic Basin, Vogt *et al.* (1979:1087) comment on the transform faults on Heezen and Tharp's chart: "Contrary to the representation on the map the magnetic lineations are relatively continuous and execute smooth bends. The anomaly pattern suggests transform faults at only a few spots. Elsewhere, sharp offsets attributable to transform faults would have to be of small enough displacements (10 km or less) to escape resolution". Using newer, classified submarine data and re-evaluating the old, they also found that the central rift valley position of the Nansen-Gakkel Ridge may be up to 50 km displaced from that shown on the Heezen-Tharp chart.

Sobczak's Arctic Bathymetry

In 1978 the Earth Physics Branch of EMR published as part of Arctic Geophysical Review (Sweeney, 1978) a new map of the Arctic Ocean Basin. It was compiled by Sobczak and Sweeney (1978) at a scale of 1:7 500 000 and is, beyond the 200-m isobath, contoured at 500-m intervals. Although nearly 250 000 digitized soundings were used, the distribution is very uneven. For example, not a single sounding is available from the Laptev Shelf side of the Eurasia Basin south of 85°. The data used by Sobczak, and earlier by Heezen and Tharp, originate from the same sources, yet the interpretation is quite different. As an example, Sobczak's contouring north of 85° is depicted in Figure 15 (from Sobczak, 1979) with all the sounding data superimposed; dots represent soundings taken from the ice surface, straight lines indicate the location of the submarine traverses along which Beal (1969) determined water depths. The drawing illustrates the paucity of sounding data over the Nansen-Gakkel Ridge. Sobczak replaced Heezen and Tharp's elaborate diagrammatic representation of the Nansen-

