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Maps of the Arctic Basin Sea Floor Part II: Bathymetry and Gravity of the Alpha Ridge: The 1983 CESAR Expedition[1]

J.R. WEBER[2]

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ABSTRACT. The general scarcity of geophysical data in the Arctic Ocean Basin and the lack of knowledge about the evolution of the Amerasia Basin and of the nature and origin of the Alpha Ridge led, in 1983, to the undertaking of a multidisciplinary polar expedition, code-named CESAR 83 for *C*anadian *E*xpedition to *S*tudy the *A*lpha *R*idge. The expedition was supported by the Canadian Armed Forces, first by parachuting 18 airborne engineers onto the CESAR site to build a 1.6 km long airstrip on the pack ice, and then by deploying and two months later evacuating the expedition by military Hercules aircraft. The search for a suitable site on the sea ice was facilitated by a preceding side-looking airborne radar (SLAR) reconnaissance survey of the area.

One of the major CESAR accomplishments was a regional bathymetric and gravity survey over the Ellesmere Island continental shelf and eastern part of the Alpha Ridge. Using the CESAR data as well as all publicly available data collected over the past 35 years, 100 m contour interval bathymetric maps and 5 mGal contour interval gravity free-air anomaly maps were compiled. These extend from the Ellesmere Island coast to the 116°W meridian. The sea floor maps depict the Alpha Ridge as a very broad mountain complex of rugged topography with ridges and valleys trending parallel to the ridge axis. A prominent east-southeast trending valley centered along 86°N latitude between 110° and 125°W longitude was named Cesar Trough and the adjoining ridges Cesar North Ridge and Cesar South Ridge. The Alpha Ridge is separated from the Ellesmere Island continental shelf by a trough 1800-2000 m deep. Over the ridge the free-air anomalies mirror the bathymetry. Elliptically shaped positive anomalies centered over the continental shelf break suggest that the continental margin adjacent to the Alpha Ridge has the typical Atlantic-type structure characteristic of the rest of the North American polar margin. Preliminary interpretation of the gravity field indicates that the Alpha Ridge crust is composed of very thick rocks of laterally uniform density and composition. It is suggested that the eastern part of the Alpha Ridge may be a massive accumulation of mafic rocks of probable oceanic origin formed by volcanic activity.

This article is identified as Part II of a series on "Maps of the Arctic Basin Sea Floor" and is preceded by "A History of Bathymetry and its Interpretation" (Weber, 1983).

Key words: CESAR 83 expedition, Alpha Ridge, bathymetry, gravity, sea ice SLAR imagery

RÉSUMÉ. La rareté générale des données géophysiques recueillies dans le bassin de l'océan Arctique et la nécessité d'élargir les connaissances sur l'évolution du bassin de l'Amériasie et sur la nature et l'origine de la dorsale Alpha ont amené les scientifiques à réaliser, en 1983, une expédition polaire pluridisciplinaire codifiée "CESAR 83" à partir de son appellation anglaise *"Canadian Expedition to Study the Alpha Ridge"* (Expédition canadienne chargée d'étudier la dorsale Alpha). Les Forces armées canadiennes ont appuyé l'expédition. Elles ont d'abord parachuté sur le site 18 membres d'une troupe de génie qui ont, sur la banquise, construit une piste d'atterrissage d'une longueur de 1,6 km; puis, elles y ont transporté le personnel et l'équipement dans des avions de type Hercules. Enfin, deux mois plus tard, elles se sont chargées du rapatriement des personnes et du matériel. Un levé de reconnaissance effectué précédemment au-dessus de la mer gelée au moyen d'un radar aéroporté à antenne latérale (SLAR) a permis la localisation de l'emplacement qui convenait à l'expédition.

L'expédition CESAR a mené à bien plusieurs projets importants; entre autres, elle a effectué un levé bathymétrique et gravimétrique au-dessus du plateau continental de l'île Ellesmere et de la partie orientale de la dorsale Alpha. A partir des données fournies par l'expédition CESAR et celles de nature publique recueillies au cours des 35 dernières années, il a été possible de compiler des cartes bathymétriques à écart de 100 m entre les courbes et des cartes des anomalies gravimétriques à l'air libre à écart de 5 mGal entre les courbes. Ces cartes couvrent la région comprise entre la côte de l'île Ellesmere et 116° de longitude ouest. Sur les cartes des fonds marins, la dorsale Alpha ressemble à un très vaste ensemble montagneux à topographie accidentée où, de manière générale, dorsales et vallées s'étirent parallèlement à l'axe principal. Une importante vallée, d'orientation est sud-est, centrée sur la latitude 86°N et entre les longitudes 110° et 125° 0 a été appelée "Cesar Trough". Les crêtes adjacent ont été appelées "Cesar North Ridge" et "Cesar South Ridge". La dorsale est séparée du plateau continental de l'île Ellesmere par une dépression dont la profondeur varie de 1800 à 2000 m. Au-dessus de la dorsale Alpha, les anomalies à l'air libre reflètent la bathymétrie. Des anomalies positives de forme elliptique concentrées autour de la bordure du plateau continental laissent supposer que la marge continentale adjacent à la dorsale Alpha possède la structure typique de la marge de l'Atlantique, qui caractérise le reste de la marge polaire nord-américaine. Une interprétation préliminaire du champ gravimétrique révèle que la croûte très épaisse de la dorsale Alpha est constituée de roches de densité et de composition latéralement uniforme. Il semble que le côté de la dorsale Alpha puisse être un massif de roches mafigues résultant de l'activité volcanique sous-marine.

Mots clés: Expédition CESAR 83, dorsale Alpha, bathymétrie, gravité, imagerie SLAR des glaces de mer

Traduit par P. Morel à l'Huissier, département de l'énergie, mines et ressources.

РЕЗЮМЕ

В 1983 году, с целью сбора недостающих геофизических данных по Арктическому бассейну, а также с целью получения полностью отсутствовавших в то время сведений о развитии Амеразийского бассейна и о природе и происхождении хребта Альфа, была организована комплексная полярная экспедиция под кодовым названием "ЦЕЗАР 83" ("CESAR 83": Canadian Expedition to Study the Alpha Ridge - канадская экспедиция по изучению хребта Альфа). Экспедиция получила значительную помощь со

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[2]Geophysics Division, Geological Survey of Canada, 1 Observatory Crescent, Ottawa, Ontario, Canada K1A 0Y3

стороны канадских вооруженных сил, которые высадили на выбранное для нее место парашютный десант в составе 18 саперов, расчистивших на паковом льду летную полосу длиной 1,6 км, а затем доставили и два месяца спустя вывезли ее участников с помощью военных транспортных самолетов "Геркулес". Место для высадки экспедиции было выбрано на основе данных радиолокационной разведки, произведенной посредством РЛС бокового обзора.

Одним из важнейших результатов работы экспедиции явилось проведение батиметрической и гравиметрической съемки континентального шельфа острова Элсмир и восточного склона хребта Альфа. Данные, полученные экспедицией "ЦЕЗАР", в сочетании с данными, собранными и опубликованными за последние 15 лет, были использованы для составления батиметрических карт с изобатами через 100 м и гравиметрических карт аномалий в свободном воздухе с изоаномалами через 5 мГал. Эти карты покрывают район от побережья острова Элсмир до 116° з.д. На картах морского дна хребет Альфа имеет вид очень широкого горного комплекса с неровным рельефом; входящие в него горные цепи и долины вытянуты вдоль его оси. Четко различимая долина, вытянутая в направлении восток-юго-восток, центральная часть которой лежит вдоль 86° с.ш. между 110° и 125° з.д., получила название впадины ЦЕЗАР, а прилегающие к ней горные цепи названы Северным хребтом ЦЕЗАР и Южным хребтом ЦЕЗАР. Хребет Альфа отделяется от континентального шельфа острова Элсмир впадиной глубиной от 1800 до 2000 м. Отмеченные над хребтом Альфа аномалии в свободном воздухе отражают данные батиметрии. Сосредоточение эллиптических положительных аномалий над бровкой континентального шельфа свидетельствует о том, что участок окраины континента, примыкающий к хребту Альфа, имеет типичную атлантическую структуру, характерную для всей полярной окраины Североамериканского материка. Предварительное изучение гравитационного поля показывает, что очень мощная кора хребта Альфа состоит из пород горизонтально-однородной плотности. Предполагается, что восточная часть хребта Альфа представляет собой массивное скопление мафических минералов, образовавшихся, по всей вероятности, в результате подводной вулканической деятельности.

Настоящая статья является частью II серии "Карты дна Северного Ледовитого океана"; первая статья этой серии называется "История батиметрии и расшифровка батиметрических данных" (Weber, 1983).

Ключевые слова: экспедиция "ЦЕЗАР 83", хребет Альфа, батиметрия, гравиметрия, разведка морских льдов с помощью РЛС бокового обзора.

INTRODUCTION

Morphological Background

The Arctic Ocean consists of a deep ocean basin, submarine ridges, continental shelves and marginal plateaus (Fig. 1). Five major epicontinental seas, the Barents, Kara, Laptev, East Siberian and Chukchi seas, are located on the very wide European and Siberian continental shelves. The much smaller Beaufort and Lincoln seas overlie part of the generally narrow continental shelves that fringe the North American and Greenland margins of the Arctic Ocean. The regular pattern of continental margins is interposed by five marginal plateaus, the Morris Jesup and Yermak plateaus off the Greenland and Svalbard shelves and Northwind Ridge, Chukchi Cap and Arlis Plateau off the Chukchi Shelf. The Lomonosov Ridge, which crosses near the North Pole, divides the Arctic Basin into Eurasia and Amerasia basins. In 1979 the Department of Energy, Mines and Resources (EMR), Ottawa, undertook a large-scale multidisciplinary expedition to the polar area to study the Lomonosov Ridge. The operation was code-named LOREX, for Lomonosov Ridge Experiment (Weber, 1979), and some of the results were reported in *Arctic* (Weber, 1983).

