

# Physiographic provinces of the Arctic Ocean seafloor

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## ABSTRACT

The International Bathymetric Chart of the Arctic Ocean (IBCAO) grid model has been used to define the first-order physiographic provinces of the Arctic Ocean, which in this study is taken to consist of the oceanic deep Arctic Ocean Basin; the broad continental shelves of the Barents, Kara, Laptev, East Siberian, and Chukchi Seas; the White Sea; and the narrow continental shelves of the Beaufort Sea and the Arctic continental margins of the Canadian Arctic Archipelago and northern Greenland. The first step in this classification is an evaluation of seafloor gradients contained in a slope model that was derived from the IBCAO grid. The evaluation of this slope model, which emphasizes certain process-related seafloor features that are reflected in the bathymetric information, is subsequently used along with the bathymetry to classify the first-order physiographic provinces. The areas of the provinces so classified are individually calculated, and their morphologies are subsequently discussed in the context of the geologic evolution of the Arctic Ocean Basin as described in the published literature. In summary, this study provides a physiographic classification of the Arctic Ocean seafloor according to the most up-to-date bathymetric model, addresses the geologic origin of the prominent features, and provides area computations of the defined first-order physiographic provinces

and of the most prominent second-order features.

**Keywords:** Arctic Ocean, physiography, bathymetry, ocean ridges, ocean basins.

## INTRODUCTION

Early characterizations of Arctic Ocean physiographic provinces include contributions by Dibner et al. (1965), Hunkins (1968), and Treshnikov et al. (1967), which were based on laboriously accumulated spot soundings and precision depth recorder records from drifting ice stations. The first continuously recorded echo-sounder profile across the center of the Arctic Basin, collected by the USS *Nautilus* (SSN 571) in 1958, and data from subsequent U.S. Navy nuclear submarine cruises enabled Dietz and Shumway (1961) and Beal (1969) to define the first-order geomorphology of the basin. However, uneven distribution of the data remained an obstacle to a quantitative basin-wide assessment 30 yr later (Johnson et al., 1990). The most recent contribution to a characterization of the Arctic Ocean physiography consists of the Russian “Orographic Map” published by Naryshkin and Gramberg (1995). This map is based on bathymetric information and a thorough analysis of the seafloor topography without relating it to existing geologic or geophysical results.

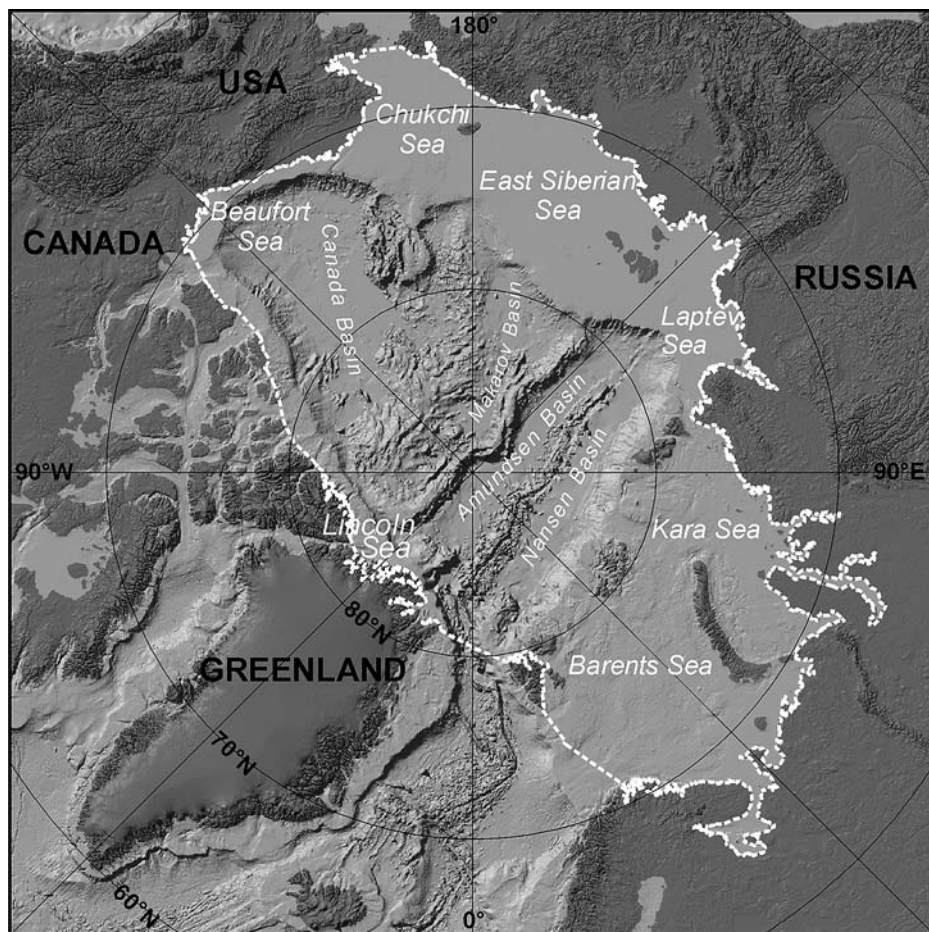
The International Bathymetric Chart of the Arctic Ocean (IBCAO) is a model, based on a 2.5 × 2.5-km gridded model, that provides a detailed and coherent description of the morphology of the Arctic Ocean seafloor and surrounding land areas north of 64°N (Jakobsson

et al., 2000). Its definition of the seabed represents a significant improvement over previous portrayals (e.g., Canadian Hydrographic Service, 1979; Perry et al., 1985) because it incorporates quantities of legacy and modern data sets that were previously unavailable.

The present paper utilizes the updated IBCAO grid model (Jakobsson and IBCAO Editorial Board Members, 2001) to define the physiographic provinces of the Arctic Ocean, which here is taken to consist of the oceanic deep Arctic Ocean Basin; the broad continental shelves of the Barents, Kara, Laptev, East Siberian, and Chukchi Seas; the White Sea; and the narrow continental shelves of the Beaufort Sea and the Arctic continental margins of the Canadian Arctic Archipelago and northern Greenland (Fig. 1). Advances in computer technology have facilitated experimentation with digital data sets and the testing of advanced segmentation and classification methods for resolving seafloor morphology (e.g., Fox and Hayes, 1985; Neumann and Forsyth, 1995). Here, we adopt a simple approach to perform an initial segmentation of the Arctic seabed through the evaluation of a slope model of the seafloor that has been derived from the IBCAO grid. A slope model emphasizes certain process-related seafloor features that enhance the bathymetric information. The concept of using slope information for morphologic studies has previously been applied to the ETOPO 5 worldwide 5 × 5-minute gridded data set (Moore and Mark, 1986).

In the present study, the result of the slope segmentation is combined with the bathymetric information to classify first-order physio-

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**Figure 1.** The Arctic Ocean, its shallow marginal seas, and major basins. The dashed white line circumscribes the area of the Arctic Ocean that was adopted for this study.

graphic provinces of the Arctic Ocean. The areas of these provinces are individually calculated, and the morphology of each province is then discussed in the context of the geologic evolution of the Arctic Ocean Basin. Finally, the outlined first-order physiographic provinces are further subdivided and classified in terms of their geologic origin.

## METHODS

Prior to classifying the Arctic Ocean into general physiographic provinces, we performed an initial segmentation in six semiautomatic steps:

1. A bottom-slope model was constructed from the IBCAO data set by calculating the slope of the seabed at every grid point using the approach described in Jakobsson (2002).

2. The slope model was draped directly onto the IBCAO bathymetry for interactive visualization (e.g., Figs. 2A and 2B). This visualization was done in three dimensions by

using the Fledermaus software (Mayer et al., 2000).

