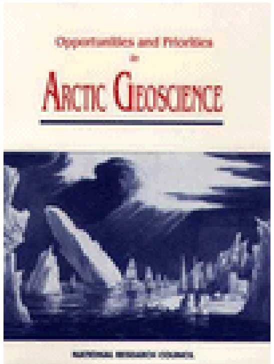

Opportunities and Priorities in Arctic Geoscience

Committee on Arctic Solid-Earth Geosciences, National Research Council

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Opportunities and Priorities in ARCTIC GEOSCIENCE

Committee on Arctic Solid-Earth Geosciences
Polar Research Board
Commission on Geosciences, Environment, and Resources
National Research Council

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Executive Summary

There is broad agreement in the scientific community that the floor of the Arctic Ocean Basin contains potential answers to major unsolved problems in the earth sciences and that many of them pertain to questions that are of global scientific significance or pressing societal concern. However, because of the perennial sea ice, harsh climate, high field costs, and the absence of research platforms suitable for many types of investigations, this region is also one of the most poorly known on earth. Recent political and technological developments, including the apparent end of the Cold War and the prospective availability of nuclear submarines and powerful icebreakers as arctic research platforms, appear to provide possible means to overcome these formidable obstacles and, therefore, have the potential to enable revolutionizing our knowledge of the solid earth beneath the Arctic Ocean Basin. Some of the details of the circum-arctic geology are becoming known from efforts by government agencies, academic institutions, and industry. Because of the prospective logistic opportunities, and because of the disparity in geologic understanding that exists between the Arctic Ocean Basin and the circum-arctic landmasses, the Committee on Arctic Solid-Earth Geosciences recommends that the Arctic Ocean Basin and its margins, instead of the circum-arctic landmasses, be the focus of the next major augmentation of solid-earth geoscience research in the Arctic.

Aspects of arctic solid-earth geoscience with important implications for science and society beyond the Arctic include its tectonic evolution, resource potential, paleoceanographic and climatic history, and geologic processes. A satisfactory level of understanding of the plate tectonic history of the Northern Hemisphere cannot be achieved until sufficient geologic and geophysical data to reconstruct the plate tectonics of the Arctic are obtained. Such reconstructions will improve understanding of the geologic structure and history of all of the Northern Hemisphere and provide valuable insights into the origin and distribution of the mineral fuels and other mineral deposits of the northern continents and their continental shelves. The gas hydrate (probably methane hydrate) deposits of the Arctic Ocean Basin, for example, may contain more than 1,000 times the volume of natural gas in the Prudhoe Bay field.

Paleomagnetic data indicate that one of the earth's magnetic dipoles, and therefore presumably also the geographic North Pole, have resided in or near the Arctic Ocean Basin since it began to form in Jurassic time. Thus, the sediments of the Arctic Ocean Basin and its margins contain a 200-million-year record of earth's north polar climate and oceanographic history and document the climatic deterioration from temperate conditions in the Cretaceous to cyclic glaciation in the Late Tertiary and Quaternary. Because the polar regions contain perhaps the most sensitive indicators of climate change, and because current evidence suggests a major difference in timing of chilling in the Northern and Southern Hemispheres, the arctic record is critical to understanding the evolution of global climate and may contribute to understanding the mechanisms of climate change. The availability of both the marine and the nonmarine records of environmental conditions in the Arctic will permit comparison of oceanographic changes in the Arctic Ocean with terrestrial conditions on the adjacent arctic landmasses, and with coeval conditions in the Atlantic and Pacific Oceans. The records will provide close correlation between marine and continental conditions during the crucial transitions from an ice-free to an ice-covered Arctic Ocean and from nonglacial to glacial regimes on the surrounding continents. Comparison of the arctic marine paleoenvironmental record with the record being obtained from the Greenland, arctic island, and antarctic ice sheets or ice caps will also provide data critical to understanding the history and mechanisms of global climate change. This presents an unparalleled opportunity to devise and test theories of global change in relation to natural and anthropogenic forces and to develop useful models for forecasting climate change.

A better understanding of arctic geologic processes will improve our ability to interpret the geologic record of environmental change in ancient polar regions throughout the geologic column. Especially important are the effects of perennial sea ice and glacial cycles on the marine record. An understanding of arctic geologic processes is also necessary for the planning of economic development, environmental management, and environmental monitoring in the Arctic, particularly on the arctic continental shelves and coasts. The Arctic is strongly affected by processes and conditions such as sea ice, subsea permafrost and gas hydrate accumulations, and exceptionally strong seasonal control of sedimentation and erosion for which adequate analogs do not exist in more southerly regions. Human activities in the Arctic can have adverse impacts on, and can be negatively affected by, some of these processes and conditions.

The Committee on Arctic Solid-Earth Geosciences believes that a three-part program of solid-earth studies in the Arctic Ocean Basin would address the identified opportunities for geoscience research in the Arctic Ocean region and would serve societal needs by increasing understanding of the earth's crust beneath the Arctic Ocean Basin, thereby expanding our data base on resources, climate, and basic geologic processes. Part one, Geologic Framework and Tectonic Evolution, which concentrates on the less-understood Amerasia Basin, includes selected problems in the Eurasia Basin and proposes extensive studies of arctic continental margins. Knowledge of the structural character and history of the arctic margins is necessary to reconstruct the tectonic character and history of the Arctic Ocean Basin and the circum-arctic landmasses and is of direct relevance to the discovery of nonrenewable resources in arctic shelves and landmasses. Special studies that would advance understanding of the geologic framework and evolution of the Arctic are seabed imaging and digital mapping of the Arctic Ocean Basin from nuclear submarines; magnetic and gravity surveys of the Arctic Ocean Basin from submarines or airplanes; comparative studies of trans-arctic geologic structure and stratigraphy; paleomagnetic analysis of arctic tectonic problems, particularly on the basis of studies of terranes near the margins of the Arctic Ocean Basin; and seismological investigations based on an improved network of standardized digital circum-arctic seismograph stations.

Part two of the program, The Sedimentary Record and Environmental History, proposes a detailed exploration of the 200-million-year-old record of arctic climate, oceanographic conditions, and faunal evolution and migration that is incorporated in the arctic and circum-arctic sedimentary record. This rich record has both terrestrial and marine components of great variety, has the potential for closely comparing marine and nonmarine conditions in the Arctic through geologic time, and has bearing on global change studies. For example, the Quaternary part of this record would be especially informative if it were to be closely correlated and compared to the record in ice cores from the polar ice sheets and ice caps. The committee believes that an extensive program of piston coring, gravity coring, and shallow-core drilling sited on the basis of improved bathymetric and seismic reflection data from the ridges and plateaus of the Arctic Ocean Basin can provide a general stratigraphic column and marine environmental history of the Arctic Ocean region. This record would not be as complete as one that might be obtained by continuous deep coring in the Arctic Ocean Basin, but there is no present technological assurance that deep coring can be accomplished in the Arctic except in the marginal ice zone or at times and localities with especially favorable sea-ice conditions. A complementary record on arctic shelves and coastal plains, perhaps not as complete as the marine record in some aspects, would be available for drilling and sampling with present technology.

Part three, Arctic Geologic Processes and Environmental Indicators, examines a variety of processes and conditions that are either unique to or well-developed in the Arctic and that, if better understood, would improve our ability to interpret the environmental history of the Arctic and, therefore, to predict climate change. They include chemical and mineralogic indicators of past environmental conditions in the stratigraphic record from which estimates of past conditions can be made, an examination of the processes and environmental significance of the accumulation and transportation of continental shelf and other sediment by rafting in arctic sea ice, and study of arctic sedimentation—including variations in the character and quantity of sediment derived from glacial and nonglacial sources in the circum-arctic landmasses in modern and Quaternary times and the processes whereby these sediments are transported and deposited in the Arctic Ocean Basin. Proposed studies include the evolution of the arctic biota through time, their adaptation to the special conditions of temperature and winter darkness in the Arctic, and their migrations into and out of the Arctic in response to changes in environmental conditions and the oceanic and epicontinental pathways by which the Arctic was episodically connected with other parts of the world ocean. Examination of the hypothesis that the presence of the north magnetic pole produced a detectable enrichment of extraterrestrial material or collision products of cosmic radiation in the sediments of the Arctic Ocean Basin or deep arctic lakes is suggested as a possible way to study solar-terrestrial interactions and variations in strength of the earth's magnetic field through time. Further, the committee proposes a study of the three-dimensional distribution and stability of gas hydrate deposits known to underlie the continental slopes of the Arctic Ocean Basin and to be associated with permafrost deposits beneath arctic coastal plains and inner continental shelves. The volume and stability of these deposits under changing climatic conditions are of great interest because greenhouse gas methane is believed to be the principal gaseous component of arctic hydrates. If the stability of arctic hydrate deposits is susceptible to climatic change, these large deposits may play a significant role in future changes in climate.

Recent technologic developments have provided the means for conducting research on the solid earth beneath the Arctic Ocean Basin, and recent political developments have made it conceivable that nuclear icebreakers and nuclear submarines may be available for nonmilitary research in the Arctic. Icebreakers could serve as moving platforms for seismic refraction, seismic reflection, bathymetric, and other geophysical measurements as well as for subseabed coring, shallow drilling, heat flow measurements, and dredging operations. Icebreakers and ice-capable vessels now available in the western world could conduct such activities, provided that the nuclear icebreakers of the USSR could be chartered to supplement and assist them. However, to ensure that U.S. science is not dependent on another country's scientific and political priorities, the committee reaffirms a Polar Research Board recommendation that an ice-capable vessel able to operate routinely in the central Arctic Ocean be added to the U.S. icebreaker fleet (NRC, 1988b).

If a sufficiently strong commitment were made to an augmented arctic geoscience program, nuclear submarines could map the arctic seabed with side-scan sonar and echo sounders, record its potential field with gravimeters and magnetometers, and probe its subseabed geologic structure and stratigraphy with continuous seismic reflection profiling methods. Over-ice surveys by air-transportable snow vehicles and by icebreaker-transportable amphibious vehicles capable of working in areas of mixed ice and open water would permit the collection of relatively low-cost seismic reflection, refraction, and other types of data in selected areas. If nuclear submarines were not available or if the submarine tracks were too widely spaced to provide adequate coverage, aeromagnetic and aerogravity coverage of the entire Arctic Ocean Basin could be accomplished by long-range aircraft. Global Positioning System satellites have greatly simplified arctic navigation; they have improved accuracy by orders of magnitude. The continuing reduction in size and weight of modern geophysical instruments has reduced significantly the logistic requirements for many types of field studies. Together, these technological developments can revolutionize our understanding of the character of the solid earth beneath the Arctic

Ocean Basin. The scientific information thus acquired will address quickly and economically some current societal concerns and contribute insight into scientific issues of global interest.

A comprehensive arctic solid-earth geoscience program requires a substantial measure of international cooperation, which could now be facilitated in part by the newly established International Arctic Science Committee and by an organized effort in bibliographic and translation programs. In addition, such research would benefit from the establishment of a directory of arctic geoscientists and research projects and from the conduct of small meetings of working scientists to encourage cooperation in recommended studies and the exchange of data and information.

1

Introduction

The Committee on Arctic Solid-Earth Geosciences was established by the Polar Research Board of the National Research Council to undertake a study in the board's "Polar Research-A Strategy" series, designed to guide the evolution of polar research into the next century. A companion study in this series, a summary of antarctic solid-earth geosciences, was published in 1986. Thus, a parallel activity for the Arctic was considered appropriate and timely, particularly in view of continuing interests in U.S. arctic research and policy. The committee's charge was to identify and address the gaps in scientific understanding of arctic solid-earth geosciences and in current research programs, the needs related to support and management of recommended research, and the coordination of research effort. In developing this report, which is the result of its deliberations, the committee benefited from the advice and assistance of many scientists in the United States, Canada, the Soviet Union, and in other countries. Other reports in the "Strategy" series, e.g., *Permafrost Research: An Assessment of Future Needs* (NRC, 1983a), *Snow and Ice Research: An Assessment* (NRC, 1983b), *The Polar Regions and Climatic Change* (NRC, 1984a, b), and *Recommendations for a U.S. Ice Coring Program* (NRC, 1986) are closely related to parts of this report. Therefore, we discuss such subjects only when they are pertinent to the record of arctic environmental change preserved in the solid earth.

The committee recommends that arctic solid-earth geoscience in the last decade of the 20th century focus on three broad research areas: (1) the geologic framework and tectonic evolution of the Amerasia Basin of the Arctic Ocean, which is of direct relevance to the discovery of nonrenewable resources in arctic shelves and landmasses, (2) the environmental history of the Arctic Ocean Basin, which is a basic component of global change studies, and (3) arctic geologic processes that are of societal concern or which, if better understood, would improve our ability to interpret the environmental history of the Arctic from its sedimentary record. Establishing a detailed and, where possible, quantified paleoenvironmental history of the Quaternary of the Arctic is a major and pressing challenge because the Arctic and Subarctic may contain some of the most sensitive systems for documenting global change.

Recent technological and political developments have made many of the proposed investigations feasible for the first time. They include the availability of icebreaking vessels capable of supporting scientific research in the high Arctic, a change in political climate toward openness and collaboration among the arctic nations (e.g., the newly formed International Arctic Science Committee has among its members representative organizations from the eight arctic countries and from six non-arctic countries), and a growing recognition that several problems of global scientific and societal concern have components that can be addressed only within the Arctic. However, the greatest advances in understanding of the solid earth beneath the Arctic Ocean await the use of nuclear submarines as research platforms. This is technologically feasible and would revolutionize our knowledge of one of the least-understood regions on Earth.

A growing awareness of the relevance of scientific knowledge of the Arctic to national as well as global issues and problems led to enactment of the Arctic Research and Policy Act of 1984. It is our hope that the present report will foster the development of an arctic solid-earth geoscience research initiative and support infrastructure for the United States, will augment existing research activities, and will help to reinforce international research efforts.

In this regard, we thank the Academy of Sciences of the USSR for hosting a meeting, Arctic Research Priorities in Solid-Earth Geosciences, in Moscow, November 16–17, 1987, and for subsequent meetings with Soviet arctic geoscientists at the scientific and technical complex Sevmorgeo in Leningrad. These sessions provided the committee with the opportunity to exchange views on arctic solid-earth geosciences with leading Soviet scientists and offered opportunities to improve communication and collaboration between Soviet and U.S. geoscientists working in the Arctic.

A chart showing the standard chronostratigraphic terms and ages for the Cretaceous, Tertiary, and Quaternary periods of the geologic time scale used in this report is shown as Figure 1.

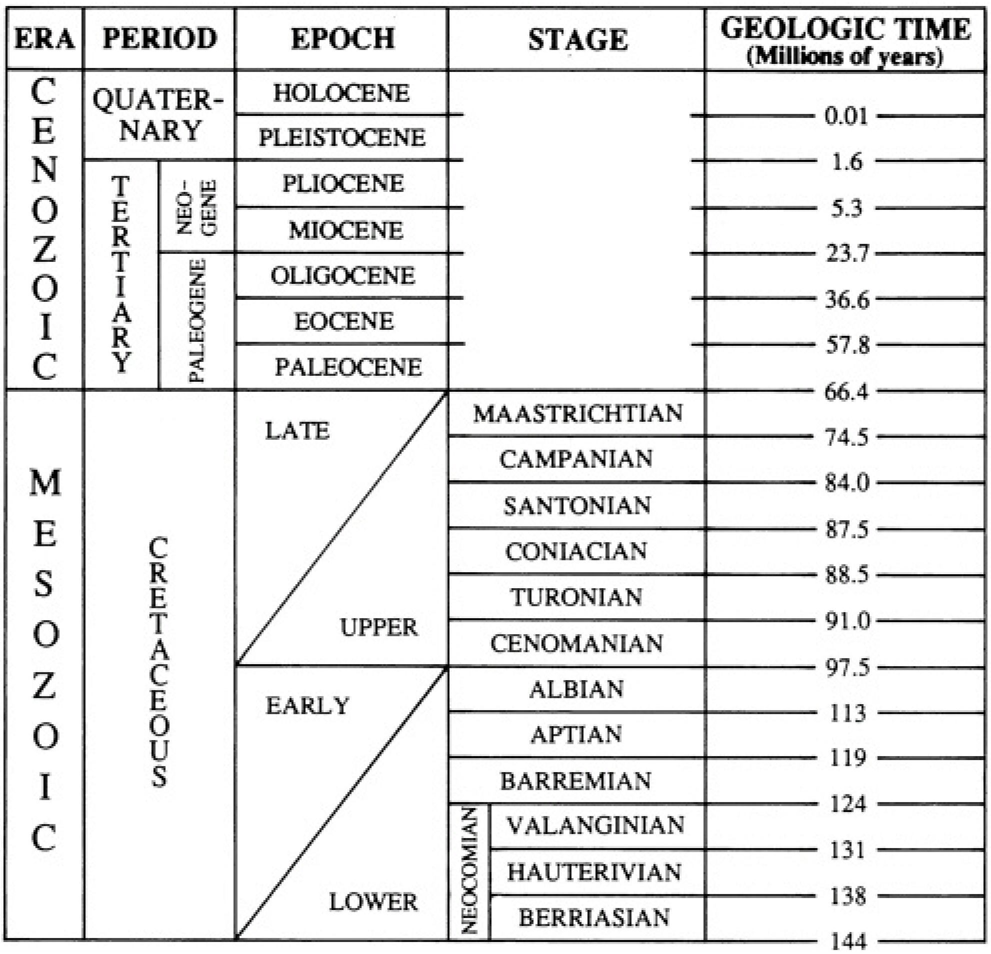

FIGURE 1 Subdivisions of the Cretaceous, Tertiary, and Quaternary periods of the geologic time scale (from Palmer, 1983) that are widely used in this report.

2

Physiography

The Arctic consists of a ring of mainly mountainous continental landmasses that surround a small but bathymetrically complex sea, the Arctic Ocean (see Figure 2). Although the surrounding mountains are of only low to moderate heights, continental and mountain glaciation and extreme physical weathering have sculptured a rugged landscape.

Deeply eroded orogenic belts, sedimentary basins of diverse Phanerozoic and Precambrian ages, and prograded continental shelf and slope deposits underlie the coastal plains and continental shelves that fringe the Arctic Ocean Basin (Okulitch et al., 1989; Grantz et al., 1990a). The shelves, which include some of the widest and narrowest on Earth, owe their low relief to glacial erosion as well as to the more common processes of marine abrasion and progradational clastic sedimentation. Islands on the outer Barents-Kara Shelf and on the Laptev-East Siberian-Chukchi Shelf are at present our principal source of geologic framework and history of these broad continental shelves.

A complex of ridges, small basins of oceanic depth, and an active spreading center that is propagating into the Eurasian continent comprise the deep Arctic Ocean Basin, which lies at the heart of the north polar region (Perry and Fleming, 1986; Johnson et al., 1990). The basin is divided by the Lomonosov Ridge into the younger and deeper Eurasia Basin and the older and larger Amerasia Basin. The Lomonosov Ridge is a narrow sliver of continental crust 1,700 km long and 50–150 km wide that extends across the entire Arctic Ocean Basin. Most of its crest lies 2,000 m to 500 m below sea level, and the ridge therefore exerts a major influence on Arctic Ocean Basin oceanography.

Broad areas of the Eurasia Basin are more than 4,000 m deep, and small, isolated basins along the axis of the spreading Arctic Mid-Ocean Ridge are deeper than 5,000 m. The Amerasia Basin is divided by the Alpha Ridge into the Makarov Basin to the north and the Canada Basin to the south. Both basins reach maximum depths of almost 4,000 m. The Alpha Ridge, which is thought to be underlain by volcanic rocks, is 600 km wide and 1,000 km long and has crustal depths of 1,100 m to 2,000 m below sea level. Near 84°N, 180°W, it joins the Mendeleev Ridge, which is also bathymetrically complex but somewhat deeper, at right angles. Summit elevations on the Mendeleev Ridge lie 1,500 to 2,500 m below sea level. Near 79°N, the Mendeleev Ridge merges with the north-trending, flat-topped Arlis Ridge, the westernmost of a group of morphologically similar ridges and plateaus that form the Chukchi Continental Border land. Ridge and plateau summits in the borderland are subhorizontal or gently sloping and lie mostly between 280 m and 1,500 m below sea level. Small, deep northerly-trending basins that lie between the ridges are included in the borderland. The morphology of the ridges and plateaus of the borderland permits the interpretation that the ridges are continental fragments, but definitive data are lacking.