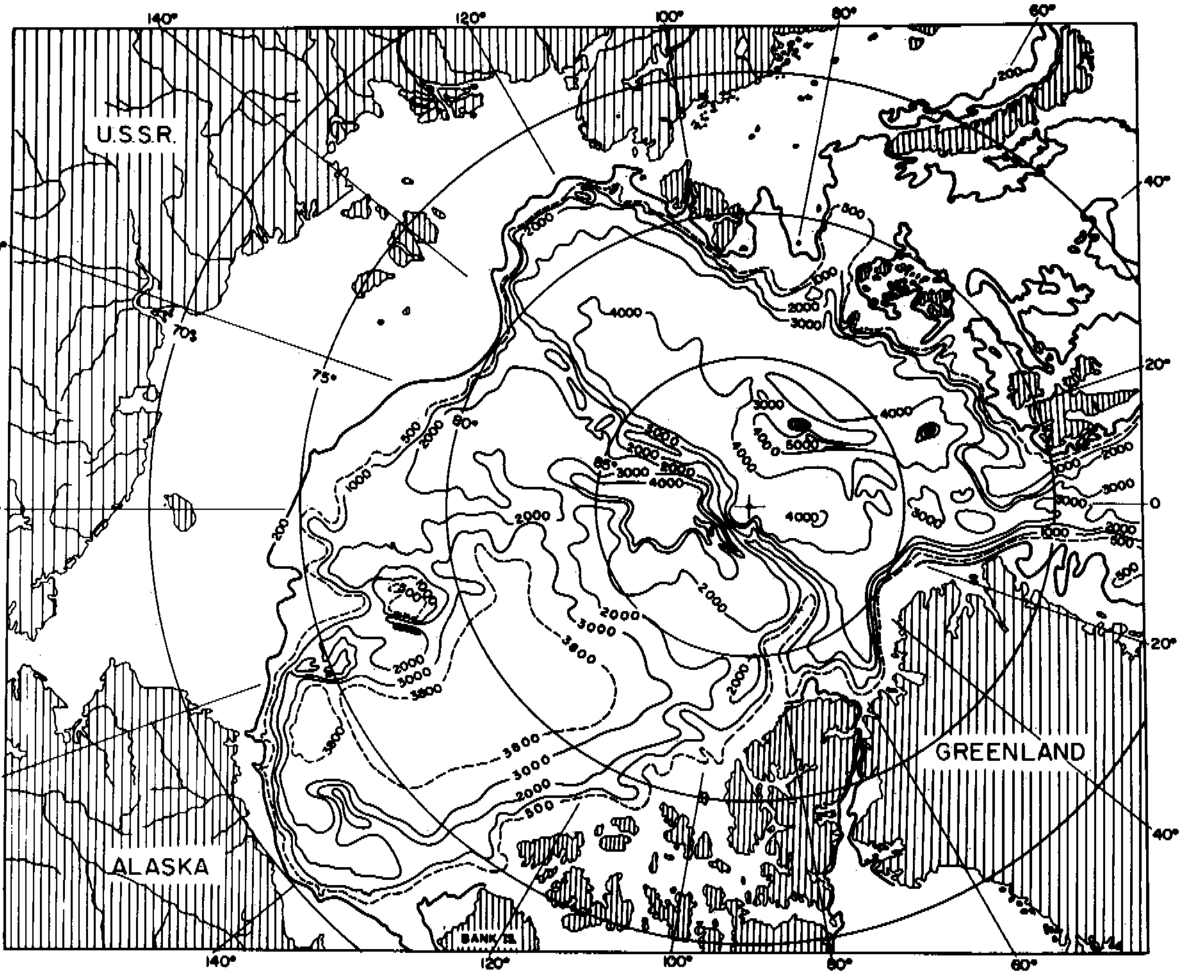
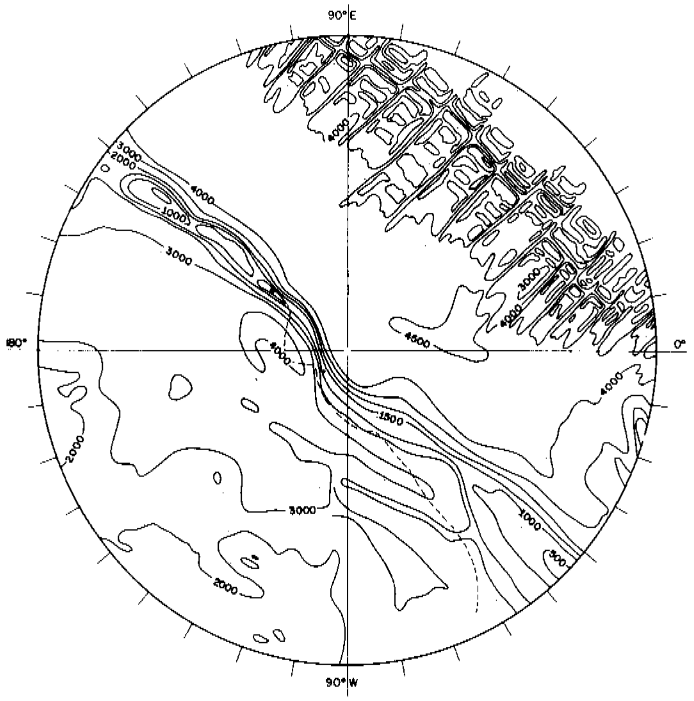


FIG. 13. Ostenso's 1962 bathymetry of the Arctic Ocean.



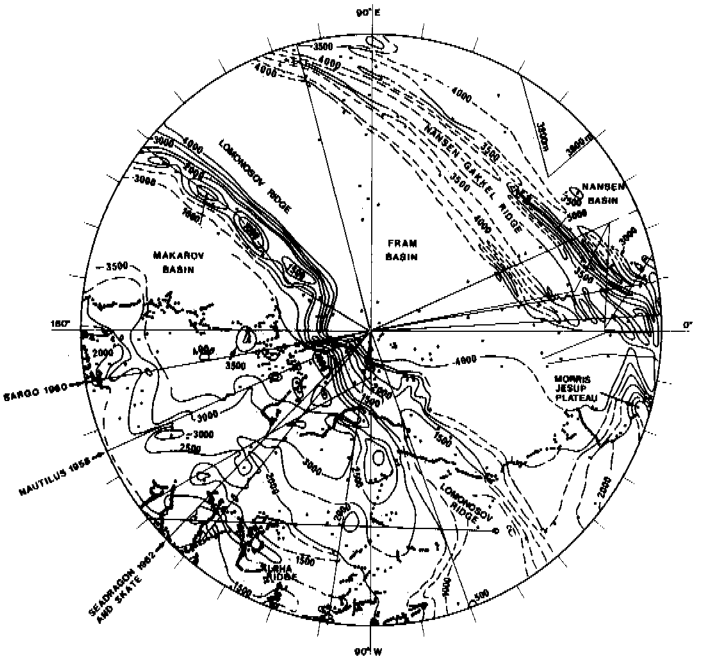


FIG. 14. 500-m contours of Heezen and Tharp's 1965 bathymetric chart north of 85°, superimposed on LOREX profiles (heavy line).

