LOREX

CANADA
DEPARTMENT OF ENERGY, MINES AND RESOURCES

EARTH PHYSICS BRANCH

GEOMAGNETIC REPORT

No. 80-2

THE LOREX MAGNETIC GRADIENT AND TOTAL FIELD EXPERIMENT.

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ABSTRACT

During Operation Lorex 1979, manned ice camps drifted over the Lomonosov Ridge and the Makarov and Fram Basins in the Arctic Ocean. Magnetic sensors were operated at two of the camps. At each camp, one sensor was operated at the surface, while a second was suspended below the ice. In spite of instrumental and data recovery problems, the results indicate that the part of the ridge that was crossed has a strongly magnetic crust, between approximately 7 km and 17 km depth, that the strong magnetization extends, at depth, beyond the southern flank of the ridge, and that there are some shallower magnetic sources in the ridge which may be localized intrusions.

INTRODUCTION

In 1979, the Lomonosov Ridge Experiment (Lorex), a multi-disciplinary geophysical and oceanographic project, was conducted from the sea ice of the Arctic Ocean near the North Pole (Weber 1980). The main geophysical objective was to further the understanding of the nature of the Lomonosov Ridge and the adjacent basins. The actual field program lasted from March to June , 1979.

Among the geophysical experiments were several magnetic surveys. Magnetic induction and magnetotelluric surveys, making use of the time variations in the geomagnetic field to study the conductivity structure of the Lomonosov Ridge, were conducted (Camfield et al. 1980). Total field magnetometers were operated in gradiometer configurations at two of the manned camps as they drifted over the Ridge. In a related program, a series of airborne magnetometer survey lines were flown over the Ridge (Hood and Bower, 1980).

Previous studies of the Lomonosov Ridge have been summarized, for example, by Sweeney et al. 1978. Although when compared with the Alpha Ridge the magnetic anomaly signature of the Lomonosov Ridge was known to be subuded, high-level airborne surveys (King et al. 1966, Riddihough et al. 1973) had shown the existence of an anomaly "high" over the southern flank of the Lomonosov Ridge near the North Pole. As the LOREX plan was to drift over the Ridge near the Pole, it was considered useful to include the magnetic field sensors at the drifting ice camps in order to investigate more closely this, and perhaps other magnetic anomalies.

One of the major problems in magnetic surveying under such conditions is dealing with magnetic storms and substorms which often seriously degrade the crustal anomaly signal. There is little knowledge of the morphology of these disturbance fields in this region, and in any case the nearest fixed observatory is Alert, some 500 km away. One way of removing such effects can be by measuring the vertical gradient of the anomaly field with two sensors separated by a distance of a few hundred metres. In this arrangement, both sensors respond almost identically to time-varying fields from the ionosphere and magnetosphere but differ in their response to anomalies of crustal origin. A similar experiment under Arctic conditions was reported by Heirtzler (1967).

INSTRUMENTATION

The magnetic gradiometer system consisted of two proton precession magnetometers (PPM), sensors, electronic control unit, incremental cassette tape recorder, strip chart recorder, power supply, and storage batteries. One PPM sensor was mounted on a wooden tripod 1m above the sea-ice; the second PPM sensor was suspended below the ice from a shielded twin-conductor (18 ga. copper) cable through a hole adjacent to the surface PPM. The bottom sensor was intended to be about 300 m below the surface, although as described later this was not possible. The electronics and other components of the system were housed in a building 80 m from the surface sensor.

The bottom sensor consisted of a toroidal coil of 18 ga. copper wire mounted in a spherical fibreglass shell (diameter 25 cm), with naphtha as the proton-rich fluid. The shell consisted of two flanged hemispheres, bolted together, the lower one having a tail extension for pressure equalization. An underwater cable-connector linked the sensor to the main underwater cable. The surface sensor was a standard PPM two-bottle AMOS-type sensor, again using naphtha.

The gradiometer system is summarized in block form in Fig. 1. The two PPMs were EDA Model PM 101 magnetometers. The PPM sensors were polarized from a pile of ten snowmobile batteries, providing 120 volts D.C. To avoid damage to relay contacts in the PPM units, a power transistor switch was used to activate the polarizing current through each sensor. The clock-driven microprocessor controlled the switching of the PPMs and of the transistor switch. The timing sequence is shown in Fig. 2. Outputs from the PPMs were sent to the microprocessor which formatted the information and wrote it on the cassette tape recorder. The microprocessor also computed the difference between the signals from the surface and underwater sensors. This difference and the signal from the surface sensor were fed via a D//A convertor to the strip chart recorder.

The 120 volt battery pile was trickle-charged from the rectified 120 volt station generator supply. The PPMs and chart recorder operated directly from the generator supply. Regulated 12 volt supplies from the PPMs powered the cassette recorder and trickle-charged the battery powering the clock and microprocessor.

The system provided magnetic field measurements at 10 minute intervals, except during instrument down time and generator maintenance. The battery internal to the clock assured time continuity during the latter.

NAVIGATION

Three manned ice-camps were operated during the LOREX project, a main camp and two "satellite" camps (Weber 1980). Magnetic gradiometer systems were installed at the two "satellite" camps, SNOWSNAKE and ICEMAN. Position information for the camps was derived from SATNAV satellite navigation systems (Wells and Popelar, 1979). The final accuracy of positions for individual gradiometer data values is 1 km or better.

PROBLEMS IN OPERATION

As noted earlier, the original intention had been to operate the bottom sensors at about 300 m below the surface. However, at the time of installation, it was impossible to obtain a satisfactory signal from the bottom sensors (even when operated at the surface), as a result of the signal degradation caused by the long cable. By shortening the cable and adjusting the tuning of the magnetometer, it was possible to obtain a signal that appeared satisfactory from the bottom sensor at SNOWSNAKE. Although a similar procedure at ICEMAN produced an apparently satisfactory signal, subsequent data processing showed that the signal was in fact faulty.

Therefore, the gradiometer at SNOWSNAKE was operational from April 17 to May 20, but with a sensor separation of only 137 m, whereas at ICEMAN only the surface sensor was operational, from April 24 to May 26.

SNOWSNAKE began its drift in the Makarov Basin, passed over the Lomonosov Ridge and travelled over the northern flank of the ridge. The ICEMAN sensors could not be installed until the camp was moving away from the ridge and out over the Fram basin.