The Eurasia Basin (Fig. 1) is believed to have been formed by sea floor spreading centered around the Nansen-Gakkel Ridge (Feden *et al.*, 1979). The opening was initiated between 65 and 56 Ma ago by a continental sliver, the proto-Lomonosov Ridge, breaking off the Barents and Kara shelves (Vogt *et al.*, 1979; Kristofferson, 1982; Weber and Sweeney, 1985). The Amerasia Basin is divided into Canada Basin and Makarov Basin by the Alpha and Mendeleev ridges. The deepest part of the Canada Basin is the remarkably flat, 3800 m deep Canada Plain (Fig. 2). A smaller, 2900 m deep abyssal plain, the Mendeleev Plain, lies between Chukchi Cap and Mendeleev Ridge. Between the Lomonosov Ridge and the Alpha-Mendeleev Ridge lies the Makarov Basin. It contains two abyssal plains: the Wrangel Plain at 2825 m depth adjoins the East Siberian Shelf and connects, via Arlis Gap, with the deeper Siberia Plain at a depth of 3940 m (Kutschale, 1966). The Makarov Basin is wedge-shaped, in excess of 500 km wide along the East Siberian Shelf, and narrows to a point toward Ellesmere Island.

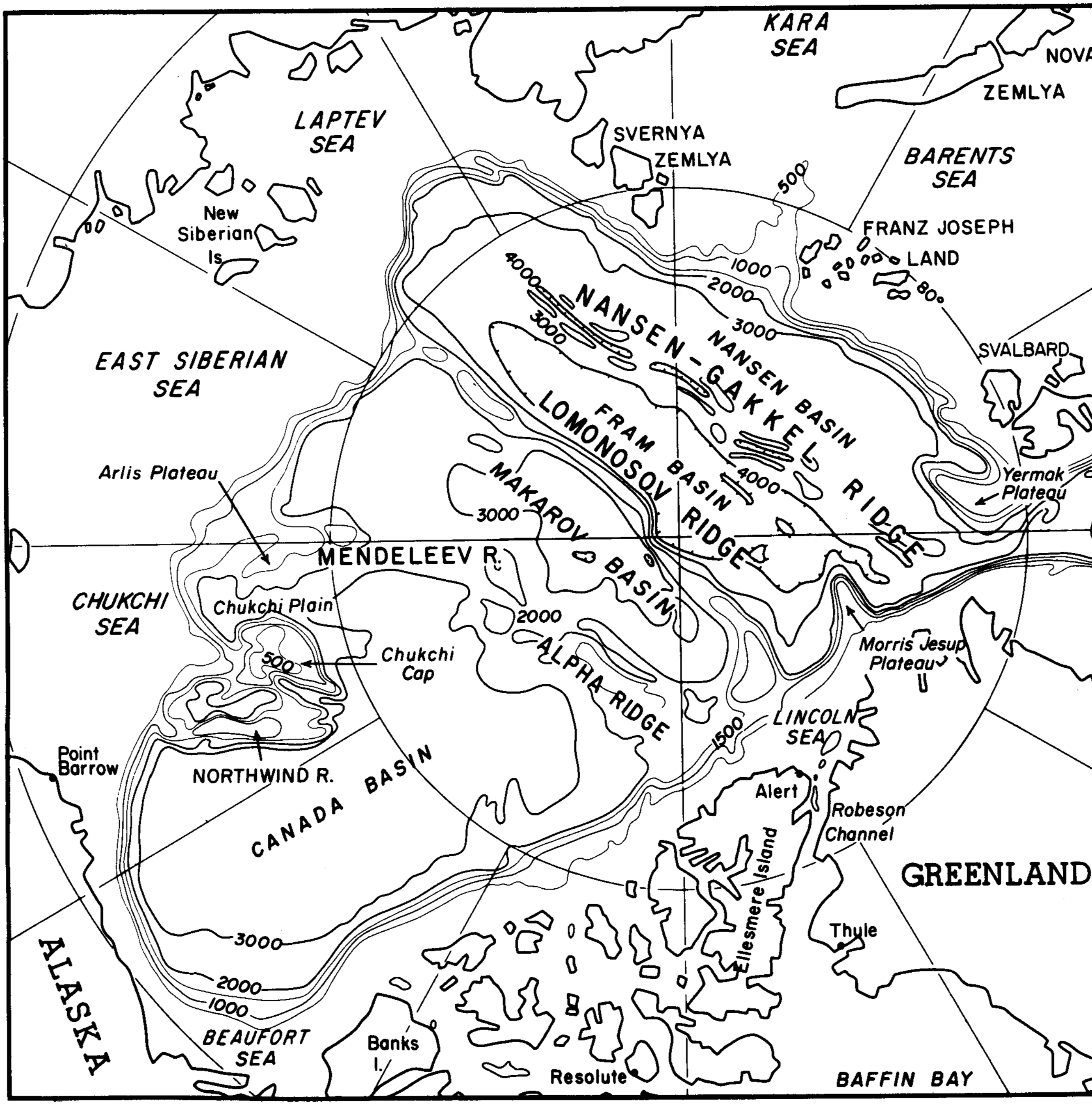

FIG. 1. Overview map of Arctic Ocean with names used in text.

The narrow Marvin Spur (indicated by a line of dots in Figure 2) juts out some 120 km (at the 3000 m isobath) into the Siberia Plain. The flank facing the Lomonosov Ridge extends in the opposite direction toward Ellesmere Island for at least 400 km parallelling the 40°W/140°E meridian. Its presence was discovered from the ice island T-3 using a seismic array. Crary (1954) compiled a remarkably good sea floor map delineating 300 km of the Marvin Spur as a long, steep, continuous and northerly facing escarpment with rises from 500 to 1500 m and slopes of up to 23°.

The Alpha-Mendeleev Ridge is the largest submarine mountain complex in the Arctic Ocean. In areal extent it exceeds that of the Alps. The ridge is about the same length as the Lomonosov Ridge, slightly deeper, much wider and morphologically much more complex. Topographically the two ridges merge some 350 km off the coast of Ellesmere Island. At the junction with the Ellesmere Island continental shelf the Alpha-Lomonosov complex is about 700 km wide above the 3000 m isobath. Seaward the Alpha-Mendeleev Ridge narrows to 120 km midway between North America and Eurasia, where Belov and Lapina (1958) report the ridge to be bisected by a deep trough with a maximum depth of 2700 m. This depression, named Cooperation Gap by Treshnikov (1966), divides the ridge into two distinct topographic features, the Alpha Ridge on the Canadian side and the Mendeleev Ridge on the Siberian side. The Mendeleev Ridge widens southward and joins the East Siberian Shelf via the Arlis Plateau. The transition from ridge to shelf appears smooth with no apparent trough separating the two.

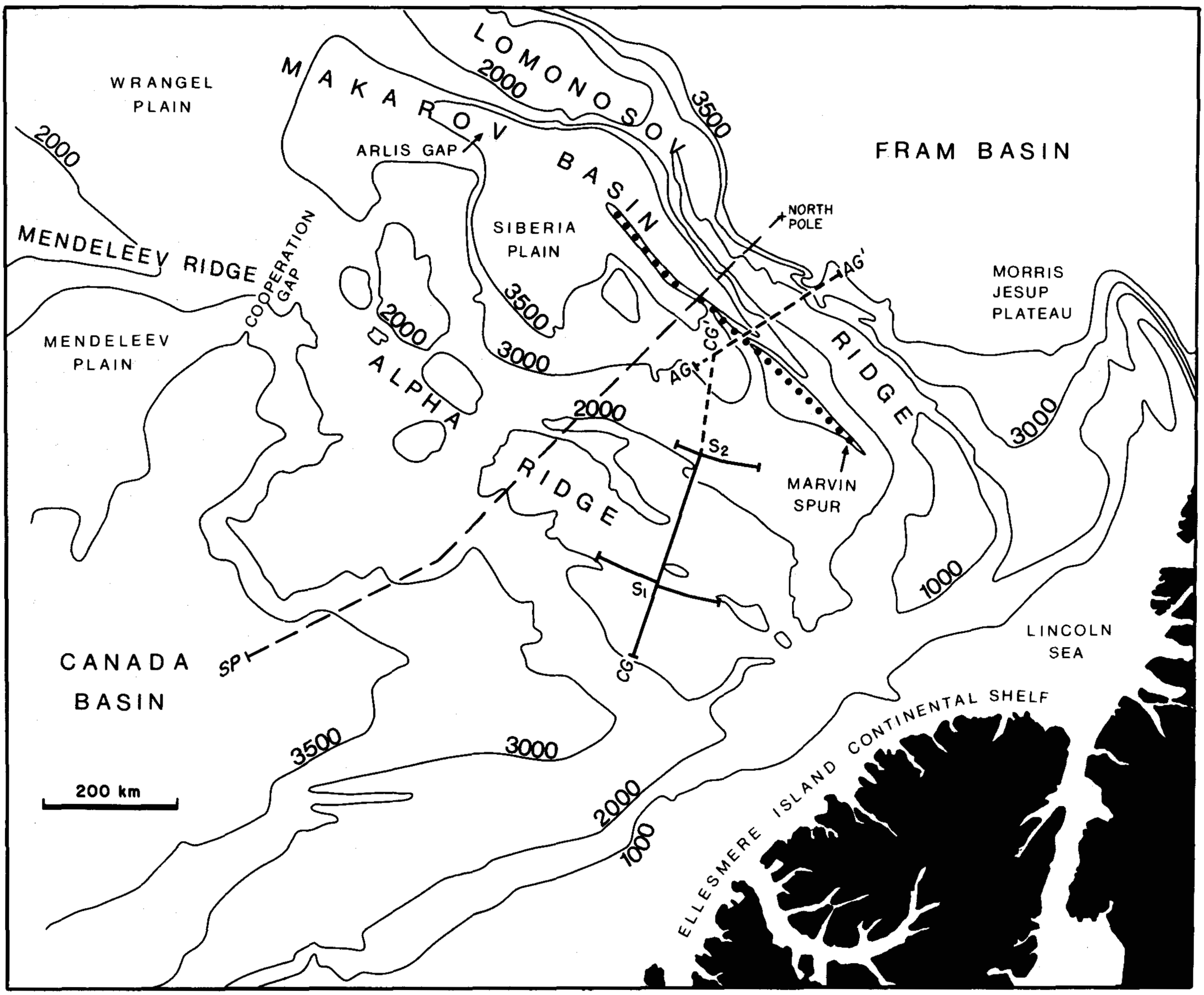

FIG. 2. Generalized bathymetric map of the Alpha Ridge. Dotted line shows location of Marvin Spur. Depth contours are from Perry *et al.*, 1985. Broken lines denote: SP, *Skate* and *Seadragon* submarine tracks of Figure 8; AG-AG′, Arlis II gravity profile (km 0-360, Fig. 10); CG-CG′, CESAR gravity profile (km 360-680, Fig. 10). Solid lines indicate location of CESAR seismic refraction profiles.