3. With the interactive tools available in Fledermaus, the color scale for the slope model was reduced, after visual iteration, to three intervals: (1)  $0.0^\circ$  to  $0.5^\circ$ , (2)  $0.5^\circ$  to  $1.5^\circ$ , and (3)  $>1.5^\circ$ . These intervals were selected because they appeared to generally correspond, on visual examination, to the first seven classes of physiographic provinces listed in Table 1, which are characterized mainly by their slope and overall morphology. The remaining provinces shown in Table 1 could not be characterized solely by bottom slope. In certain locations, the gradual nature of the changes in bottom inclination made it difficult to detect transitions between the continental rise and slope, as well as between the rise and abyssal plain; in these cases, some manual intervention was required. This manual adjustment of the boundaries between the physiographic provinces is explained in step 6. The final outcome of step 3 was to divide the study area,

with the exception of topographic highs, into zones or segments according to their slope intervals.

4. The draped-slope model was redrawn to show the regional distribution of the segments produced in step 3 (Figs. 2C, 2D, 2E), and these data were then used to create a two-dimensional raster image (Fig. 3A). The generally smooth nature of the IBCAO grid minimized, but did not totally prevent, the appearance of singularities within the visualized slope model. Therefore, the image was filtered in Intergraph's Modular GIS Environment (MGE; GIS—geographic information system) Image Analyst software by a linear-feature-preserving (LFP) convolution filter with a kernel size of  $9 \times 9$ . This procedure removed the smaller singularities in the image and smoothed its appearance (Fig. 3A).

5. MGE GIS tools were used to generate polygons that enclosed the slope-defined areas, which were then assigned to specific physiographic provinces (Fig. 3B).

6. Bathymetric profiles from the IBCAO grid model (Figs. 3A and 4) were generated to help define the transitions between the continental shelf and continental slope (the shelf break), the continental slope and rise, and the continental rise and abyssal plain. Inspection of the profiles resulted in minor modifications of the shelf break and, in some areas, pronounced modifications of the transitions from continental rise to abyssal plain. In particular, in the Canada Basin we found that the transition from continental rise to abyssal plain was very gradual; thus the relatively high cut-off slope value of  $0.5^\circ$  was not appropriate in this area.

Areas of the classified physiographic provinces (Table 2) were calculated by using Bentley's CAD (computer-assisted design) software MicroStation and Intergraph's GIS tools from the MGE (Modular GIS Environment) family of software applications. All areas, consisting of the polygons created during the seafloor-classification process, were calculated on a Lambert's Equal Area projection.

## RESULTS

An assessment of the characteristics of the bottom-slope model has allowed a delimitation of the Arctic Ocean's physiographic provinces (Tables 1 and 2). The geographic distribution of the physiographic provinces in the Arctic Ocean is illustrated in Figure 3B.

### Continental Shelf

The Arctic Basin is almost completely landlocked; Fram Strait, between Greenland and

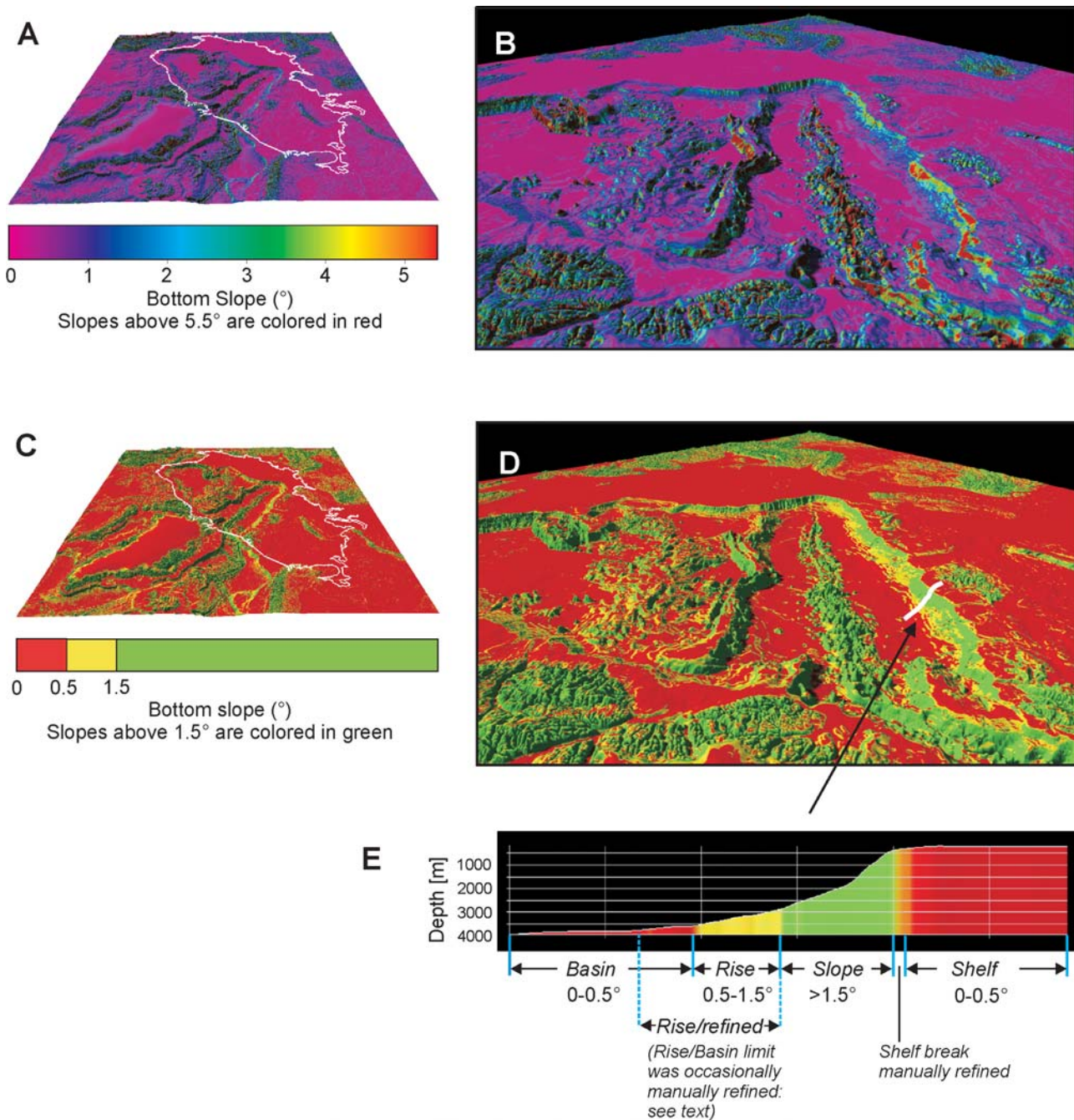


Figure 2. Illustration of the first semiautomatic steps used to classify first-order physiographic provinces underlying the Arctic Ocean. (A) Bottom-slope model rendered in a normal spectral color band and draped upon an oblique view of the IBCAO bathymetry grid, looking north along the Greenwich meridian. (B) Same information as in A, but looking eastward along the Gakkel Ridge. (C) Redrawn bottom-slope model, now rendered in only three colors and draped upon the IBCAO bathymetry grid (Note that all seafloor areas with slopes higher than 1.5° are colored in green). (D) Same information as in C, but looking eastward along the Gakkel Ridge. (E) Depth profile across edge of the Barents continental shelf (white line in D), illustrating variability of bottom slope in three colors.