FIG. 15. Sobczak's bathymetry north of 85° including meridional tracks of the U.S. submarines *Seadragon* and *Skate* (1962), *Nautilus* (1958) and *Sargo* (1960).

Gakkel Ridge (Fig. 14) with a much simpler model consisting of a series of narrow, parallel ridges somewhat similar in character to Heezen and Ewing's (1961) original concept (Fig. 12). Where the contouring is necessarily speculative, the isobaths are represented by broken lines; this contrasts with Heezen and Tharp's map in which the reader cannot distinguish between fact and speculation.

The GEBCO Map of 1979

In 1979 the Canadian Hydrographic Service published Chart No. 517 of the General Bathymetric Chart of the Oceans under the authority of the International Hydrographic Commission. It encompasses the arctic regions north of 64° and is printed at a scale of 1:6 000 000. The topographic and bathymetric colour scheme is the same as for Heezen and Tharp's chart. The contour intervals range from 1000 m to 100 m depending on the sounding density. Unlike Heezen and Tharp's chart, however, the location of surface ship, submarine, and drifting station tracks, as well as individual soundings, are plotted, and areas with high density soundings, such as over the Canadian polar continental shelf, are delineated. This allows the user to gauge the reliability of the chart for any particular area. Contouring is conservative, and in the Arctic Ocean is generally the same as Sobczak's 1978 chart (but with greater contour density) since Sobczak was a principal compiler. Nevertheless, some of the speculative diagrammatic contouring of Heezen and Tharp, suggestive of transform faulting, has been retained — over Sobczak's objections (Sobczak, 1979; Monohan, 1979).

Residual Magnetic Anomaly Chart of the Arctic Ocean Region

In 1982 the Naval Research Laboratory and the Naval Ocean Research and Development Activity published a residual anomaly chart of the Arctic Ocean at a scale of 1:6 000 000. Printed over the coloured bathymetric chart are aeromagnetic profiles along the flight tracks with positive anomalies in red and negative anomalies in green. Printed in black on the back of the chart, for viewing on a light table, are earthquake epicentres and magnetic lineations. Although it is a specialized geophysical map it is mentioned here because the contours of the bathymetric base map are those of the GEBCO chart, except for the Lomonosov Ridge near the North Pole where the contours were corrected based on the LOREX bathymetry (Weber, 1979).

COMPARISONS AND CONCLUSIONS

Comparison of the LOREX 79 bathymetric map with the 1979 GEBCO chart, and with the 1975 Heezen and Tharp chart, reveals large discrepancies. The superimposition of the contours of the two charts on the LOREX 79 map is illustrated in Figures 16 and 17. The crest of the Lomonosov Ridge is offset by as much as 34 km on the GEBCO chart and by as much as 77 km on the Heezen and Tharp map.

Out of curiosity I made the same comparison with the 1954 Soviet map (taken from the DRB chart, Fig. 10). Surprisingly, this 25-year-old map agreed much better with the LOREX 79 survey (Fig. 18) than do the recent maps. For most of its length the location of the ridge crest lies within the positioning accuracy of the LOREX 79 survey. This at first seem unexpected since the Soviet surveys were carried out in the "horse and buggy" days of wire winches and sun positioning, long before sophisticated radio and satellite navigational aids became available and many years before nuclear-powered submarines began to cruise under the arctic pack ice.