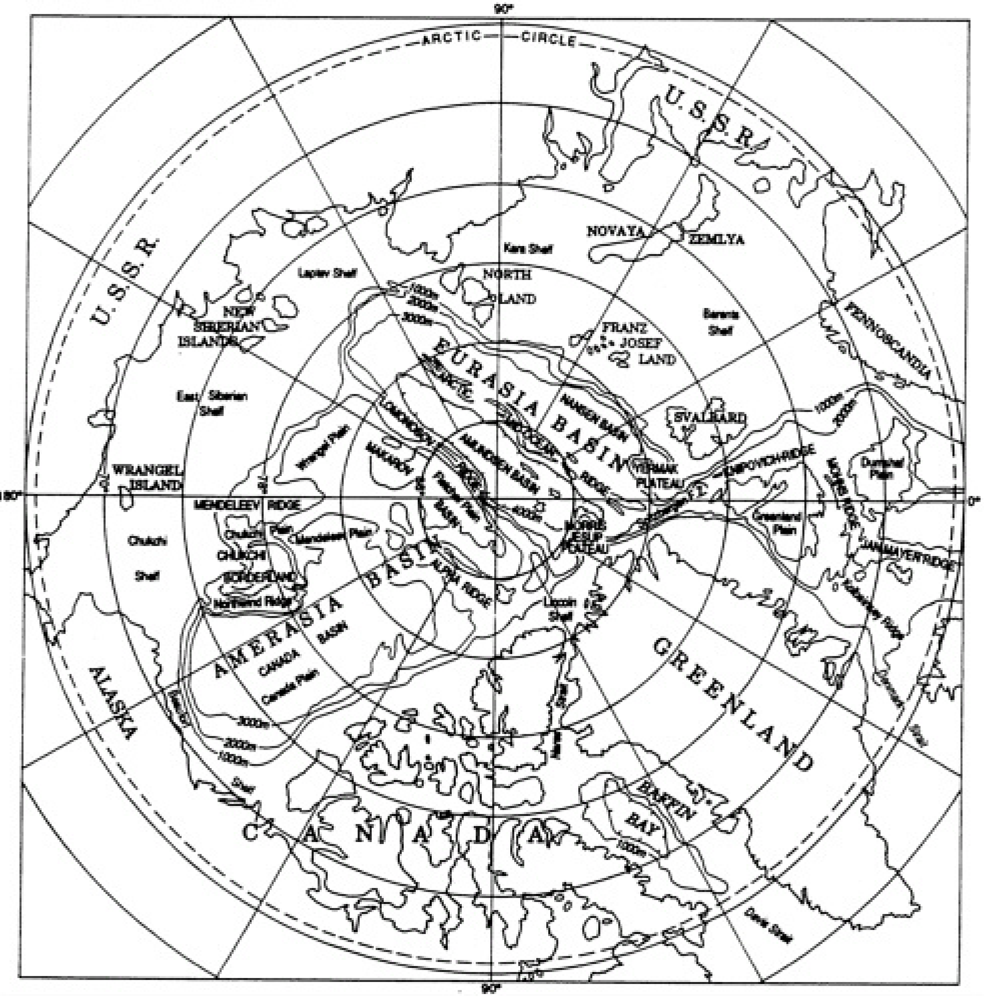

FIGURE 2 Principal geographic and physiographic features of the Arctic Ocean region (from Perry and Fleming, 1986).

3

Role of the Arctic in Global Solid-Earth Geoscience

GEOLOGIC FRAMEWORK AND TECTONIC EVOLUTION

The Arctic Ocean Basin is a virtually closed basin, surrounded by the largest continents (Africa-Eurasia and Greenland-North America). A full understanding of its tectonic history is vital to the development of a plate tectonic model for the Northern Hemisphere. The study of the tectonic development of the Arctic has two main themes, both with broad implications for global tectonics. One is the kinematics of the processes by which the small but complex Arctic Ocean Basin was created by two systems of rifting, one Late Mesozoic and one Cenozoic, within the margins of the supercontinent of Laurasia. The second is the interaction, within the arctic region, of the extensional stresses that have entered it from the Atlantic and the convergent stresses that have influenced it from the Pacific. These stresses, acting since Late Mesozoic time, must have been resolved in the arctic region, perhaps through transformation along major but presently unrecognized faults within the Arctic Ocean Basin.

Seismic reflection data collected from the Beaufort Sea suggest that the oceanic arctic basin was initiated by poorly understood rifting events within the periphery of the supercontinent of Laurasia (the Canadian Shield plus Eurasia) beginning in Jurassic time (see Figure 3). For example, east-west striking rift structures have been identified beneath parts of the Beaufort Sea shelf and slope, but the Jurassic rifting did not culminate in continental breakup and seafloor spreading (Grantz and May, 1983; Grantz et al., 1990b). It was premonitory, however, to renewed rifting and seafloor spreading which created the proto-Arctic Ocean at the site of the present Amerasia Basin by mid-Cretaceous time. The early deep-water connection of the new basin to the world ocean was with the paleo-Pacific, though the geometry of this connection is not yet known. Connection with the Atlantic came much later. In the absence of definitive data, the geometry, kinematics, and timing of rifting and the nature of the requisite involvement of the surrounding continents are in dispute; many alternative models have been proposed (see Lawyer and Scotese, 1990b).

Northward migration of lithotectonic terranes of southern origin along the Pacific margins of nuclear Eurasia and North America is thought by some to have created a broad isthmus between Alaska and Eurasia in Late Jurassic and Early Cretaceous time that isolated the deep circulation of the oceanic proto-Arctic Basin from the paleo-Pacific (Churkin and Trexler, 1981; Fujita and Newberry, 1983). The geometry and timing of the closure are uncertain. Shallow seaways connected the Arctic Ocean Basin with the ancestral Gulf of Mexico in Late Jurassic and Cretaceous time, with the North Pacific until Albian time, and with the Tethyan realm in Late Jurassic to Paleogene time. However, detailed knowledge of their history and location and possibly other connections between the Arctic and more southerly oceans is lacking. The history, location, and geometry of these seaways are critical to a number of paleoceanographic, paleontologic, and tectonic studies.

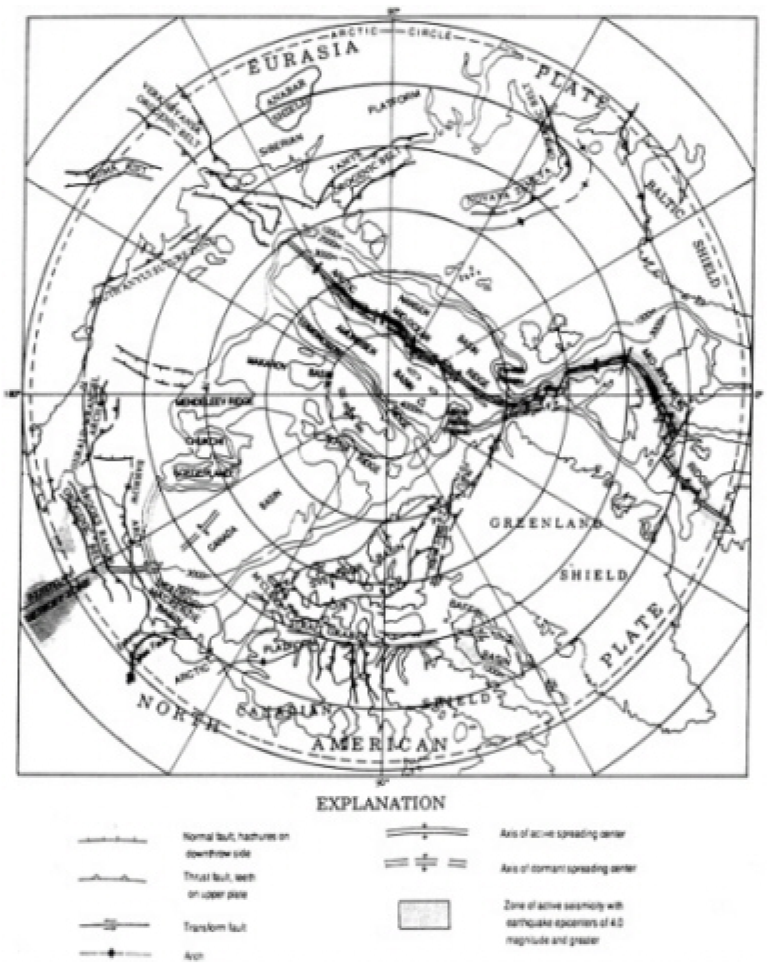

FIGURE 3 Major structural features of the arctic region (from Grantz et al., 1990a).

Connection of the Arctic and Atlantic Oceans began with Early Jurassic intracontinental rifting in Northwest Europe (Ziegler, 1988). Rifting progressively separated Greenland and Eurasia from North America and then in Paleocene time split Greenland from Europe. Paleocene rifting along the Arctic Mid-Ocean Ridge also initiated separation of the Lomonosov Ridge from the Barents Shelf to create the proto-Eurasia Basin and a shallow seaway between the

Arctic and Atlantic Oceans (Wilson, 1963; Kristoffersen, 1990a, b). This seaway, which developed into an oceanic rift that separated Svalbard from Greenland, permitted the interchange of deep water between the Arctic and the Atlantic by Middle Miocene time. Growth of the Eurasia Basin by spreading along the Arctic Mid-Ocean Ridge almost doubled the area of the Arctic Ocean Basin in Cenozoic time. The precise timing and geometry of the opening to the Atlantic and the tectonic history of the Lomonosov Ridge are questions with important implications for arctic paleoclimate, paleogeography, and paleobiogeography. The structures along which a southerly-trending extension of the Arctic Mid-Ocean Ridge entered the Eurasian continent in the Laptev Sea and was transformed to southwesterly-trending transpression in Northwestern Siberia tie mid-Atlantic extension to circum-Pacific compression. A detailed understanding of their geometry and history would provide a type example for such transitions elsewhere and in the geological record.

Postrifting tectonic events were significant in the development of the Arctic Ocean Basin. For example, geophysical data and a single dredge sample of alkaline basalt from the Alpha Ridge suggest that the ridge may be the trace of a Late Cretaceous hot spot that now underlies Iceland (Forsyth et al., 1986). It is important to test this hypothesis because knowledge of the age and migration path of such a hot spot would help to define the tectonic motion of the crust with respect to the mantle in the Arctic during Cretaceous and Early Tertiary time. A broad zone of latest Cretaceous or earliest Tertiary extensional faulting on the Chukchi Shelf extends into the Chukchi Borderland (Grantz et al., 1990b), where extensional features of similar trend occur. These extensional features perhaps join the generally coeval rift structures of Baffin Bay via an as yet-unrecognized route across the Amerasia Basin. Surprisingly, Pacific-North American convergence also appears to reach the Arctic Ocean Basin. In the eastern Beaufort Sea, compressional structures of Eocene to Holocene age extend from the northeastern Brooks Range to the continental rise as far as 170 km north of the coastline (Grantz et al., 1990a, b). These northward-vergent geologic structures may connect, via a transcurrent shear zone and a band of earthquakes, with the north end of the modern Aleutian Benioff Zone in southern Alaska. The apparent propagation of Cenozoic convergent forces across Alaska from the Pacific Rim to the Arctic Ocean Basin raises questions about the character and geometry of the structures (e.g., transcurrent and detachment faults) that could transmit the required stresses through the continental crust for distances exceeding 1,000 km.

MINERAL RESOURCES

Although the deep Arctic Ocean Basin offers slim prospects for economic deposits of minerals or hydrocarbons, major deposits of oil, gas, and coal have been found beneath its extensive continental shelves (Hale, 1990; Haimila et al., 1990). They include the cluster of giant and supergiant oil and gas fields on the North Slope and Beaufort Shelf near Prudhoe Bay, Alaska; probable supergiant gas fields in the southeastern Barents and southern Kara Seas; and large deposits of bituminous coal beneath the eastern Chukchi Shelf. A comprehensive understanding of the plate tectonic history and kinematics of the Arctic would provide important background to the search for additional deposits on arctic continental shelves and coastal plains. For example, the oil and gas deposits near Prudhoe Bay owe their accumulation and trapping to complex structural and sedimentational processes along the mid-Cretaceous rift that created the Amerasia Basin, and many of the potentially significant oil and gas discoveries of the Canadian Beaufort Shelf occur in progradational sedimentary prisms deposited in the rifts that created the Amerasia Basin.

The broad continental shelves of the Arctic also contain lithotectonic terranes that have been displaced large distances from their places of origin. Tectonic reconstructions of the arctic region may suggest places where continuations of these terranes, and of the large petroleum deposits, coal fields, and mineral districts that some of them contain, may be sought in other parts of the Arctic.

Seismic reflection data suggest that large amounts of solid gas hydrate (clathrate) underlie the continental margin of the Beaufort Sea. Most of the hydrate gas is probably methane. The seismic data also indicate that free gas is trapped beneath the hydrate deposit over large areas. The hydrate deposits occur within the upper 300 to 700 m or more of soft sediment on the continental slope and rise. By extrapolating to the entire Arctic, one can estimate speculatively that more than 10^{15} m^3 (35,000 Tcf) of methane at standard temperature and pressure may be tied up in hydrate deposits beneath the margins of the Arctic Ocean Basin (Kvenvolden and Grantz, 1990). Smaller deposits of hydrates are associated locally with permafrost beneath the inner arctic shelves. There appear to be no present or foreseeable technologies by which the hydrate-bound methane deposits of the Arctic Ocean Basin can be commercially developed, but the possible size of the resource, more than 1,300 times the volume of natural gas in the Prudhoe Bay field, makes acquisition of definitive information on the gas hydrate deposits of the Arctic Ocean Basin an important goal of arctic geoscience. Development of even a small part of the speculatively estimated resource would be an energy event of global significance.

ENVIRONMENTAL HISTORY AND GLOBAL CHANGE

The north magnetic dipole and, according to paleomagnetic theory, the north geographic pole have remained within or near the Arctic Ocean Basin since its inception in Early Jurassic time (Gordon et al., 1984). As a result, the basin contains a sedimentary record of up to 200 million years (Jurassic to Holocene) of north polar climate and oceanography. Because climatic conditions at the poles are perhaps the most sensitive indicators of world climate, this record can make a fundamental contribution to the understanding of global climate and oceanography for a major interval of geologic time. This interval encompasses dramatic changes in global climate, including the transition from widespread temperate climates in the Late Cretaceous to colder, more strongly zoned climates in the Paleogene, and the onset of the ice ages in the Late Neogene. Especially if correlated with events in Antarctica (which are also poorly known), this history would provide a data base critical to evaluating worrisome climatic and oceanographic changes, possibly in part anthropogenic, now affecting our planet. It would also significantly improve the usefulness of the geologic record for testing global models of climatic change.

Tectonic reconstructions of the Arctic Ocean Basin show that it was landlocked, or nearly so, during much of its existence (Lawver et al., 1990a). The environmental conditions that this paleogeography imposed on the Arctic Ocean Basin are only beginning to be understood (Thiede et al., 1990). An isolated or semi-isolated arctic mediterranean sea with a temperate or polar climate surrounded by major continents probably received a greater inflow of nutrient-and sediment-rich river water, relative to its volume, than other oceans and probably had lower evaporation rates. Analogy with the Black Sea, which also receives major rivers and has only a tenuous connection with the world ocean, suggests that an isolated Arctic Ocean would have lower surface-layer salinity than normal seawater.

The isolation may have allowed other deviations from world norms in salinity, temperature, nutrient levels, and stratification in the Arctic Ocean to reach stages of development not attainable in the world ocean, where extreme conditions tend to be precluded by mixing. Isolation may thus have maximized the amplitude of some kinds of environmental signals in the arctic sedimentologic record. On the other hand, during periods of improved connection between the deep waters of the arctic and world oceans, extreme conditions were probably modulated. Comparisons between paleoenvironmental conditions recorded in Arctic Ocean Basin sediments with coeval conditions in other oceans should provide valuable insights into past oceanic circulation.

The utility of arctic stratigraphy for understanding modern changes and predicting future changes in world climate and sea level is greatest in the Neogene and Quaternary marine record. This record, especially if correlated with that in arctic ice caps and nonmarine sediments, can provide a detailed history of Late Cenozoic climate, oceanography, glaciation, and sea ice in the Arctic. This history—and improved knowledge of the processes involved, such as the amplitude of the environmental changes and the rates of onset and collapse of continental glaciation and other extreme conditions—would provide insight into the dynamics of past and present world climate. They would improve the understanding of Quaternary climate gained from the Climap, Comap, and other programs, but much more information is needed, and is available, in the arctic stratigraphic record to elucidate the processes involved.

Pilot studies have demonstrated the potential of arctic paleoecology and paleontology for documenting the Cenozoic migration history of some circum-arctic terrestrial organisms between Eurasia and North America and of some marine taxa between the Atlantic and Pacific Basins via the Arctic (Marincovich et al., 1990). More details on these migrations would improve understanding of marine benthic faunal relationships and correlations between the eastern and western hemispheres. Arctic terrestrial taxa were adapted to long periods of winter darkness and summer daylight, and as the climate changed, the successful terrestrial and marine organisms adapted to cold. Study of the adaptations that permitted these organisms to flourish under polar conditions and comparison of their taxonomic and paleobiogeographic relations to kindred forms at lower latitudes should contribute significantly to interpretation of the fossil records elsewhere, and possibly of the mechanisms and rates of evolution and of the adaptations of organisms to extreme environments.

As noted earlier, a large volume of the greenhouse gas methane is apparently held in gas hydrate deposits beneath the Arctic Ocean. Although not unique to the Arctic, the volume of methane estimated to reside in arctic hydrates makes its stability a significant concern. Either warming of arctic bottom waters during interglacial ages (such as the present time) or lowering of sea level during ice ages, acting alone, could cause partial decomposition of methane hydrates and foster the release of methane to the environment. Because the release of large volumes of methane to the atmosphere could have severe and sudden climatic consequences and because decomposition of methane hydrates may provide positive feedback to processes of climate change, the distribution, volume, composition, and stability of the large gas hydrate deposits of the Arctic Ocean Basin are of global concern. Modeling the effect of change in sea level and bottom water temperature on the stability of hydrate deposits in the Arctic would enable assessment of the role of gas hydrate in global climate change.

More speculative opportunities for polar geoscience research with global significance involve the high magnetic flux and steep magnetic lines of force that occur near earth's magnetic poles. Because of this configuration of the lines of force, the modest shielding from charged particles that is provided by earth's magnetic field is weakest in the polar regions. As a result, these regions are characterized by a relatively high flux of cosmic radiation and extraterrestrial particulate matter that possibly has imprinted the fossil and sedimentary record in the Arctic Ocean Basin. It is important to know whether Arctic Ocean Basin sediments contain elements, such as beryllium, osmium, and iridium, in amounts significantly exceeding their crustal abundance and how such anomalous amounts, if found, vary with time. Such variations might provide a geologic-scale record of solar-terrestrial interaction and perhaps augment other observations of variations in the strength of earth's magnetic field through time.

ARCTIC GEOLOGIC PROCESSES

Many geologic processes and biological adaptations are best developed and therefore can be best studied in the Arctic. In this report, we focus on those geologic processes and environments that are most apt to have left a record in the solid earth that is useful for interpreting ancient environments. Examples include the character and volume of clastic and organic sediment incorporated in sea ice and the mechanisms by which this sediment is entrained and expelled from the sea ice to rain on the seabed, minerals that record ancient physical conditions in marine sediments, and organic compounds in fossil organisms that record ancient oceanographic conditions. This understanding would be most useful when applied to the Late Neogene and Quaternary stratigraphic record in the Arctic, which was affected by periodic episodes of continental glaciation and perennial sea ice. It would also contribute to our ability to interpret glacial and periglacial deposits in more ancient strata throughout the world. Many arctic geologic processes are important because they affect human economic activities in the region, and some of these economic activities could have adverse impact on the arctic environment.

4

Rationale for Focusing on the Arctic Ocean Basin and its Margins

Our knowledge of the earth beneath the circum-arctic landmasses is significantly greater than our knowledge of the Arctic Ocean Basin. As a result, we have insufficient scientific understanding to address confidently such national goals and societal concerns as global climatic change, nonrenewable mineral resources in the Arctic, and coastal and offshore management in the Arctic. The disparity in data and the consequent need to focus the next stage of arctic solid-earth geoscience on the Arctic Ocean Basin are illustrated by comparing current levels of data in the circum-arctic landmasses and the Arctic Ocean Basin.

Topographic maps at reconnaissance scales (1:500,000 or 1:250,000) are available for all the arctic landmasses, and large areas of the North American and Eurasian Arctic are covered by detailed topographic maps (scales 1:100,000 or larger). In contrast, only a few continental shelf areas have been mapped at scales of 1:250,000 or larger offshore (see Figure 4). Except in a few coastal areas, there is no organized effort to map systematically the bathymetry of the Arctic Ocean Basin, aside from classified efforts on behalf of the naval forces of the major powers. Long-range side-scan sonar acoustic backscattering images (sonographs) of the seafloor, of great utility for morphologic, structural, and sedimentologic studies of the ocean basins, have been obtained for the entire Exclusive Economic Zone of the United States except for the Arctic (Bering Sea EEZ-SCAN scientific staff, 1991).