Magnetic storm conditions occurred for several days beginning April 24.

DATA PROCESSING

The data were transcribed from the original cassettes to 7-track, and subsequently 9-track, magnetic tape. A series of clean-up and editing procedures were carried out to remove or correct bad or faulty data values. Plots of magnetic anomaly field and gradient versus time were produced as part of these procedures. The edited magnetic data were merged with position data.

TOTAL MAGNETIC FIELD RESULTS

Plots of the total field anomalies, relative to the International Geomagnetic Reference Field (IGRF) are shown in Fig. 3, along with an indication of the bathymetry (Weber 1980), and also one profile of total field residuals relative to IGRF obtained from the high-level three-component airborne magnetometer survey in 1970 (Haines and Hannaford 1974, Riddihough et al. 1973). The LOREX profiles are severely biassed negatively, as a result of the inadequacy of the IGRF in this region at this time.

A distinct anomaly "high" of about +400 nT amplitude is found in the SNOWSNAKE data over the southern flank of the ridge, as was suggested from the 1970 airborne data. A second anomaly high occurs on the northern flank where the bathymetry indicates a localized high, above 1600 m. Near the end of the SNOWSNAKE track, a magnetic high is associated with a narrow section of decreased bathymetric depth (1700 m).

Total field data along the SNOWSNAKE track in the Makarov Basin and along the ICEMAN track in the Fram Basin show no distinct magnetic anomalies of likely crustal origin. In fact, the shorter wavelength variations cannot be reliable measures of crustal anomalies, because of disturbance fields. The short-wavelength 'anomalies' seen at the southern foot of the Lomonosov Ridge on the SNOWSNAKE track, and at the ridge end of the ICEMAN track, are caused by magnetic storm disturbances, which correlate well between the two data sets, and which were also monitored at Alert. The magnetograms from Alert show that the geomagnetic field activity during April and May, 1979, varied from quiet to highly disturbed, with most of the time being unsettled (having variations of many tens of nanotesla over periods of several hours).

MAGNETIC GRADIOMETER RESULTS

After screening and editing the data to remove spikes and other known bad data points, the gradiometer data, i.e. the difference between bottom and surface sensors, from SNOWSNAKE were plotted as a function of time. The data contained short period (less than 2 hours, mainly) noise with amplitudes of the order of 1 nanotesla. This noise almost completely obscured any longer period signals which might be related to crustal sources.

To remove this noise, the data were filtered using a Butterworth filter with -6db cutoff at 4 hour period. Longer-period variations then became apparent, particularly a prominent periodicity near 5 hours. This filtered data set is shown in Fig. 4. A region of high gradient anomalies occurred over the northern flank of the ridge. The 5-hour periodicity occurs throughout the data set. The normal total-field vertical gradient produces a difference between bottom and surface sensors of 3.5 nT; this regionally constant difference has been removed from the data shown in Fig. 4.

The periodicity of about 5 hours is puzzling, and certainly is not of crustal origin. The data were filtered with a -6db cutoff at 8 hours. The result is shown in Fig. 5. As expected, the 5-hour effect was removed, but the possible presence of longer-period non-crustal phenomena cannot be ruled out. A change in the gradient is found over the southern flank of the ridge. A strong positive gradient occurs near a localized bathymetric high on top of the ridge, and other strong positive gradients are found on the northern flank of the ridge.

The gradient data, considered simply as a time series, were subjected to spectral analyses, using the maximum entropy method. Some results are shown in Fig. 6, for subsets corresponding to the Makarov Basin, Lomonosov Ridge, and Fram Basin/northern ridge flank sections.

The spectra show effects resulting from external time-varying disturbance fields, from crustal anomalies as the sensors drift over then, and from extraneous undefined sources possibly related to the equipment or experimental arrangement. All the spectral plots show a peak near 5 hours period, as expected from the spatial plots of the data. Any peaks at longer periods are not resolved.

A striking feature in the spectral plots of Fig. 6 is the prominent peak at about 0.77 hr^{-1} (about 1.3 hr period). This is not seen in the filtered plots, of course, but is definitely a persistent effect in all but the early data over the Makarov Basin. Its amplitude increases with time, as the station drifts from the Makarov Basin and over the Ridge. Its cause is unknown. Other less correlatable peaks in the plots are also of unknown origin.

INTERPRETATION

No satisfactory explanation has been found for the 5-hour periodicity, whose peak-to-peak amplitude is of the order of the gradients of crustal origin and is essentially the same as the regional normal field gradient. Attempted explanations in terms of bottom sensor movement (such as was experienced by Heirtzler (1967)), or of variations in electronic components, or of external field variations, have been unsuccessful. Explanations in terms of tidal currents have not been able to account for the 5-hour periodicity or the amplitude of the field variation. Further, because of this uncertainty, the longer period variations must be suspect. The large amplitude anomalies on the northern flank of the ridge occurred at a time when high bottom-water currents were recorded on a flow-meter in that region, deployed by Dr. Knut Aagaard (personal communication 1979). In view of the general uncertainty about other parts of the gradiometer signal, this possibly correlated phenomenon casts doubt on these large gradient anomalies. An examination of the characteristics of the data during the period Day 126 through Day 135 suggests that one or both of the PPMs may not have been functioning in a reliable manner. Many small spikes appeared in the difference signal, and although these were screened out, broader but abrupt changes in level were not. The data shown in Figs. 4 and 5 are filtered data and so these sudden changes become smoothed out. It may be that as the sensors drifted through the broad regional changes in the earth's main field, the limits of the tuning range of the PPMs were being approached, causing spurious values.

A further complication arose when the Alert magnetograms were examined. Apart from the full magnetic storm on Day 115, April 25, the external field was for the most part relatively quiet. However, in this polar cap region, the external magnetic field is influenced by charged particle precipitation events (J.C. Gupta, G. Jansen van Beek, personal communications 1980) which can result in abrupt changes in field level. Such a level change, of about 160 nT, occurred between 1800 UT and 1900 UT on Day 125. This seriously distorts the total field and in effect renders virtually impossible a quantitative interpretation of the total field anomaly which appears to be present in that part of the Lorex SNOWSNAKE track. Qualitatively, one can say that in this plateau-like part of the northern flank of the ridge there is a shallow source (judging from the gradient signal, if reliable) that is highly magnetic, according to the total field anomaly of about 300 nT, albeit distorted by the external field effect. Another major level change, greater than 200 nT, was observed at Alert on Day 128; again, its quantitative effect on the Lorex data is unclear.