Svalbard, is the basin’s only deep connection to the World Ocean. The Arctic margins of the surrounding landmasses are fringed by extensive continental shelves, defined as the area between the mainland coast or barrier islands

and the shelf break. These shelves cover by far the largest area of the Arctic Ocean seabed, encompassing both the wide shelves north of Russia and western Alaska and the relatively narrow shelves off northern Alaska, Canada,

and Greenland (Fig. 3B). In aggregate they make up as much as ~52.7% of the total area of the Arctic Ocean (Fig. 5 and Table 2). This calculation excludes the area of all islands that are situated on the shelves and the areas of the

TABLE 1. MAJOR CLASSES OF PHYSIOGRAPHIC PROVINCES OF THE ARCTIC OCEAN

Physiographic province	Slope
1. Continental shelf	0.0°–0.5°
2. Continental slope	>1.5°
3. Continental rise	0.5°–1.5°
4. Perched continental rise	0.5°–1.5°
5. Abyssal plain	0.0°–0.5°
6. Perched abyssal basin	0.0°–0.5°
7. Isolated basin	0.0°–0.5°
8. Ridge	
9. Submarine highland (isolated or clusters)	

*Note:* Defined in this study. The first seven provinces are provisionally delimited by characteristic bottom slopes of the IBCAO model.

ridges that are physiographically connected to the shelves.

### Continental Slope

Continental slopes nearly enclose the Arctic Ocean. The only break is located at the Fram Strait (Fig. 3B), where the North Atlantic joins the Arctic Ocean in a bathymetrically complex linear connection that is ~2500 m deep at its shallowest point and ~50 km wide at the 2500 m isobath at its narrowest point. Continental slopes makes up ~5.7% of the entire area of the Arctic Ocean (Fig. 5 and Table 2).

### Continental Rise

This province (Fig. 3B) features gently sloping seafloor that is underlain by wedges of clastic sediment that originated in the adjacent continents. Most of the continental rises extend from the foot of a continental slope to an abyssal plain, but some of them, e.g., the Chukchi and Wrangel Perched Continental Rises (see subsequent descriptions), begin at the continental slope and extend only as far as sediment dams that are located from 1 to 1.5 km above the abyssal plain that lies downslope. Continental rises form an irregular band that almost completely encircles the deep Arctic Ocean with major breaks only at Fram Strait and the base of the Northwind Escarpment, the east face of the Northwind Ridge.

The Mackenzie Continental Rise (Mackenzie Rise—which lies between the narrow continental slope that forms the front of the Mackenzie Delta and the Canada Abyssal Plain) and the Lena/Amundsen Continental Rise (Lena/Amundsen Rise—which lies between the continental slope that fringes the Laptev Shelf and the Pole Abyssal Plain) feature the most gradual transitions from continental rise to abyssal plain in the Arctic Ocean (Fig. 4). In these areas, the transitions between the rise

and abyssal plain were defined largely through an analysis of bathymetric profiles (see profiles 2 and 4, respectively, in Fig. 4). Continental rises, excluding the perched rises described in the next paragraph, underlie ~7.7% of the area of the Arctic Ocean (Fig. 5 and Table 2).

### Perched Continental Rise

The continental-rise sedimentary prisms that formed off the western Chukchi and East Siberian shelves are separated from the Canada and Fletcher Abyssal Plains by the Northwind Ridge, the Chukchi Spur, the Chukchi Plateau, the Mendeleev Ridge, and the Lomonosov Ridge, which abut this sector of the continental margin. As a result these sedimentary prisms appear to be dammed at the narrow passages between the ridges and are perched from a few hundred to more than 1000 m above the abyssal plain that lies downslope (Fig. 3B). These perched continental rises underlie ~3.8% of the Arctic Ocean (Fig. 5 and Table 2).

### Abyssal Plain

Four abyssal plains underlie the Arctic Ocean (Fig. 3B). All are deep-water areas of low relief underlain by flat-lying or almost flat-lying sedimentary deposits. These deposits are several kilometers thick beneath the Barents and Pole Abyssal Plains of the Eurasia Basin (Jokat et al., 1995) and 6 to 14 km thick beneath the Canada Abyssal Plain of the Amerasia Basin (Grantz et al., 1990)—the thickest sedimentary deposits in the Arctic Basin. The smaller Fletcher Abyssal Plain of the Amerasia Basin, which lies between the Lomonosov and Alpha Ridges, is underlain by 3.5 km or more of flat-lying sedimentary deposits, as estimated from a seismic reflection profile presented in Figure 3 of Jokat et al. (1992). Abyssal plains underlie ~11.8% of the Arctic Ocean and are the third most extensive physiographic province (Fig. 5 and Table 2).

### Perched Abyssal Basins

Two small basins are perched above the northern part of the Canada Abyssal Plain. They are subcircular to equilateral, have diameters of ~400 km, and open into the northwestern and northeastern corners of the Canada Basin (Fig. 3B). The abyssal basin that opens into the northwestern Canada Basin is herein named the “Nautilus Basin” after the USS *Nautilus* (SSN 571), which traversed the

basin during its historic first crossing of the Arctic Ocean by any vessel via the North Pole in 1958. The basin that opens into the northeastern Canada Basin is called the Stefansson Basin (VNIIOkeangeologia, 1999). The floor of the Nautilus Basin consists of irregularly shaped plains lying at depths of 3200 to 3800 m through which rise submarine highlands as shallow as 2300 m. The basin is surrounded on the west, north, and northeast by the Alpha-Mendeleev Ridge and on the south by the ridges of the Chukchi Continental Borderland, which is comprised of the Chukchi Spur, Chukchi Plateau and the Northwind Ridge. On the southeast, the Nautilus Basin is bordered by the Canada Abyssal Plain, which lies ~100 to 500 m below the floor of the basin. The floor of the Stefansson Basin is smoother than that of the Nautilus Basin. It lies at depths of 3000 to 3500 m and contains isolated submarine highlands with peaks that reach to 2000 m below sea level. The basin lies between the Canadian continental slope, Alpha Ridge, and Nautilus Spur on the east, north, and west and the northeastern Canada Basin on the south. The perched abyssal basins, including the area of their submarine highlands, underlie ~2.3% of the Arctic Ocean (Fig. 5 and Table 2).