The contrast between geological and geophysical mapping of the arctic landmasses and the Arctic Ocean Basin is also great. Onshore, national surveys have completed generalized geological maps of all the arctic lands, and active programs are under way to complete systematic coverage at the intermediate scale of 1:250,000. In Fennoscandia, the USSR, and Alaska, intermediate-scale mapping is either completed or nearly so, and more than one-half the Canadian Arctic lands have been mapped at this scale (see Figure 5). Local geological and geophysical mapping at large scales (1:100,000 or larger) and numerous oil and gas test wells have produced abundant detailed information in many areas of the onshore Arctic. Most onshore sedimentary basins of Arctic Alaska and Canada and the adjacent continental shelves as far north as Banks Island have been explored by reconnaissance or detailed networks of multichannel seismic reflection profiles obtained by both governmental and private organizations. The same holds true for the European Arctic, the arctic areas of the West Siberian Lowland, and the continental shelves in the southern Barents and Kara Seas. In addition, academic institutions and both private and governmental organizations involved in natural resource exploration are engaged in special-purpose mapping and topical geologic and geophysical studies at numerous onshore sites in the Arctic, and they have conducted extensive geologic and geophysical mapping and prospecting in areas where bedrock is exposed.

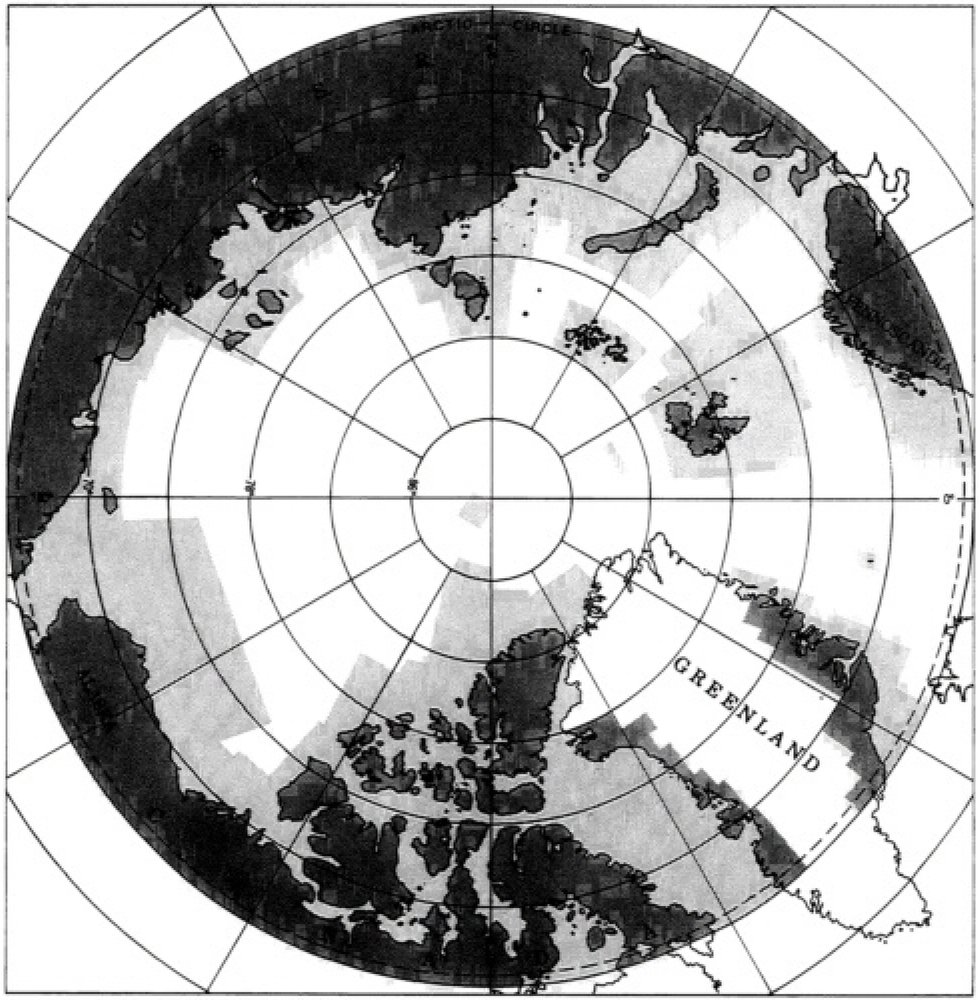

FIGURE 4 Recent status of published topographic and bathymetric mapping in the Arctic Ocean region. Topographic mapping (darker shading) is at scales of 1:250,000 or larger; bathymetric mapping (lighter shading) is at scales of 1:500,000 or larger. (Data from Parry and Perkins, 1988; and national topographic, hydrographic, and geological surveys of the arctic nations.)

Beyond the continental shelves, definitive information on pre-Neogene bedrock in the Arctic Ocean Basin comes from only seven piston cores and one dredge sample. Detailed seismic reflection surveys, from which detailed geological maps can be drawn, are restricted to the continental shelves of Alaska and the eastern Canadian Beaufort Sea. Almost everywhere else in the basin, seismic reflection data consist only of widely scattered single-channel profiles of poor quality and erratic geometry obtained from drifting ice. Exceptions are a multichannel reflection profile collected from ice floes in Fram Strait, several multichannel seismic reflection profiles in the southeast Canada Basin, and about 150 km of single-channel profiles collected from an icebreaker over Northwind Ridge. The disparity in seismic refraction data is not as great, but the offshore data base is still meager. Several high-quality crustal seismic refraction profiles have been collected on the mainland and continental shelves of the North American Arctic, and the acquisition of additional lines is planned. In the Arctic Ocean Basin, several refraction lines have been shot from sea ice, but they are widely scattered, and they are of variable quality as a result of adverse field conditions.

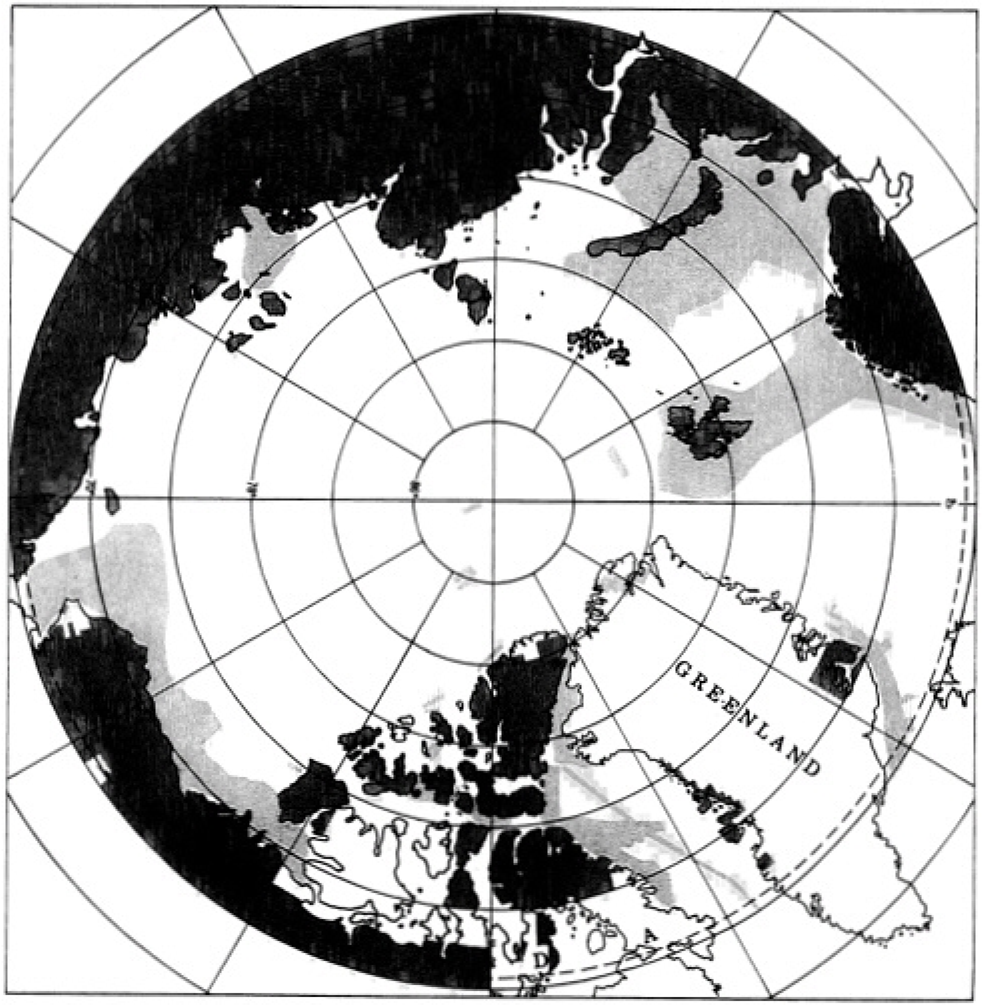

FIGURE 5 Recent status of onshore geologic mapping in the Arctic Ocean region. Mapping at scales of 1:250,000 or larger (darker shading) and of offshore seismic reflection surveys with line spacings not exceeding 20 km (lighter shading). (Data from Hall, 1973; Weber, 1979; Jackson et al., 1985; and national geologic surveys of arctic nations.)

Except for Greenland, most of North America and Europe have been covered by regional gravity surveys and about one-half this area by regional low-level aeromagnetic surveys (see Figures 6 and 7). Offshore, publicly available aeromagnetic coverage has been obtained over most of the Arctic Ocean Basin west of a line between Point Barrow and Franz Josef Land by U.S. and Canadian organizations, and generalized anomaly maps have been constructed for the Arctic from magnetic data collected by the National Aeronautics and Space Administration's Polar Orbiting Geophysical Observatory and by its magnetic satellite. Most of the aeromagnetic lines are too widely spaced, however, to address the important structural and plate tectonic questions of the Arctic. Further, navigation errors were much larger in these vintage data than would result from modern Global Positioning System (GPS) navigation. More closely spaced coverage exists over the Beaufort and Chukchi Shelves and the southern part of the adjacent Northwind Ridge in the North American Arctic, but it is proprietary. Gravity data in the public domain in the Arctic Ocean Basin consists of a 10-km grid of gravity readings from ice floes in the Canadian Beaufort Sea, measurements from several drifting ice stations, some aircraft landings on ice floes, and a few icebreaker tracks.

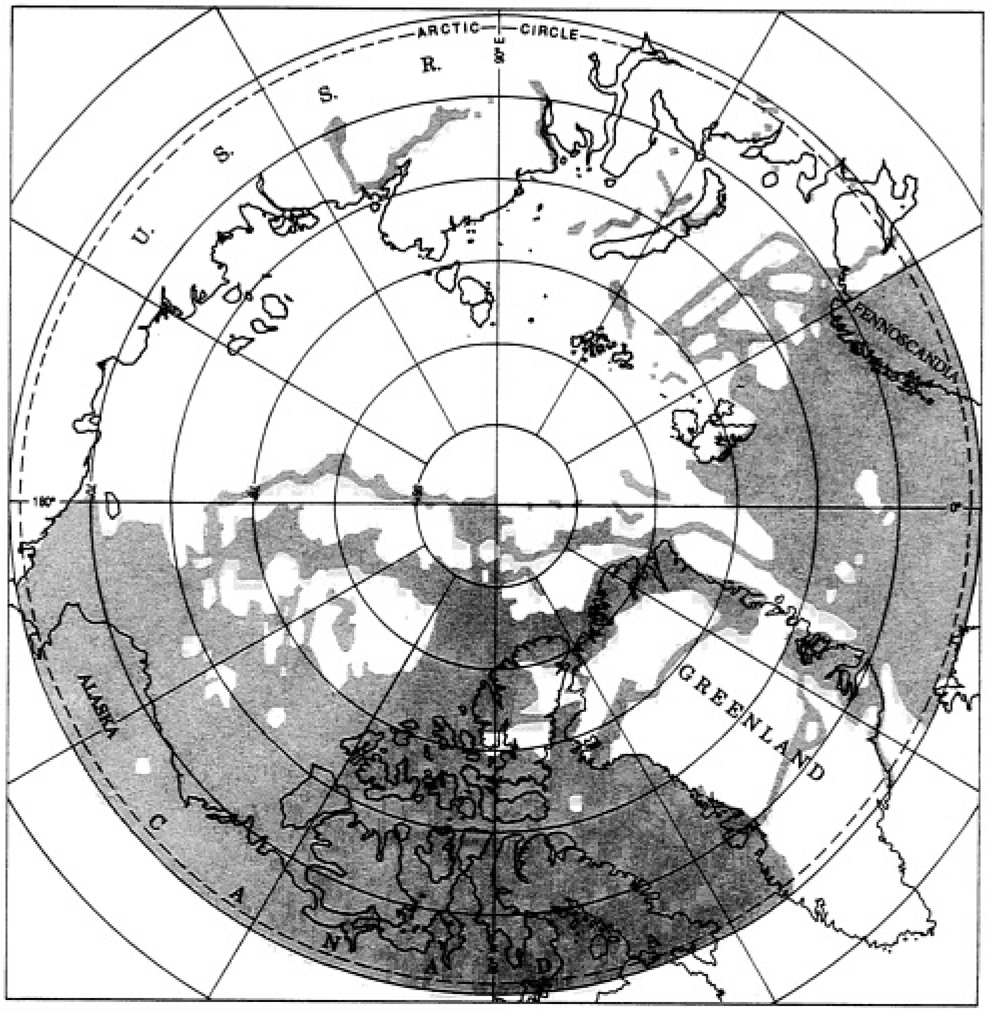

FIGURE 6 Recent status of gravity field surveys in the Arctic Ocean region at scales of 1:250,000 or larger or with data-point spacing not exceeding 30 km. (Data from Sobczak et al., 1990b.)

In view of the present need for more definitive understanding of the character, environmental history, and geologic processes of the solid earth in the Arctic Ocean Basin and the disparity between our knowledge of the physiography, geology, and geophysics of the solid earth in the circum-arctic landmasses and the Arctic Ocean Basin, the committee recommends that the next expansion of effort in solid-earth geoscience in the Arctic focus on the Arctic Ocean Basin. This region offers the most significant scientific challenges and a greater potential for major scientific breakthroughs of global significance.

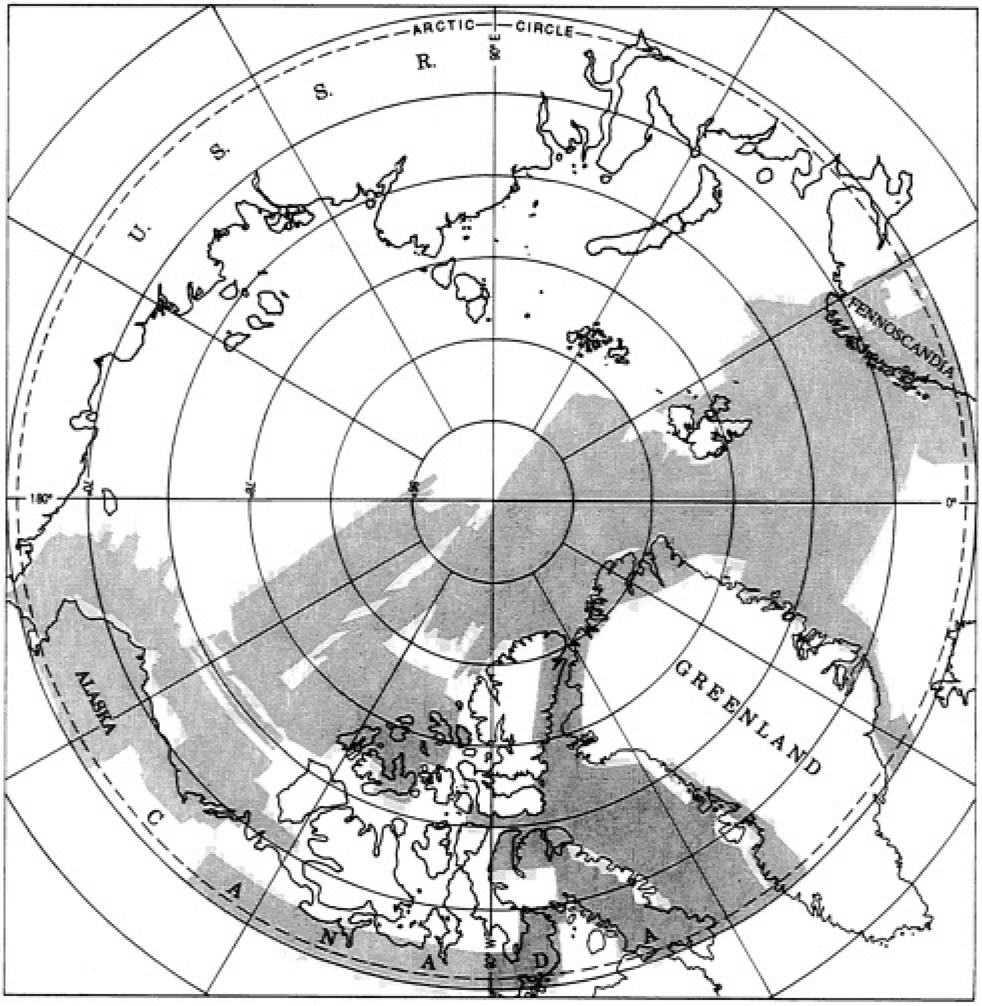

FIGURE 7 Recent status of aeromagnetic field surveys in the Arctic Ocean region at scales of 1:250,000 or larger, or with line spacing not exceeding 30 km. (Data from Macnab et al., 1990; and national geologic surveys of the arctic nations.)

5

The Next Stage of Arctic Solid-Earth Geoscience Research

GEOLOGIC FRAMEWORK AND TECTONIC EVOLUTION

Major Problems and Research Questions

The kinematics and history of the opening of the Arctic Ocean Basin within the margin of the supercontinent of Laurasia, the history and kinematics of the interaction in the Arctic of relatively orderly North Atlantic extension and highly mobile and complex Pacific Basin convergence, and the history of the interchange of seawater and biota between the Arctic and more southerly seas are first-order scientific problems awaiting solution in the Arctic. Our knowledge of the geologic framework of the ridges and subbasins of the Arctic Ocean, and of the age of its large areas of oceanic crust, is insufficient for solving these problems. However, this knowledge does provide some guidance in identifying the most productive regions for focusing our limited resources for support of research and in designing appropriate investigations.

A meaningful analysis of the geologic framework and tectonic evolution of the Arctic Ocean Basin would require that all the larger basins and ridges that comprise it be individually investigated and that the character of the geologic structures that bound these first-order features and of the continental margins be determined. Because the polar ice pack precludes acquisition of the required data from conventional research ships, more specialized and expensive platforms or logistic procedures would be required. Partly offsetting this difficulty is the circumstance that the Arctic is a small, almost landlocked basin most of which is no more than 700 km from bedrock outcrops on the circum-arctic landmasses or continental shelf islands. Extrapolation of geologic features from the surrounding continents could thus provide significant insight into the tectonic character of the basin. The proximity of the surrounding landmasses would also facilitate the testing of plate tectonic reconstructions by matching of geologic terranes and structures of known character and age across the basin. Paleomagnetic studies of the surrounding landmasses would provide important insights into past plate motions in the Arctic, and seismic studies based on a modern, standardized network of broad-band circum-arctic seismograph stations would tell us much about modern plate geometry and motions.

Tectonic Problems in the Amerasia Basin

The key to understanding the tectonic history of the Arctic lies in learning the geologic framework and tectonic history of the bathymetrically complex Amerasia Basin, one of the most inaccessible and poorly known areas on Earth. There are many quite divergent hypotheses but no general agreement as to its origin and age (Lawver and Scotese, 1990b). In contrast, it is widely accepted that the origin of the smaller, structurally and bathymetrically simpler, and more accessible Eurasia Basin formed by seafloor spreading along the Arctic Mid-Ocean Ridge beginning between chrons 29 and 25 (65 to 59 million years) on the geomagnetic polarity time scale (Kristoffersen, 1990a, b). The committee therefore recommends that the predominant focus of geologic framework and tectonic studies in the Arctic Ocean Basin be the Amerasia Basin, but selected studies in the Eurasia Basin are also recommended.

Ridge Systems

A three-phase program is recommended for study of the geologic framework of the four large ridge systems of the Amerasia Basin (see Figure 2). All four ridges meet the margins of the surrounding continents abruptly at linear or curvilinear continental slopes that have the morphologic appearance of major structural boundaries, and the ridges are therefore thought to be structurally isolated from the surrounding continents. Data on the geologic character and structural history of these ridges is required before well-constrained plate tectonic reconstructions of the Arctic Ocean Basin and its environs can be made.

Phase one would acquire regional physiographic and geophysical data. They would consist of systematic digital seabed side-scan sonar imagery and bathymetry of the entire Amerasia Basin, uniform mapping of its magnetic and gravity fields, establishment of a modern circum-arctic seismograph network, and a program of circum-arctic paleomagnetic studies. Phase two, guided in part by the regional data generated by phase one, would focus on the lithology and shallow geologic structure of the ridges. It would consist of extensive sampling of the ridges by coring, dredging, and shallow drilling; coarse grids of seismic reflection and sonobuoy refraction profiles; and paleomagnetic study of core samples. Phase three would seek to determine the deep crustal structure of the ridges through the acquisition of deep (crustal) seismic refraction and heat flow data and seismic surface wave propagation studies. The proposed investigations appear feasible with present or foreseeable logistical platforms and technology, as discussed in Chapter 6.