Although isolated areas of the ridge had first been discovered earlier by the Soviets (Gordienko and Laktionov, 1960), the Alpha Ridge was first recognized as a distinct submarine feature by U.S. scientists aboard the drifting station Alpha during the International Geophysical Year (IGY) (Hunkins, 1961), from which it derives its name.

Much of the topography of the Alpha-Mendeleev Ridge is known from the soundings carried out from U.S. drifting ice stations Alpha 1957-58 (Cabaniss, 1962), T-3 1953-57, 1962-63, 1966-74 (Hunkins and Tiemann, 1977) and Arlis II 1962-64 (Wold, 1973) and from early submarine echograms (Beal, 1969). Hall (1970) carried out a comprehensive study of the Alpha-Mendeleev Ridge based on sounding, seismic, gravity, magnetic and coring results collected on board these drifting stations.

Unlike the Eurasia Basin, whose tectonic evolution is fairly well understood, the origin of the Amerasia Basin is poorly known. In particular the nature and origin of the Alpha and Mendeleev ridges have been an enigma since their discovery nearly 30 years ago (Coles *et al.*, 1978). In order to clarify some of its mystery, EMR conducted a large-scale multidisciplinary expedition to the Alpha Ridge in 1983. The operation, code-named CESAR 83 for *C*anadian *E*xpedition to *S*tudy the *A*lpha *R*idge, was similar in nature and size to LOREX.

This paper summarizes the logistics of the CESAR operation and describes the results of the bathymetry and gravity measurements over the Alpha Ridge.

THE CESAR 83 EXPEDITION

Canadian Armed Forces Support

The scientific program was planned and coordinated by the Earth Physics Branch (EPB) of EMR and logistic support was provided by the Polar Continental Shelf Project. As on the LOREX expedition four years earlier, the Canadian Armed

Forces again played an important part in the operation. They agreed to carry out deployment and evacuation of the whole CESAR operation on a cost recovery basis by airlifting all equipment, supplies and personnel by C-130 Hercules aircraft from Resolute to a prepared ice runway at the CESAR camp and at the end of the operation to evacuate personnel and equipment to Resolute. The Department of National Defence also agreed to prepare a 1600 m long ice runway as a military exercise, provided EMR could locate a suitable site. The requirement called for a nearly 2 km long, 40 m wide piece of straight, smooth ice at least 1.6 m thick. That meant finding a long enough lead of first-year ice that originated as a crack in the old pack ice during the previous October and had remained more or less intact while it grew to the required thickness during the polar winter. Such long leads are not common and it appeared questionable that one might be found within the narrow window allocated for the search in the rigid timetable of a military operation.

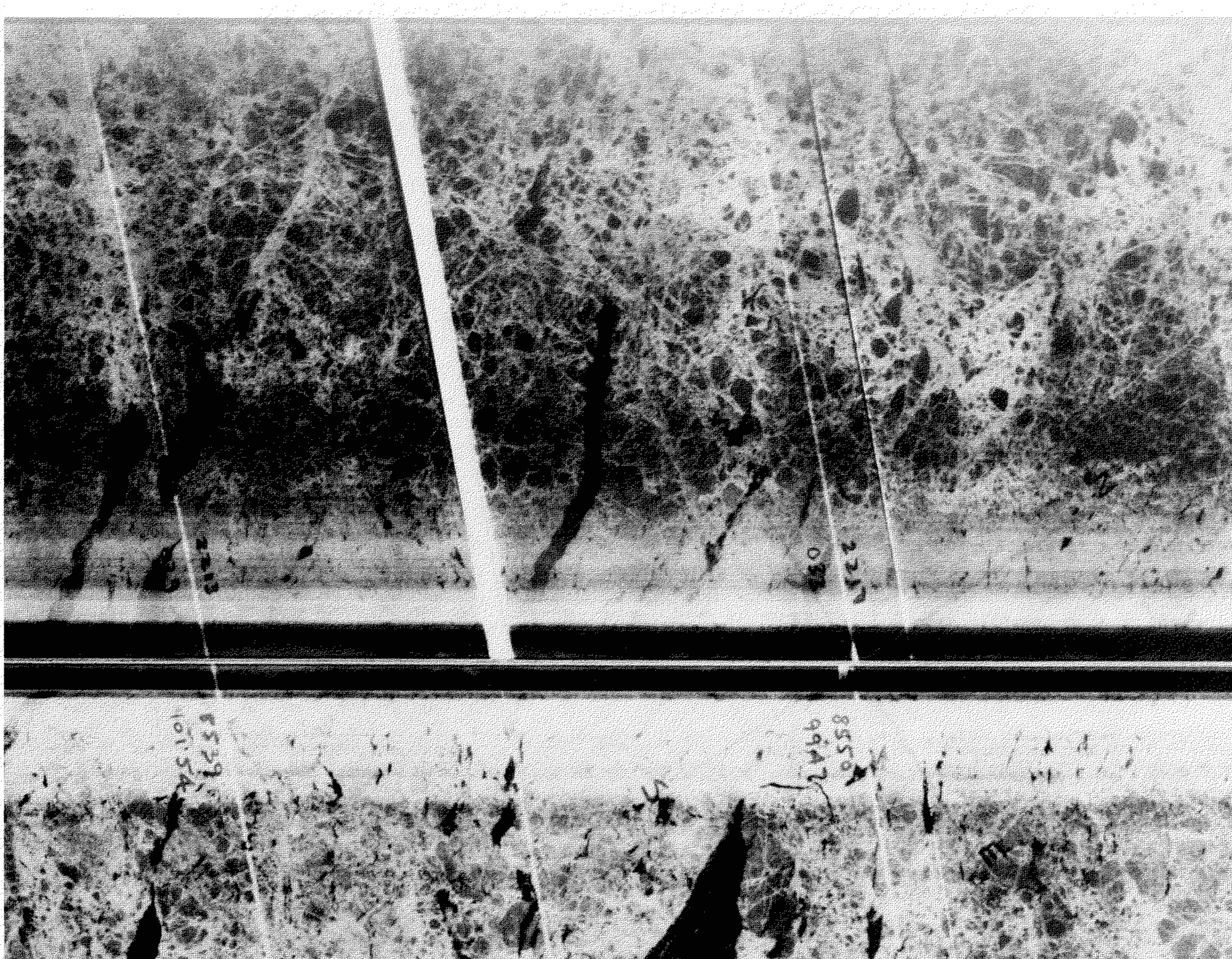

FIG. 3. Side-looking airborne radar (SLAR) image of the sea ice in the vicinity of 86°N, 100°W, measuring about 50 km by 50 km. Black areas represent leads of first-year ice or possibly open water. Reconnaissance flown by the ice patrol of the Atmospheric Environment Service on 9 February 1983 in search of a suitable CESAR campsite.

Ice Reconnaissance

Fortunately the Ice Patrol of the Atmospheric Environment Service, Department of Environment, agreed to include a side-looking airborne radar (SLAR) reconnaissance survey over the proposed CESAR area as part of its synoptic northern ice reconnaissance. On 9 February 1983, using Resolute Bay as a base, 500 line km of SLAR covering some 45 000 km^2 within an area bounded by 84°30′-87°15′N latitude and 89°-120°W longitude were flown. Figure 3 shows a photograph of part of the radar mosaic image of the sea ice surface from about 30 km of flight line with a swath width of 25 km on either side. The aircraft flew at an altitude of 1500 m in the direction from bottom to top on the photograph. The darker the radar reflection on the map appears, the smoother the ice is. It is not possible to estimate the ice thickness from the radar images. Gray areas represent relatively smooth multi-year ice, while the white reflections are caused by very rough ice surface features such as pressure ridges. We were looking for areas with many leads such as the long lead on the left center on the photograph (Fig. 3). The SLAR mosaic of the reconnaissance area showed that, generally, the sea ice consisted mostly of multi-year floes typical of the top left quarter of Figure 3. There was only the one large area of many leads with a good potential for finding favourable ice.

Over the next 31 days, until the search for a campsite started, this area's position was estimated by plotting the drift path of the Soviet drifting station NP25 and of two data buoys of the Arctic Ocean Buoy Program (Colony and Munoz, 1985), all located within a 350 km radius of the SLAR area.

Search, Airlift and Evacuation

On 12 March the search for the CESAR site began using two Twin Otter aircraft starting from Eureka on Ellesmere Island. Because of the low sun angle and light ice fog, visibility was poor and individual ice features on the SLAR mosaic could not be identified. However, the aircraft concentrated their search in the area where the SLAR mosaic indicated an abundance of new leads, and on the second day of the search a suitable lead of 1.83 m thick first-year ice was located at 85°56′N, 112°35′W. The search party set up camp and made radio contact with Alert, while the two aircraft returned to Eureka. A few hours later four fully equipped military Hercules aircraft that had been standing by in Trenton, Ontario, took off for Thule, Greenland. On 14 March the two Twin Otter aircraft returned with fuel, equipment and supplies, then headed for Alert to pick up the six-man military team responsible for flagging the drop zone and controlling the paradrop operation from the ground. On 15 March three Hercules aircraft with 18 airborne engineers, all volunteers from No. 2 Combat Engineering Regiment Petawawa, equipment and supplies departed from Thule and arrived overhead the CESAR site at 11:45 CST. A few minutes later men and equipment parachuted from 400 m altitude, making a perfect landing with no injuries and no equipment damage. The air temperature at the time was –42°C, with a 20 km·h^{-1} wind blowing. Within minutes a bulldozer, a grader weighing over 12 tons and three snowmobiles were running. The engineers set up camp and radio communications and during the next eight days built a 1600 m long, 30 m wide runway (Fig. 4). Using explosives and the bulldozer they demolished pressure ridges that crossed the runway, removed the snow with the grader and smoothed the runway by flooding the ice with seawater pumped from below the ice. During that time the wind chill factor dropped as low as –90°C. In the meantime, in Resolute, equipment and supplies were lashed to Hercules pallets by military personnel ready for loading into the aircraft. Between 24 and 30 March, CESAR personnel and some 500 000 kg of cargo, including 1200 drums of fuel, were transported in 30 trips from Resolute to the newly built runway. While the airlift was going on, CESAR personnel built up the facilities to house 44 scientists and support personnel including laboratory huts and four hydroholes with winches.