In spite of these difficulties, a general model for the main Lomonosov Ridge can be produced, as shown in Fig. 7. Data from the section of the SNOWSNAKE drift track which was approximately normal to the ridge were projected onto a profile normal to the ridge. Also shown is the 1970 airborne total field data, again projected onto the normal profile. The sharp peaks between -5 km and 0 km in the Lorex data result from a small bathymetric high on the ridge which appears to be a shallow magnetic source. The shape of the main anomaly calls for a magnetic source which extends, at depth, several kilometres south of the ridge flank. The depths to top and bottom of the source body were chosen on the basis of constraints from the gravity (Weber 1980) and seismic (Mair 1980) models.

The difference field (dashed line) shown in Fig. 7 was derived from the section of data approximately normal to the ridge, shown in Fig. 5. Data north of the 0 km point in Fig. 7 was unreliable for reasons noted earlier. The observed variations were modelled by the small-scale relief on the top of the source body. The basic uncertainties in the data did not warrant further attempts to refine the fit.

CONCLUSIONS

1. As a result of the many problems noted earlier, the information return from this experiment has been disappointing. However, a general magnetic model for the Lomonosov Ridge in the region surveyed has been produced. It shows a highly magnetic (susceptibility 0.06 SI) crust between about 7 km and 17 km depth beneath the ridgee. Such a model is consistent with a continental crust of dioritic nature (Coles and Currie, 1977, Fig. 4) of typical density 2800 kg m^{-3}, as chosen for the gravity model (Weber 1980).

2. Problems in experimental arrangements caused primarily by the use of non-optimum underwater cable (a matter of expense) should be resolved before any similar experiment is performed in the future. The equipment should be tested as a complete system before it is shipped to the field.
3. Bearing in mind the problems experienced, it is difficult to assess the value of such an experiment. However, if the instrumentation/cable problems had been resolved, and the observed periodicities accounted for, the difference signal (i.e. gradiometer signal) should have been able to resolve some structural details on the ridge.

ACKNOWLEDGEMENTS

The work of several colleagues contributing to this project is gratefully acknowledged. W. Hannaford, D. Trigg, and R. Charbonneau designed and assembled the system in the laboratory. P.A. Camfield, M.J. Drury, R.D. Kurtz, and E.R. Niblett installed and retrieved the systems at the LOREX camps. M. Lowings and B. Allan supervised the instruments at SNOWSNAKE and ICEMAN, respectively.

These and other colleagues are thanked for many discussions regarding the problems and the interpretations.

REFERENCES

Camfield, P.A., Kurtz, R.D., Drury, M.J., and Niblett, E.R. 1980. Magnetovariational and magnetotelluric studies over the Lomonosov Ridge and the Makarov and Fram Basins of the Arctic Ocean: Operation Lorex. (abstract). EOS Trans. Am. Geophys. U., 61, 277.

Coles, R.L., and Currie, R.G. 1977. Magnetic anomalies and rock magnetizations in the southern Coast Mountains, British Columbia: possible relation to subduction. Can. J. Earth Sci., 14, 1753-1770.

Haines, G.V., and Hannaford, W. 1974. A three-component aeromagnetic survey of the Canadian Arctic. Pub. Earth Phys. Br. 44, 209-228.

Heirtzler, J.R. 1967. Measurements of the vertical geomagnetic field gradient beneath the surface of the Arctic Oceean. Geophys. Prospect., 15, 194-203.

Hood, P.J., and Bower, M.E. 1980. Aeromagnetic reconnaissance: Lorex Project. (abstract) EOS Trans. Am. Geophys. U., 61, 277.

King, E.R., Zeitz, I., and Alldredge, L.R. 1966. Magnetic data on the structure of the central Arctic region. Geol. Soc. Am. Bull. 77, 619-646.

Mair, J.A. 1980. Structure of the Arctic Ocean. (abstract) EOS Trans. Am. Geophys. U., 61, 276.

Riddihough, R.P., Haines, G.V., and Hannaford, W. 1973. Regional magnetic anomalies of the Canadian Arctic. Can. J. Earth Sci. 10, 147-163.

Sweeney, J.F., Coles, R.L., DeLaurier, J.M., Forsyth, D.A., Irving, E., Judge, A.S., Sobczak, L.W., and Wetmiller, R.J. 1978. Arctic geophysical review - a summary. Pub. Earth Phys. Br., 45, 101-108.

Weber, J.R. 1980. Exploring the Arctic seafloor. Energy Mines and Resources Canada, GEOS, Summer 1980, 2-7.

Wells, D., and Popelar, J. 1979. Preliminary satellite navigation results on LOREX-79, 22p. unpublished.

FIGURE CAPTIONS

Fig. 1. Block diagram of instrumentation.

Fig. 2. Timing sequence of PPM operations.

Fig. 3. Total field anomaly profiles for SNOWSNAKE and ICEMAN. Bathymetry is in metres. Days are marked along the profiles.

Fig. 4. Difference field from SNOWSNAKE (lower PPM2 - upper PPM1), filtered with cutoff at 4 hours.

Fig. 5. Difference field from SNOWSNAKE, filtered with cutoff at 8 hours.

Fig. 6. Maximum entropy method spectral analyses for various subsets of the unfiltered SNOWSNAKE difference field data. The power scale is linear, but with baselines for the spectral curves offset to avoid overlaps.

Fig. 7. A suggested magnetic source within the crust below the Lomonosov Ridge. The model total field and gradiometer difference field (solid lines) are compared with the SNOWSNAKE data (dashed lines) and 1970 airborne data (dot-dash line). The location of the profile AA' is shown in Fig. 3.