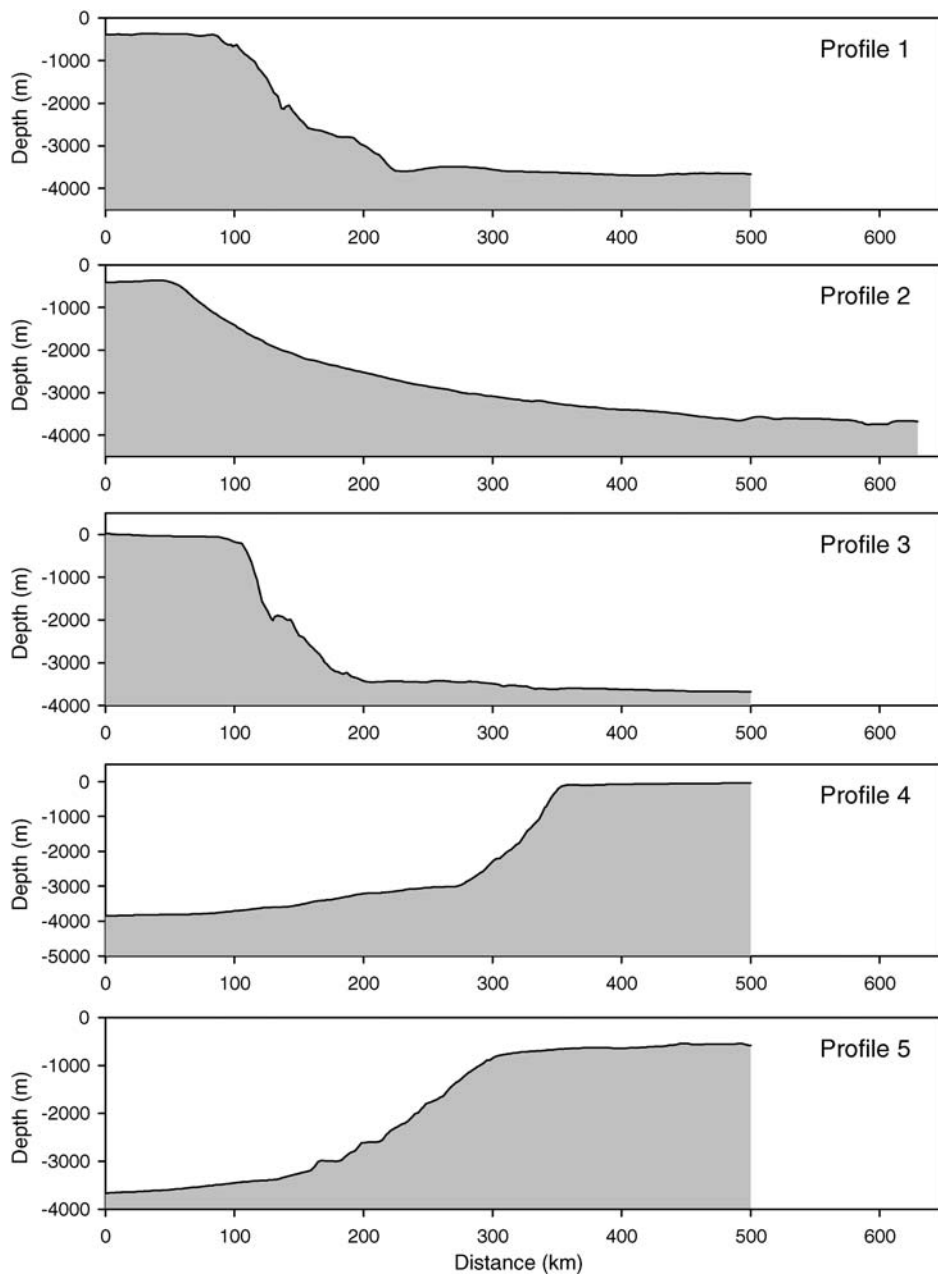
### Isolated Basin

The north-trending ridges comprising the Chukchi Continental Borderland enclose an extensional basin with a generally flat seafloor at depths of ~2000 m that contains several small, generally north-trending submerged ridges. This is the Northwind Basin that, because of its unique physiography, led to the creation of the physiographic province “isolated basins,” which underlies ~0.2% of the Arctic Ocean (Fig. 5 and Table 2). The estimated area of the Northwind Basin includes the small north-trending ridges in the basin.

### Ridges

This physiographic province encompasses all of the Arctic Ocean submarine ridges, irrespective of their geologic origin (Fig. 3B). This province includes two components of the worldwide Mid-Ocean Ridge system that enter the Arctic Ocean: the large Gakkel (Arctic Mid-Ocean) Ridge, which bisects the Eurasian Basin, and a short, irregular unnamed ridge segment in Fram Strait that links the Gakkel Ridge to the Mid-Atlantic Ridge in the Greenland Sea. A new era of bathymetric swath mapping has made the axial part of the Gakkel Ridge one of the better-surveyed spreading





**Figure 4.** A selection of bathymetric profiles that were analyzed to delineate the shelf break and the transition between the continental rise and abyssal plain in the Arctic Ocean. The location of these profiles is shown in Figure 3A.

centers in the global ocean (Kurras et al., 2001). West of 70° E, the rift valley is filled with sedimentary deposits, and the topography is therefore subdued. The deepest part of the axial valley, as indicated on the IBCAO bathymetry, is ~5243 m below sea level close to the Laptev Sea margin near 81°20' N, 120° 45' W. Note that this depth is derived from the interpolated IBCAO grid cell of 2.5 × 2.5 km rather than from a direct observation.

North of 80° N, the mid-ocean ridge seg-

ment in Fram Strait is composed of a well-defined but unnamed isolated ridge east of Lena Trough, and the poorly defined counterpart of the unnamed ridge that lies between Lena Trough and northeast Greenland.

The largest ridge in the Arctic Ocean is the Alpha-Mendeleev Ridge, a submarine mountain system that follows an arcuate trend across the Arctic Ocean Basin from the Canadian Continental Margin northwest of Ellesmere Island to the Russian Continental Margin

north of Wrangel Island. It is a broad, morphologically complex feature with numerous seamounts and sea valleys and summit elevations that range from more than 2000 to ~740 m below sea level. A large projection of the Alpha-Mendeleev Ridge into the Canada Basin near 150° W is here named the Nautilus Spur.

A narrow linear feature crosses the Arctic Ocean Basin from northern Greenland to the western part of the East Siberian Sea near the New Siberian Islands. This is the Lomonosov Ridge, which divides the Arctic Ocean Basin into its two major components, the Eurasia and Amerasia Basins. The Lomonosov Ridge, which is more than 1500 km long and rises from water depths of more than 4200 m to reach elevations of less than 700 m below sea level, is the second largest ridge in the Arctic Ocean (Table 2).

The smaller ridge systems in the Arctic Ocean consists of the Northwind Ridge and the Chukchi Spur–Chukchi Plateau composite ridge of the Chukchi Continental Borderland, which trend northward into the Amerasia Basin from the Chukchi Shelf. These ridges are characterized by relatively steep slopes, flat to gently convex crests that reach to just less than 250 m below sea level (Chukchi Plateau), and margins that are composed of predominantly linear slope segments.

Also included in the ridge physiographic province are the smaller Yermak Plateau and Morris Jesup Rise, which straddle the western end of the Eurasian Basin. These flat-topped features merge with the continental shelves northwest of Svalbard and north of Greenland, respectively. The total area of the Arctic Ocean that is underlain by submarine ridges is ~15.8%, which makes this physiographic province the second largest in Arctic Ocean (Fig. 5 and Table 2).

**Submarine Highlands**

This province (Fig. 3B) comprises a miscellany of small, irregularly shaped and unevenly distributed seafloor elevations with low to moderate relief that are discussed in greater detail in a subsequent section. Combined they underlie ~0.7% of the Arctic Ocean (Table 2).

**DISCUSSION**

In this section we interpret the geologic character of the physiographic provinces of the Arctic Ocean on the basis of our assessment of published literature (Table 2 and Figs. 6 and 7).