For all the ridges or ridge systems, seismic profiling across their boundaries with the adjacent continental margins would be required to establish their tectonic character and history. Determination of the stratigraphy and environmental history of the sedimentary sections that cap or drape over the ridges would also be required. This history would establish the age of the ridges as independent tectonic entities, the history of their subsequent vertical movements, and their influence on the oceanography of the Arctic Ocean Basin through geologic time. The record of vertical movements of the ridges with respect to sea level through time would provide important insights into their tectonic character and development.

Lomonosov Ridge: Based on physiographic and gravity data and on crustal velocity structure, it has been inferred that the Lomonosov Ridge is a sliver of continental crust separated from the Barents-Kara Shelf by rifting in the Eurasia Basin (Weber and Sweeney, 1990). A series of bedrock samples along the ridge would be needed to test the rifting hypothesis for the origin of the Eurasia Basin and to determine the direction of opening with respect to the basin axis by seeking specific lithologic ties with the outer Barents-Kara Shelf. This shelf is relatively well known from reconnaissance geologic mapping of the many islands that rise above the outer continental shelf between Svalbard and the Taymyr Peninsula.

A series of transverse seismic reflection profiles across the Lomonosov Ridge may resolve the character of its bounding fault systems and thereby provide crucial data on the origin of the Amerasia Basin. If the boundary between Lomonosov Ridge and Makarov Basin consists of extensional faults, it would support suggestions that the Amerasia flank of the ridge is a passive margin and that the Makarov Basin formed by seafloor spreading away from the Lomonosov Ridge. If the boundary consists of transcurrent faults, it would support suggestions that the basin formed by spreading parallel to the Lomonosov Ridge, which carried Arctic Alaska and Chukotka away from Arctic Canada. Understanding the character and age of this feature is basic to constructing an adequate tectonic model for the Arctic Ocean Basin.

Alpha Ridge: Seismic refraction and reflection data, gravity modeling, a large positive magsat anomaly, aeromagnetic anomalies with amplitudes exceeding 1,500 nT, and a single sample of alkaline basalt collected by the Canadian CESAR expedition in 1983 suggest that the Alpha Ridge may be near a volcanic pile as much as 40 km thick (Forsyth et al., 1986; Weber and Sweeney, 1990). Other hypotheses of origin include a spreading center subduction zone, a transcurrent fault, a hot spot track, or a displaced fragment of continental crust. The inferred volcanic basement is overlain by Campanian and younger biosiliceous pelagic oozes, but sampling is insufficient to demonstrate that they are the oldest sediments that rest on the volcanic rocks. Its bathymetry suggests that the Alpha Ridge has been extensively block faulted.

Regional sampling on the numerous fault scarps that characterize Alpha Ridge would be needed to verify the petrographic character and age of its acoustic basement and to document the age of the oldest sediments that overlie this basement. Seismic reflection profiles would be needed to record the thickness and seismic stratigraphy of the locally thick and faulted sediments and to identify sites where the oldest sedimentary strata and complete stratigraphic sections can be sampled. Seismic reflection profiles would also be needed to document the geologic structure and tectonic style of the ridge and the character of its boundaries with the flanking basins and the magnetically contrasting Mendeleev Ridge.

Mendeleev Ridge: Mendeleev Ridge resembles Alpha Ridge in having rough bathymetry and extensively faulted and tilted sedimentary rocks draped over basement of high acoustic impedance at moderate depths (Hall, 1973, 1990), but even less is known about it, at least in the western literature. The two ridges meet at about a 135° angle near Cooperation Gap, near the center of the Arctic Ocean Basin. Of particular significance is the observation that the large positive Magsat anomaly that coincides with Alpha Ridge begins to drop in amplitude near Cooperation Gap and dies out along the Mendeleev Ridge, suggesting that these ridges are underlain by different rock types (Haines, 1985).

Side-scan imagery and seismic reflection profiling should serve to locate sample sites at which basement lithology and the character and environmental history of the overlying sediments can be determined. A major objective of the sampling would be to learn why the large amplitude magnetic anomaly of Alpha Ridge dies out over the Mendeleev Ridge. Suites of samples and seismic reflection data across the ridge would be needed to establish its geologic framework and environmental history and allow assessment of its tectonic character and its place in arctic tectonics.

Chukchi Borderland: The fourth ridge province in the Amerasia Basin is the cluster of north-trending flat-topped ridges and plateaus, the Chukchi Borderland, which lies between the Chukchi Shelf and the center of the Amerasia Basin (Hall, 1973, 1990). Seismic reflection profiles indicate that flat-lying to gently dipping well-bedded sedimentary rocks, in places 1 km or more thick, cap the ridges. These low-dipping strata overlie more strongly deformed beds of higher acoustic impedance that, in one area of Northwind Ridge, consist of marine foraminifer-bearing lutite of Middle Albian age (Grantz et al., 1990b). Elsewhere, they overlie rocks that generate high-amplitude magnetic anomalies. The high-standing flat-topped physiography of the ridges and the presence, at least locally, of moderately to highly magnetic rocks at high structural levels within them suggest that they are underlain by wave-truncated continental or volcanic rocks. A few bathymetric and seismic reflection profiles indicate that the borderland is broken by northerly-trending normal faults that are geologically young.

A plate tectonic model for the Amerasia Basin must accommodate the Chukchi Borderland, which projects into the basin in a manner that has no obvious tectonic explanation. Tomographic inversion of trans-arctic seismic surface wave velocities suggests that the ridges of the borderland are of continental thickness (Jih et al., 1988), but additional surface wave studies and seismic refraction measurements are needed to confirm this point. Reconnaissance seismic reflection profiles indicate that the sediments capping the flat-topped ridges of the borderland are less intensely faulted than those of the Alpha and Mendeleev Ridges (Hall, 1973), suggesting significant differences in tectonic origin and deformational history. The primary research goal in the borderland would be to determine the age, lithologic character, and stratigraphy of acoustic basement in the ridges and plateaus of the borderland and of the capping sedimentary section by a comprehensive program of subseabed sampling, seismic reflection, and seismic refraction profiling. Seismic profiling would also be needed to delineate the northerly-trending normal faults that, at least locally, traverse the borderland and perhaps form major structural boundaries between its ridges and basins. Acquisition of three piston core samples of Albian marine sedimentary rock from the east flank of Northwind Ridge from an icebreaker in 1988 suggest that suitable sampling sites for coring and shallow drilling pre-Quaternary rocks can be found in the borderland.

Subbasins

Satisfactory plate tectonic reconstructions of the arctic region will require understanding of the character and age of the seafloor beneath the subbasins of the Amerasia Basin. Acquisition of the required data should therefore be a primary objective of any program of solid-earth geoscience research in the Arctic. The program would have to be conducted in several parts of the Amerasia Basin, however, because it consists of two large subbasins of irregular shape and perhaps of compound origin and two small isolated subbasins.

The large subbasins are the elongated Makarov Basin, which lies between the Lomonosov and Alpha-Mendeleev Ridges, and the broader Canada Basin, which is bordered by Canada, Alaska, the Chukchi Borderland, and Alpha Ridge. These subbasins are nearly 4,000 m deep, even though they contain thick sedimentary fills, suggesting that they are underlain by oceanic crust. In the Canada Basin, the thickness of the fill exceeds 12 km, and in the Makarov Basin, 6 or 8 km. Seismic refraction data have revealed a velocity-depth curve similar to that of oceanic crust beneath the southern Canada Basin and part of the Makarov Basin (Weber and Sweeney, 1990; Forsyth et al., 1986), but whether linear seafloor magnetic anomalies are present is controversial. Available aeromagnetic profiles are too widely spaced to confirm unequivocally the presence of magnetic anomalies that can be ascribed to seafloor-spreading in the southern Canada Basin on the basis of the low amplitude anomalies that have been found there; according to some investigators, the magnetic anomalies near the North Pole in the Makarov Basin are the product of structural relief in magnetic basement (Taylor et al., 1981). The small Chukchi and Northwind subbasins in the Chukchi Borderland are also underlain by thick sections of young flat-lying sediment, but the thickness of these fills is not known. In the absence of definitive seismic refraction and aeromagnetic data, we can only speculate that these small heavily sedimented subbasins rest on either oceanic or tectonically thinned continental crust.

A three-phase program of geoscience studies is proposed for the subbasins of the Amerasia Basin. The first phase would supplement existing deep seismic refraction data in the subbasins with modeling of aerogravity and aeromagnetic data, seismic surface wave studies, and seismic reflection profiling. A primary objective of phase one would be to determine, with submarine or airborne surveys, whether the subbasins contain magnetic anomalies indicative of seafloor spreading. The geometry of such anomalies, if they exist and can be mapped, is basic to plate tectonic reconstructions in the Arctic Ocean Basin. Delineation of these anomalies has proven difficult because the subbasins are relatively small and because they contain terrigenous sedimentary fills as much as 12 km thick that have depressed the subjacent oceanic crust and significantly reduced, and perhaps obscured, the magnetic signal. The amplitude of the presently mapped aeromagnetic anomalies in the southern Canada Basin, which some suggest originated in seafloor spreading, averages about 200 nT (Taylor et al., 1981). Continental margin geology suggests that much of the Canada Basin formed during the Cretaceous magnetic quiet interval (Albian to Santonian) and may lack seafloor-spreading anomalies that are mappable (Grantz and May, 1983). Magnetic and gravity surveys across the southern Canada Basin should therefore be spaced as closely as would be commensurate with our present estimate of the depth of the subjacent oceanic crust, about 10 km.

Second-phase studies would obtain additional refraction and heat flow data in the subbasins at sites selected after the analysis of phase one data would be complete. Determination of the thickness of sedimentary fill in the subbasins, the character and thickness of the underlying crust, and the relation of heat flow, basement elevation, and age for the various subbasins of the Amerasia Basin would be major objectives of phase two. Heat flow measurements collected from Ice Island T-3 from the mid-1960s to the early 1970s are consistent with the interpretation that parts of the Canada Basin and Alpha and Mendeleev Ridges are 10^8 years old or older (Langseth et al., 1990). However, the northwest part of the Canada Subbasin and part of the Makarov Subbasin exhibit heat flow that is higher than would be expected from Mesozoic oceanic lithosphere. Did these areas form later than other subbasins in the Amerasian Basin, or did they and possibly the Alpha Ridge near the North American margin undergo magmatic or tectonic rejuvenation in Early Tertiary time? Additional heat flow data from these subbasins, especially when interpreted in conjunction with side-scan sonar imagery and seismic reflection data, would reveal whether the heat flow anomalies are related to Early Tertiary volcanism or tectonism and address the question of whether the Canada and Makarov Subbasins contain major subdivisions of disparate ages.

Third-phase studies, based on deep scientific drilling of the subbasin fills, would be a major scientific achievement. With the possible exception of a few sites near their margins, however, there appears to be little prospect that the technological and financial resources to achieve significant stratigraphic penetration of the thick sedimentary fill in the subbasins could be mustered until well into the 21st century. Stratigraphic coring and shallow drilling at dispersed sites on the crests and flanks of the numerous ridges of the Amerasia Basin would offer a more favorable current prospect for piecing together a stratigraphic section, albeit noncontinuous, representing the entire history of the Amerasia Basin. Such a dispersed section could be obtained in conjunction with other data sets and at considerably less cost than by deep drilling.

Selected Tectonic Problems in the Eurasia Basin

Fram Strait

Fram Strait is the major gateway for deep-water communication between the Arctic and the water masses of lower latitudes. Seafloor magnetic anomalies suggest that the initial plate boundary in this area was a passive margin that was also the site of Late Eocene volcanism (Soper et al., 1982). The volcanism formed the Morris Jesup Rise and at least part of Yermak Plateau during shear or transpressive motion between Greenland and Svalbard. The gateway appears to have opened after an Early Oligocene change to oblique rifting and the thermal subsidence of Yermak Plateau, and it became an effective channel for deep-ocean circulation in Middle Miocene time (Kristoffersen, 1990b). The geometry, kinematics, and timing of the early evolution of the Fram Strait gateway need to be documented in detail by seismic reflection profiles and sampling, because interconnection of the deep Arctic Ocean Basin with the world ocean was an event of far-reaching oceanographic and climatic influence. Associated problems are the timing and geometry of the volcanic construction of Morris Jesup Rise, the possible dual crustal origin of Yermak Plateau, and the significance of the high heat flow along the western margin of the plateau (Crane et al., 1982). These problems could be addressed by over-ice seismic surveys, geological sampling, and heat flow measurements across Morris Jesup Rise. The southern half of Yermak Plateau is accessible to conventional marine multichannel surveys in good ice years (Sundvor et al., 1982). Basement sampling by several shallow (less than 100 m) drill holes is also recommended.

The Slow-Spreading Arctic Mid-Ocean Ridge

The evolution of the Eurasia Basin and the Arctic Mid-Ocean Ridge are relatively well understood, but it remains necessary to characterize the lithosphere of this very slowly-spreading young ocean basin in terms of heat flow and basement elevation versus age (Vogt et al., 1979b). These relations would be valuable for comparison with similar measurements on other Cenozoic basins in an effort to determine the global variability of parameters that control lithospheric evolution.

Seafloor at the Arctic Mid-Ocean Ridge is formed at a rate of 0.8-1.5 cm/yr, which is the slowest of any present part of the mid-ocean ridge system. East of 120°E, the ridge is progressively buried by sediments, but water depths in the axial valley of the western part of the ridge reach 5,000 m and are the deepest in the Arctic Ocean. Scattered bathymetric profiles obtained by submarines across the western part show a morphology similar to other slow-spreading ridges with indications that the width of the axial valley decreases with spreading rate. Another unique feature of the Arctic Mid-Ocean Ridge is the thin oceanic crust (2 km) that was observed on its northern flank, which may also be characteristic of slow-spreading ridges (Jackson et al., 1982).

The low rate of spreading and volcanism at the Arctic Mid-Ocean Ridge makes it an end-member representation of magmatic and tectonic processes at spreading ridges. Important aspects of such slow-spreading ridges are large heat loss and the role of oceanic crustal strength in maintaining a steady-state ridge morphology (Sleep and Rosendahl, 1979). These problems would best be addressed by a concentrated effort in a restricted area analogous to the French-American Mid-Ocean Undersea Survey (FAMOUS) of the Mid-Atlantic Ridge. Multichannel seismic reflection and refraction data; gravity, magnetic, and heat flow measurements; and detailed bathymetry mapping and geological sampling would be needed to provide the necessary constraints for a better understanding of slow-spreading ridges.

Recent studies have demonstrated that active spreading centers release large amounts of heat into the oceans, but the possible effects of the heat released by the active spreading system in the Eurasia Basin have received little attention. Although it is difficult to assign good numerical estimates to the thermal energies involved, it is reasonable to assume that the Arctic Mid-Ocean Ridge was (and is) releasing energy at a rate of about 10^{18} to 10^{19} joules per year. The effects of releasing this amount of energy into the Eurasia Basin prior to the opening of the deep-water connection with the Atlantic about 15 million years ago could have significantly altered its thermal stratification, salinity, and chemistry, and perhaps its biota (Thiede, 1979). The climatic effects of slightly elevated surface water temperatures in a closed polar sea might also be significant.

Continental Margins

A diversity of first-order tectonic features that in large part shaped the physiography and geologic framework of the arctic region underlie the continental margins of the Arctic Ocean Basin, and an understanding of their structural character and age is an essential prerequisite for understanding arctic tectonics. The arctic margins include passive margins of Cretaceous and Tertiary age, transform margins of Tertiary and perhaps Cretaceous age, and in the eastern Beaufort Sea, a convergent margin of Cenozoic age. The arctic margin is also one of the few places on Earth where an active spreading ridge, the Arctic Mid-Ocean Ridge, trends into a continent (Kristoffersen, 1990a). It is suspected that some of these margins may be of compound origin. An example is the continental margin that borders Greenland and the Canadian Arctic Islands, which is thought to be a transform fault of Cenozoic age between Svalbard and Greenland and a passive or transtensional margin of Cretaceous age opposite the Canadian Arctic Islands (Vogt et al., 1979a; Sweeney et al., 1990).

Continental margin structures in the Beaufort and Laptev Seas have been studied during favorable ice years with multisensor marine geophysical surveys. The continental margin in the Beaufort Sea north of Alaska is of the Atlantic type and appears to have experienced premonitory rifting in Jurassic time and breakup in Hauterivian (Early Cretaceous) time. Recent Soviet seismic reflection and gravity measurements in the Laptev Sea found extensional faults subparallel to the Arctic Mid-Ocean Ridge on the broad Laptev Shelf (Kogan, 1974; Nalivkin, 1983; and Kristoffersen, 1990a), but apparently, their surveys did not reach the continental margin. Data on the continental margins are lacking elsewhere in the Arctic, where they would have to be studied in ice-covered seas using logistically difficult field methods. The tested methods include aeromagnetic profiling, seismic refraction and reflection profiling on pack ice in spring, and coring and shallow drilling from icebreakers. Partially tested methodologies include aerogravity profiling and seismic reflection profiling in multiyear sea ice from icebreakers.

Because of the broad area of scientific interest along the arctic continental margins and the logistic difficulty and expense of acquiring geoscience data on sea ice, a realistic program to study the arctic margins must focus on key areas with well-defined structural targets. Long-range side-scan imaging surveys and detailed bathymetry would greatly assist the site selection process. Existing data and anticipated geophysical work by industry and governments would provide guidance in the Beaufort and eastern Chukchi Seas, but basic data are inadequate or lacking for other arctic margins. Compilation of a definitive list of key study areas is therefore not feasible, but suggestions based on current understanding follow.

For each of the key study areas, the committee recommends acquisition of geophysical and geologic data along transects normal to the continental margin. The transects should be anchored at tie points near the mainland, outer shelf islands, or existing geophysical surveys, and they should extend at least 100 km basinward of the shelf break. The general location of the suggested transects is shown in Figure 8. Each transect would consist of two or more parallel geophysical lines along which geological samples and both low-frequency and high-resolution seismic reflection, seismic refraction, gravity field, heat flow, and bathymetric data would be obtained.

Canada Basin

Onshore-offshore transects across the continental margins on opposite sides of the southeast Canada Basin would test various hypotheses that have been proposed for their origin, including formation by rotational rifting about a pivot in the Mackenzie Delta region in mid-Cretaceous time. The transects proposed for the Canada Basin should extend completely across its southeastern corner to search for multistage rifting and transform faulting along the opposing, possibly conjugate margins. Determining whether the margin at the Canadian Arctic Islands was the site of multiple deformations would be a major objective. The study would provide new data on the structural deformation that Cenozoic convergence, originating at the distant Pacific Rim, has imposed on the sedimentary column in the southeastern Canada Basin.

Tromso-Mackenzie Lineament

An alignment of continental margins and fracture zones, the Tromso-Mackenzie lineament, extends for almost 4,000 km along the western Barents, northern Greenland, and Canadian Arctic Islands continental slopes from near Tromso, Norway, to the Mackenzie Delta in Canada. The lineament is the locus of Cenozoic transcurrent transform faulting on the Spitzbergen fracture zone in Fram Strait and probable Jurassic and Cretaceous transcurrent and extensional faulting off the Queen Elizabeth Islands of Arctic Canada (Vogt et al., 1979b). Better understanding of this interregional tectonic feature is needed for plate tectonic reconstruction of the arctic region, including the surrounding northern continents.

The Tromso-Mackenzie lineament could be better understood by concentrating research along six transects (see Figure 8). Such transects would also provide important new information on the geology of the Arctic Mid-Ocean Ridge and the Spitzbergen fracture zone in Fram Strait, the Morris Jessup Plateau, and the Lomonosov and Alpha Ridges near their junctions with North America. Sea-ice conditions along the lineament from the Queen Elizabeth Islands to Greenland appear to be especially unfavorable for icebreaker operations (Hibler, 1980). Over-ice surveys would thus be more favorable than icebreaker surveys in the area.

Laptev-Mackenzie Margin

Some tectonic models suggest that the long curvilinear continental margin that lies north of Alaska and Eurasia between the Mackenzie Delta and the Laptev Sea is a passive margin of Jurassic and Cretaceous age that is conjugate to the Tromso-Mackenzie lineament (Lawver and Scotese, 1990b), but this interpretation is supported by seismic reflection data only in the Beaufort and eastern Chukchi Seas. The absence of data west of the eastern Chukchi Sea and the right-angle junctions of the ridges of the Chukchi Borderland and Mendeleev Ridge with the Laptev-Mackenzie margin require that a high priority be given to determining the tectonic character and history of this margin. For this purpose, we suggest establishing six transects of the type proposed for the Tromso-Mackenzie lineament. These transects would also address the tectonic character of the junctions with the ridges of the Chukchi Borderland and Mendeleev Ridge and provide data for a critical comparison of the Laptev-Mackenzie margin with the Tromso-Mackenzie lineament. They may help to determine whether the western part of the margin has been affected by transform faulting from the Eurasia Basin. All these questions are critical to understanding the plate tectonic development of the Arctic Ocean Basin.