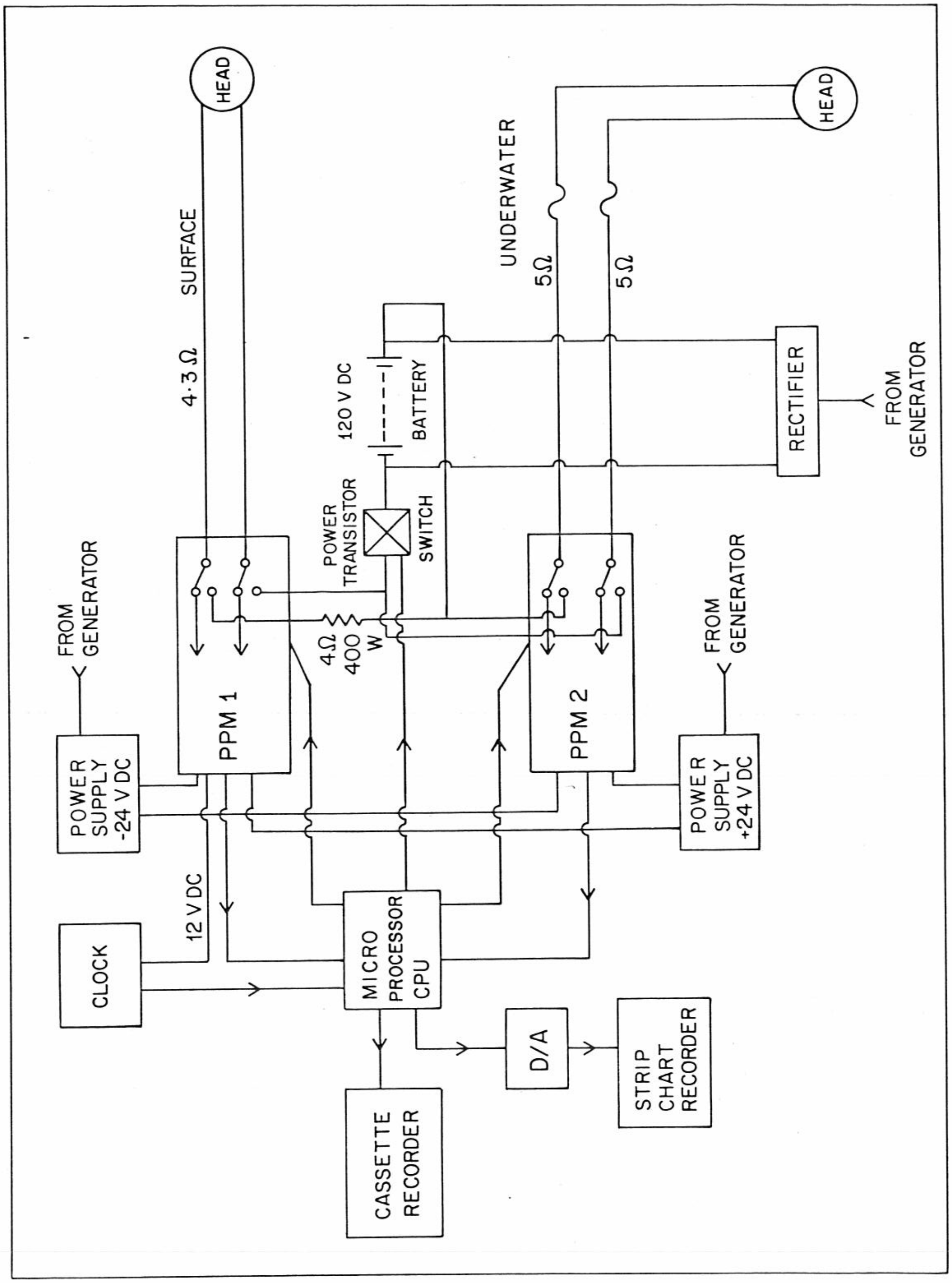

HEAD
SURFACE
4·3 Ω
HEAD
UNDERWATER
5Ω
5Ω
120 V DC
BATTERY
RECTIFIER
FROM GENERATOR
POWER TRANSISTOR
SWITCH
4Ω 400 W
FROM GENERATOR
PPM 1
PPM 2
FROM GENERATOR
POWER SUPPLY -24 V DC
POWER SUPPLY +24 V DC
CLOCK
12 V DC
MICRO PROCESSOR CPU
D/A
STRIP CHART RECORDER
CASSETTE RECORDER