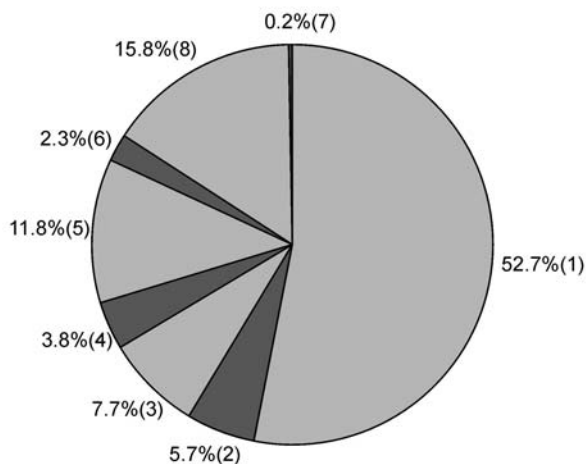
PHYSIOGRAPHIC PROVINCES OF THE ARCTIC OCEAN SEAFLOOR

TABLE 2. PHYSIOGRAPHIC PROVINCES OF THE ARCTIC OCEAN AND THEIR CALCULATED AREAS

Physiographic province	Area ( $\times 10^3$ km <sup>2</sup> )	Relative area (%)	Subclassification considering geologic origin	Area ( $\times 10^3$ km <sup>2</sup> )	Relative area (%)	Feature in province	Area ( $\times 10^3$ km <sup>2</sup> )	Relative area for feature (%)
1. Continental shelf	5025	52.7	No further subdivision					
2. Continental slope	541	5.7	No further subdivision					
3. Continental rise	733	7.7	Continental rises	733	7.7	Mackenzie Rise (MR) Mackenzie Rise (seismic data) Canada-Greenland Rise (CGR) Barents/Kara Rise (BKR) Lena/Nansen Rise (LNR) Lena/Amundsen Rise (LAR) Beaufort Rise (BR) Yermak Rise (YR)	178 (301) 249 124 67 77 23 15	1.9 (2.5) 2.6 1.3 0.7 0.8 0.2 0.2
4. Perched continental rise	362	3.8	Perched continental rises	362	3.8	Chukchi Perched Rise (CR) Wrangel Perched Rise (WR) Ailis Perched Rise (AR)	43 239 80	0.5 2.5 0.8
5. Abyssal plain	1122	11.8	Abyssal plains	1122	11.8	Barents Abyssal Plain (BA) Pole Abyssal Plain (PA) Fletcher Abyssal Plain (FA) Canada Abyssal Plain (CA) Nautilus Basin (NB) Stefansson Basin (SB) Northwind Basin (NBA)	295 291 42 494 124 98 23	3.1 3.0 0.4 5.2 1.3 1.0 0.2
6. Perched abyssal basin	222	2.3	Basins underlain by oceanic volcanic rock	222	2.3			
7. Isolated basin	23	0.2	Structural basin underlain by continental rocks	23	0.2			
8. Ridge	1506	15.8	Mid-ocean ridges	332	3.5	Gakkel Ridge (GR) Unnamed ridge segment in Fram Strait (UN)	295 37	3.1 0.4
			Ridges underlain by continental rocks	427	4.5	Lomonosov Ridge (LR) Northwind Ridge (NR) Chukchi Ridge (CP + CS) Alpha-Mendelev Ridge (AM), including Nautilus Spur (NS)	307 120 708	3.2 1.3 7.4
9. Submarine highland	(69)	(0.7)	Submarine highlands	(69)	(0.7)	Yermak Plateau (YP) Morris Jesup Rise (MJ) Sever Spur (SS) Pearya Spur (PS) Miscellaneous submarine highlands	35 5 (27) (6) (36)	0.4 <0.1 (0.3) (0.1) (0.4)
Total (rounded from sum of nonrounded original calculations)	9534	100						

Note: The acronyms used in Figures 3B, 6, and 7 are shown within parentheses for each named feature. Note that for Sever and Pearya Spurs in the submarine highland province, their areas are shown in parentheses: in view of their geologic origins, they are more properly accounted for as components of Stefansson Basin in the perched abyssal plains province. Note also that the area for Mackenzie Rise is shown in parentheses to indicate its alternative derivation from seismic reflection data; this is not included in the total area shown for the continental rises province. Furthermore, the total area of continental shelves presented in this table is  $\sim 5025 \times 10^3$  km<sup>2</sup>, which is  $\sim 27 \times 10^3$  km<sup>2</sup> smaller than reported by Jakobsson (2002). The reason for this discrepancy is that Chukchi Spur is in here classified as a ridge, whereas it was included in the Chukchi Shelf Sea in Jakobsson (2002).

## Physiographic provinces of the Arctic Ocean



**Figure 5.** Relative areas of classified first-order physiographic provinces underlying the Arctic Ocean and its shallow marginal seas. Numbers within parentheses refer to the physiographic provinces (the same numbers are used in Tables 1 and 2 and Figs. 3B and 7): 1—continental shelf; 2—continental slope; 3—continental rise; 4—perched continental rise; 5—abyssal plain; 6—perched abyssal plain; 7—basin; 8—ridges; 9—submarine highlands.

### Eurasia Basin

Seafloor magnetic anomalies parallel to the length of the Eurasia Basin and its axial ridge (the Gakkel Ridge) were first described by Karasik (1968, 1974) and Vogt et al. (1979). These anomalies demonstrate that the Eurasia Basin was probably initiated by seafloor spreading during the opening of the Norwegian-Greenland Sea in the late Paleocene (Vogt et al., 1979).

### Lomonosov Ridge

This significant physiographic feature, which we assign to the category “ridge underlain by continental rocks,” has a profound influence on the oceanographic circulation in the Arctic Ocean (e.g., Anderson et al., 1994; Rudels et al., 1994). On the basis of the first continuous depth profile across the Lomonosov Ridge, Dietz and Shumway (1961) suggested that the ridge is a fault block rather than a volcanic construction. Subsequently, Wilson (1963) envisaged the ridge to be a continental sliver rifted off the outer continental shelf of Eurasia between the northern Svalbard and Severnaya Zemlya during late Paleocene to Holocene propagation of the Mid-Atlantic Ridge into the Arctic Ocean (Karasik, 1968, 1974; Rassokho, 1967; Vink et al., 1984; Vogt et al., 1979). Multichannel seismic reflection data acquired during the 1990s strongly support this interpretation by demonstrating an asymmetric internal architecture

of the ridge consisting of older prograding sequences on the Amerasia Basin side and a steep, fault-bounded margin (Fig. 6) on the Eurasia Basin side (Jokat et al., 1992).

The generally flat crest of the Lomonosov Ridge was inherited from a prominent unconformity that lies ~500 m below the ridge crest and is overlain by a cap of flat-lying sedimentary deposits. This unconformity is thought to have formed from subaerial and shallow-marine erosion when the ridge first subsided below sea level at ca. 50 Ma (Jokat et al., 1995). The areas of the ridge crest above ~1000 m of water depth have been affected by an extensive erosional event during the late Pleistocene, resulting in a prominent unconformity in the upper stratigraphy (Jakobsson, 1999).

### Yermak Plateau and Morris Jesup Rise

These plateaus, which flank the western end of the Eurasia Basin, are conjugate features with respect to the Gakkel Ridge (Figs. 6 and 7). They were considered by Feden et al. (1979) to have, in part, a common origin as a single Iceland-like volcanic massif formed by excessive volcanism in middle Eocene–Oligocene time. Differences in magnetic signature and crustal structure suggest, however, that the western and southern part of Yermak Plateau may consist of continental crust (Jackson et al., 1984). In this case, Yermak Plateau and possibly Morris Jesup Rise may be composite volcanic ridges.

### Gakkel Ridge

The pattern of earthquake epicenters and a few scattered soundings (Gakkel, 1962) led Heezen and Ewing (1961) to extend the Mid-Atlantic Ridge into the Arctic Ocean along the Gakkel Ridge and show that the Eurasia Basin was formed by seafloor spreading. Early traverses by submarines revealed that the western part of the Gakkel Ridge consists of relatively shallow submarine ridges separated by an axial valley (Feden et al., 1979).

The gravity signature suggests that seafloor spreading may continue more than 200 km farther east of the morphologically visible axial valley, beneath the sedimentary deposits of the Laptev Sea continental margin (Laxon and McAdoo, 1997). Seafloor spreading on the Gakkel Ridge is the slowest of the global mid-ocean ridge system (Coakley and Cochran, 1998) because the rate of opening tends to zero as the ridge approaches the pole of rotation between Europe and North America, which is located in Russia near the Lena River delta. The morphological manifestation of slow seafloor spreading is extreme axial-valley depths (>5 km) and relatively rough basement topography.

### Continental Rises and Abyssal Plains

The Gakkel Ridge is flanked by the Pole and Barents Abyssal Plains of the Amundsen and Nansen Basins (Figs. 6 and 7). A major part of Amundsen Basin is deeper than 4000 m whereas the floor of the Nansen Basin is characterized by a gentle northward slope and water depths that are generally less than 4000 m. Johnson (1969) ascribed this difference to larger input of terrestrial sediment to the Nansen compared to the Amundsen Basin because the Nansen Basin lies adjacent to the Kara-Laptev Sea margin, whereas for most of its length, the Amundsen Basin is isolated from the Eurasia continental margin by the Gakkel Ridge. In addition, input from glacial erosion on the Barents-Kara shelf may have been an even more important source of detrital input to the Nansen Basin than terrestrial sediment from the Eurasian landmass (Elverhøj et al., 1998). We observe no continental rise along the foot of the Lomonosov Ridge in the Amundsen Basin, but an extended continental rise occurs at both the east and west ends of the basin. These rises reflect terrestrial-sediment source regions at the Laptev and Greenland margins, respectively (Figs. 6 and 7).