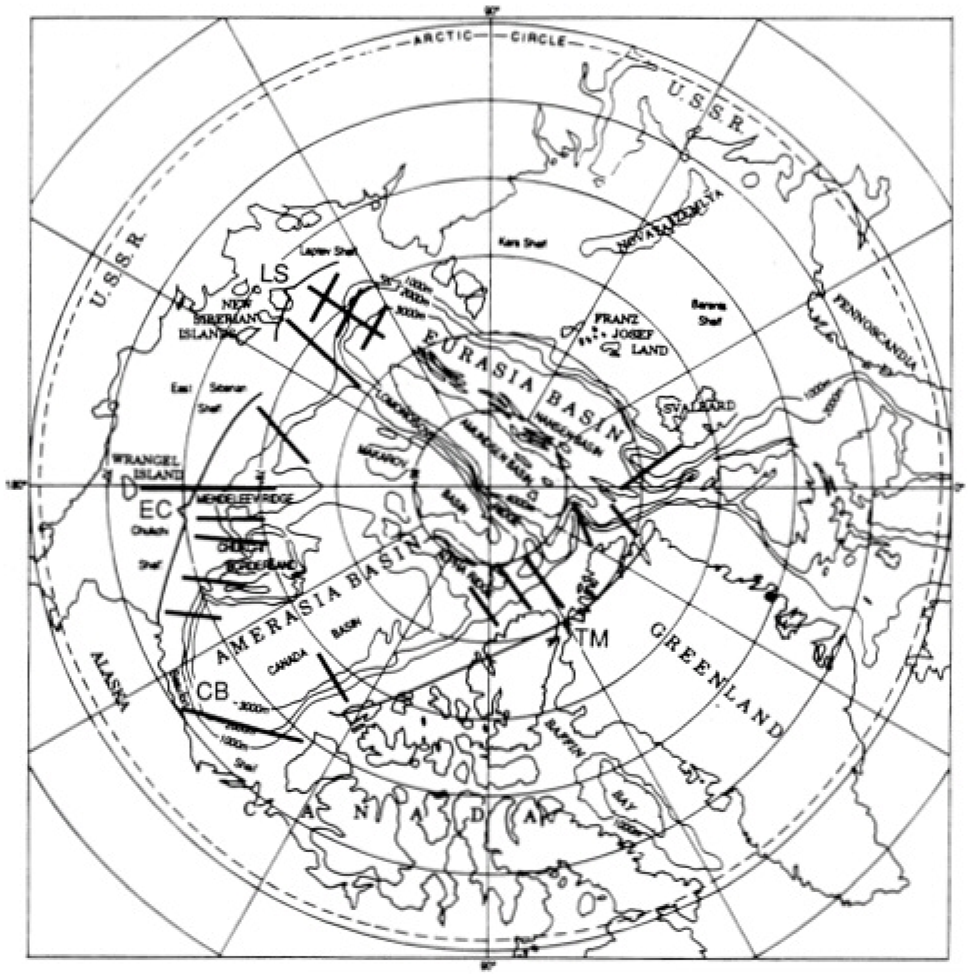

FIGURE 8
Location of proposed continental margin transects in the Arctic Ocean region. TM=TromsoMackenzie Lineament, C B=Canada Basin, EC=East Siberian-Chukchi Seas, LS=Laptev Sea.

Laptev Sea

A transition from rifting by seafloor spreading to rifting by crustal extension in continental rocks can be studied at the junction of the slow-spreading Arctic Mid-Ocean Ridge and the continental margin in the Laptev Sea. Aeromagnetic data and plate tectonic considerations suggest that more than 300 km of the 400 km of extension represented by Cenozoic oceanic crust in the eastern Eurasia Basin were imposed on the Laptev Shelf, where the crust has a continental thickness of more than 30 km (Kogan, 1974). How extensional strain is accommodated across the Laptev transition from oceanic to continental crust and the nature and stability of the thermal regime along the extensional axis across the transition are important tectonic problems. These studies could also provide information on the metamorphic effects and changes in physical properties of the ocean crust that may have resulted from thermal blanketing by thick sediments in the axial valley of the Arctic Mid-Ocean Ridge near the Laptev Shelf.

A long seismic refraction profile colinear with the axis of the Arctic Mid-Ocean Ridge and three perpendicular lines across the Laptev Shelf and the upper and lower Laptev slopes are proposed. Additional required data are multichannel seismic reflection profiles and gravity, magnetic, and heat flow measurements along the refraction lines. Combined use of passive and active seismic monitoring using ocean bottom seismometers and land-or ice-based arrays would provide important additional information.

A transect from the continental shelf north of the New Siberian Islands to the axis of the Eurasia end of the Lomonosov Ridge is proposed to be undertaken in conjunction with the Laptev margin studies. A rigorous understanding of the kinematics of rifting in the Laptev transition requires knowledge of the geometry and amount of transform motion, if any, between the Lomonosov Ridge and the east Siberian-Laptev Shelf.

Special Studies

Comparative Studies of Trans-Arctic Geologic Structure and Stratigraphy

The character, distribution, and structure of the geologic formations and lithotectonic terranes that encircle the Arctic Ocean Basin provide important constraints on regional plate tectonic models. Because most of the circum-arctic continents and islands have been mapped at reconnaissance or larger scales, it would appear to be a simple matter to compile the information, as many investigators are presently doing, and test proposed models against this body of data. In practice, however, this test has been difficult to apply. Barriers of language, lack of awareness of or access to the pertinent scientific investigators or literature, and national differences in scientific perspective and terminology commonly obscure or make unavailable structural and stratigraphic data critical to useful tectonic and geologic comparisons.

Small-scale map compilations of circum-arctic geology or tectonics (e.g., Okulitch et al., 1989) are also of limited usefulness for trans-arctic correlation and tectonic interpretation. Such maps provide useful overviews of the distribution of chronostratigraphic units around the Arctic, but they tend to be compilations of conventional wisdom. In addition, because the primary data sources for these compilations are often not provided, it is difficult to separate observations from interpretations. An example of the need for comparisons at larger scales is found in Alaska and northeast Siberia, which appear to be amalgamations of numerous exotic lithotectonic terranes with extensive accretionary histories (Fujita and Newberry, 1983; Zonenshain et al., 1990). Careful large-scale mapping and interpretation is a prerequisite for meaningful trans-arctic comparisons within these geologically complex terranes.

Until recently, national policy and logistics considerations in many of the arctic nations severely restricted working visits by scientists of other nations to their territories, and those that were allowed were commonly structured as formal scientific exchanges or field excursions with planned itineraries. Such programs have been productive, but until access to the relevant terranes of the arctic rim is permitted, the key questions of trans-arctic geologic correlation and arctic tectonic evolution will not be answered. The committee places a high priority on comparative trans-arctic geological, geophysical, and tectonic field studies by individuals or small groups of investigators. Such studies will be most productive when conducted as collaborative studies among investigators of the regions under comparison.

Paleomagnetic Analysis of Arctic Tectonic Problems

Although there are abundant paleomagnetic data for the circum-arctic cratons, there are few data, at least in the open literature, from rocks at the immediate margins of the Arctic Ocean. Most of the published work comes from Spitzbergen and surrounding islands, Ellesmere and nearby islands in Arctic Canada (Wynne et al., 1983), and from the Brooks Range and North Slope in Alaska (Harbert et al., 1990). Some summary paleomagnetic data are also available from the Soviet Union (Kharmov, 1989a, b), but with a few notable exceptions, insufficient supporting data are provided to assess the likelihood of magnetic overprinting. Such assessment is needed because pervasive overprinting has been found in the Alaskan Arctic.

A common problem in making paleomagnetic studies in both modern and ancient high arctic rocks is the steep inclination of the earth's magnetic field, which degrades declination measurements. The steep inclination, and the fact that many key localities have complex reformational histories that introduce uncertainties in restoring paleohorizontal indicators to modern horizontal, have led many investigators to rely more on paleolatitude than on paleomagnetic pole positions (Stone, 1989). Fortunately, most tectonic reconstructions of the Arctic imply paleolatitude changes well within the resolution of the paleomagnetic technique.

The movement of the major circum-arctic cratons has been defined fairly well from paleomagnetic measurements and seafloor magnetic anomalies, but the motions of the smaller crustal fragments nearer the margins of the Arctic Ocean Basin are largely unconstrained. Because many arctic tectonic models make different predictions concerning plate translations and rotations, they are especially amenable to paleomagnetic testing. For example, the displacements of the paleomagnetic poles that would have occurred had large parts of Chukotka and Alaska rotated about a pivot in the Mackenzie Delta area are quite different from those required by translation of Chukotka-Alaska from a location adjacent to the Lomonosov Ridge (Halgedahl and Jarrard, 1987). A paleomagnetic sampling program in the circum-arctic rim to test major tectonic hypotheses for the arctic region and to provide critical benchmarks for constructing new or revised hypotheses is therefore proposed. Initial investigations should also include the Mesozoic rocks of the New Siberian Islands that are key to rotational models for the Arctic and the assorted lithotectonic terranes and ancient island are sequences that lie between the Siberian shield and nuclear North America. The latter samples would test and help to resolve the timing of the postulated isolation of the Arctic from the Pacific Ocean in Late Mesozoic time.

Seismologic Investigations

Earthquake Seismology

Teleseismic studies offer considerable potential for study of the tectonics and deep crustal structure of the Arctic Ocean Basin and can provide continuous remote monitoring of current tectonic activity (e.g., Fujita et al., 1990). The acquisition of high-quality seismological data from the Arctic is hampered, however, by a lack of seismic stations near the coast and by the low quality of the few existing stations. In addition, few accessible standardized seismic data are available from the large Soviet sector of the Arctic. These factors have resulted in a relatively high detection threshold, about $m_b \geq 4.5$ for earthquakes in the central Arctic Ocean and have limited our ability to conduct detailed tectonic and structural studies of this seismogenic region. This handicap would be removed if a permanent network of modern broad-band digital stations were installed in boreholes at coastal stations and islands around the Arctic Rim. Borehole instruments are needed in the Arctic to reduce noise from seasonal melting and freezing of permafrost. The network should feature standardized formats to facilitate the transfer of earthquake data to researchers worldwide.

The continuous record of seismicity that such a network would compile would be especially useful for studying the central Arctic Ocean Basin, where seismogenic structures appear to generate low-to moderate-magnitude earthquakes with long recurrence intervals. The network would greatly improve understanding of the structure and rheology of the crust and upper mantle, the nature of the continent-ocean transition zones, plate interactions, and neotectonics in the Arctic.

The broad-band stations should be sited to create favorable source-receiver paths for surface wave and tomographic inversions across the Arctic Ocean Basin. Existing seismic stations with long operating histories should be upgraded and ice stations should operate seismographs where feasible. The broad-band stations should be supplemented with local networks in areas of tectonically significant seismicity such as northeastern Alaska, the Mackenzie Delta, and the southwestern Canadian Arctic Islands. Such local networks provided important supplementary data in northern Alaska and the Canadian Arctic from 1975 to 1982.

Structure and Rheology of the Crust and Upper Mantle

A primary objective of seismological research in the Arctic Ocean Basin is to determine the structure of the crust and upper mantle beneath the basins, ridges, and continental margins of the Amerasia Basin. Tomographic inversion of surface-wave phase velocities can provide information on the structure of the crust and upper mantle at wavelengths of 100 km or less with resolution in depth of 10 km (Yu and Mitchell, 1979). Because regional body wave phases are also well excited along most earthquake paths that cross the Arctic Ocean, three-dimensional elastic and anelastic modeling of these phases would provide insights into the structure beneath the large bathymetric features of the Arctic Ocean Basin, information that would be especially useful when interpreted in conjunction with improved potential field and long-offset seismic refraction data. Reflected body wave phases could also be used to constrain further the elastic and anelastic parameters of near-surface features. The present paucity of high-quality seismograph stations in the Arctic, particularly in the Soviet sector, limits the number of ray paths that can be studied. The lack of stations on arctic continental margins also makes it difficult to separate the contributions of ocean and continental crust to the dispersion curves. High-quality stations can also serve as anchors for regional arrays, similar to those envisioned by PASCAL, which can better constrain near-source and near-station structure through the calculation of source and receiver functions. High-priority targets for seismic crustal structure studies include the Chukchi Borderland, Mendeleev Ridge, the Canada Plain, and the East Siberian and Barents Shelves. Improved earth structure models would also enhance moment tensor inversion and other source process studies. Further, more numerous and improved seismograph stations, possibly including ocean-bottom seismometers, would aid in the study of ocean-floor anisotropy and the details of regional surface wave dispersion.

Continent-Ocean Transition

Some segments of the arctic continental margin display high seismic activity. Along the Canadian Arctic Islands, for example, clusters of earthquakes with magnitudes approaching 6 are associated with positive gravity anomalies. Both sediment loading (Hasegawa et al., 1979) and deglaciation stresses (Stein et al., 1979) have been proposed as causative factors. More precise location of the low-to moderate-magnitude events would provide significant insight into the structural character and geodynamics of these margins.

It is curious that earthquake clusters with events as large as magnitude 7 lie landward of the continental slope near some aseismic arctic continental margins. These clusters occur within continental shelf basins or along subbasin structures, and their study may provide important insights into the development of structurally controlled sedimentary basins within passive continental margins.

Plate Interactions

Delineation of microseismicity and transform faults along the Arctic Mid-Ocean Ridge and its junction with the Laptev Shelf and identification of volcanic earthquakes along the ridge axis would provide important insights into the mechanisms that operate at slow-spreading mid-ocean ridges. Such studies would require the deployment of ocean-bottom seismometers along the ridge.

Earthquake focal mechanisms suggest that rifting associated with the Arctic Mid-Ocean Ridge continues at least 600 to 700 km into the Eurasian continent (Fujita et al., 1990). The North America-Eurasia pole of rotation lies near the rift zone, which is a major plate tectonic boundary. This provides an opportunity to investigate seismically variations in the rupture processes along a rift as a function of spreading rate. Examination of detailed source parameters and of Soviet geologic data along this boundary would provide insight into the mechanics of the rifting process and place constraints on material properties of the crust. These data would also provide an opportunity to study the geometry and kinematics of the junction of this transpressive boundary with the convergent structures of the Pacific Rim. These studies would require geologic fieldwork in addition to deployment of fixed and portable seismic stations in the northeastern USSR and marine geophysical surveys on the adjacent continental shelf.

Neotectonics

Pistal compressional effects of Pacific subduction on the overriding plate appears to have extended into the Arctic Ocean Basin in northeastern Alaska, the northern Yukon Territory, and the southeastern Canada Basin (Grantz et al., 1990c). This deformation provides an opportunity to study the distal structural effects of modern subduction in continental crust and the differing mechanical responses of continental and oceanic crust to compression. In contrast, virtually all previous comparisons of continental and oceanic crustal strength have been confined to responses to extension. Both thin-skinned (i.e., a deformed, detached upper plate) and thick-skinned tectonic models have been proposed for this arctic deformation. Although the seismotectonic regime of northeastern Alaska has been studied, the short duration of local seismic network data combined with the low frequency of moderate to large earthquakes in the area provide an inadequate data base. An adequate seismotectonic analysis of this region, including the subsurface structure of the deformation front and its hinterland and the location and character of the stress regime boundary, would require the reinstallation of a local seismograph network.

Seabed Imaging and Mapping

The Arctic Ocean Basin encompasses a great variety and complexity of submarine landforms that are known only from sparse bathymetric profiles and soundings. Nevertheless, enduring insights into the tectonics, sedimentology, and oceanography of the Arctic Ocean Basin have been derived from our present imperfect knowledge of its morphology. Thus, S.W. Carey (1955) suggested largely on morphologic grounds that the Amerasia Basin is a sphenochasm that opened by rotational rifting of Alaska away from the Canadian Arctic Islands, and morphology led Tuzo Wilson (1963) to suggest that the Lomonosov Ridge was separated from the Barents Shelf by rifting along an arctic extension of the Mid-Atlantic Ridge.

More accurate and detailed knowledge of the bathymetry of the Arctic Ocean Basin would help to understand its geologic structure, sedimentation, and oceanography, especially when supplemented by continuous, overlapping side-scan sonar imagery. Such data would, for example, provide the first definitive information on the character, depth, and morphology of the Arctic Mid-Ocean Ridge and end speculation about the presence and character of associated transform faults. The data would delineate the young extensional structures that disrupt the continental shelf and slope of the Laptev Sea where the Arctic Mid-Ocean Ridge enters the Eurasian continent, the fault scarps that offset the seabed on the Alpha and Mendeleev Ridges, and any of the distal compressional structures that were produced in the eastern Beaufort Sea by Pacific-North American convergence. Detailed bathymetric mapping and imagery would also map the seamounts that occur in the region of anomalously high heat flow in the northwest part of the Canada Basin and Mendeleev Plain, provide insight into the structural significance of the linear ridged topography that lies between the Alpha and Lomonosov Ridges, and map the complex paths by which turbidity currents distribute clastic sediment from the arctic rivers to the perched depositional basins and remote abyssal plains of the Arctic Ocean Basin. Delineation of the turbidity-current channels and flow paths of the Arctic Ocean Basin, coupled with the interpretations of sediment type and sedimentary and erosional processes that can be made from side-scan sonographs would, for the first time, provide a unified overview of the modern sedimentary framework of the entire Arctic Ocean Basin. This framework would be particularly useful in interpreting past sedimentary environments of the Arctic Ocean Basin from cores and seismic reflection profiles.

Simultaneous digital imaging and bathymetric mapping of the Arctic Ocean Basin is now possible by means of the GLORIA Mk III digital long-range side-scan sonar imaging system, which collects phase bathymetry as well as backscatter imagery (EEZ-SCAN scientific staff, 1988). Simultaneous acquisition of subbottom seismic reflection profiles and magnetic and gravity data during GLORIA profiling would greatly enhance the information return. Experience in other ocean basins demonstrates that the acquisition of GLORIA imagery for the entire Arctic Ocean Basin would advance understanding of its geology, sedimentation, and oceanography.

The permanent polar ice pack requires that GLORIA imaging and mapping in the Arctic Ocean be conducted from submarines. Evaluations by the Institute of Oceanographic Sciences of the United Kingdom on behalf of the U.S. Geological Survey and the U.S. Navy indicate that a digital image mosaic of the entire Arctic Ocean Basin deeper than 500 m could be obtained with the GLORIA system from one submarine in two years.

Magnetic and Gravity Data

Reconnaissance aeromagnetic surveys have delineated a pattern of seafloor magnetic anomalies in the Eurasia Basin from which a generally accepted model for its plate tectonic development has been derived (Vogt et al., 1979a). The relatively wide spacing of aeromagnetic profiles and the presence of a thick sedimentary cover have precluded the derivation of a similarly definitive model for the larger Amerasia Basin. Magnetic and gravity surveying would be needed in the basin to identify, and if possible to date, areas of ancient oceanic crust with magnetic stripes, and to delineate ancient spreading ridges and transform faults. The data would also contribute to knowledge of the geologic character of the many ridges and plateaus of the basin and help to delineate major structural boundaries and other tectonic features beneath its margins and thick sedimentary fills. Because of the basin's physiography and complex geology, potential field coverage of the Arctic Ocean Basin would have to be extensive and uniform to be useful and would have to consist of relatively closely spaced track lines rather than the more economical swath coverage. A regional low-altitude (150 m) aeromagnetic and aerogravity grid survey of the entire Amerasia Basin with a line spacing of 20 km would therefore be needed early on.

Both aircraft and submarines are good vehicles for magnetic and gravity surveys in remote areas with harsh environments (Sobczak and Halpenny, 1990a). Airborne gravity data are more difficult to record than aeromagnetic data, but both can be acquired more rapidly and inexpensively from aircraft than from surface platforms. The principal limitations in aerogravity surveys are the precision with which the motions and accelerations of the aircraft can be measured, recorded, and compensated. Recent advances in radar altimetry, GPS, and inertial navigation indicate that aerogravity surveys with acceptable accuracy for geologic interpretation should be available for arctic deployment within a few years (Brozena, 1984).

Airborne magnetic data can be reduced, plotted, and interpreted easily by established methods. The results yield important information about the regional geologic structure of the earth's crust and the thickness of sedimentary basins (Grantz et al., 1990c), especially when used in conjunction with local seismic surveys. The reduction of aerogravity data, in contrast, is more time consuming and expensive. But because integrated interpretations of magnetic and gravity data are more powerful than interpretations based on either alone and because of the expense of arctic aerial surveys, the committee recommends that aeromagnetic and aerogravity data be recorded simultaneously over the Amerasia Basin, even if funds are initially available only for the reduction of the aeromagnetic data.