The scientific program started on 3 April and lasted until 20 May, when the first Hercules aircraft arrived to start the evacuation. A major storm on 9 and 10 April left the camp area and runway intact, but many leads opened up in the surrounding area after the storm had subsided. On 23 May a second major storm

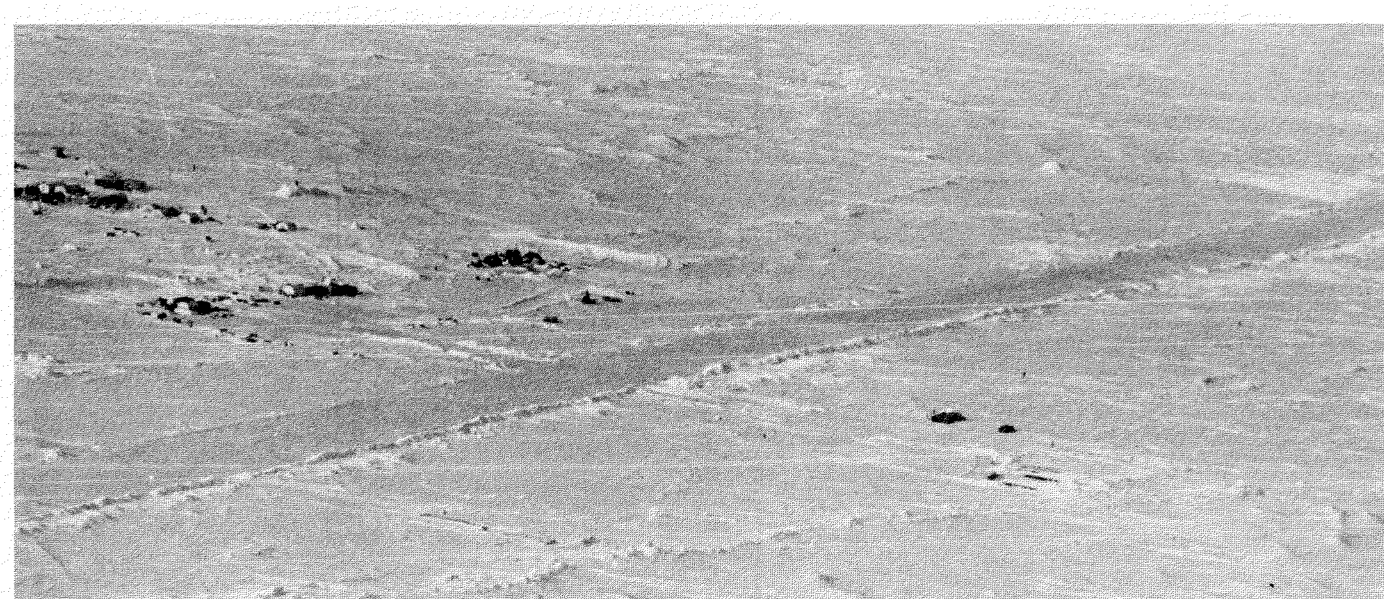

FIG. 4. View of the CESAR camp in April with part of the 1600 m long sea ice runway built by the military.

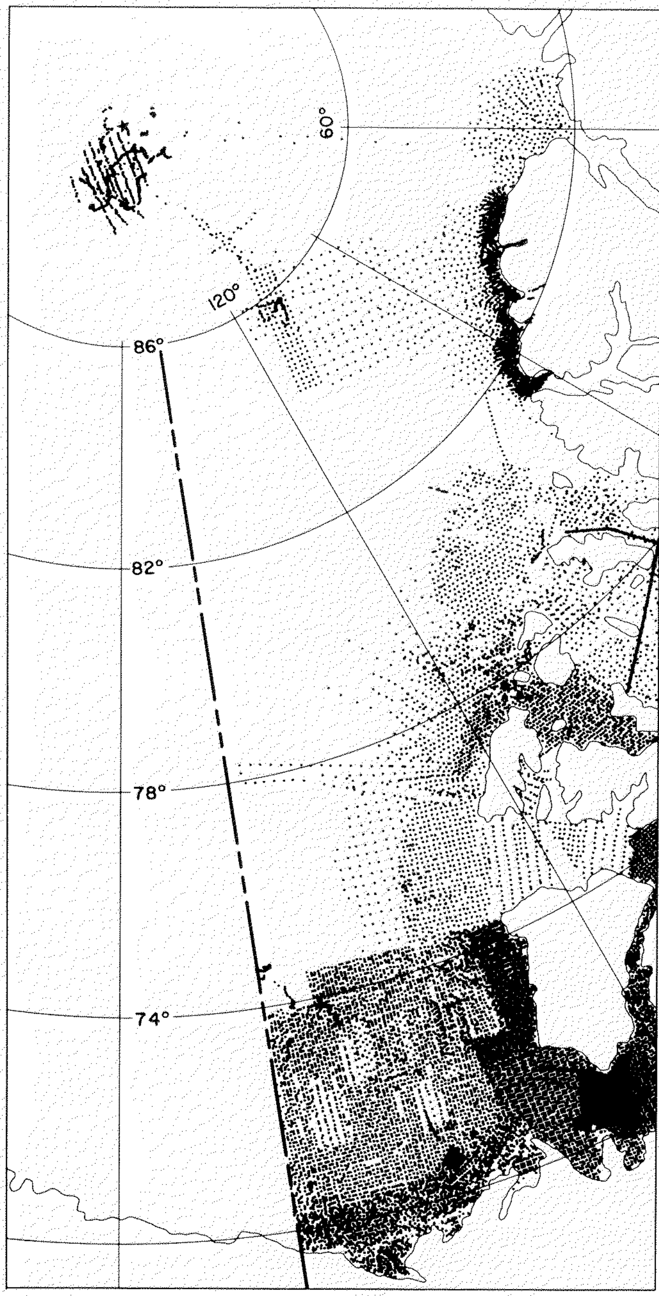

FIG. 5. Plot of Canadian bathymetric and gravity stations established on the Arctic Ocean and adjoining inter-island waters as of 1985. Stations near the North Pole were established primarily on LOREX in 1979 and those off Ellesmere Island on CESAR in 1983. Lines of stations off Axel Heiberg Island are located along seismic lines established from an ice island by EPB and Atlantic Geoscience Centre, EMR, in 1985. The ice island, used as forward base, has been occupied by PCSP since 1984 (Weber *et al.*, 1984).

started and the runway began to buckle just as the seventh and last Hercules took off for Resolute with the remaining equipment and personnel. A reconnaissance flight with two Twin Otters to the CESAR site a few days later revealed a jumble of broken ice with no trace of either campsite or runway.

The Scientific Program

Four Doppler satellite receivers provided precise navigation for positioning of the CESAR camp and mobile sites. The satellite navigation (SatNav) data was processed on an HP9000 computer, providing positions to an average accuracy of $\pm$ 16 m horizontally and 0.4 m vertically. The computer was also used to monitor Decca and Omega radio navigational positions for comparison and evaluation, gravity, wind speed and direction, air temperature and pressure, humidity and solar radiation data. The Twin Otter aircraft and the two helicopters were equipped with Omega receivers, whose positional accuracy is of the order of $\pm$2 km.

The disciplines studied during the operation were bathymetry, gravity, intermediate depth reflection seismic, crustal refraction seismic, heat flow, magnetotellurics, biological studies, chemical oceanography, bottom current measurements and marine geology consisting of shallow seismic profiling, coring with gravity and piston corers, dredging, bottom photography, sediment dynamics and measurement of organic flux.

BATHYMETRY OF THE ALPHA RIDGE

The Survey

A combined bathymetric-gravity survey over the Ellesmere Island Continental Shelf to the 1000 m isobath was carried out by the Canadian Hydrographic Service (CHS) with EPB support as a regular survey of the Polar Continental Shelf Project. It filled the gap in survey coverage between Lincoln Sea and Nansen Sound. Each of the three Bell 206B helicopters used on the survey was equipped with Miniranger and Decca navigation, a 12 kHz through-the-ice echo-sounder and a LaCoste-Romberg gravimeter. CHS established a total of 850 spot soundings and gravity stations at a grid interval of 6 km (Fig. 5).

The CESAR bathymetric survey portion, seaward of the 1000 m isobath, was a cooperative venture between EPB and CHS. Some 440 helicopter spot soundings and gravity observations were made at a grid interval of 20 km, except for a 50 km wide strip at the western end of the survey area, where the grid interval was 10 km. The survey covers a strip 250 km wide and 360 km long extending over the Alpha Ridge. A traverse of spot soundings toward the Lomonosov Ridge was also completed. Water depths were determined partly by echo sounding through the ice (CHS) and partly by the seismic reflection method using explosives (EPB). In addition to the spot soundings, the Atlantic Geoscience Centre operated two echo sounders continuously, one at the main camp (12.5 kHz from day 91 to 141) and the other at the remote camp (3.5 kHz from day 107 to 131). Two-way travel times of the soundings were converted to water depths using Mathews' Tables (Mathews, 1939).

Figure 5 shows a plot of Canadian bathymetric and gravity stations established on the Arctic Ocean as of 1985. Comparison with a corresponding station plot as of 1980 in Weber (1983: Fig. 4) indicates the extent of the CESAR survey.