### Amerasia Basin

North-northwest-striking aeromagnetic anomalies (Taylor et al., 1981; Kovacs et al., 1985;

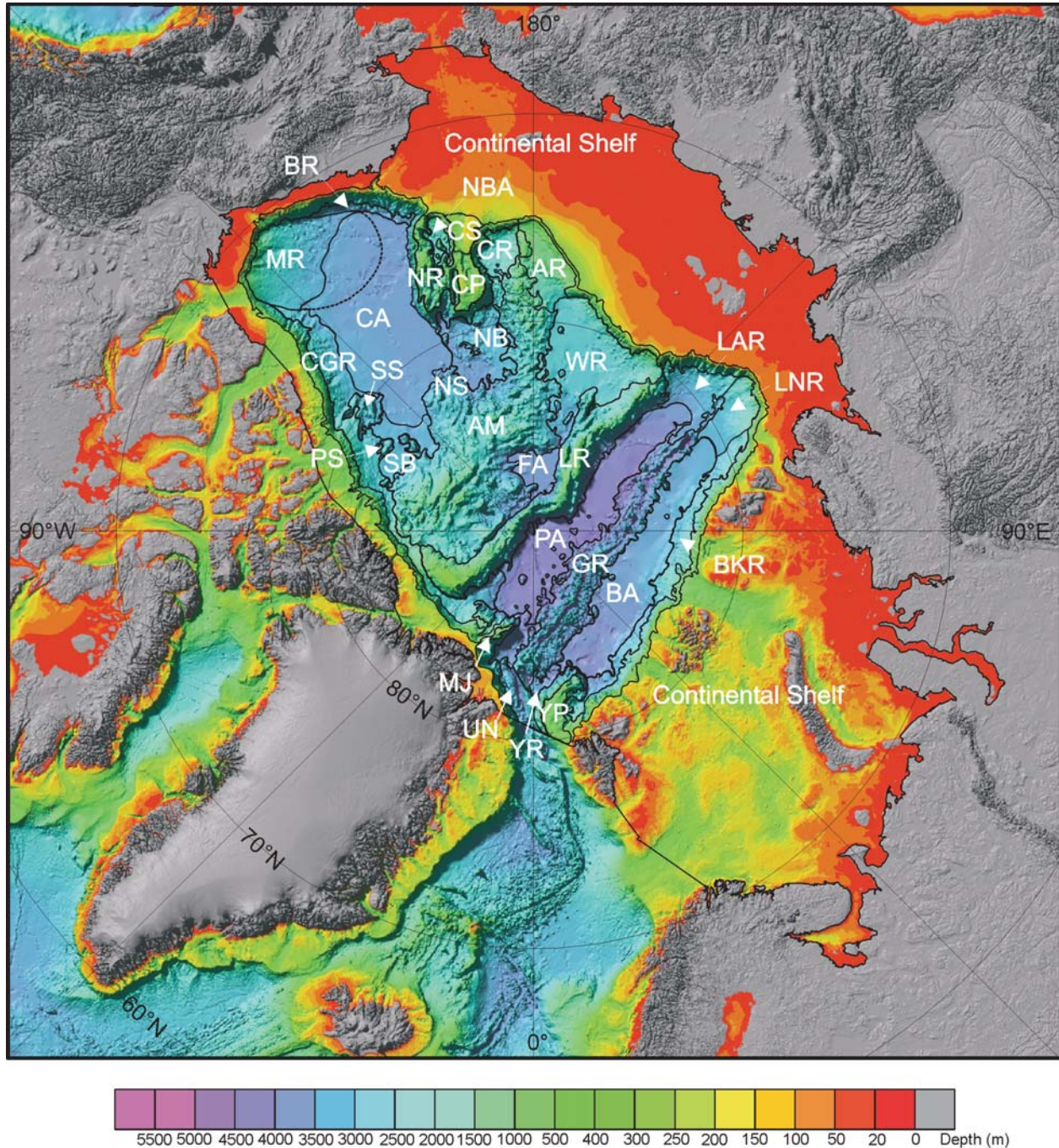


Figure 6. Boundaries of the classified first-order physiographic provinces of the Arctic Ocean, shown together with a shaded relief map of IBCAO bathymetry. Scale is depth (in m). See caption to Figure 3 for an explanation of abbreviations.

Roest et al., 1996) and a negative gravity anomaly coincident with the symmetry axis of the aeromagnetic anomalies (Laxon and McAdoo, 1997) indicate that the Canada Basin, the largest deep basin in the Amerasia Basin, opened by seafloor spreading about a pole of rotation in the lower Mackenzie River valley. Stratigraphic relationships in the continental margin of Arctic Alaska and the character of the magnetic anomalies

in the basin (Grantz et al., 1990) indicate that breakup and seafloor spreading began by the Hauterivian and were completed by middle Aptian time.

**The Alpha-Mendelev Ridge, Including Nautilus Spur**

The Alpha-Mendelev Ridge system, including Nautilus Spur, is characterized by

complex morphology and a planimetrically irregular outline (Figs. 6 and 7), but a generalized surface drawn across the ridge from its crest to its outer limits would have only moderate gradients over the ridge flanks. In these characteristics the Alpha-Mendelev Ridge differs significantly from the morphology of oceanic ridges underlain by continental crust, such as the Lomonosov and Northwind Rid-