Presumed oceanic crust in the southern Canada Basin, which apparently contains low-amplitude (200 nT) magnetic anomalies, is overlain by 6 to 12 km of clastic sediment (Jackson and Oakey, 1990). It has been suggested that the magnetic anomalies are products of seafloor spreading in Jurassic and Early Cretaceous time (Taylor et al., 1981), but a more closely spaced grid survey would be needed to confirm their identification as spreading anomalies and unequivocally establish their geometry and age. Because confirmation and dating of seafloor spreading anomalies in the southern Canada Basin would constitute a breakthrough in understanding of arctic tectonics, the committee proposes that a relatively close spaced aeromagnetic and aerogravity survey (line spacing 10 km x 20 km) be flown across this area. The main profiles should trend east-west, normal to the anticipated trend of the magnetic anomalies, and extend from the Alaska continental margin to 78°N lat. A detailed survey with northerly trending profiles of similar spacing is also recommended for the Makarov Basin to ascertain whether apparently lineated magnetic anomalies in this basin represent seafloor spreading or subbasement structural relief.

SEDIMENTARY RECORD AND ENVIRONMENTAL HISTORY

The Arctic Ocean is environmentally unique not only because of its ice cover and restricted connections to the world ocean but also because of the ice caps on some of the adjacent landmasses. This environment has strongly influenced global atmosphere, hydrosphere, and sea level. Indeed, earth's climate, including its atmospheric and oceanic circulation, is primarily controlled by temperatures at the poles and by the equator-to-pole atmospheric thermal gradient. Tracing and understanding the evolution of arctic climate and oceanography since mid-Cretaceous time is therefore a major scientific goal. Fortunately, an abundant lithostratigraphic and biostratigraphic record of this evolution is preserved in three distinct arctic environments: the sediments of the Arctic Ocean Basin (Thiede et al., 1990), the sediments of arctic continental shelves and coastal plains (Marincovich et al., 1990), and the ice caps of Greenland and other high arctic islands (Robin, 1983; NRC, 1984a, b). The systematic and detailed interpretation of the environmental history that resides in these records represents one of the outstanding challenges and opportunities in the geosciences today.

The Record in Circum-Arctic Nonmarine and Paralic Sediments

Cretaceous Sediments

During the Cretaceous, the Arctic was essentially free of sea ice, permafrost was absent from arctic coastal plains, and mixed forest extended at least to 85°N (Smiley, 1967; Spicer and Parrish, 1986, 1990). The mid-and late-Cretaceous river-dominated Corwin and Umiat deltaic complexes of Arctic Alaska contain nonmarine fossils that allow high resolution reconstruction of this temperate polar regime, providing a sensitive and detailed geologic record of a previous greenhouse world.

The Corwin and Umiat delta complexes are also of great economic importance because they are estimated to contain more than 2.7 trillion short tons of low-sulphur, low-ash coal that represents one-third of the reserves of the United States (Sable and Stricker, 1987). Exceptional coal accumulation was due to high summer productivity coupled with minimal decay of shed organic material during the winters (Spicer et al., in press). Pollens in the coals show stratigraphic variations from bed to bed on the millimeter scale that promise to advance understanding of both the swamp flora that formed under these exceptional conditions and the changes in quality of coal (Youtcheff et al., 1987). Studies of the pollen would also expand understanding of the source vegetation of spores and allow dispersed palyno-debris in both marine and nonmarine sediments in the Arctic to be used for improved stratigraphic resolution and climate research.

Plant fossils show that the Cretaceous polar climate was mild, but not static. Rich plant megafossil assemblages in Arctic Alaska record climatic changes from mild conditions in the latest Early Cretaceous (Albian, possibly Aptian) time to a climate with periglacial conditions below elevations of 1,000 m in latest Cretaceous (Maastrichtian) time (Parrish and Spicer, 1988; Spicer and Parrish, 1986, 1990; and Parrish et al., 1987). Leaf physiognomy and wood structure indicate that early Late Cretaceous mean annual air temperature (MAT) in Arctic Alaska was 10°C with cold-month means no lower than-11°C. Precipitation was high and periglacial conditions were absent, though winter temperatures were at or below freezing.

Floral diversity declined through the Late Cretaceous as the climate cooled. Late Cretaceous plants indicate that MAT had dropped to between 2.5° and 5°C, that periglacial conditions remained absent at sea level, and that permanent ice fields may have existed in the Brooks Range above 1,000 m. Abundant fossil charcoal and a diminution of coal abundance and quality suggest that later Cretaceous vegetation experienced frequent wildfires.

During the Late Cretaceous time, northern Alaska experienced three to four months of continuous winter darkness. Trees were small, forests were open, and the vegetation may have approached that of modern taiga. In spite of the highly seasonal climate and winter cold, dinosaur tracks and fossils are relatively common in the Cretaceous of northern Alaska, which raises important questions regarding dinosaur physiology and migratory behavior.

Siberian nonmarine sequences and flora appear to have much in common with those of Alaska, and the committee recommends closer cooperation with Soviet investigators to facilitate the documentation of the evolutionary sequences, migrationary pathways, and high resolution climatic signals in the widespread and well-developed Cretaceous record of the circum-arctic region.

Tertiary and Quaternary Sediments

A better understanding of the Cenozoic evolution of arctic climate and oceanography would aid in the interpretation of the present ocean-atmosphere system and its sensitivity to future climate change. Although the main controls of arctic climate and oceanography during the Cenozoic may have been variations in the earth's orbit and solar-terrestrial interactions, plate tectonic events may have indeed had significant impacts and could have been dominant (Berggren, 1982; Barron, 1985). These events enlarged the Arctic Ocean Basin, established its deep circulation with the North Atlantic, and produced changes in the distribution and height of arctic highlands. The climatic changes that accompanied these shifts increased the pole-to-equator temperature gradient and transformed the Arctic from a cool temperate landscape to one of tundra and continental glaciers (Barnosky, 1987).

For Early Tertiary time, arctic terrestrial deposits such as the Eocene Eureka Sound Group of the Canadian Arctic Islands record warm temperate to temperate climates at 75°N paleolatitude (Tauxe and Clark, 1987). Rhino, hippopotamus, tapir, giant turtle, and a primitive form of the saki monkey lived in forests of cypress, redwood, hickory, birch, fern, and several broad-leafed plant taxa now known only from Indo-China (McKenna, 1980; Hickey et al., 1983). The animals survived at this latitude despite months of darkness. A major concern for studies of global climate change is to determine what geologic factors (e.g., changes in paleogeography, orography, and oceanographic conditions) contributed to the cooling of the moderate terrestrial climate that supported the Eureka Sound biota.

A lack of mid-Tertiary sedimentary samples from the Arctic Ocean Basin (see Figure 9) and a meager fossil record from Arctic North America preclude reconstruction of the climatic change from the temperate Eocene landscapes to tundra and continental glaciation in the Late Pliocene and Quaternary. On land, only bits and pieces of fossiliferous sedimentary sections fill part of the gap. The Haughton Astrobleme on Devon Island in Arctic Canada, which became a lacustrine depocenter about 23 million years ago and preserves a rich biota that includes rhinoceroses and swans, records most of what is known in North America about arctic biota between 40 and 20 million years ago (Whitlock and Dawson, 1990). The missing record is probably preserved elsewhere in the North American or Soviet Arctic, and a major goal of arctic solid earth geoscience should be to close this gap with sediment samples from both the Arctic Ocean Basin and the arctic rim.

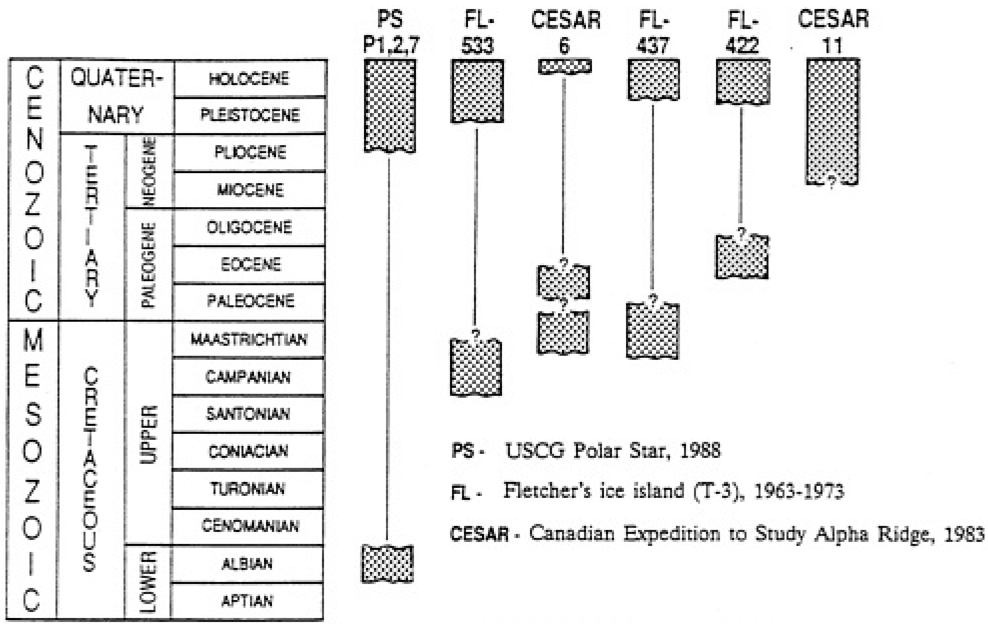

FIGURE 9
Location of proposed continental margin transects in the Arctic Ocean region. TM=TromsoMackenzie Lineament, C B=Canada Basin, EC=East Siberian-Chukchi Seas, LS=Laptev Sea.

Plant fossils in the Beaufort Formation of the western Canadian Arctic Islands record a gradual cooling in Neogene time in the Arctic. Early Miocene forests of redwood, hickory, hemlock, walnut, and pine were replaced by forests of pine, spruce, cedar, walnut, basswood, and hickory during the Middle to Late Miocene, and by cool forest and tundra during the mid-Pliocene (Matthews and Ovenden, 1990). During this interval, the Arctic Ocean Basin took on its modern configuration, and oceanic gateways opened to both the Atlantic and the Pacific (Einarsson et al., 1967; Lawver et al., 1990a). Because of inadequate dating of the limited terrestrial sequences, the origin and developmental history of the endemic biota and environments of the Neogene Arctic remain unclear.

Permafrost apparently first developed at low altitudes in high latitudes between 3 and 2.5 million years ago, and was broadly time transgressive to the south (Julie Brigham-Grette personal communication, 1991). If arctic oceanography changed during the progressive cooling represented by the southward extension of permafrost, correlation of the changes with the spread of permafrost may provide semiquantitative data on the mechanism of Late Cenozoic global cooling. It has been suggested that gradual submergence of the broad Laptev, East Siberian, and Chukchi Shelves may have precipitated development of the arctic ice cover (Barry, 1989). This important hypothesis could be tested by high-resolution seismic reflection profiles and two or three boreholes about 1 km deep into the Neogene strata of these shelves.

As recently as 2 million years ago, when the Arctic Ocean was largely ice-free, trees extended to the arctic coast in Greenland and Alaska (Brigham-Grette and Carter, in press). Sediment budgets along arctic coasts and shelves then must have been drastically different from today, when sediment transport is largely restricted to two or three months of the year. Coring such sediments promises to provide an important record of the onset of sea ice in the Arctic. On the basis of recently collected high-resolution seismic reflection profiles and drill cores from the Canadian Beaufort Shelf, it is inferred that arctic shelves contain a rich stratigraphic record of

Late Cenozoic sea level change, regional glaciation, shelf aggradation, and paleoclimate that would strongly complement the well-documented record of eustatic high stands of sea level on the Alaskan Arctic Coastal Plain (Blasco et al., 1990; Dinter et al., 1990). An important advance in understanding of these events would be achieved by coring the 100^{+} m Late Cenozoic sedimentary sequence at several additional sites on both the Alaskan and the sectors of the Beaufort Shelf.

A major stumbling block in paleoclimatic research is our inability to model adequately the effects of future temperature changes in the Arctic. The Quaternary stratigraphic record on arctic shelves and coastal plains may be useful for creating such models because it is located in the zone of glacial-eustatic transgressions and regressions of sea level and encompasses times when conditions were warmer than at present. This record may reveal correlations between Northern Hemisphere climatic and oceanographic changes and waxing and waning of the Greenland Ice Sheet and arctic sea ice that may suggest causes and rates of climate change. Arctic coastal deposits show that such changes occurred as recently as 1.5 to 1 million years ago and perhaps as recently as 125,000 years ago. A series of 30-m cores across the Beaufort Shelf would be an effective way to study these changes at moderate cost.

Lack of sea ice and large ice sheets in the Arctic 1.5 to 1 million years ago and perhaps 125,000 years ago produced major differences in albedo and heat budget with respect to the present Arctic. Documenting and dating of these intervals of low albedo would address the susceptibility of arctic sea ice to modification by orbitally forced (Milankovitch-driven) climatic change, orographic influences on air masses from lower latitudes, or more random causes of climate change. Such paleoclimatic studies may be useful for modeling the future impacts of warmer climate.

Determination of the role of perennial and seasonal sea ice in glacial/interglacial cycles of the past 900,000 years is needed to understand the processes that drove climatic change during the Quaternary. These cycles occurred about every 100,000 years (Berger, 1988), but glacial intensity and interglacial warming were not uniform from cycle to cycle. Evidence on the lead time between the onset of forcing conditions in the ocean-atmosphere system and the onset of glaciation or deglaciation is especially needed. Continuous drill cores from the Arctic Ocean Basin and from shelves and coastal plains that escaped Quaternary glaciation would provide key data on past and future global climatic change. High-latitude lakes with thick sedimentary sections beyond the limits of Quaternary glaciation would also provide promising drilling targets (Andrews and Brubaker, in press).

A special focus of research should be the most recent periods of major transition, in particular, the late glacial to Holocene transition, when dating control would be best, and the last glacial/interglacial/glacial cycle (150,000 to 80,000 years ago). The latter could be compared with the forthcoming data from the Greenland Ice Sheet Project II. Coordinated interpretation of arctic sediment and Greenland ice cores would provide an especially powerful data base for climate modeling.

Useful assessments of past and future climate change in the Arctic will also come from detailed studies of Holocene terrestrial and continental shelf deposits. It is now known that the warmest postglacial period in the Arctic occurred during the mid-Holocene, when insolation was high and the thickness of the active layer in areas of permafrost increased (Bradley, 1990). The recognition of this mid-Holocene warm interval in cores and outcrops from the Arctic Ocean Basin and from the arctic shelf and coastal plain, and in ice cores from Greenland and the Canadian Arctic Islands, would establish an important environmental datum. This might establish criteria by which similar events could be recognized in pre-Holocene sections.

In summary, our knowledge of the environmental evolution of the Arctic will be greatly advanced by a focused effort to recover a detailed stratigraphic record of the last 65 million years from several areas of the Arctic. The last 3 million years, and especially the last 900,000 years of this record, are critical to understanding the nature and causes of alternating glacial and interglacial climates in high latitudes and the sensitivity of the Arctic to future anthropogenic global change.

The Record in the Arctic Ocean Basin

Cretaceous and Tertiary Sediments

Seven piston cores—six Cretaceous and one Early Cenozoic—constitute the entire existing stratigraphic record of pre-Late Cenozoic deep-ocean sediments in the Arctic Ocean Basin (see Figure 9) (Clark, 1988; Phillips et al., 1990). Three cores from Northwind Ridge consist of Lower Cretaceous (Albian) bioturbated siltstone, and one core from Alpha Ridge consists of Upper Cretaceous (Campanian) organic-rich mud composed of abundant plant material in a matrix of marine phytoplankton. Two cores of Maastrichtian age and one of Eocene age from Alpha Ridge consist largely of siliceous plankton skeletons.

The pre-Pliocene arctic piston cores contain important paleoenvironmental information, but they are far too few to constitute a history of its arctic environmental evolution. The paucity of the record does not enable resolution of some basic controversies about the significance of the few samples that are in hand. For example, Upper Cretaceous and Eocene sediments in four of the cores contain species of dinoflagellates, diatoms, and silicoflagellates known also from coeval sediments at lower latitudes. Mutual occurrence of so many species in widely separated water masses suggests to some investigators that there was substantial interocean circulation of relatively warm water between the Arctic and more southerly oceans at these times (Clark and Kitchell, 1979; Kitchell and Clark, 1982). Other investigators, however, on the basis of shallow-water marine invertebrate faunas near the Cretaceous-Tertiary boundary, suggest that the Arctic Ocean was isolated during at least part of this interval (Gartner and Keany, 1978). The presence in the Maastrichtian and Eocene cores of laminations consisting of layers rich in diatom resting spores in alternation with layers rich in their vegetative cells suggests strong Late Cretaceous and Paleogene seasonality in the Arctic Ocean (Kitchell et al., 1987).

There is a significant gap in the Arctic Ocean Basin sedimentary record between the Eocene and the Pliocene. The gap may result from the same Late Miocene unconformity that is widely recognized on arctic shelves, but it is more likely a result of inadequate sampling. In contrast, many samples of Plio-Pleistocene glacial-marine sediment have been obtained from the ridges and slopes of the Arctic Ocean Basin; many samples of Quaternary turbidites have also been obtained from the continental rises and abyssal plains (Clark et al., 1980; Campbell and Clark, 1977). These younger sediments contrast strongly in lithologic character with the older sediments of the basin. Evidently, the Late Cretaceous-Early Cenozoic earth had a much warmer Arctic Ocean than has existed at any time during or since the Pliocene or perhaps in earlier Neogene time. This change in arctic climate, its correlative oceanographic conditions in the arctic and other oceans, and its significance for modern world climate need to be documented by detailed studies of the stratigraphic record that is available in the Arctic Ocean Basin. More samples would be needed to document the changes in sea level, climatic cycles, circulation patterns, and current regimes in the Arctic Ocean Basin through time; chemical cycles of silica, carbon, and phosphorous; patterns of interaction between sediment and fauna; diagenesis; and many other aspects of the lithologic and biotic record in ancient Arctic Ocean sediments. Such data are necessary to understand the paleoclimatic and paleooceanographic history of the Arctic Ocean and the mechanisms of global climatic change. An important ancillary question is whether the Arctic Ocean Basin was a site for evolution and adaption of marine life to cooler conditions and, ultimately, sea ice.

Arguably, the unique characteristic of the Arctic Ocean is its perennial cover of sea ice (Clark, 1990a). The geographic extent, distribution, and thickness of the ice cover exert a major influence on global climate today, as they undoubtedly did in the past. We do not know when the ice cover first formed, the detailed chronology of its waxing and waning during the Late Cenozoic, and the environmental conditions that caused it to form, melt, and reform periodically. The known effect of the size of the polar ice pack on modern climate suggests that its history would be of relevance to understanding past and predicting future global climatic change. This record would be particularly useful when discrepancies between interpretations based on deep-sea sediments and those based on sections from the continental margin, the circum-arctic, and the ice cap are resolved and unified interpretations become available (Clark, 1990b).

Accumulating field experience suggests that a composite stratigraphic section representing all the major time units and the principal Late Mesozoic and Cenozoic paleoenvironments of the Arctic Ocean Basin could be obtained from long piston cores and shallow rotary drill holes sited on the basis of seismic reflection profiles and bathymetry. The committee recommends that a coring program be initiated. Sample sites would have to be on the crests and flanks of ridges and from continental slopes that are isolated from the deltas of major river systems. Existing cores and seismic reflection records collected from ice island T-3, the LOREX, CESAR, and FRAM I–IV experiments, and the U.S. Coast Guard cutter *Polar Star* provide an adequate basis for initiating a coring program, but additional seismic reflection data would be needed to achieve optimum stratigraphic coverage. The cores would provide answers to many questions concerning the paleoenvironment and tectonic history of the Arctic and its role in world climate. For example, they would fill in the gap in sediment samples between the Eocene and Pliocene in the Arctic Ocean Basin, when the major transformation from an ice-free to an ice-covered Arctic Ocean occurred. They would also provide data on oceanic circulation in the Cenozoic Arctic, faunal interchange between the Arctic and more southerly oceans, and the evolution of the arctic ecosystem from a warmer ocean in mid-Cretaceous time to modern conditions.

Sampling of pre-Pliocene sediments would significantly increase the observational data base for hindcasting and testing climatic models and improve understanding of the natural history of the Arctic Ocean and its relation to global climatic change. For example, what conditions enhanced the thermal stratification in the Arctic Ocean that fostered the development of sea ice, and how often were these conditions repeated during the past 3 million years of earth history? How did changes in bottom water formation in the Norwegian and Greenland Seas during glacial/interglacial cycles affect the physical and chemical oceanography of the Arctic Ocean Basin? Ongoing research in the more southerly ocean basins is attempting to address these and similar issues, but these studies would benefit from closer integration with studies of the sedimentary record in the Arctic Ocean Basin and its continental shelves and coastal plains.