Map Compilation

Figure 6 shows a 100 m contour map of the CESAR camp and surrounding area compiled from the spot soundings together with main and remote camp echo soundings. Intervals along drift track represents 3 hours. The bottom topography is complex, ranging in depth from 2536 m in the Cesar Trough to less than 1100 m on the Cesar North and South ridges. It appears roughest where the sounding density is greatest. Consequently there are many short wave-length topographic features visible

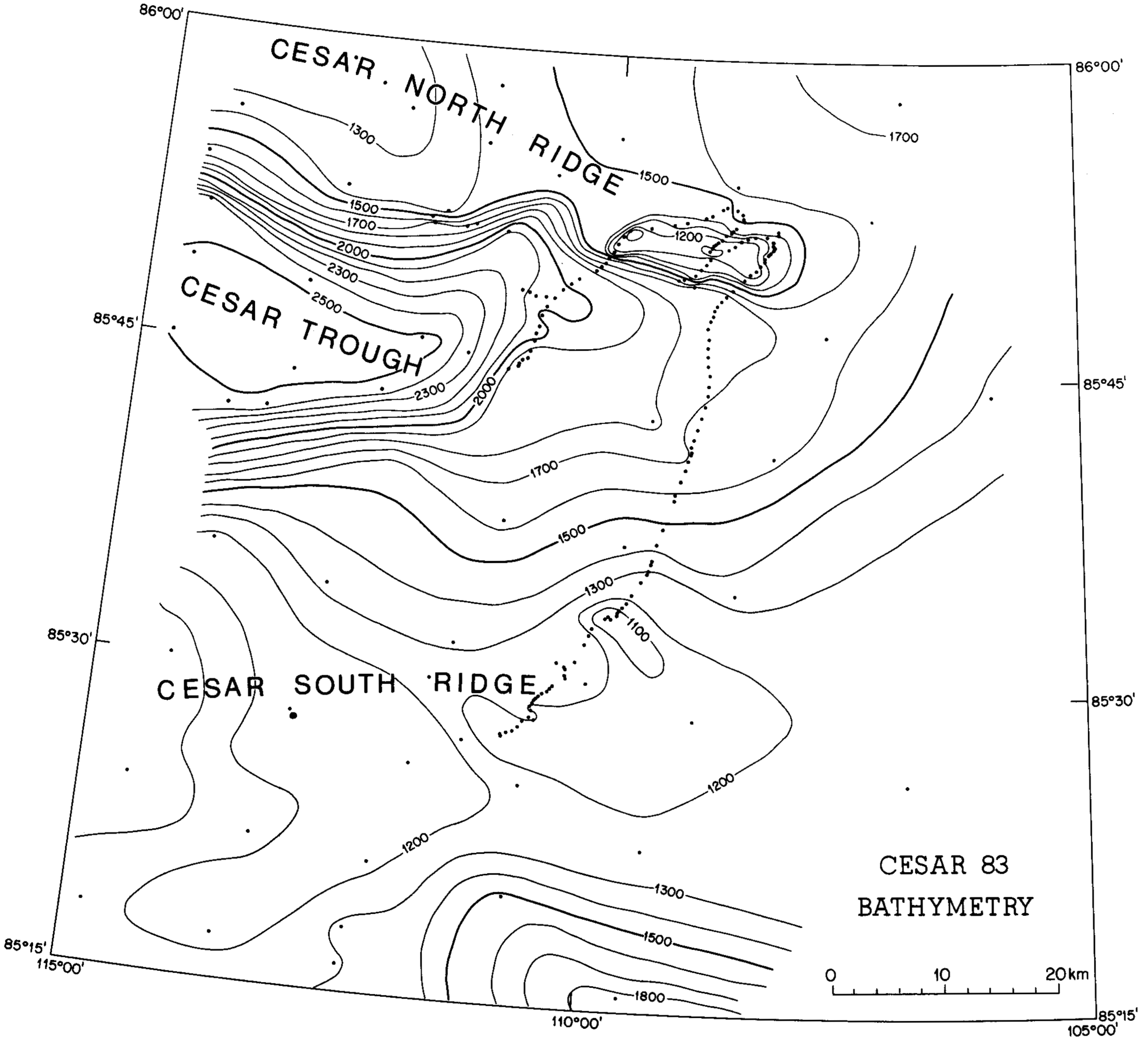

FIG. 6. Bathymetric map of the CESAR area with 100 m contour interval. Drift track of main camp and remote camp is shown as consecutive dots at 3 hr intervals. Also shown are locations of spot soundings and gravity observations. The prominent valley and the two ridges were named Cesar Trough and Cesar North and South ridges.

on the continuous echo sounder and shallow seismic records along the drift track that remain unresolved in the 10 km grid of spot soundings, the smallest grid interval that could be surveyed during the time available (Weber and Jackson, 1985).

All publicly available sounding data from U.S. stations T-3, Alpha, Arlis II, U.S. airlifted stations, CHS stations, Canadian North Pole Expeditions 1967 and 1969, LOREX 79 and CESAR 83 have beem compiled on a 100 m contour map. The chart extends from the Ellesmere Island Continental Shelf across Alpha Ridge, Makarov Basin and Lomonosov Ridge to the North Pole area. The chart is divided into three maps, as illustrated in Figure 7a-c. Dots indicate the sounding locations used for contouring. Blank areas, where no data are available, were filled in with 500 m contour lines (broken) taken from the latest preliminary "Bathymetric Map of the Arctic Ocean" (Perry *et al.*, 1985). These contours, in the unexplored areas of the Arctic Ocean, may have been compiled in part from echograms from early U.S. submarine cruises and in part from classified U.S. submarine data whose reliability is difficult to verify. Two of these echograms, from the *Skate* and the *Seadragon*, which sailed from the North Pole across the Lomonosov and Alpha ridges in 1962, are reproduced from Beal (1969) in Figure 8, top. Their cruise track is shown in Figure 2. These submarines were equipped with an early version of an inertial navigation system that was quite inaccurate, and they had to surface from time to time to obtain celestial position fixes (Beal, 1983; Lyon, 1984). In these echograms echo travel time is converted to depth without correction for the variation of water velocity with depth, so that the basins appear some 100 m too shallow. The bathymetric profile at the bottom of Figure 8 has been obtained by adjusting the *Skate* echogram vertically and horizontally to the newly compiled bathymetric data.

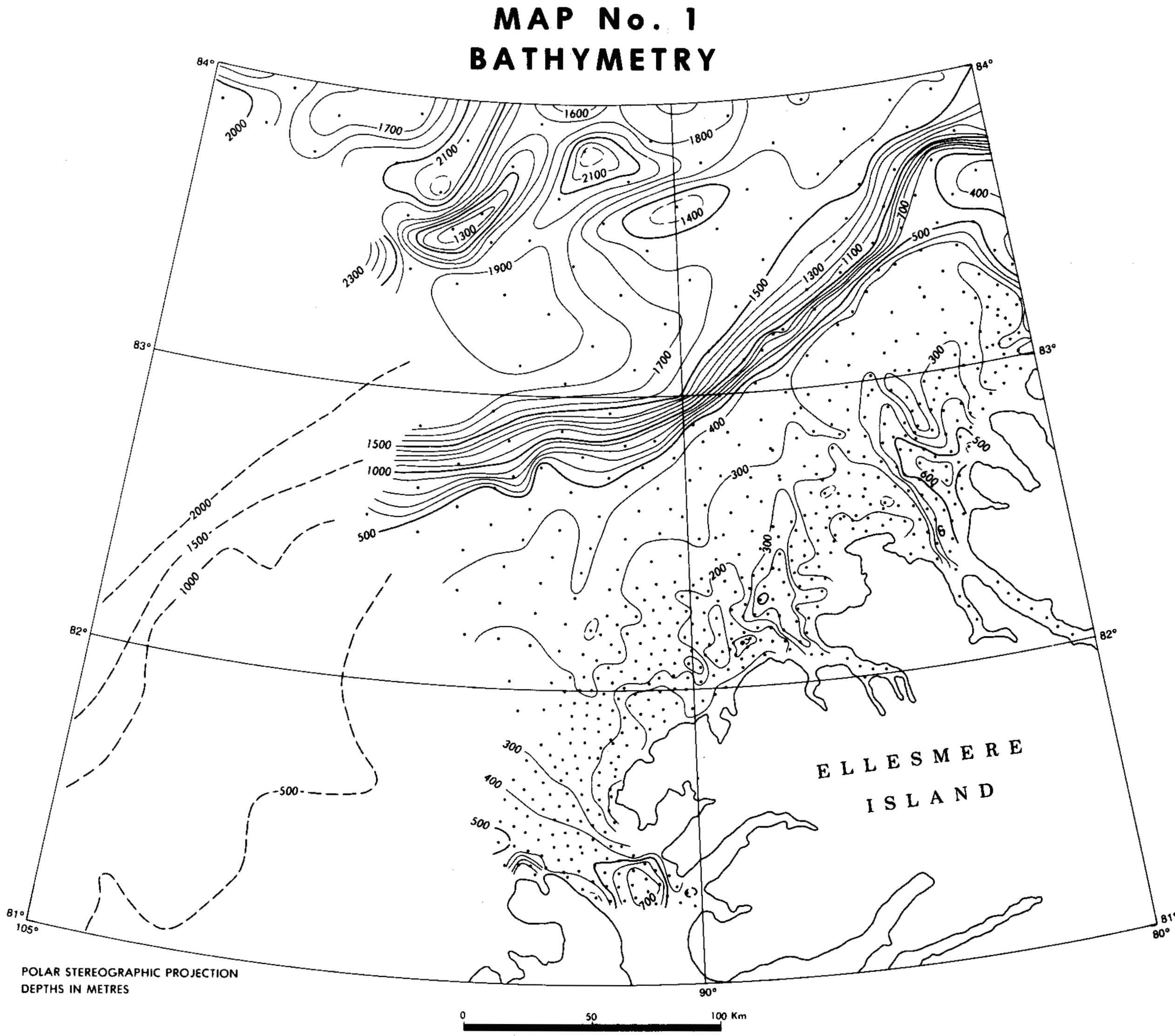

FIG. 7A-C. CESAR 83 bathymetric maps. Contour interval 100 m. Consecutive dots are drift tracks of ice stations, individual dots are locations of spot soundings. Uncharted areas have been filled in by 500 m dashed contour lines taken from Perry *et al.*, 1985.