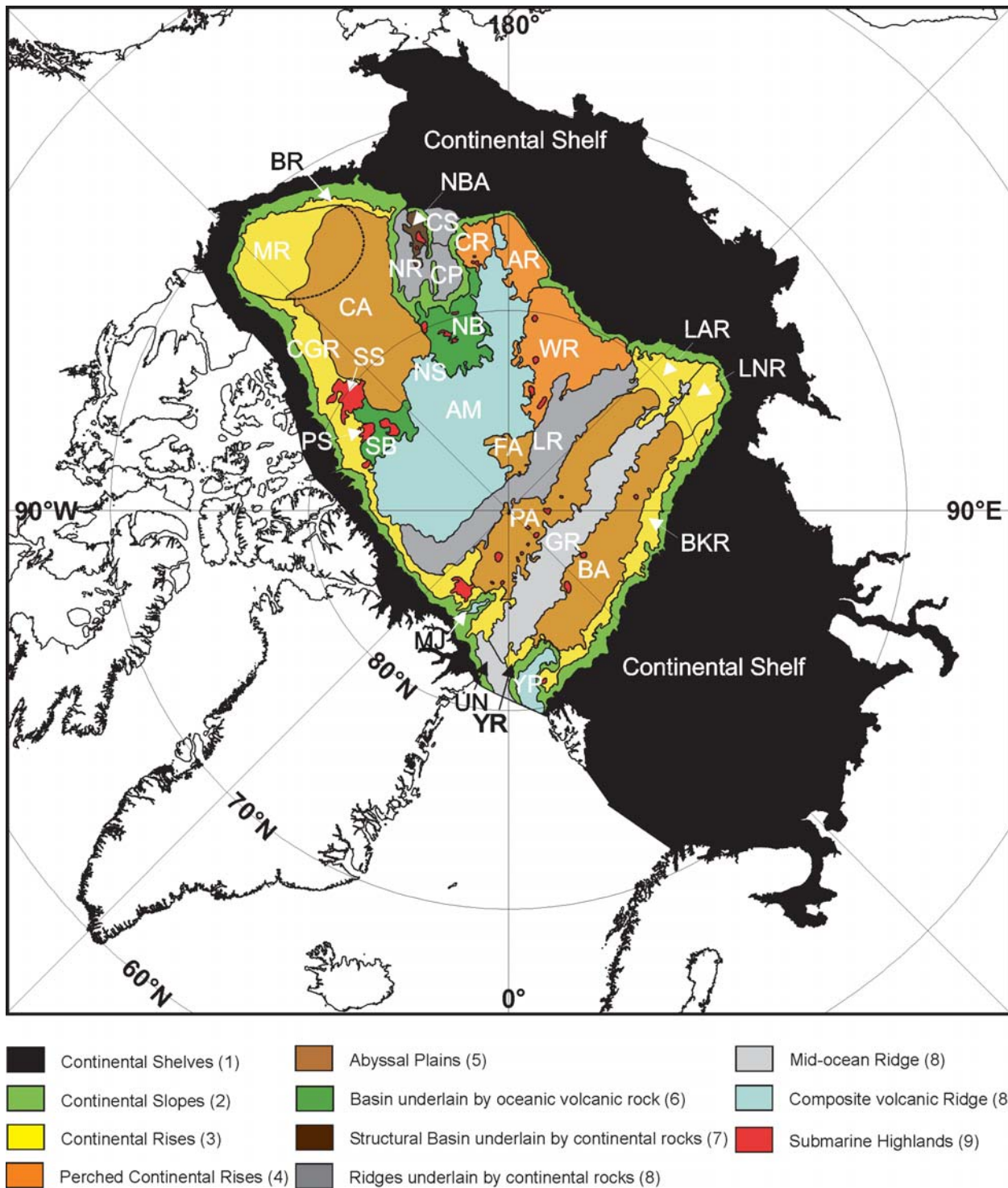


Figure 7. Assessment of the geologic characters of the first-order physiographic provinces of the Arctic Ocean, based on a review of the available geologic literature (see text). Calculated areas of the provinces are presented in Table 2. See caption to Figure 3 for an explanation of abbreviations.

es, which have flat or only gently convex crests and steep slopes.

Aeromagnetic data (Roest et al., 1996) show that the Alpha-Mendeleev Ridge, in-

cluding Nautilus Spur and the crust beneath the adjacent Nautilus and Stefansson Basins, all lie within a single, extensive field of strongly magnetic rocks with a distinctive

anomaly pattern that lies wholly within the confines of the oceanic Arctic Ocean Basin. Numerous kinds of geophysical evidence (e.g., Forsyth et al., 1986; Jackson et al., 1986;

Jokat, 2003; Weber, 1990; Weber and Sweeney, 1990) indicate that the Alpha-Mendelev Ridge consists of volcanic rocks generated at a “hotspot” or “melting spot” within the mantle that were erupted onto oceanic crust. In this case, magma from the hotspot may have been funneled to the spreading axis that created the Amerasia Basin of the Arctic Ocean at ca. 130 to 120 Ma and built a volcanic pile ~35 km thick on the newly generated oceanic crust as it formed at, and moved away from, the seafloor spreading axis. The geometry of spreading may have given the ridge system its west-northwest–east-southeast elongation. Forsyth et al. (1986) and Weber (1990) suggested that the Alpha-Mendelev Ridge may be similar in origin to the oceanic Iceland-Faroe Ridge, a volcanic feature of similar aeromagnetic character and thickness that is now forming at a hotspot localized at the actively spreading Mid-Atlantic Ridge. We classify the Alpha-Mendelev Ridge system as a “composite volcanic ridge” (Table 2, Figs. 6 and 7).

#### *Nautilus and Stefansson Basins*

The floor of Nautilus Basin, which lies 100 to 500 m above the level of the Canada Abyssal Plain, contains numerous abyssal hills and seamounts. It is therefore inferred that the basin is underlain by bedrock at and near the seafloor and that it is only a bathymetric, and not also a sedimentary, basin. The floor of Stefansson Basin, which lies 0 to 500 m above seafloor in the Canada Basin, also contains seamounts and seamount clusters, but the main part of the basin appears to be underlain by continental-rise and abyssal-plain deposits that originated in the Canadian Continental Margin. The morphology of both basins distinguish them from the main part of the Canada Basin, which lacks seamounts and is underlain by 6 to >14 km of sedimentary strata (Grantz et al., 1990). Aeromagnetic data (Roest et al., 1996) indicate that the volcanic rocks that are interpreted to underlie the Alpha-Mendelev Ridge system also underlie the Nautilus Spur and Basin and Stefansson Basin and that, tectonically, both basins are part of the Alpha-Mendelev Ridge in the oceanic composite volcanic ridge subprovince. Therefore, the Nautilus and Stefansson Basins are here grouped under the category “basins underlain by oceanic volcanic rocks” (Figs. 6 and 7).

#### *Chukchi Continental Borderland*

The Chukchi Continental Borderland consists of a tightly clustered group of generally high-standing, north-trending ridges that en-

close the extensional Northwind Basin (Grantz et al., 1999). The ridges are characterized by steep slopes and flat to gently rounded crests and, in these respects, resemble Lomonosov Ridge, Morris Jesup Rise, and the Yermak Plateau. The Northwind Ridge on the east side of the Chukchi Continental Borderland and the Chukchi Spur–Chukchi Plateau composite ridge on the west side are the largest ridges in the borderland. In addition, several much smaller ridges rise above the floor of the Northwind Basin, which lies between the Northwind Ridge and the Chukchi Spur–Chukchi Plateau.

Piston cores (Grantz et al., 1998) indicate that the south-central part of the Northwind Ridge is underlain by fossiliferous sedimentary rocks of continental-shelf and continental-slope lithofacies and biofacies that range in age from Late Cambrian to Pliocene. Only the Silurian and Devonian Systems are not represented by core samples. The Northwind Ridge is therefore classified as a “ridge underlain by continental crust” (Figs. 6 and 7).

Viewed broadly, the Chukchi Spur and the Chukchi Plateau constitute a single feature (the Chukchi Ridge) that, like Northwind Ridge, is ~600 km long. The Chukchi Ridge narrows from ~165 km at the north end of the Chukchi Spur, at ~76° N, to ~110 km at 76.5° N. This narrow “waist” separates the Chukchi Spur on the south from the Chukchi Plateau on the north. A narrow north-trending morphological basin near the axis of the ridge (probably a graben) contributes to the separation. The broad and nearly flat crests and steep slopes of the Chukchi Ridge and its proximity to the similarly trending Northwind Ridge, of similar morphology and known continental character, suggest that the Chukchi Ridge is also a fragment of continental crust.

#### *Northwind Basin*

The north-trending Northwind Basin has a generally flat floor that slightly exceeds 2000 m in maximum depth. Several narrow, north-trending, smaller ridges rise as much as 1500 m above the basin floor. Seismic reflection profiles, bathymetry, and gravity modeling indicate that the Northwind Basin consists of extended, thinned, and subsided continental crust (Grantz et al., 1999) with horst and graben structure. The morphology of the basin, together with the geophysical data and stratigraphic and structural data extrapolated from the Northwind Ridge and the Chukchi Shelf suggest that the basin formed by rifting that separated the Northwind Ridge from the Chukchi Ridge by east-west extension in Late

Cretaceous or early Tertiary time (Grantz et al., 1999). The Northwind Basin is classified as a “structural basin underlain by continental rocks” (Table 2 and Figs. 6 and 7).