Fig. 1

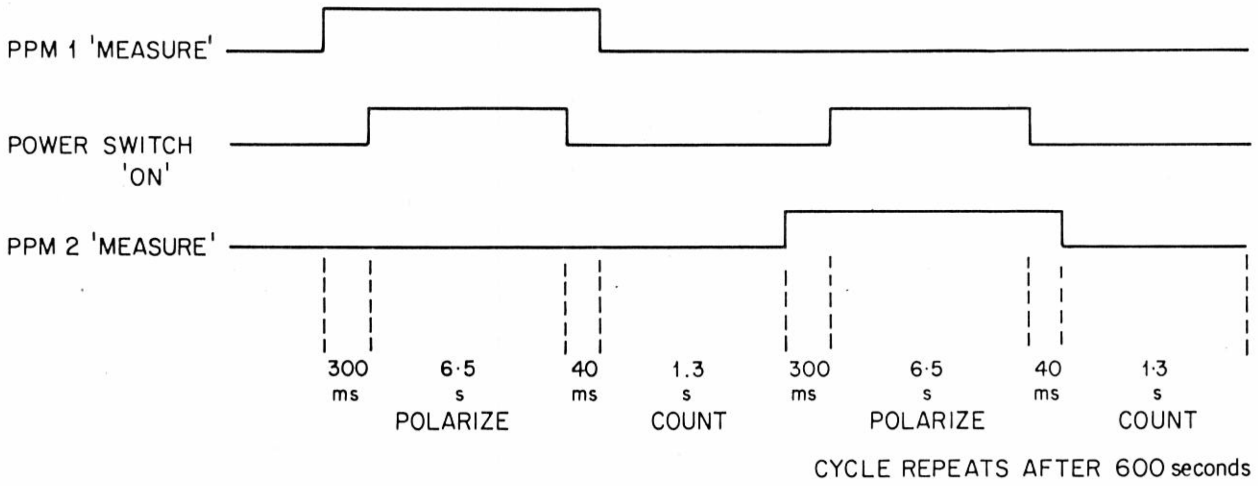
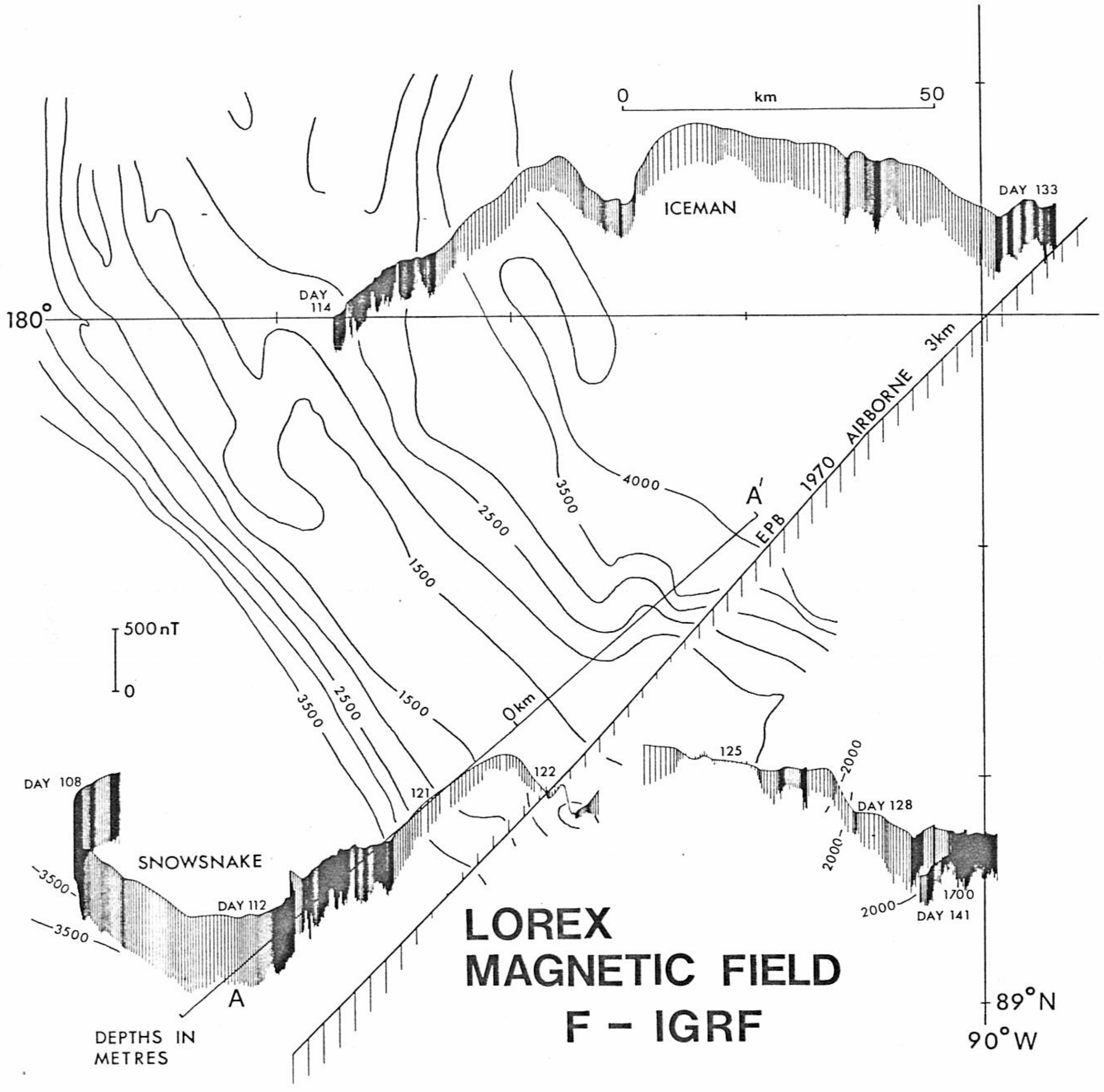

PPM 1 'MEASURE'
POWER SWITCH 'ON'
PPM 2 'MEASURE'
300 ms
6·5 s POLARIZE
40 ms
1.3 s COUNT
300 ms
6·5 s POLARIZE
40 ms
1·3 s COUNT
CYCLE REPEATS AFTER 600 seconds