Interpretation

The Alpha Ridge is a very rugged, broad, fractured arch consisting of seamounts, depressions, long ridges and valleys striking parallel to its axis. Hall (1970) reported 100-1200 m sediment thicknesses on the ridge. A similar range of values was obtained by the CESAR expedition, confirming that relief on the basement is also rugged. Shallow seismic profiles recorded from CESAR (Jackson, 1985) as well as from T-3 show many short wave length bathymetric features not revealed by the CESAR regional bathymetric survey used to map the ocean floor. Numerous graben-like troughs bounded by steep faults were reported from the Alpha Ridge by Hall (1970), and a similar structure, named Cesar Trough (Fig. 6), was traversed by ice station CESAR (Jackson, 1985). The ridge is separated from the Ellesmere Island Continental Shelf by an 1800-2000 m deep trough.

Along the eastern end of the Makarov Basin the Alpha Ridge is bounded by the Marvin Spur (Fig. 2). As the spur trends out of the Siberia Plain toward Greenland it becomes strongly asymmetric and its northern (Lomonosov Ridge-facing) flank becomes a steep scarp. Ice station Arlis II found a steep scarp with 1650 m of relief at the north flank of the spur when it drifted north on the 150°W meridian in 1964 (Ostenso and Wold, 1977). Spot soundings taken during the LOREX and CESAR expeditions along the 160°W and 125°W meridian showed elevation changes of 748 m and 554 m respectively at the scarp. This long, steep and continuous escarpment is identified on older maps (e.g., Heezen and Tharp, 1975) as the Lomonosov Ridge-facing flank of the Marvin spur, and Beal *et al.* (1966) proposed that it is an independent feature bisecting the Makarov Basin. Submarine echograms (Fig. 8, and Weber and Sweeney, 1985:Fig. 5), Arlis II data as reinterpreted by Weber and Sweeney (1985) and CESAR seismic refraction results that show a crustal depth of 23 km just south of the Marvin Spur (Forsyth *et al.*, 1986) suggest that this escarpment is probably the Lomonosov Ridge-facing flank of the Alpha Ridge. The part of the Siberia Plain lying between the escarpment and

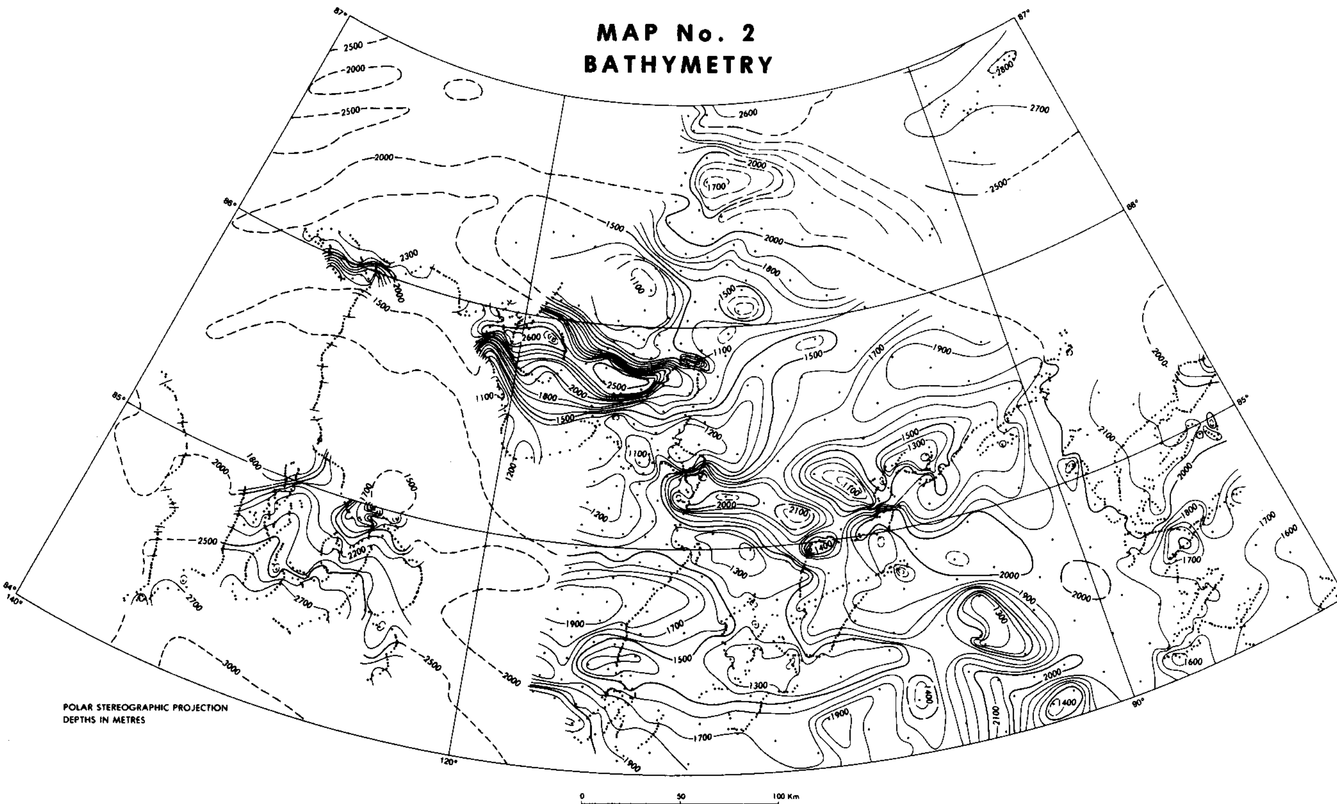

FIG. 7B.

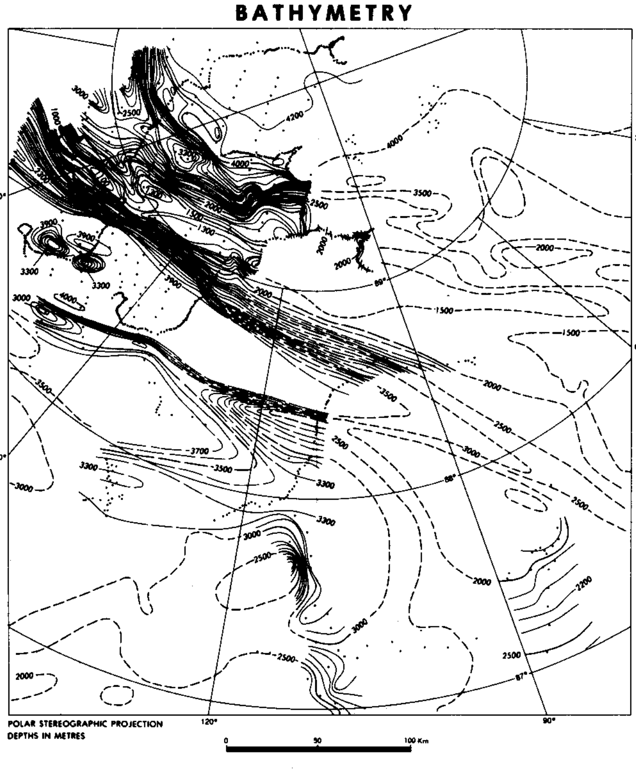

FIG. 7C.

Lomonosov Ridge, the eastern end of the Makarov Basin, consists of a wedge-shaped graben 70 km wide at its junction with Siberia Plain, but narrowing to a point where, morphologically, the Alpha and Lomonosov ridges merge near the Lincoln Sea.

A number of cones protrude through the sediments of the eastern end of the Makarov Basin. These cones, which form seamounts rising as much as 700 m above the abyssal plain (Sobczak and Sweeney, 1978), were referred to as the Marvin Seamounts by Sobzak (1977). Air-gun seismic reflection profiles (Blasco *et al.*, 1979) show that these cones were formed before the basin fill was deposited, and an analysis of the gravity observations indicates that the cones consist of rocks higher in density ($3.15\ g \cdot cm^{-3}$) than those exposed in the escarpment ($2.5\ g \cdot cm^{-3}$) (Weber, 1980). These cones may therefore represent mafic extrusions in the form of volcanos that originated at the time the Markarov Basin was first formed.

THE GRAVITY FIELD

Survey and Map Compilation

Spot soundings and gravity measurements were carried out by helicopter and from the CESAR camp, which was equipped with continuously recording gravimeter and echo sounder. The CESAR gravity data were reduced and free-air anomalies merged with those obtained from earlier expeditions into this part of the Arctic Ocean.

L.W. Sobczak of EPB has collected all published foreign gravity observations in the Arctic north of 64° latitude, including, in the area concerned, data from the U.S. drifting stations T-3, Alpha, Arlis II, and U.S. airlifted stations (Sobczak *et al.*,

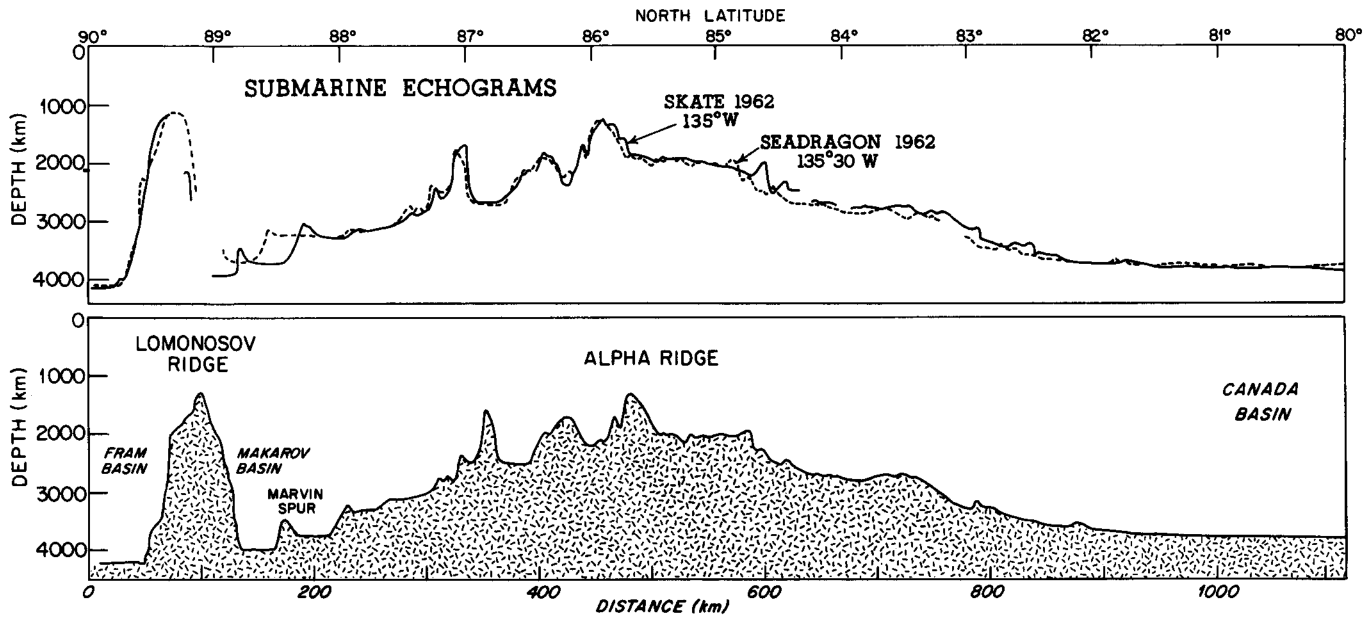

FIG. 8. Top: Echograms of the U.S. nuclear submarines *Skate* and *Seadragon* that sailed from the North Pole along the 135°W meridian in 1962. Track is shown in Figure 2. Bottom: Depth profile compiled from the *Skate* echogram corrected vertically and horizontally.