#### *Sever (North) and Pearya Spurs*

Two seamount clusters and four isolated seamounts protrude from the Canada Continental Rise and nearby areas of the Canada Abyssal Plain in the northeastern Canada and Stefansson Basins (Figs. 6 and 7). The larger cluster, collectively called Sever (North) Spur on the VNIIOkeangeologia (1999) chart of the Arctic, is ~170 km in diameter and is centered at 80° N (Figs. 6 and 7). Its peaks rise from depths of 3200 m and 2800 m to a seamount that reaches 1816 m below sea level. The smaller cluster, here named “Pearya Spur,” is ~90 km in diameter and centered at 81.7° N. It rises from depths of 3200 to 2800 m, and the highest peak is 2236 m below sea level. The geologic character of Sever and Pearya Spurs and the isolated seamounts is unknown, but their proximity to the Alpha-Mendelev Ridge suggests that they may include rocks of the oceanic volcanic complex thought to underlie that ridge system.

#### *Chukchi, Arlis, and Wrangel Perched Continental Rises*

The Chukchi, Arlis, and Wrangel Continental Rises are irregularly shaped areas of low-gradient seafloor that are isolated from other continental rises in the Arctic Ocean Basin by high-standing ridges that merge with the adjacent continental slopes. The Chukchi Rise lies between the Chukchi Ridge (Chukchi Spur plus Chukchi Plateau) and the Mendelev Ridge; the Wrangel Rise lies between the Mendelev Ridge and the Lomonosov Ridge. The bathymetry suggests that the low hills form sediment dams behind which the sedimentary prisms that underlie the low-gradient Chukchi and Wrangel Continental Rises accumulated. Because these dams are 1 to 1.5 km above the Canada and Fletcher Abyssal Plains, which are situated down the depositional slope, we refer to them as “perched continental rises.” The surface of the Arlis Perched Continental Rise (Arlis Perched Rise) is banked against the Eurasian end of the Mendelev Ridge and is in consequence several hundred meters higher than the upper surfaces of the adjacent Chukchi and Wrangel Perched Rises.

The proximal source of the sediment that created the Chukchi, Arlis, and Wrangel Perched Continental Rises was the outer continental shelf of the Chukchi and East Siberian Seas. The primary sediment source for the

Chukchi Rise was probably detritus transported across the broad Herald Bank–Herald Island–Wrangel Island Ridge of the central Chukchi Sea shelf in the broad Herald Sea Valley at 175° W. The primary source of the sediment that created the Wrangel Rise was probably detritus from the Indigirka River that was carried across the East Siberian Shelf in the Indigirka Sea Valley. Detritus from the Kolyma River carried across the shelf in the more distant Kolyma Sea Valley may also have contributed to the sedimentary prism that underlies the Wrangel Perched Rise.

#### *Canada-Greenland Continental Rise*

The Canada-Greenland Continental Rise stretches from Morris Jesup Rise to the Mackenzie Continental Rise, from which the Canada-Greenland Rise is separated by the steep, strongly gullied north-trending extension of the continental slope that lies off Banks Island of the Canadian Archipelago. The south end of the Canada-Greenland Rise terminates against this extension of the slope near 75° N, 131° W, where the rise lies several hundred meters above the surface of the Mackenzie Rise to the west. The surface of the steeper Canada-Greenland Rise and the more gently sloping Mackenzie Rise merge near the 3500 or 3600 m isobath, ~180 km northwest of 75° N, 131° W.

The Canada-Greenland Rise is narrower and steeper than the Mackenzie Rise and more strongly sculptured by sea valleys and gullies. Seamounts and seamount clusters (Sever and Pearya Spurs) exist within its confines, features that are absent from the Mackenzie Rise. The sediment, which underlies the Canada-Greenland Rise, presumably consists principally of outwash from the outlet glaciers of the Laurentide Ice Sheet.

#### *Mackenzie Continental Rise*

The Mackenzie Rise is a physiographically distinct feature (Figs. 6 and 7) that occupies a large part of the Canada Basin. The continental rise heads in the Mackenzie Delta and was constructed mainly by sediment brought to the Canada Basin by the Mackenzie River, which drains a large part of the western interior of Canada and transported large volumes of glacial detritus during the late Pliocene and Quaternary. The volume of the sediment supplied to the Canada Basin by the Mackenzie River overwhelmed that from all other sources. The head of the Mackenzie Rise lies near the 800 to 1200 m isobaths at the Mackenzie Delta and gradually deepens westward. Seismic reflection profile (profiles 93–11 and 93–12, Grantz et al., 2003), which crosses the foot of

the rise, shows that the Pleistocene sedimentary prism that provides the rise with its distinctive morphology wedges out near 75.3° N, 150.5° W, at a depth of ~3813 m. This is significantly deeper than the position of the boundary as estimated from bathymetric data alone because the IBCAO model did not resolve the wedging of the sedimentary prism owing to limited data available from this area in the compilation (Fig. 6). Using the seismic reflection data as a basis for defining the Mackenzie Rise increases its area by ~70%. The positions of the foot of the Mackenzie Rise based on both the IBCAO gridded bathymetry model and on seismic reflection data are both shown in Figures 3B, 6, and 7.

#### *Canada Abyssal Plain*

The abyssal plain of the Canada Basin occupies the western part of that basin between the foot of the Beaufort Rise in the south and the Stefansson Basin in the north. The Canada Abyssal Plain lies mainly between ~3840 m and ~3900 m below sea level. The surface of the abyssal plain is underlain by thick Holocene deposits which, in a core take near 74.7° N, 156.1° W, are more than 8.47 m thick and were deposited at a rate of ~1 m/k.y. (Grantz et al., 1996).

### CONCLUSION

An analysis of the newly updated digital International Bathymetric Chart of the Arctic Ocean (IBCAO) has yielded a classification of the physiographic provinces of the Arctic Ocean. The area of each physiographic province was calculated and its geologic character interpreted on the basis of our assessment of published literature. For the purposes of this analysis, the Arctic Ocean was taken to consist of the deep central basin, the broad continental shelves off Eurasia, and the narrow continental shelves off North America and northern Greenland.

Continental shelves are the largest physiographic province and make up as much as 52.7% of the total area of the Arctic Ocean. The deep central Arctic Ocean Basin consists of four abyssal plains separated by submarine ridges. These abyssal plains together underlie ~11.8% of the Arctic Ocean, whereas the ridges underlie 15.8%, which makes them the second largest physiographic province after the continental shelves.

Our assessment of the geologic origin of the physiographic provinces concludes that flat-topped, high-standing ridges interpreted to consist of blocks or slivers of continental crust that were detached from the continental

shelves by plate-tectonic processes underlie ~4.5% of the Arctic Ocean. These ridges consist of the Lomonosov Ridge, which separates the Eurasia from the Amerasia Basin, and the ridges comprising the Chukchi Continental Borderland in the Amerasia Basin. Yermak Plateau and Morris Jesup Rise, two relatively small features that together occupy less than 0.5% of the Arctic Ocean, are thought to be flat-topped composite ridges composed of both continental and volcanic rocks. The Amerasia Basin contains the morphologically irregular and deeper submarine ridges of the extensive Alpha-Mendeleev Ridge system, the largest in the Arctic Ocean covering 7.4% of the seafloor area. This system is considered to be a large igneous province (LIP) consisting of volcanic rocks deposited within the deep Amerasia Basin, perhaps at a “hotspot” or “melting spot” that was localized along the spreading axis, which opened the Amerasia (including the Canada) Basin. The Eurasia Basin contains an active mid-ocean ridge (the Gakkel Ridge and an unnamed ridge segment in Fram Strait) that underlies 3.5% of the Arctic Ocean.

The physiographic classifications and area calculations that were developed in the course of this study were derived largely by numerical methods and preserved in a digital form that is amenable to handling and visualization by GIS tools. They therefore offer a flexible framework for more detailed physiographic analyses, as well as investigations in related fields such as sedimentation, ocean circulation, and plate tectonics.

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