Fig.2



LOREX MAGNETIC FIELD F - IGRF

Fig. 3

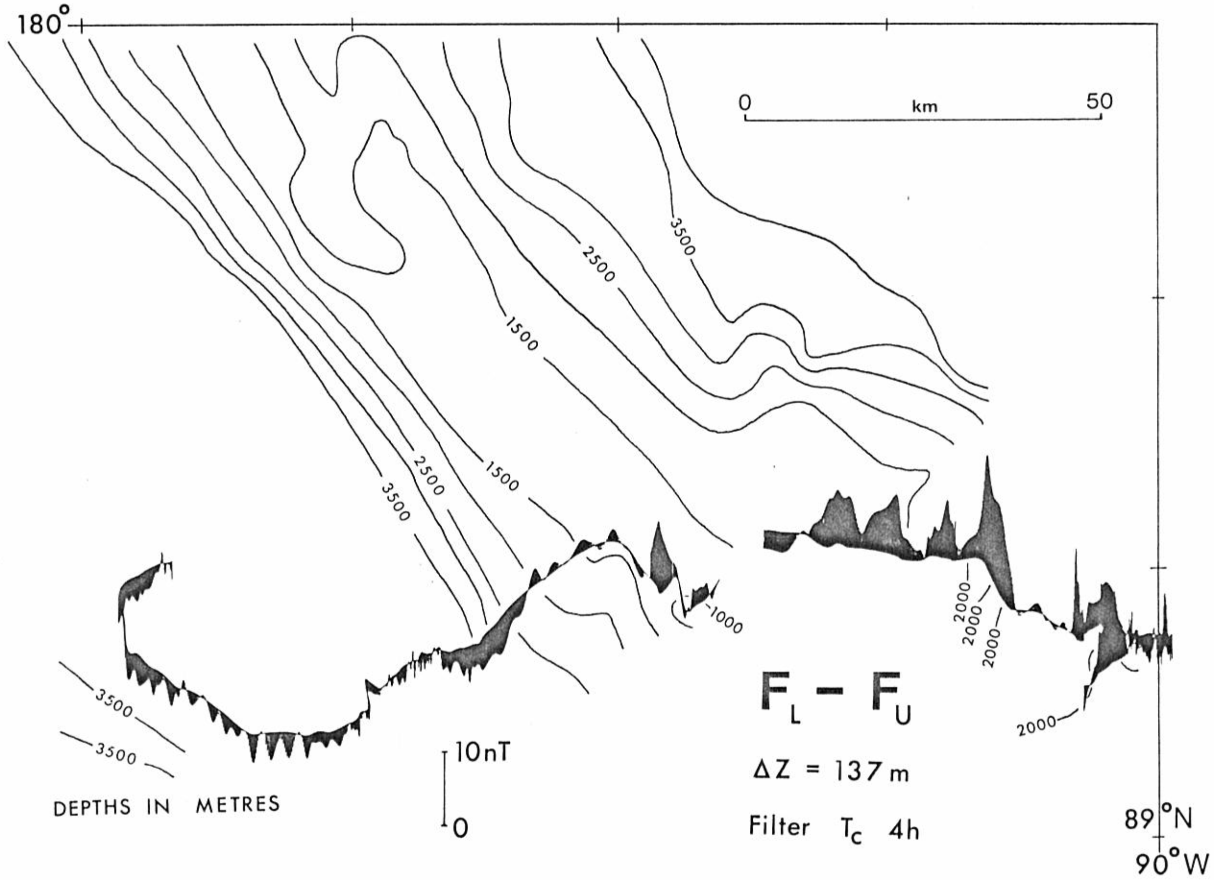
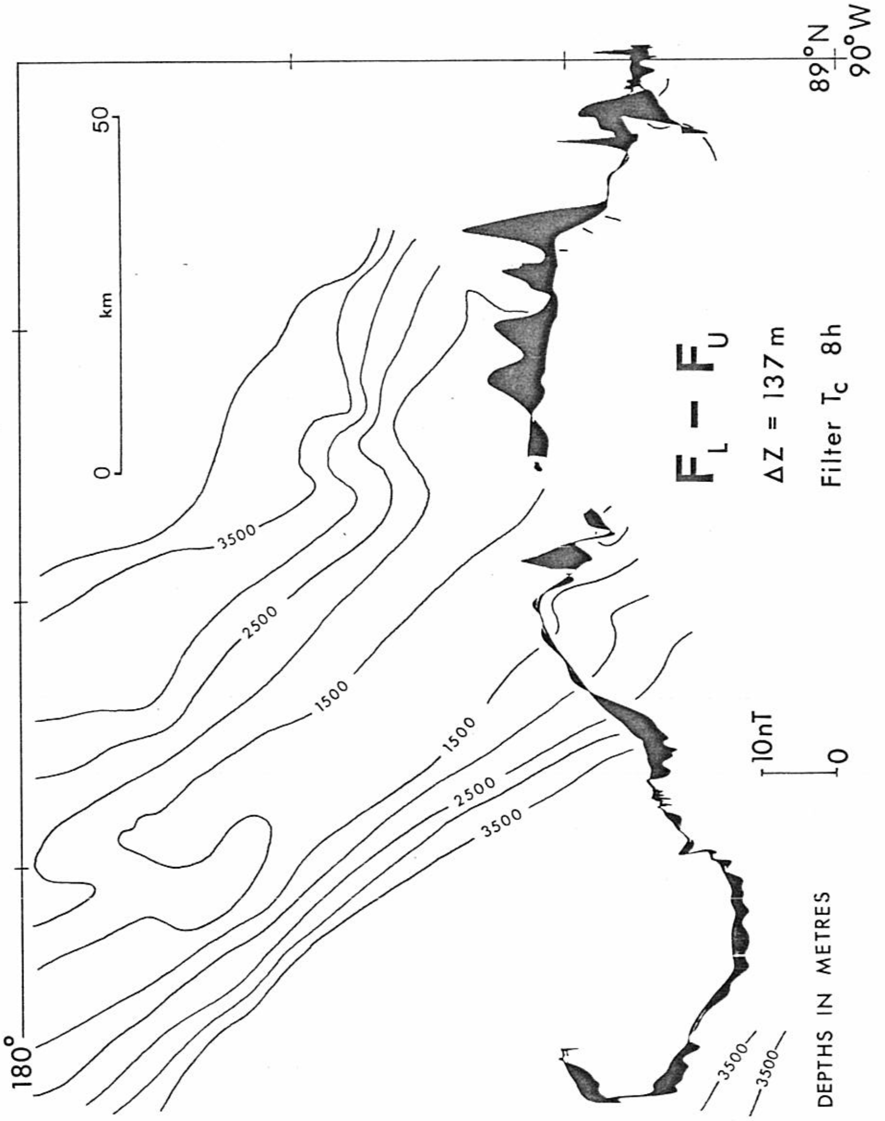

180°
0 km 50
3500
2500
1500
1500
2500
3500
1000
2000
2000
2000
2000
3500
3500
DEPTHS IN METRES
10nT
0
$F_L - F_U$
$\Delta Z = 137$ m
Filter T_c 4h
89°N
90°W