Quaternary Sediments

Our present understanding of the Arctic Ocean is comparable to our understanding of oceans at lower latitudes 20 years ago. Fundamental questions concerning the Arctic Ocean during the Quaternary need answers before we can fully evaluate its role in global climate. The Quaternary record in the Arctic Ocean Basin contains a wealth of information on the character, detailed chronology, and possible causes of the glacial/interglacial cycles that have dominated global climate during the Late Cenozoic. Better understanding of this record would improve evaluation of the environmental record contained in older sediments in the Arctic Ocean Basin.

A central question for understanding the Quaternary environment in the Arctic Ocean Basin is how and why it alternated between ice-free and ice-covered states. A well-constrained and detailed chronology from arctic subsea sediment cores would greatly assist in this task, but techniques used widely in lower latitude ocean basins (stable isotopic measurements, biostratigraphic indices, and radiometric dating) have proven difficult to apply. Recent experience suggests that better prospects for dating arctic cores may lie in paleomagnetic stratigraphy derived with sensitive cryogenic magnetometers that permit extensive demagnetization of samples without sacrificing sensitivity and in radiocarbon ^{14}C dating by accelerator mass spectrometry (AMS). Radiocarbon dating allows individual components of the sediment to be dated, thus eliminating the spuriously old ages caused by detrital limestone grains or reworked fossils in bulk sediment samples dated by conventional methods.

A second major issue is how Arctic Ocean Quaternary sedimentation rates and sediment composition differ between glacial and interglacial times. What can the differences tell us about glaciological processes? Although there has been much controversy regarding the rates of sedimentation in the Amerasia Basin (Clark et al., 1980; Sejrup et al., 1984; and Macko and Aksu, 1986), it is now widely accepted that rates were low (2 to 3 mm/1,000 years) throughout the Late Quaternary and that the lithostratigraphy of Clark and others (1980) is largely supported by new studies of the paleomagnetic chronostratigraphy (Jones, 1987; Witte and Kent, 1988).

Sedimentation rates in the Eurasia Basin, on the other hand, are found to be nearly an order of magnitude larger (Mienert et al., 1990).

Realistic interpretation of the Quaternary and older stratigraphic record and reconstruction of the Late Quaternary climate and oceanography of the Arctic Ocean Basin require precise understanding of the sedimentary processes by which modern and Holocene sediments were transported to the basin and deposited and altered within it. Many of these questions can be addressed with sediment traps; buoys for measuring ongoing physical, chemical, and biological processes; and new box cores from a wide range of sedimentary environments in the Arctic Ocean Basin. Existing samples in core repositories are, with few exceptions, inadequate. Box cores enable recovery of undisturbed samples of a large cross section that include the sediment-water interface and as much as 50 cm of the underlying sedimentary column. In the Arctic Ocean Basin, cores 50 cm long can recover sediments of both the Holocene and the last glacial maximum and contain sufficient material for study and intercomparison by a variety of analytical techniques. Giant gravity and large-diameter piston cores can recover samples of the entire Late Quaternary sequence in sufficient volume for analysis by multiple techniques. Such analyses would clarify the role of the Arctic in the earth's carbon cycle and measure other environmentally significant components such as nitrogen, phosphorus, and silica.

Even though overall sedimentation rates in the Amerasia Basin appear to have been low, little is known about their variations in time and space. Radiocarbon dating by AMS allows for the first time to direct measurement of sedimentation rates during the Holocene interglacial and the last glacial maximum. Preliminary results show that Holocene sedimentation rates in the Arctic Ocean Basin are approximately 10 to 20 times greater (1 to 2 cm/1,000 yrs) than those of the last glacial maximum (0.05 to 0.1 cm/1,000 yrs) (Mienert et al., 1990). What environmental conditions and processes were responsible for these variations? Did they exist during earlier glacial and interglacial intervals? Are they compatible with overall Quaternary sedimentation rates for the Arctic Ocean Basin? A detailed chronology of variation in Arctic Ocean sedimentation rates, especially when closely correlated with temporal changes in lithology, fossils, chemistry, and other physical and paleobiologic features of the sediments through time, should be a major objective of solid-earth geoscience in the Arctic.

The lithologic component of arctic sediments offers opportunities for identifying and dating major arctic climatic events. For example, paleomagnetic chronostratigraphy suggests that prior to approximately 1.5 million years ago, little ice-rafted detritus and virtually no detrital carbonate entered the Arctic Ocean Basin (Jones 1987). Preliminary data suggest that since that time floods of lithologically distinctive sediment from the Queen Elizabeth Islands entered the Amerasia Basin approximately every 400,000 years. Were these islands glaciated less frequently than the approximate 100,000-year cycle of ice sheet growth and decay observed elsewhere? Or did the outwash go elsewhere during some glaciations? Since the last glaciation has removed most of the traces of prior glacial events in the circum-arctic landmasses, the arctic marine detrital record is essential for the study of Quaternary glaciations.

Insights into the mechanism of global change may result from such correlations because they would provide close correlations between accelerated erosion and glaciation events in the circum-arctic landmasses with paleoceanographic conditions in the Arctic Ocean Basin. Preliminary studies suggest that it may be possible to identify the provenance of the sediments that periodically flooded the central Arctic Ocean Basin by comparing their mineralogy, petrography, and perhaps isotopic character with lithologically unique terranes in the circum-arctic land-masses. If successful, such studies would enable interpretation of when specific circum-arctic terranes were glaciated, thereby providing insights into the chronology and dynamics of Quaternary continental glaciation.

The lateral variability in thickness and lithology of the biogenic and nonbiogenic Late Quaternary sediments of the central Arctic has important implications for sedimentary processes in the Arctic Ocean Basin. In the past, it was assumed that virtually the entire basin, particularly the Canada Basin, contained the same sequence of synchronous sediments, as demonstrated by the core-to-core correlations for the Canada Basin illustrated by Clark and others (1980). It is now possible to test this hypothesis with AMS ^{14}C dating. Time slices of the last 40,000 years can now be constructed with unprecedented resolution by this method to test whether Late Quaternary sedimentary units are synchronous or time transgressive across the Arctic Ocean Basin. Such studies would provide data concerning supply and transport in the basin and the relative strength and duration of sediment sourcelands during latest Quaternary time.

The stratigraphic record of deglaciation in the Arctic Ocean Basin and its comparison with the record at lower latitudes provide useful information for both Quaternary studies and climate modeling. Numerous competing theories of glaciation/deglaciation exist, and many predict explicit configurations of ice masses through time in the Arctic Ocean Basin and its environs. Unfortunately, the age of the successive deglaciations in the Arctic Ocean Basin is poorly known (e.g., Denton and Hughes, 1981). Detailed mineralogical and stable isotopic analyses of the sediments deposited during each deglaciation, combined with AMS ^{14}C dating, would reveal how this region moved from glacial to interglacial conditions and the chronology of that transition. Combining these data with the better-understood deglaciation sequences of the Norwegian-Greenland Sea and the North Atlantic would show when the Arctic was oceanographically reconnected with the world ocean and whether deglaciation in the Arctic was earlier, later, or coeval with deglaciation in other ocean basins. Insights into the dynamics of ice-sheet decay and ocean circulation would be gained from such studies.

The Record in Arctic Ice Cores

Drill cores from the massive ice caps of Greenland and the Canadian Arctic Islands provide a record of the last 130,000 years of the earth's climatic and environmental history (Robin, 1983; NRC, 1984a, b). According to the Committee on the Role of the Polar Regions in Climatic Change of the Polar Research Board (NRC, 1984b, p. 47), ice at the base of the ice sheet in south-central Greenland could be as old as 1 million years. An ice core to bedrock would provide an invaluable complement to the record preserved in the terrestrial and marine sedimentary rocks of the Arctic. Some of the ice core data, such as its detailed record of variation in atmospheric composition, including CO_2 content, atmospheric turbidity, and micrometeorite flux, may be obtainable by no other method. The climatic and environmental history embedded in ice cores will be most fully understood when it is supplemented and complemented by evaluation of the sedimentary record preserved in the Arctic Ocean Basin and its continental shelves and bordering lowlands.

ARCTIC GEOLOGIC PROCESSES AND ENVIRONMENTAL INDICATORS

Knowledge of the influence of glacial and interglacial climates on the chemistry, mineralogy, lithology, and texture of arctic biogenic and clastic sediments is meager, but recent observations suggest that certain features of the arctic sedimentary record may enable interpretation, and in some cases quantification, of past environmental conditions and processes in the arctic sedimentary record (Thiede et al., 1990). Quantification, if achievable to a significant degree, would provide the ability to test climatic and oceanographic models by hindcasting from present conditions to numerical data points at specific times in the geologic past.

Paleoenvironmental Indicators

Detailed analyses of both organic and inorganic materials plus isotopic measurements of a few light elements can provide the basis for estimation of environmental conditions in ancient seas and their shallow sediments. Bottom water temperature, for example, can be inferred from the presence of calcite pseudomorphs after ikaite ($CaCO_36\ H_2O$) which forms where organic-rich sediment accumulates rapidly in normal seawater near and below O°C (Suess et al., 1982; Jansen et al., 1987). Paleoenvironmental conditions in modern and Late Cenozoic sediments can also be estimated from analyses of certain organic compounds (biomarkers) in sediments and fossils. Long-chain alkanes in certain species of algae and dinoflagellates, for example, have been used to estimate paleotemperature in subsea cores from mid-latitude oceans (Eganhouse and

Kaplan, 1988) and an antarctic lake (Volkman et al., 1988), and the method may be applicable to Arctic Ocean Basin sediments.

The ratio of $^{18}O/^{16}O$ in biogenic carbonate in marine sediments that have not experienced diagenesis by burial deeper than 200 m reflects primarily variations in the volume of the continental ice sheets, which contain more of the lighter ^{16}O isotope than seawater (Hoefs, 1987). In the absence of salinity anomalies, water temperatures during sedimentation in ancient oceans can be interpreted from this ratio. Ratios of $^{18}O/^{16}O$ in calcareous marine organisms, particularly foraminifera, can therefore serve as an index for glacial versus interglacial climatic conditions in Late Cenozoic marine sediments (Shackleton and Opdyke, 1973; Aksu, 1985). Increases in $^{13}C/^{12}C$ ratios in fossil planktonic marine organisms and organic matter may reflect variations in biological productivity or sedimentary carbon flux from the continents (Aksu, 1985; Darby et al., 1989). Although carbon and oxygen isotopic ratios and their interpretation are most reliable in diagenetically unaltered rocks, interpretations of these ratios have been made from strata as old as Early Cretaceous (Douglas and Savin, 1975) and Devonian (Brand, 1989). If useful interpretations can be made from rocks as old as Early Cretaceous, they would enable interpretation of important aspects of arctic paleooceanography and climatic history.

Stratigraphic variations in oxygen and carbon ratios in the arctic sedimentary record are difficult to establish because of sampling problems resulting from bioturbation and because of the dominance of foraminifera-poor zones representing glacial intervals. Relatively large differences in salinity between near surface and deeper water in the Arctic Ocean also complicate interpretation of the data. As a result, mainly interglacial events are available for isotopic study in arctic cores. Gaps in the arctic isotopic record may be represented by foraminifera-bearing strata in the adjacent Greenland or Norwegian Seas (Henrich et al., 1989), where sea ice may have been thinner or intermittent and biological productivity higher than in the Arctic Ocean during the ice ages. Correlation of variations in oxgen and carbon isotope ratios with changes in biostratigraphy and lithology in Late Cenozoic arctic cores would provide insights into the onset, timing, and character of glacial/interglacial cycles and oceanographic conditions in the Arctic during the Quaternary.

Sedimentation

Several aspects of sedimentation of the Arctic Ocean Basin are unusual, and a basic question is how, and to what degree, the Late Cenozoic climate imprinted the arctic sedimentary record. Clastic deposition rates in the arctic marine environment are largely dependent on continental denudation rates, involving glacial outwash, river runoff, eolian supply, and coastal erosion. However, the flux of such materials in density currents, sea ice, and winds from the continents and continental shelves to the Arctic Ocean Basin is poorly known. Aerosols, for example, are estimated to contribute between 1 and 10 percent of the yearly accumulation of arctic sediment (Mullen et al., 1972; Darby et al., 1974), but quantitative data to constrain this range are lacking. Further, the sediment load of not a single arctic stream has been gauged in Alaska, and the proportion of sediment in the sediment/ground ice mix that is eroded annually from the arctic coastal plains and shallow shelves by marine abrasion and transferred to the shelf is too poorly known to allow adequate estimation of the sediment budget on arctic shelves (Reimnitz et al., 1988). Only a start has been made in assessing the mineralogy, sedimentation rate, and provenance of arctic clastic and biogenic sediments from cores and in mapping the areal variations in thickness and character of the youngest sedimentation units on seismic reflection profiles.

Characterization and quantification of the clastic and biogenic sediment now being contributed to the Arctic Ocean Basin by winds, sea ice, icebergs, and turbidity currents, and by chemical, biological, or biochemical processes in the water column and in the shallow sediments would significantly improve interpretation of the lithostratigraphic record in arctic cores. Sampling of the water column and ice canopy for the clastic and biogenic components by sediment traps, ice coring in different parts of the Arctic Ocean Basin (Barnes et al., 1982; Honjo et al., 1988), and knowledge of overall water and ice circulation patterns would also be required. Quantification of the flux of fine-grained biogenic and clastic particles from the seabed to the sea-ice canopy in frazil ice, their residence time in the canopy, and their dispersal to the Arctic and North Atlantic Basins would help to establish a sediment budget for these materials. Modern atmospheric circulation patterns in the Arctic are understood in sufficient detail to identify the sources of particulate matter. With modern conditions as a guide, some insight into arctic paleoatmospheric circulations might be gained if the eolian component in arctic sediment cores was to be identified and quantified. Such data would provide a means for recognizing and dating glacial/interglacial cycles in the marine sedimentary record.

Viewed globally, arctic continental denudation rates are low, and consequently, sediment supply to the sea by rivers is also low (Milliman and Meade, 1983). Greater amounts of mobile sediment are presently being supplied to the seafloor and water column by coastal and inner shelf erosion, driven largely by sea-ice bulldozing, ice rafting, and current scour and resuspension of sediment around grounded ice (Barnes et al., 1988). The balance in sediment supply between marine inner shelf and upland sources must have been different in the past, when glaciers were more extensive and large alluvial fan systems on arctic coastal plains delivered large volumes of sediment to the sea. When in the glacial/interglacial cycle, and under what climatic conditions, were these remarkable fans active? If we could distinguish sediment deposited when inner marine shelf erosion was dominant from sediment deposited when alluvial outwash systems were dominant, we could improve our ability to distinguish glacial/interglacial cycles, and perhaps even stages in these cycles, in the lithostratigraphic record.

A detailed understanding of the lithology and flux of arctic shelf sediments during the transition from full glacial to full interglacial conditions may permit better interpretation and dating of Late Cenozoic glacial/interglacial events in the arctic sedimentary record than can be achieved from the terrestrial record alone. A core drilling program along several inner-shelf to upper-slope transects would characterize the hydraulic cross-shelf and along-shelf sediment transport systems that operate on ice-covered arctic shelves, which are now poorly understood, and assess the character, geologic history, and economic potential of the gravel deposits that have been found beneath the outer Beaufort Shelf.

Associated with sea-ice formation on arctic shelves is the formation of dense, cold brine rejected from the growing and recrystallizing of nearly salt-free sea ice (Aagaard et al., 1983). These dense brines flow down submarine valleys on the shelves (Garrison and Becker, 1976) into the deep Arctic Ocean Basin in winter outbursts (Honjo et al., 1988) that may imprint the sedimentary record. Thus, some of the well-laminated sediment in Barrow Sea Valley and the Arctic Ocean Basin may be deposits from brine-charged density currents rather than from turbidity currents. If brine density current deposits could be recognized (e.g., from the presence of ikaite) in the lithostratigraphic record, they might identify former periods of sea-ice formation on arctic shelves. Their efficacy for transporting fine-grained clastic and biogenic sediment may also warrant attention.

Role of Sea Ice in Arctic Sedimentation

The Pleistocene lithostratigraphic record in Arctic Ocean cores shows repeated alternations of intervals with and without ice-rafted materials and thus yields information on the sea-ice cover (Henrich, 1990; Henrich et al., 1989). Sediment with ice-rafted clasts and abundant foraminifera is commonly held to indicate interglacial conditions, and fine-grained sediment without these materials to indicate glacial conditions. There is general agreement that the coarse detritus was deposited from glacial ice or sea ice, but the strata that lack coarse ice-rafted elastics are controversial. The lack of foraminifera in such intervals has been attributed, for example, to low surface water salinity and decreased nutrient levels (Herman et al., 1989), dissolution of foraminifera tests, high sedimentation rates, and thicker-than-present ice cover (Aksu, 1985). A research goal would be to determine the origin of the foraminifer-poor, fine-grained intervals which become thicker and muddier toward the basin margins. How, and under what oceanographic conditions, did the intervals form? Were they deposited during the initial phases of deglaciation, when melting glacial ice released large quantities of silt-and clay-size sediment into the basin that may have masked biologic productivity, or were foraminifera preferentially dissolved from these beds (Henrich et al., 1989)? Under what conditions could dissolution of foraminifera occur at the relatively shallow depths at which some of these beds occur?

The foregoing speculations recognize the importance of ice-rafted deposits in the Arctic Ocean Basin but are based on meager data on sediment in modern sea ice. The significance of sediment in sea ice is indicated by recent investigations suggesting that turbid, sediment-bearing sea ice on the Alaskan Beaufort Shelf may, in some years, transport 16 times more sediment than the yearly input from rivers feeding the same region (Kempema et al., 1989). Turbid ice forms from rising frazil ice that is suspended in the water column, where it was formed under turbulent, super-cooled, open-water conditions. The rising frazil ice appears to collect fine particulate matter and plankton from the water column and possibly directly from the seafloor and carry them to the sea surface. Upon reaching the surface, the frazil ice forms a layer of sediment-laden slush ice that soon congeals into sea ice. On sandy, gravelly, or shelly substrates shallower than 30 m, anchor ice forms when frazil is present. The anchor ice, sometimes carrying with it seabed sediment and biota, also rises to the sea surface to be incorporated as patchy inclusions in sea ice (Reimnitz et al., 1987).

Recrystallization in multiyear sea ice aggregates the initially dispersed fine-grained sediment into cohesive mud pellets that are indistinguishable in texture, microfossil content, and composition from pellets previously thought to record rafting and deposition by glacial ice (Goldschmidt et al., in press). The presence of dropstones and sand-size sediment was also thought to record exclusively rafting by glacial ice (Clark and Hanson, 1983). Clearly, more needs to be learned about the character, provenance, quantity, and dispersal of sediment in arctic sea ice and about criteria by which such sediment can be recognized in the lithostratigraphic record. Meeting these objectives would require additional work on the conditions under which sediment is entrained in sea ice, on how sediment in sea ice affects its albedo and melting, and on patterns of sea-ice sediment release to the seabed. What is the role of wind in carrying sediment to the sea ice surface? What is the effect of sea ice on the production of those biologic organisms that constitute the paleontologic and organic geochemical record in Arctic Ocean sediments, and how does this organic productivity contrast with that at times when the Arctic Ocean was ice free?

Paleobiogeography and Paleoecology

The Arctic Ocean is the last of the world's oceans whose marine faunal history is poorly known. Recent studies nevertheless suggest that its paleobiogeographic and paleoecologic histories are closely related to Mesozoic and Cenozoic tectonic events and can therefore provide an independent set of observations for testing and dating plate tectonic reconstructions (Marincovich et al., 1990). These events are manifested in changing paleoecologic tolerances of successive faunas in the Arctic and in shifting paleobiogeographic relationships with faunas of adjacent ocean basins and epicontinental seaways. Because present knowledge of Arctic Ocean faunas is limited, the prospects for major increases of knowledge from paleontological studies are bright.

Triassic mollusks show that an ancestral Arctic Ocean was a northern gulf of the Pacific Ocean at the site of the present Amerasian Basin (Westermann, 1973). Strong genus-level molluscan ties were maintained between the Pacific and Arctic Oceans throughout the Jurassic and very Early Cretaceous, although with fewer shared species than during the Triassic. No broad Pacific-Arctic opening existed after the Neocomian, about 125 million years ago (Fujita and Newberry, 1983). The developing Mesozoic faunal provincialism in the Arctic reflected an increasingly restricted marine connection between the Arctic and Pacific Basins produced by plate tectonic movements. The co-occurrence of North Pacific and Arctic Ocean ammonites in Late Early Albian faunas of southern Alaska demonstrates that limited north-south seaways were at least intermittently present until about 110 to 105 million years ago (Williams and Stelck, 1975). By Albian time, however, Arctic Ocean faunas were of cold-temperate aspect, recording markedly cooler waters than those in the North Pacific and the epicontinental seaways of North America and western Siberia. Study of several known but almost unstudied Jurassic and Lower Cretaceous marine molluscan faunas in Alaska and adjacent parts of Canada would help to refine these paleoecological inferences and to date the tectonic events that controlled the marine connections between the Arctic and the world ocean.