Why is it that the old Soviet map is so much more accurate than our contemporary maps? The answer is suggested in Figure 15. In the LOREX 79 survey area, i.e. between 130°W and 160°E, there are only five soundings on the Lomonosov Ridge. The compilers relied heavily on Beal's (1969) submarine data from the *Seadragon* and *Skate* (1962), from the *Nautilus* (1958), and from the *Sargo* (1960), the meridional tracks of which are indicated in Figure 15. When the sub-

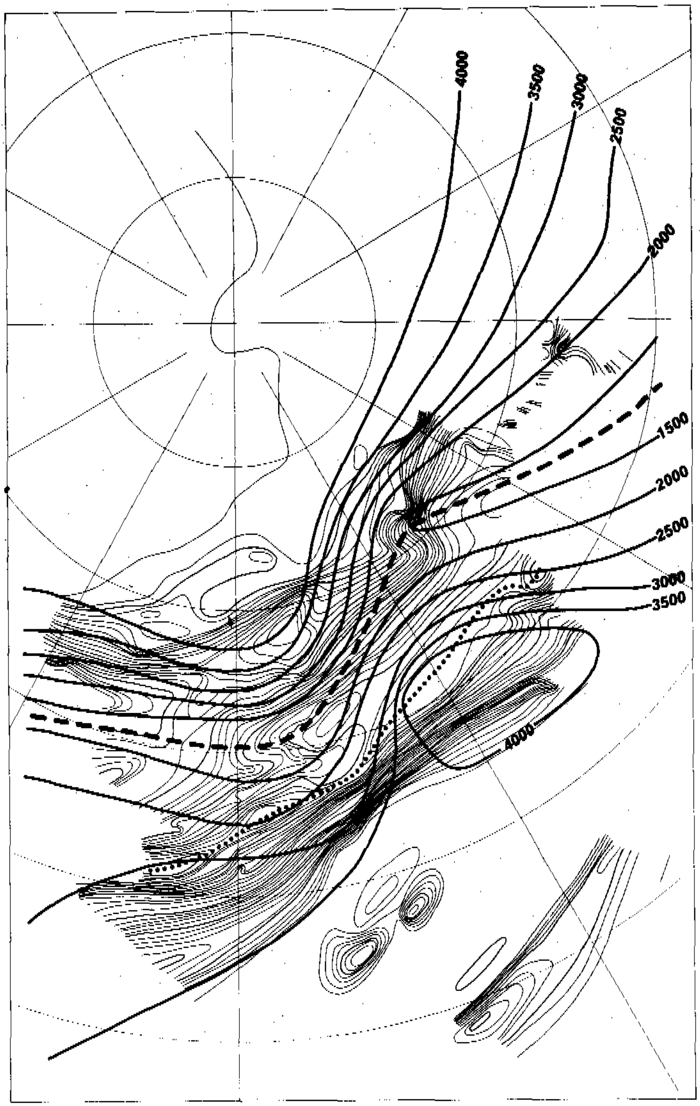


FIG. 16. LOREX 79 bathymetric map with Lomonosov Ridge crest (dotted line). Superimposed are the 500-m contour lines and ridge crest (broken line) of 1979 GEBCO chart.