1987). Many of these stations intermingle with EPB stations established by the Canadian North Pole Expeditions, LOREX, CESAR and the CHS. When all the free-air anomalies were plotted it became apparent that large discrepancies existed between the Canadian and the various foreign data sets that at first could not be explained. These early gravity observations, some dating back 33 years, were made by many different government agencies and university teams, which often published the gravity data with insufficient or no documentation. It turned out that some of the observed gravity values were based on the Potsdam (1927) and some on the International Gravity Standardization Network 1971 (14 mGal difference), some investigators used the 1930 reference ellipsoid and some the 1967 Geodetic Reference System for computation of theoretical gravity, and the University of Wisconsin and the Lamont-Doherty Geological Observatory teams used different gravity values for the same control station in Point Barrow (5 mGal difference). With perseverance and many months of painstaking work, Sobczak and D.B. Hearty of EPB gradually untangled the many mismatched data sets and compiled, for the first time, a unified gravity map of the Arctic north of 64° latitude at the scale 1:6 000 000 (Sobczak *et al.*, 1987).

The same data set was used to compile a 5-mGal contour interval free-air gravity map of the polar region and Alpha Ridge. This larger scale map, with more detail, shows all the points used for contouring. The maps are illustrated in Figure 9 a-c and cover the same area as the bathymetric maps of Figure 7 a-c except that the unexplored regions were left blank. Where T-3, Arlis II and Alpha tracks overlap the CESAR and LOREX survey area the data correlate well.

Gravity Field and Structure

On Figure 9c the free-air anomalies range from 85 mGal over the Lomonosov Ridge to –60 mGal in the Makarov Basin along the Arlis II track and have been discussed by Sweeney *et al.* (1982) and Weber and Sweeney (1985). Over the Alpha Ridge the anomalies range from 80 mGal over the Cesar South Ridge to –50 mGal in the Cesar Trough (Fig. 9b) and correlate with the bathymetry. Over the continental margin (Fig. 9a) the gravity field is characterized by elliptically shaped positive anomalies of up to some 65 mGal centered over the continental shelf edge. Although subdued, because the continental shelf slope merges with the Alpha Ridge at the relatively shallow depth of 2000 m, they resemble the anomalies located all along the North American polar continental shelf break from Ellef Ringnes Island to Alaska. These anomalies are believed to be the gravitational expression of a normal passive continental margin. Their presence implies that the continental shelf adjacent to the Alpha Ridge has a similar structure as the polar continental shelf elsewhere and that, therefore, the Alpha Ridge may structurally not be connected to the continent.

The bathymetric, shallow seismic reflection and gravity measurements carried out from the ice island Arlis II when it drifted across the Marvin Spur, Makarov Basin and the Lomonosov Ridge during 1964 (Ostenso and Wold, 1977) were reinterpreted by Weber and Sweeney (1985) in the light of the LOREX studies, and a composite gravity-density structural model (Weber and Sweeney, 1985:Fig. 12) was compiled along profile AG-AG′ (Fig. 2). This gravity-density model has been extended across the Alpha Ridge to the southern limit of the CESAR gravity survey at 84°N latitude (Weber, 1985) and is illustrated in Figure 10. The northern part, from 0 to 360 km, reproduces Weber and Sweeney's model across the Lomonosov Ridge, Makarov Basin and Marvin Spur. The southern part, from 360 to 680 km, represents the new section across the Alpha Ridge. The model across the Alpha Ridge is derived from CESAR gravity measurements and is constrained by seismically determined depths (Forsyth *et al.*, 1986) of 23 km located on the Alpha Ridge north flank at S_2 (Fig. 2) and km 400 (Fig. 10) and of 38 km located on the ridge crest at S_1 (Fig. 2) and km 595 (Fig. 10). The observed free-air gravity anomaly can be almost

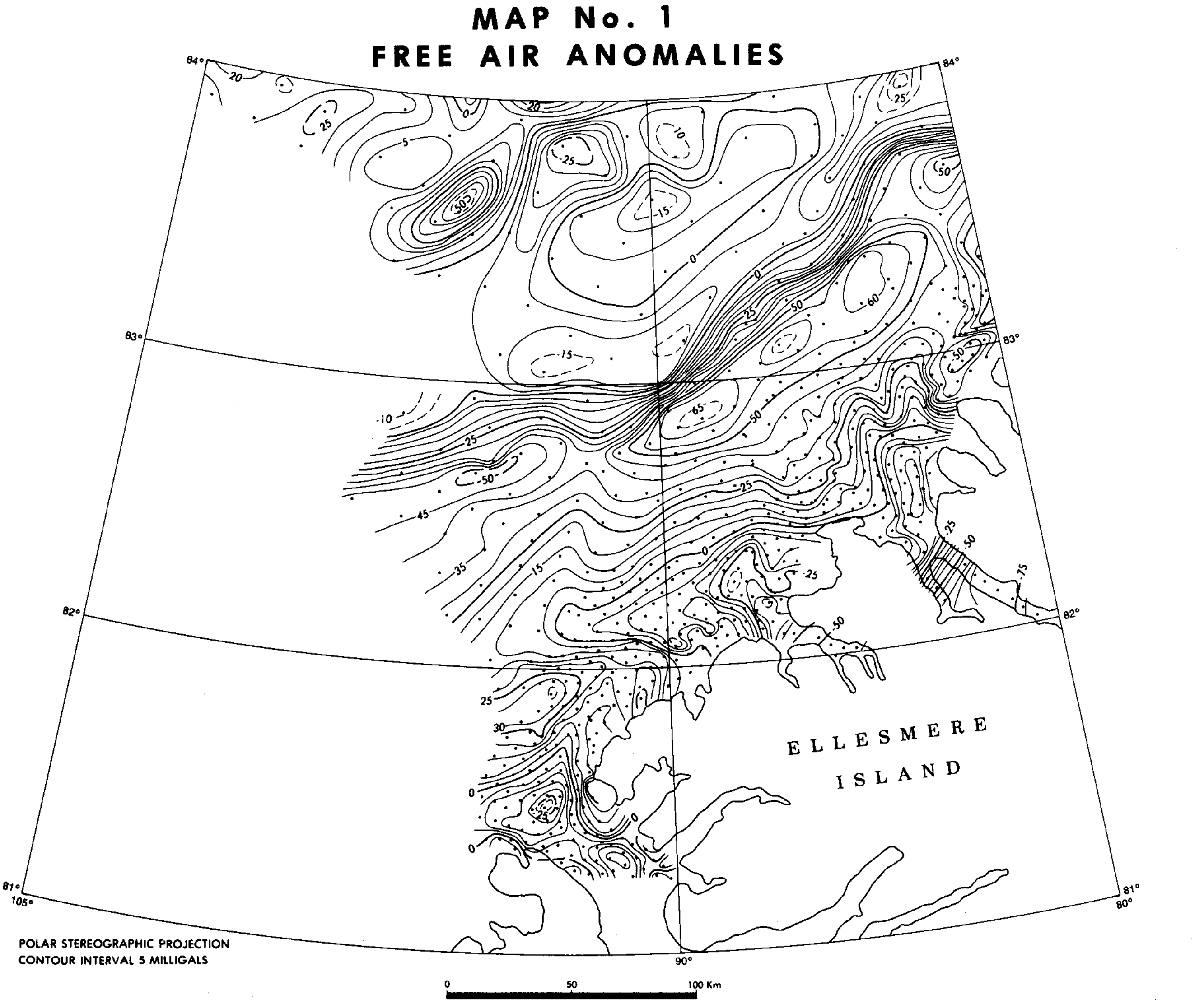

FIG. 9A-C. CESAR 83 free-air gravity anomaly maps. Contour interval 5 mGal. Station locations shown by dots are the same as the sounding locations of the bathymetric map of Figure 7a-c.

completely accounted for by a thin (up to 500 m thick) layer of unconsolidated sediments in the valley troughs over an upper crust with an average density of 2.88 g·cm^{-3} and a lower crust with an average density 3.04 g·cm^{-3} below 26 km depth. This implies an extraordinary lateral density homogeneity over a distance of nearly 500 km. There is no known exposed continental feature of that extent anywhere that displays a crust of such uniform density. The crustal densities for the upper and lower crust represent average densities used for modelling purposes, and in reality the density may increase gradually with depth. This supposition is corroborated by the seismic refraction data, which show no significant reflector in the upper crust, suggesting a gradual increase of seismic velocity within the top 23 km of the crust (Forsyth *et al.*, 1986). This gradual increase of density and seismic velocity with depth together with the lateral density homogeneity surmises an upper crust composed of rock of uniform composition. Comparison of the average crustal densities, excluding water, derived from the density model of Figure 10, show that the Alpha Ridge crust is constructed of a rock type on average 0.085 g·cm^{-3} denser than the rocks of continental origin, of which the Lomonosov Ridge crust is composed (Weber and Sweeney, 1987).