Fig. 4


180°
89°N
90°W
0
50
km
3500
2500
1500
1500
2500
3500
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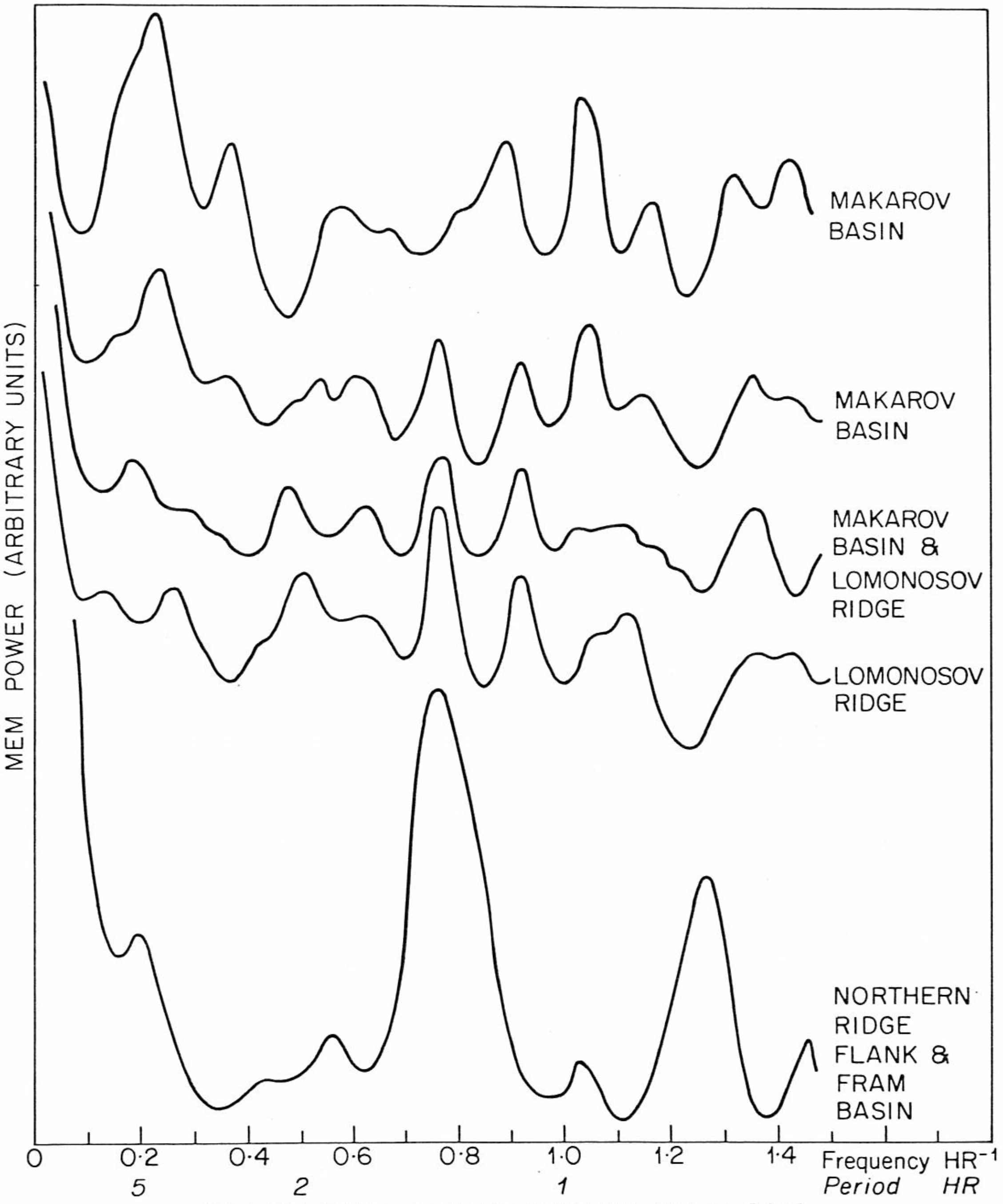
3500
10nT
0
DEPTHS IN METRES
F_L − F_U
ΔZ = 137 m
Filter T_c 8h

Fig. 5



MEM SPECTRAL ANALYSES OF GRADIENT DATA

Fig. 6

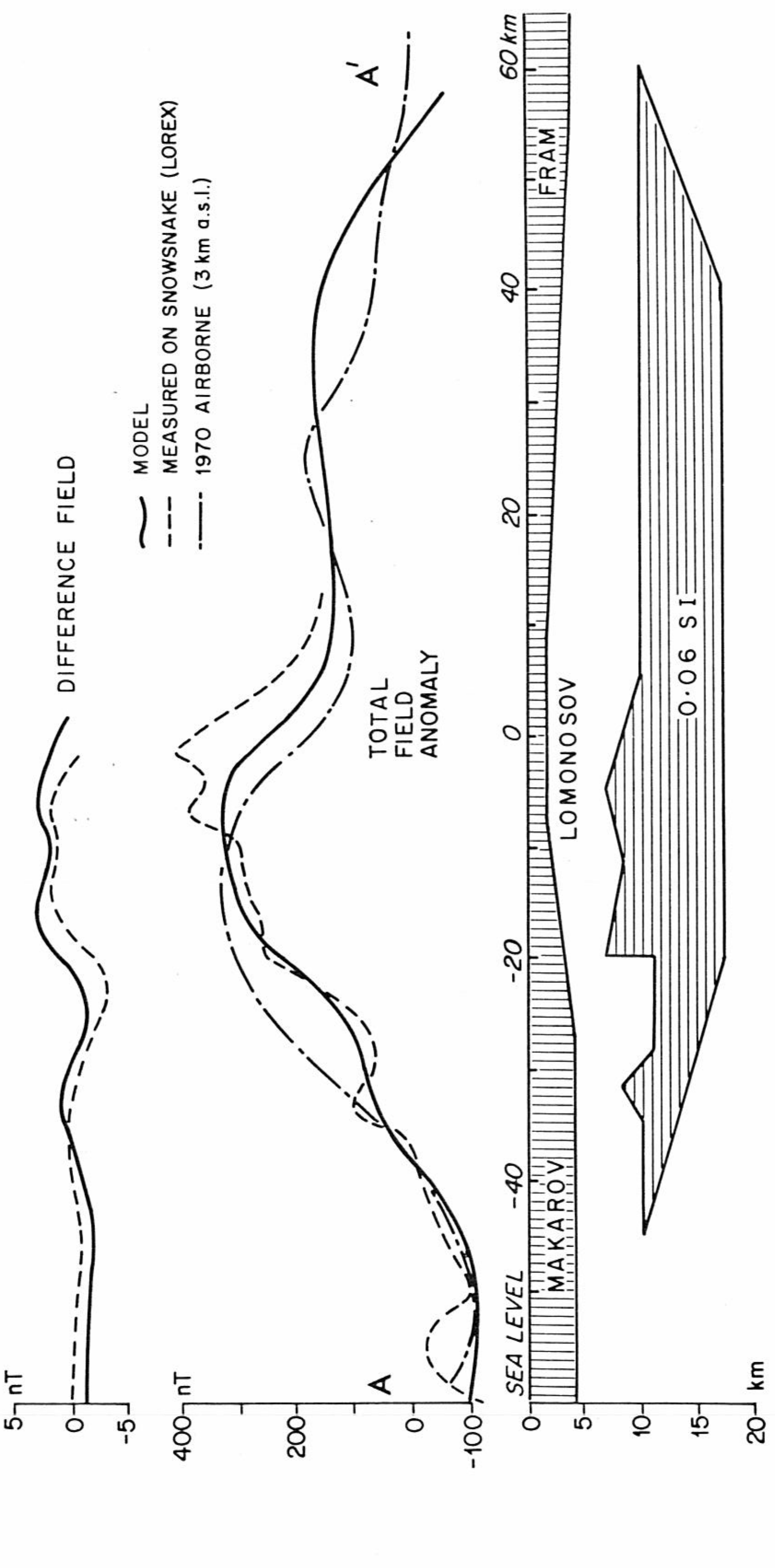

DIFFERENCE FIELD
MODEL
MEASURED ON SNOWSNAKE (LOREX)
1970 AIRBORNE (3 km a.s.l.)
TOTAL FIELD ANOMALY
A
A'
5 nT
0
-5
400 nT
200
0
-100
SEA LEVEL
0
5
10
15
20 km
MAKAROV
LOMONOSOV
FRAM
0·06 SI
-40
-20
0
20
40
60 km