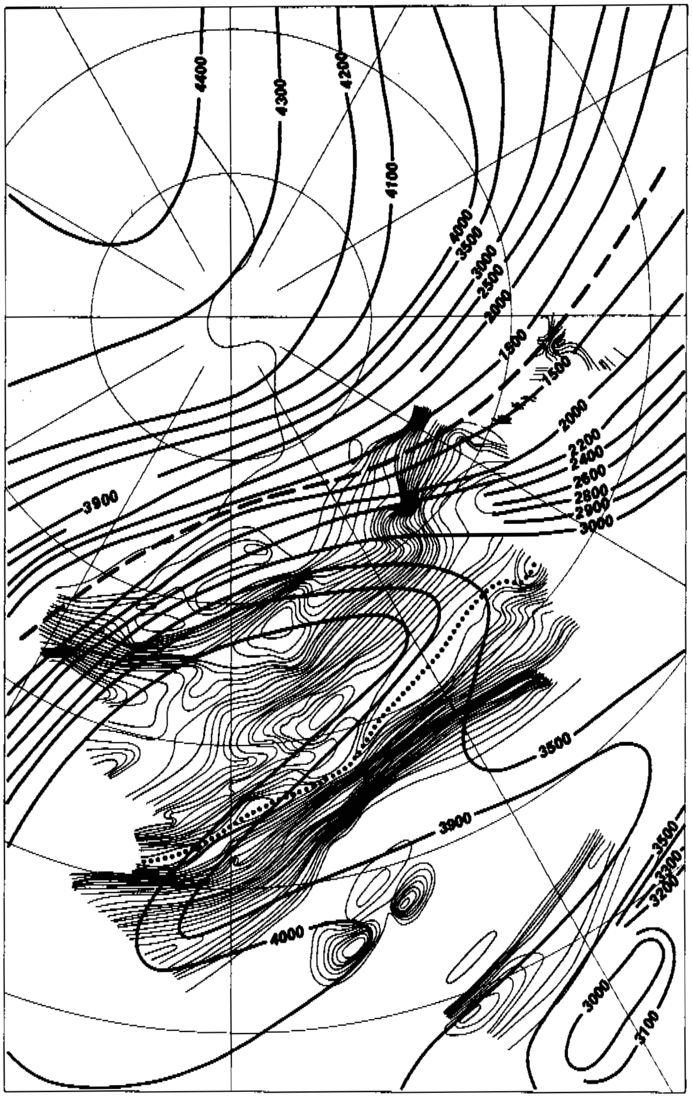


FIG. 17. LOREX 79 bathymetric map with Lomonosov Ridge crest (dotted line). Superimposed are the 500-m contour lines and ridge crest (broken line) of the 1975 Heezen and Tharp chart.

marine echogram profiles from Beal's thesis along these tracks are plotted against the LOREX 79 profiles (Fig. 19), it becomes obvious that the ship's inertial navigation system (SINS) was very inaccurate. Not only are three out of four profiles offset by as much as 40 km, but also, in the case of *Nautilus*, the ship's absolute speed must have been greater than assumed, giving the ridge the appearance of being narrower than it is. The depression in excess of 4000 m between meridians 130° and 160°W on the GEBCO map was a result of relying on the *Skate* and *Nautilus* tracks; the *Seadragon* track was ignored.

There is no reason to believe that the SINS of the submarine was more accurate elsewhere, and since many of the "blank" areas of the Arctic Ocean have been filled in, first by Heezen and Tharp and later by Sobczak, using Beal's submarine data, the bathymetry in these areas is suspect. It is the author's opinion that in areas where soundings are scarce, Ostenso's map and the DRB chart based on early Soviet data are still the most reliable maps to which the public has access.

There is no doubt that, with increasingly more sophisticated navigational aids, the U.S. and Soviet submarine fleets have gathered a wealth of accurate and detailed bathymetric data. However, as long as the two navies keep all of their bathymetric data secret, we shall continue to sound the Arctic Ocean slowly and expensively from the surface, duplicating the work that has already done from below.

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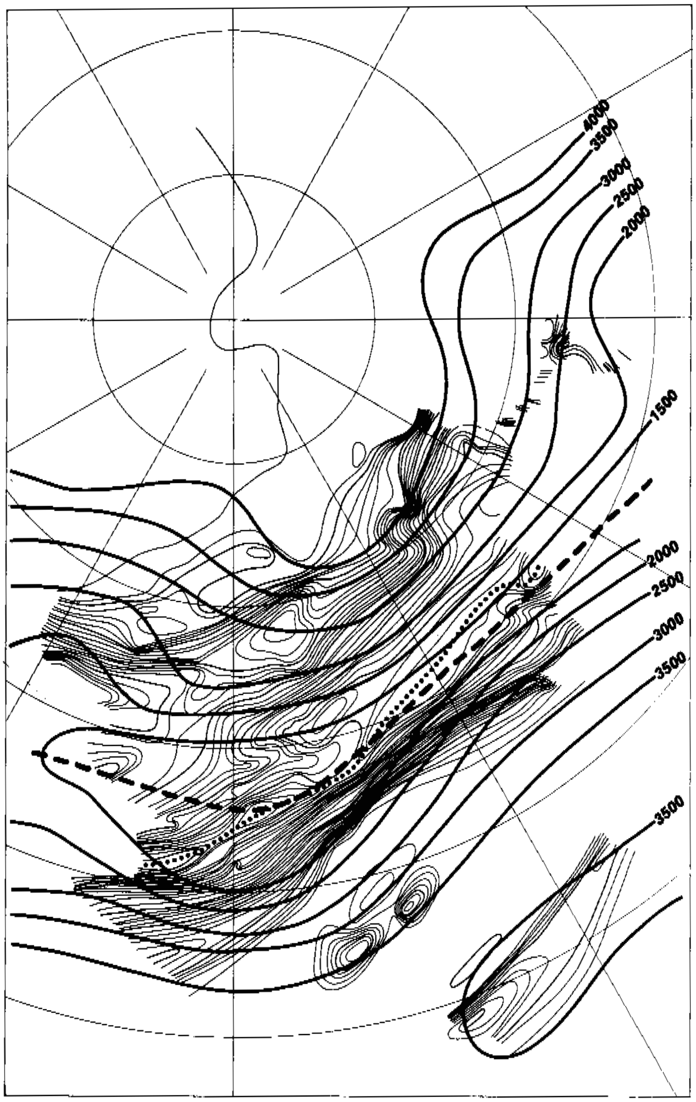