SUMMARY AND CONCLUSIONS

The Alpha Ridge, up to 500 km wide, is a rugged arch with valleys and ridges striking parallel to the ridge axis. It rises 2800 m above the adjoining abyssal plains, and in areal extent it exceeds that of the Alps. The eastern part of the Alpha Ridge between the Ellesmere Island continental margin and the 116°W meridian was investigated during the CESAR multidisciplinary operation in 1983. Deployment and evacuation of the drifting research station was carried out by the Canadian Armed Forces. A preceding side-looking airborne reconnaissance survey of the area facilitated the subsequent search for a suitable site on the sea ice. The CESAR bathymetric and gravity data and all publicly available data were used to compile detailed bathymetric and free-air gravity anomaly maps of the region between Ellesmere Island and the north polar area. Previous to 1983 the nature and origin of the Alpha Ridge were unknown and many

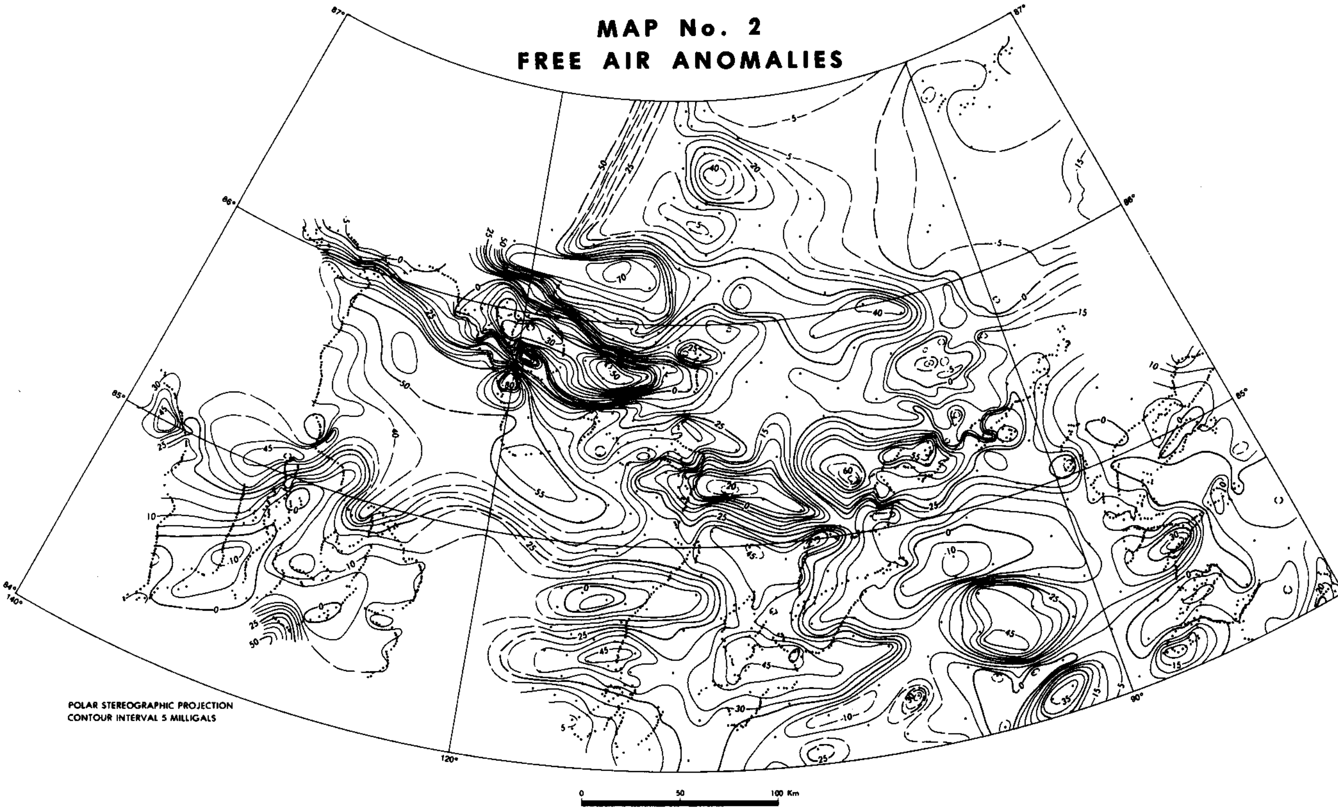

FIG. 9B.

hypotheses were postulated ranging from continental to oceanic origin. The CESAR bathymetric data reveal a hummocky high-relief crustal zone with peaks and swales unknown previously. The ridge is separated from the adjoining Ellesmere Island continental shelf by a 1800-2000 m deep trough. Positive free-air gravity anomalies centered on the continental shelf break suggest that the Ellesmere Island continental shelf is a typical Atlantic-type passive margin and that the ridge may structurally not be connected to the continent. The gravity anomalies across a 500 km wide section of the Alpha Ridge can be almost completely accounted for by topography, shallow sedimentary fill and a simple two-tier crustal model. This implies an extraordinary lateral density homogeneity unknown in continental structures of comparable size. Densities and seismic velocities in the upper crust appear to increase gradually with depth, suggesting the crust is composed of a uniform rock type. A gravity-derived density model constrained by seismic crustal depth determinations shows the crustal thickness to increase gradually from 20 km at the Marvin Spur to 38 km at the ridge crest. At a crustal thickness comparable to that of the Lomonosov Ridge, model studies indicate that the average crustal density is greater for the Alpha Ridge by some 0.085 $g \cdot cm^{-3}$ than for the Lomonosov Ridge. This implies that the Alpha Ridge is composed of considerably denser rocks than the sub-parallel Lomonosov Ridge, whose rocks originate from the Siberian continent. The apparent uniformity of rock density and composition, the greater density and the deep crustal root suggest that the eastern part of the Alpha Ridge may be a massive accumulation of mafic rocks of probable oceanic origin formed by volcanic activity.

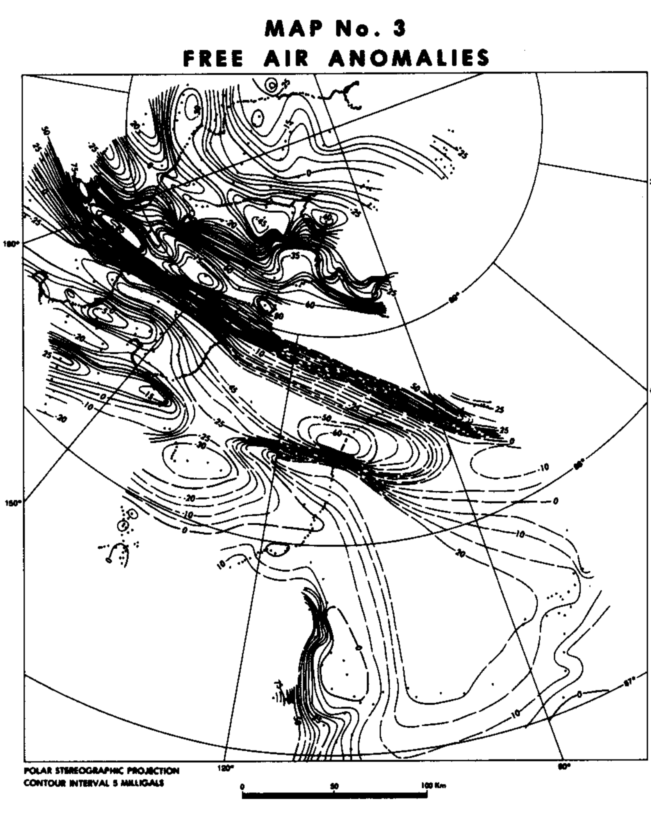

FIG. 9C.

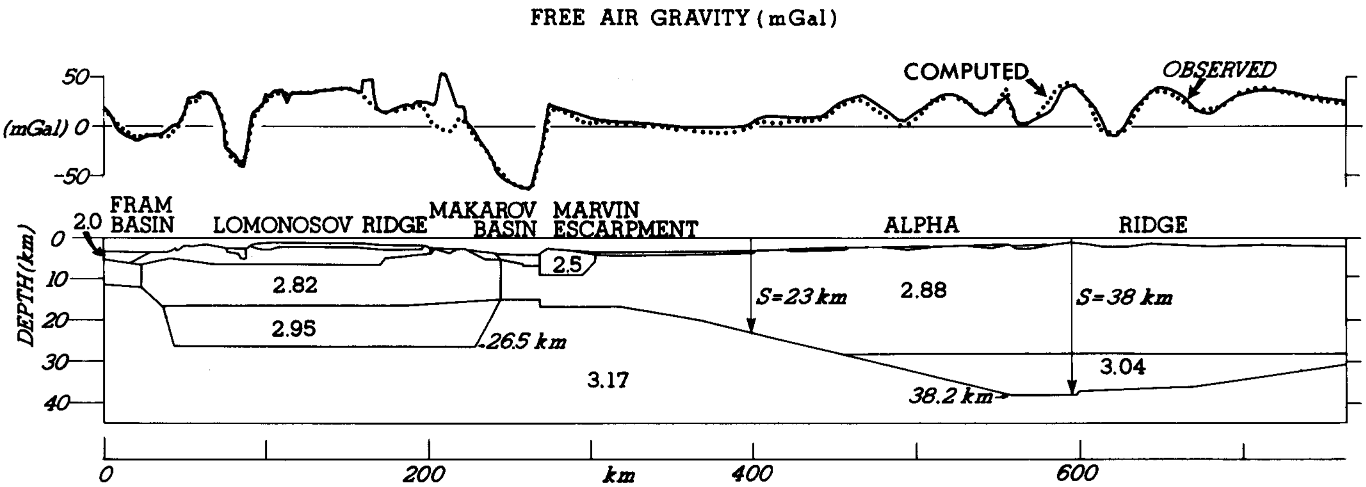

FIG. 10. Gravity-derived crustal model across Lomonosov Ridge, Makarov Basin and part of the Alpha Ridge along profiles AG′-AG and LG′-LG (Fig. 2). Densities are in units of g·cm^{-3}.

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