Fig. 7

LOREX Logistics

A scientific program as extensive as LOREX requires a long lead time to arrange the complicated provisioning, equipping, and support facilities. Logistics for Arctic activities such as LOREX are planned by the Polar Continental Shelf Project (PCSP), a branch of the Department of Energy, Mines and Resources.

The first shipment of LOREX fuel, 450 drums of turbo fuel, was airlifted early in November 1978 from a staging base at Thule, Greenland to Alert on northern Ellesmere Island, 800 kilometres from the North Pole.

Supplies are shipped to three main northern supply bases including Thule, Greenland, Canadian Forces Base Alert, and the PCSP Eastern Arctic base at Resolute on Cornwallis Island. The material is fed through these sites to the LOREX site, named Ocean Camp.

A variety of aircraft will have roles in the LOREX project. Two Twin Otters will be used in the search for a suitable location to establish the LOREX camp. One Twin Otter will be retained for transportation throughout the project. The Canadian Armed Forces is providing one of its Hercules freighters to move the heavy equipment onto the ice. Another aircraft, a Bell 205-A helicopter, will have a major role during the scientific programs.

Included in the equipment the Hercules will move onto the sea ice will be almost 11,000 kilograms (about 24,000 lbs.) of explosives for use in the seismic tests, more than 700 drums of fuel, Parcoll arctic tents, prefabricated buildings and a loader.

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The Lomonosov Ridge

The Lomonosov Ridge is a major submarine mountain range thrusting up from the depths of the Arctic Ocean. It extends from the Canadian polar continental shelf off the northern extremity of Ellesmere Island for 1,700 kilometres toward the New Siberian Islands, passing close to the geographical North Pole. The ridge bisects the Arctic basin into two sub basins: the Eurasia Basin on the European side of the ridge, and the Amerasia Basin on the North American side.

In addition, the Lomonosov Ridge, the most prominent of the sea floor features, is flanked by two other mountain ridges. One, the Nansen-Gakkel Cordillera, lies in the Eurasia Basin, while the other, the Alpha-Mendeleev Cordillera, lies in the Amerasia Basin. Both are almost parallel to the Lomonosov Ridge.

The Lomonosov Ridge has an average height above the sea floor of more than 3,000 metres. It varies in width from 64 to almost 200 kilometres. Its crest ranges in depth below sea level between 950 and 1,650 metres. Discovered in 1948-49 by a team of Soviet scientists, and made public in 1954, the ridge was named after the 18th century Russian scientist-poet-grammarian Mikhail Vasilyevich Lomonosov.

North Pole

The North Pole is the geographical position on Earth where all directions but south disappear. From it, one looks south toward Canada, Russia, Greenland and Alaska. The North Pole has neither length nor width. It is 90 degrees north latitude and zero degrees longitude. It is a mathematical position at which the imaginary line of Earth's axis intersects Earth's surface.

At the North Pole, the star Polaris, more commonly referred to as the Pole Star or the North Star, is directly overhead.

Since 1500 when Europeans first sought the Northwest Passage, explorers have been determined to reach the North Pole. Early sailing ship masters thought they could sail to the North Pole. Their hopes were dashed when they encountered the solid year-round ice pack that is constantly in motion. Massive ice floes grind against each other in the polar sea, pushing up jagged ranges of ice, then breaking apart leaving "leads" of open water before closing again.

American Robert E. Peary was credited with being the first to reach the North Pole in 1909, although controversy surrounds the claim. Another Arctic traveller, Dr. Frederick A. Cook, said he had reached the Pole a year earlier. However, a council of scientists which examined both accounts discredited Cook's report and accepted Peary's.

"Modern" technology took over in 1926 when Richard E. Byrd of the United States left Spitzbergen in a Fokker Trimotor aircraft and later reported he flew over the Pole. Recent critics, though, doubt the ability of that aircraft to make the trip successfully.

An Italian officer, Umberto Nobile, piloting the semi-rigid airship "Norge" on an expedition headed by Norwegian Roald Amundsen, passed over the Pole in a 70-hour trip from Spitzbergen to Alaska. It was just three days after Byrd's voyage in 1926.

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Mikhail Vasilyevich Lomonosov

A poet, grammarian, educator and designer of colored glass mosaics hardly seems the type of person after whom a huge international submarine mountain range would be named. Mikhail Vasilyevich Lomonosov, after whom the Lomonosov Ridge is named, was born of peasant stock near the northern Russian community of Archangel in 1711. He died in 1765, respected for his literary accomplishments, but ridiculed by critics for his views on science and education.

Despite his family's poverty, the young Lomonosov managed to attend an academy in Moscow. A brilliant student, he continued his studies in St. Petersburg and in Germany.

In 1741 Lomonosov took a position at the St. Petersburg Academy. By now a number of critics differed with his views of basic scientific thought. Lomonosov had a bad temper and great strength, a combination that landed him in jail in 1743. Undaunted, he not only continued his scientific writing, but also wrote two odes which he dedicated to the Russian empress, Elizabeth. Intrigued with the poems, she had him released.

He was appointed a professor at the St. Petersburg Academy in 1745, and from then his production of scientific works was prodigious. He wrote on the causes of heat and cold, the elastic force of air, and the theory of electricity. Granted a laboratory, he defied growing criticism and in three years recorded 4,000 experiments. One of his greatest efforts was the design and direction of construction of Moscow University.