FIG. 18. LOREX 79 bathymetric map with Lomonosov Ridge crest (dotted line). Superimposed are the 500-m contour lines of the 1954 Soviet map.

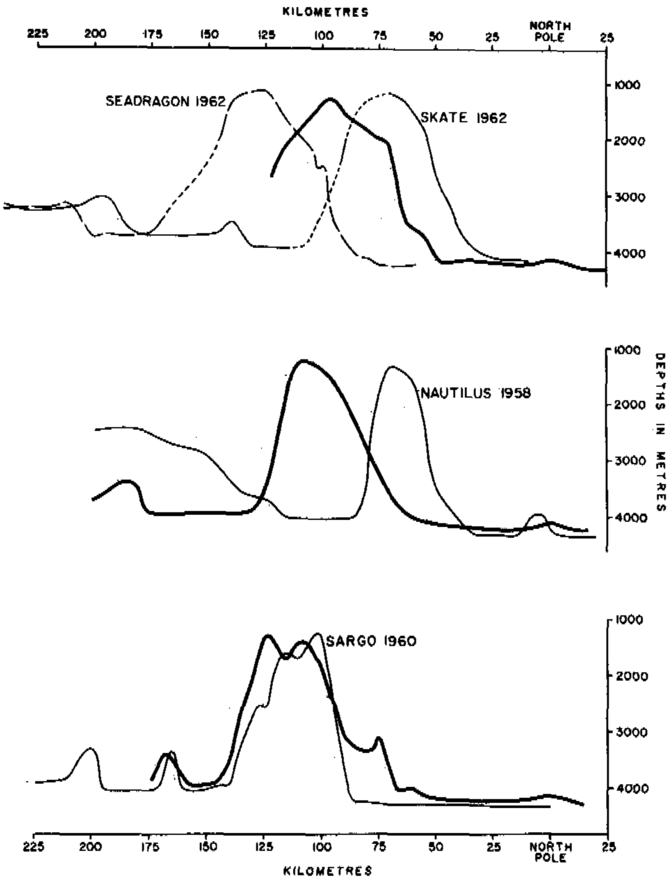

FIG. 19. Depth profiles of the submarine tracks of the *Seadragon* and *Skate* (1962), *Nautilus* (1958) and *Sargo* (1960) (cf. Fig. 15) superimposed on LOREX profiles (heavy line).

APPENDIX A

Methodology of the Early Soviet Hydrographic Surveys

Concurrently with the North Pole (NP) Series operation, the High Latitude Air Expeditions (HLAE) continued. Fuel and supplies were hauled to the NP stations and to the temporary HLAE base stations by Ilyushin IL-12 and Tupelov TU-4 aircraft (Laktionov and Shamont'ev, 1957). Two or three Antanov AN-2 aircraft stationed at the base camps were used for travel to the mainland. On the HLAE, scientists and technicians were divided into three groups: 1) a stationary unit that carried out continuous observations at the temporary base camp; 2) a hydrographic mobile unit; and 3) a geophysical mobile unit. Using LI-2 aircraft and flying in tandem, the mobile units typically established two or three stations at 150-200 km intervals before returning to base for refuelling. The hydrographic unit comprised a pilot and two hydrographers, and carried 600 kg of equipment consisting of:

Sled with gasoline engine driven winch, and 6000 m 1.2-mm diameter cable	150 kg
Bathythermographs and reversing thermometers	60 kg
Gravity corer	60 kg
Current meters	30 kg
Tent	40 kg
Manual ice auger, pick, shovel, ice net	40 kg
Explosives	50 kg
Containers for water samples	50 kg
Miscellaneous	120 kg

After selecting the ice floe and landing, the procedure for establishing a hydrographic station was as follows: measure ice thickness and blast hydro hole with explosives; unload equipment from aircraft; set up winch near hydro hole, erect tent over winch and hole, and heat tent with gasoline torches; measure depth and take gravity core; measure water temperature at standard depths and collect water samples. Astronomical station positioning, meteorological observations and snow and ice measurements were carried out at the same time by geophysicists from the second aircraft.

Observations sometimes included current measurements and at other times were limited to depth soundings and sediment sampling. Water samples were frozen and taken to the base station, and sediment samples were shipped to Leningrad for analysis. It took a maximum of 30 minutes to blast and clean out a hydro hole. A complete hydrographic station took six to eight hours, a sounding alone took three hours.

We know little of the equipment and duties of the geophysical units other than that the members of the units took astronomical and meteorological observations. Presumably they measured the force of gravity using a pendulum-type gravimeter, and observed the earth's magnetic field.

The pilots navigated by dead reckoning, by the sun and by making use of the powerful mainland- and ice-based radio beacons. Positioning of the mobile station must have been by sun and moon observation only, since viewing of stars in daylight requires a star catalogue for the particular area and time period, an impossible requirement in the pre-computer age. Depending on length of time the aircraft remained on the ground, rate of ice drift, latitude and sun angle, a position accuracy ranging between a few hundred metres and a few kilometres could be expected.

As of 1957 (Laktionov and Shamont'ev, 1957) depth was still measured by wire sounding, even at the NP stations, though experiments with echo sounders were in progress. It is surprising that the Russians were not using marine-type echo sounders, which had been in use for many years, and that they did not measure the depth at the mobile stations by the seismic method, since explosives were used for blasting the hydro holes.

The magnitude of the operations is illustrated by the fact that nearly 150 000 kg of cargo were airlifted to supply and maintain NP3 and NP4, and further that during 1954 a total distance of over one million kilometres was flown over the Arctic Ocean by all Soviet aircraft involved in these operations (Burkhanov, 1956). By way of comparison, some 230 000 kg of fuel, supplies and equipment were airlifted to the LOREX 79 camps and approximately 250 000 km were logged by all LOREX aircraft (Weber, 1979; Weber *et al.*, 1981).

The Soviet Aircraft Types

The *Ilyushin IL-12* is a twin-engine passenger and cargo aircraft with a range of 2000 km at a payload of 3000 kg. On fuel hauls to the ice station it was equipped as a tanker. The *IL-14* is a later, modified version of the *IL-12*. The *Tupelov TU-4* is a copy of the Boeing B-29 "Superfortress". The Soviet version of this four-engine aircraft was modified and widely used as civilian passenger and cargo aircraft. It has a range of 4000 km with accommodation for 72 passengers.

The *Antonov AN-2* is a large single-engine (1000 HP) biplane with STOL characteristics. Cruising at 200 km/h with a payload of 1240 kg, it has a range of 900 km. The minimum speed (40° flaps) is 64 km/h. Production started in 1950 and continued for some 20 years. It has been widely used in agriculture and surveying and as a cargo and passenger aircraft serving small settlements.

The *LI-2* is a Russian-built version of the twin-engine Douglas DC-3 aircraft.

APPENDIX B

List of Acronyms

AIDJEX	Arctic Ice Dynamics Joint Experiment (US, Canada)
DRB	Defence Research Board (Canada)
EMR	Department of Energy, Mines and Resources (Canada)
EUBEX	Eurasia Basin Experiment (US)
GEBCO	General Bathymetric Charts of the Oceans
GNS	Global Navigation System
HLAE	High Latitude Air Expeditions (USSR)
LOREX	Lomonosov Ridge Experiment (Canada)
MIZEX	Marginal Ice Zone Experiment (US)
ONR	Office of Naval Research (US)
PCSP	Polar Continental Shelf Project (Canada)
SINS	Ship's Inertial Navigation System
STD	Salinity, Temperature and Depth
VAI	Soviet All-Union Arctic Institute. After 1958 the Arctic and Antarctic Research Institute (USSR)

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