Late Mesozoic mollusks show strong biogeographic ties from northern Alaska through the Western Interior Seaway as far south as the Dakotas and down the eastern margin of North America to Nûgssuaq, West Greenland (Balkwill et al., 1983). These faunas define a cold-temperate northern faunal province centered on the Arctic Ocean. Refinement of the species-level identifications of these faunas would more precisely delineate the paleobiogeography of this Late Cretaceous arctic faunal province and document paleoecological (i.e., paleoclimatic) changes with latitude.

The Arctic Ocean may have been geographically isolated during the Cretaceous/Tertiary transition because there is no obvious faunal break in marine mollusks across this boundary in the Ocean Point beds of the North Slope (Marincovich et al., 1985, 1990). Isolation is also suggested by unrealistically high paleotemperatures calculated from preliminary 18O measurements of mollusks from Ocean Point and generally coeval Paleocene beds on Ellesmere Island; the 18O values might indicate that the Arctic Ocean was hyposaline, rather than warm. Therefore, the measurements need to be repeated and additional ones obtained from around the Arctic, and the systematics evaluated further.

If the Arctic Ocean was isolated during the Cretaceous/Tertiary transition, it may have permitted some taxa to survive longer there than elsewhere and other taxa to evolve which appeared in other oceans only later. The first appearance of previously isolated Arctic Ocean taxa in North Atlantic faunas would effectively date the earliest shallow-water connections between the two ocean basins. Integration of the mammalian and marine faunal evidence for the openings and closings of Arctic-North Atlantic seaways would require additional detailed and extensive fieldwork.

Opening of the Bering Strait allowed North Pacific mollusks and microfossils to enter the Arctic, where they rapidly displaced most of the Atlantic-Arctic holdover marine fauna evolving (Durham and MacNeil, 1967). For all its importance, the date of this onslaught is unresolved. It evidently occurred during the Early Pliocene warm interval and prior to the first appearance of Pacific mollusks below a paleomagnetically dated 3 to 3.5 million year old basalt bed on Iceland (Gladenkov, 1981). Unpublished Soviet data place the first appearance of an Atlantic-Arctic mollusk in Early Pliocene faunas on eastern Kamchatka about 4 million years ago. Resolving the time of opening of the Bering Strait would require coordinated Soviet, U.S., and Canadian biostratigraphic and taxonomic studies.

The sequence of multiple Pliocene and Pleistocene marine transgressions in northwest Canada, western and northern Alaska, and adjacent parts of the USSR show clear alternations between relatively cold and relatively warm marine faunas (Hopkins, 1967). However, the precise ages and magnitudes of the climatic fluctuations are not known, and they constitute an important subject for additional study.

Possible Record of Solar-Terrestrial Interactions

Ice caps in the polar regions collect particulate matter settling out of the atmosphere. On a macro scale, this process has been demonstrated by the large numbers of meteorites obtained from the antarctic ice sheet. Deep arctic lakes may also provide a good environment for recording the influx of exotic material because their cold bottom waters commonly produce anoxic conditions that significantly reduce bioturbation of the bottom sediments.

The annual accretion rate of extraterrestrial material onto the Earth is 10,000 tons/yr. Most of this mass occurs as particles in the 0.1 to 0.4-mm range. The flux of 0.01-mm particles is $1/m^2$/day and of 0.1-mm diameter particles about $1/m^2$/yr. The concentration of the particles in polar ice is normally quite low, but the particles can be recovered from melted fractions and positively identified because of unique properties of typical meteoritic materials. The majority of particles have undifferentiated elemental compositions that match the abundances found in the sun and primitive meteorites for the majority of condensable elements. Typical particles are composed of Fe, Mg, Si, C, Al, Ca, and Ni, in descending order of abundance. The particles also contain undepleted levels of trace siderophiles such as Ir. Typical particles also contain high amounts of solar wind He (with near solar $^{3}He/^{4}He$ ratios), they contain tracks caused by irradiation by solar cosmic rays, and they contain detectable amounts of ^{26}Al and ^{10}Be produced by irradiation in space. If variations in ^{10}Be and other marginally reactive elements could be detected in arctic sediment cores, they would permit the study of solar variability through time.

Although they have not been reported or searched for, it is possible that temporal layers enriched in extraterrestrial components may occur in detectable concentrations in lake or deep-sea sediment cores. A meteor shower, a large impact, or other disturbance in the background flux of cosmic debris could produce layers enriched in extraterrestrial dust particles in the micron to 100-micron range. If submicron particles are channeled along magnetic field lines during accretion, it is possible that the abundance of small particles could vary with magnetic reversals and field strength and be of geophysical interest.

Gas Hydrates and Offshore Permafrost

Unknown but apparently large quantities of natural gas are trapped within and beneath solid ice-like substances, commonly called gas hydrates or clathrates, that lie within the shallow sediments of large areas of the Arctic Ocean and adjacent coastal plains (Kvenvolden and Grantz, 1990). The hydrates, crystalline three-dimensional cage structures of water molecules, are initiated and stabilized by included molecules of natural gas under the conditions of low temperature and high pressure found in three arctic environments: (1) offshore within shallow sediment of the continental margin where water depths exceed 400 m and cold bottom water and hydrostatic pressure establish the necessary stability conditions, (2) onshore within and below cold, continuous permafrost more than 250 m thick, where the mean surface temperature is <-5°C, and (3) beneath the inner continental shelf where relict low temperature and deep permafrost formed under preexisting subaerial conditions persist locally after rapid transgression following the Holocene rise in sea level.

Gas hydrates are of economic interest because they lie close to the earth's surface and can be inferred to contain a major resource of natural gas. Methane hydrate, probably the most common naturally occurring variety, contains about 160 times as much methane as an equal volume of the free gas under standard conditions of temperature and pressure (Davidson et al., 1978). Thus, relatively small volumes of methane hydrate could constitute valuable energy resources if ways could be found to extract the gas safely and economically. Gas hydrates are also of environmental interest because the inadvertent melting of methane hydrate can cause profound natural and engineering disruptions through loss of strength and the uncontrolled release of free gas (Carpenter, 1981).

The distribution of free gas, probably methane, in shallow sediment suggests that the large gas hydrate deposits of the continental margin in the Beaufort Sea may leak gas to the surface. Where relict nearshore permafrost-bearing gas hydrate is being destabilized by coastal erosion and warming bottom waters, methane may also be reaching the environment (Kvenvolden, 1988). The flux of methane from the gas hydrate deposits to the environment is of concern because methane, like carbon dioxide, is a greenhouse gas that affects the radiation balance of the atmosphere and therefore climate. Atmospheric concentrations of methane are increasing at a rate of about 1 percent per year; at this rate, although future levels are difficult to predict accurately, the amount of methane in the atmosphere is expected to double in 40 or 50 years.

Definitive study of gas hydrate deposits in the Arctic is now technologically feasible, at least in areas that are seasonally ice free. Seismic reflection and refraction methods can be used to map the distribution and thickness of the continental margin hydrate deposits and to define some aspects of their internal structure. Water column and shallow sediment geochemical sampling may be able to detect and identify gases leaking from hydrate deposits in shallow sediments, and the hydrates are within reach of shallow drilling. Drilling the large hydrate deposits at the continental margin, however, presents possible safety problems of arctic gas hydrates (Sloan, 1990). But overall, current technology allows for estimation of the three-dimensional distribu tion, composition, internal structure, and stability features that are necessary for estimating the flux of hydrate gases to the atmosphere.

Study of the smaller gas hydrate deposits associated with permafrost beneath the inner continental shelves and coastal plains of the Arctic would be less costly but more difficult than study of the larger continental margin deposits. Seismic surveys, geochemical sampling, and drilling would be less expensive on the inner shelf and coastal plain, and comparatively inexpensive seismic surveys may be able to identify gas hydrates beneath permafrost. However, well logs, especially mud logs, and direct sampling with pressure core barrels are the only methods now available for reliably identifying and studying gas hydrate deposits within permafrost, although equilibrium borehole temperatures can identify the zones of hydrate stability in the subsurface (Lachenbruch et al., 1987).

6

Logistic Realities and Opportunities

The types of investigations attempted and the volume of data acquired in arctic geoscience studies have been hindered by the remoteness and harshness of the environment. There has been an inability, in part technological and in part fiscal, to apply to the Arctic Ocean the full range of geological and geophysical techniques that are available to research in marine geoscience at lower latitudes. The committee believes that the technological constraints, although still severe, are no longer paramount. With adequate funding, scientific platforms and technology capable of revolutionizing our knowledge of the solid earth beneath the Arctic Ocean could be mobilized.

The overriding problem for solid-earth geoscience in the Arctic Ocean Basin has, of course, been its inaccessibility to standard marine research vessels and drill ships. Recent cruises of icebreakers to high latitudes within the arctic ice pack and of Soviet nuclear icebreakers to the North Pole suggest that this barrier will soon be broken. Other technologies, discussed in more detail below, will soon be available to arctic science. The degree to which the scientific community can mobilize these latent technological resources will determine the extent of its contribution to both arctic and global science in the decade of the 1990s.

SUPPORT FACILITIES

There are two philosophies regarding support arrangements for arctic research. One is the concept that investigators with all levels of sophistication and preparedness for arctic conditions should utilize large, federally-supported facilities to acquire arctic data; the other is the concept that each program and their parties should secure their own logistic platforms and support.

In Alaska, the large facility concept was used by the U.S. Navy at its year-round Naval Arctic Research Laboratory at Point Barrow, which was decommissioned in 1980 owing to changing Navy priorities. It has since been refurbished by the North Slope Borough but has only limited facilities for support of large-scale investigations. On a smaller scale, the University of Alaska operates a seasonal camp at Toolik Lake, just north of the Brooks Range, that could support small-scale, local projects in the geosciences. With the development of the Prudhoe Bay and Kuparuk oil fields, it is now possible to drive motor vehicles to the coast; helicopters, fixed-wing aircraft, and small boats can be chartered for fieldwork at Barrow, Prudhoe Bay, and Kaktovik, where living accommodations are also available.

The Canadian government is heavily involved in multidisciplinary transects across the Canadian arctic continental shelf and supports these activities with airborne logistics and major camps for mobilizing field parties. Sizable camps are maintained at Inuvik, in the Mackenzie Delta, and at Alert, on northern Ellesmere Island. The program is of finite duration, however, and has limited value for long-term baseline studies.

Recent events demonstrate possible Soviet interest in opening of the Soviet Arctic to researchers from other nations. For example, the Soviets recently solicited western geoscientists for collaborative or contract work on a Soviet research vessel operating on the Siberian Shelf. Such a development would be of great utility to the arctic geoscience community because the Soviet Union, with a well-developed network of coastal settlements with scheduled air service that are visited regularly by freighters along the northern sea route as well as by established air routes, is relatively accessible to arctic research.

Also, the recent return of the USSR to the group of countries jointly participating in the Ocean Drilling Program is another encouraging sign of potential Soviet participation in international oceanographic research programs. In addition, the USSR is a signatory to the newly formed International Arctic Science Committee, a non-governmental organization established to facilitate coordination and cooperation in all fields of arctic science.

Scandinavia, like Alaska, has a number of arctic settlements, including those on Spitzbergen, from which arctic field studies could be staged. Of these, Longyearbyen, at 78°N, is the northernmost, with regular airline service and commercial facilities. The situation in Greenland is somewhat different in that the relevant facilities there are military. Denmark maintains an airfield at Station Nord (80°30'N) on east Greenland that can be used as a stepping-stone for research in the high Arctic.

The committee believes that existing commercial and government facilities in North America and northern Europe can support most of the field investigations recommended in this report. Suitable fixed wing and rotor craft and a variety of ice-reinforced ships operated by companies with arctic experience are widely available for hire, and an extensive, if not particularly dense, network of airfields and living accommodations is available for logistical base camps. Because most of the research proposed in this report requires nonrepetitive measurements and sampling, the committee recommends that arctic geoscience research funds not support permanent logistic facilities. Such facilities are costly to build, maintain, and staff; they could support only some of the logistic platforms required by the proposed research; and they would represent an impost on all geoscience research projects in the Arctic. Such facilities would also create an additional bureaucracy that might grow and drain significant funds from arctic research. Where long-term facilities are required for a particular investigation (e.g., seismograph stations) or program (e.g., coastal process studies), that investigation or program should budget the full cost. We believe that such a policy would be most cost effective and that it would also remove the influence that subsidized (and expensive) research facilities would inevitably have on where and how arctic geoscience would be conducted.

INSTRUMENTATION

The recent development of new geophysical instruments and the continuing reduction in size and weight of others will greatly advance solid-earth geoscience research in the Arctic. Important examples of such instruments are small digital recorders that can be deployed in long seismic refraction arrays on sea ice in late winter and spring, digital recorders capable of recording and processing 16 or more channels of seismic reflection data that are sufficiently rugged and compact to operate on sleds during field operations in the Arctic, gravity systems that can achieve accuracies of 3 or 4 mgals from airplanes or helicopters, and long-range side-scan imaging and digital bathymetric mapping systems that can image and map the seafloor from submarines. Many measurements that could not be made, or at least could not be made efficiently and economically, in the 1980s will be routine observations in the 1990s.

EARTH-ORBITING SATELLITES

Satellites have proven to be of great value in studying the character and motion of polar sea ice and glaciers and in imaging structural lineaments, lithologic contrasts, and morphologic and textural features of geologic interest on the circum-arctic landmass. Many of the newer satellites, particularly the Synthetic Aperture Radar (SAR) satellites, also carry radar altimeters. Analysis of the radar altimeter data on SEASAT produced pseudo-gravity maps of most of the world's oceans because the mean sea level measured by these instruments is a good approximation to the geoid. Pseudo-gravity maps are available only below about 70° latitude, however, because none of the original satellites with radar altimeters covered the polar regions. The new SAR satellites will extend the coverage to about 80°N.

Thus, the radar altimeter data collected by SAR satellites could produce a pseudo-gravity map of the Arctic Ocean Basin to 80°N. However, this would depend on the development of an algorithm to correct the differences between the returns from the sea-ice surface to sea level of the Arctic Ocean using radar altimetry. In order to obtain coverage above 80°N and to fill the data gap quickly, the committee recommends conducting a combined aerogravity/aeromagnetic survey of the Arctic Ocean Basin. Such a survey could record the near surface, short-wavelength components of the earth's gravity and magnetic fields that are beyond the reach of satellite-borne instruments. Instruments deployed in orbiting satellites, on the other hand, could provide better definition of the long-wavelength components of the gravity and magnetic fields and would provide the best means for removing the earth's main magnetic and gravity field from the airborne geopotential field measurements. Satellite data would also place the arctic data in a global context and would provide a means of relating it to areas of the circum-arctic landmasses where potential field data are sparse or of uncertain quality.

The anticipated deployment of the full complement of GPS satellites by the United States in 1992 will bring round-the-clock decimeter-level, three-dimensional satellite navigation to the entire Arctic Ocean Basin. With careful recording and processing of the satellite data, subcentimeter estimates of relative horizontal position and about 2 cm estimates of relative vertical position can be achieved for suitably founded stations (Bock and Leppard, 1990). A similar system (GLONASS) is operated by the Soviet Union. Combined with ever smaller and more sophisticated receivers, GPS and GLONASS enable the acquisition of positioning data for scientific observations in the Arctic. The levels of achievable GPS resolution are useful for measuring a number of active geological phenomena in the Arctic, such as the tectonic strain of the earth's surface; geomorphoiogic processes; and vertical and horizontal motions and ablation rates of glaciers, ice caps, and snow fields; and it can make these measurements with unprecedented ease. Satellites have proven less satisfactory for the transmission of field data from high latitudes because much of the Arctic is above the latitude at which geostationary satellites (approximately 79°N for a satellite on the same longitude) can be seen reliably from earth-based relay stations. For experiments requiring low data-transmission rates, it is possible to transmit the data during the times when available satellites, such as those of the National Oceanic and Atmospheric Administration, are visible. More data-intensive experiments, such as seismic data acquisition, require more capable satellite data relay systems. Such systems are in fact deployed, but they are not available to civilian users. Access to these or to other near real-time data transmission links would allow active geophysical experiments to be deployed in the high Arctic.

AIRCRAFT

Logistic Support

Airplanes have been central to Arctic Ocean Basin research ever since personnel of the Soviet All-Union Arctic Institute, led by I.D. Papanin, used airplanes to establish a drifting scientific station on sea ice at the North Pole in 1937. The simplified logistics, lower costs, and mobility provided by airplanes have since been the principal means by which high-latitude arctic ice stations have been established. In conjunction with helicopters, they have supported seismic refraction, seismic reflection, potential field, sea-ice sediment studies, and bathymetric surveys in ice-covered areas of the Arctic Ocean.

Magnetic and Gravity Surveys

Configurations of the earth's magnetic and gravity fields over the Arctic Ocean are most efficiently and economically investigated from aircraft because of the remoteness of the region, the perennial sea ice, and the commonly large and irregular perturbations of the magnetic field caused by magnetic storms. Submarines would be effective platforms for arctic magnetic and gravity surveys, but their cost would be much higher unless shared with other scientific or surveying missions. Correction for external field variations, however, would be more of a problem with submarines.

Total magnetic field measurements from aircraft are now routine and economical, and the equipment and algorithms to measure, record, and process the data are widely available. Acquisition of gravity data adequate for geologic interpretation has, until recently, been possible only on land, sea ice, or moving ships and submarines. This limitation has been overcome by recently developed aerogravity systems that can operate from airplanes or helicopters. Such surveys are presently available from three commercial companies in North America, and a system is also being developed by the U.S. Naval Research Laboratory (NRL). In the NRL system, GPS provides accurate positions and velocities for determination of the Eotvos correction and, by use of interferometry, can track motions of the aircraft in three dimensions with an accuracy of about 10 cm. The ability to track aircraft motion eliminates the need for radar altimeters to determine vertical motions of the aircraft. Polar elevations above sea level are especially difficult to obtain over sea ice. It is estimated that an accuracy of 3 to 4 mgals is obtainable with the NRL system.

DRIFTING STATIONS

Ships

Scientific observations within perennially ice-covered regions of the Arctic Ocean Basin were first made from ships that entered and were frozen into the polar ice pack. The earliest observations of record were made from the ill-fated *Jeannette*, on which Lieutenant George W. DeLong and his party drifted from near Wrangel Island, in the Chukchi Sea, to north of the New Siberian Islands in 1879–81. This expedition was followed by the epochal drift of Nansen's *Fram* from the New Siberian Islands to the North Atlantic in 1893–1896, during which a large body of oceanographic, geophysical, and other scientific data were acquired.

A number of proposals to emulate the drift of the *Fram* by inserting overage icebreakers or floating concrete drilling platforms into the transpolar drift as a base for oceanographic and geoscience observations—and for shallow drilling—have been made in recent years. The Norwegian Nansen Centennial Program, for example, is planning to insert a vessel in the ice pack in the Eurasia Basin for a two-year drift to gather data in several scientific disciplines. Despite vigorous advocacy by segments of the arctic scientific community, these proposals have not as yet been funded. Because of the high cost and large staffing requirements of the proposed drifting platforms and because of their slow, erratic, and unpredictable drift paths, it is the consensus of the committee that more efficient and cost-effective alternative methods are available for gathering solid-earth geoscience data in the Arctic Ocean Basin. Such methods include icebreakers, ice stations, over-ice surveys with helicopters and surface vehicles, and data buoys.

Ice Floes and Ice Islands

Ice stations on ice floes, especially on ice islands (tabular icebergs with high freeboard that are of glacial origin), are ideal facilities for long-term oceanographic and weather observations in the central Arctic Ocean Basin. First used in 1918 by Storker Storkerson of Vilhjalmur Stefansson's Canadian Arctic Expedition, ice-floe or ice-island stations became the mainstay of central arctic scientific exploration by the USSR beginning in 1937, the United States beginning in 1952, and Canada beginning in 1967. Most of our current knowledge of the geophysics, geology, and oceanography of the Arctic Ocean Basin has been gathered from these floating camps. Ice stations, however, are not well suited for gathering some types of geoscience data. Thus, although they are effective platforms for seismic refraction and local potential field surveys and sea-ice observations, their progress across the seabed is uncontrolled and too slow and erratic for the efficient collection of seismic reflection data and subseafloor rock and sediment samples. For these purposes, active platforms, which can expeditiously occupy a series of preselected survey lines and sample sites, are preferable. Stations on ice floes are also vulnerable to damage or destruction by sea-ice pressure ridging or fissuring and can be considered only temporary establishments. Large ice islands, which are much more stable platforms, are scarce in the Arctic Ocean.

OVER-ICE SURVEYS

Over-ice travel by man-hauled boats equipped with sled runners was employed by the Edward Parry party to explore the fringes of the Arctic Ocean Basin north of Svalbard as early as 1827, and dog sleds were used by the Charles F. Hall party to explore north of Greenland as early as 1871. These and a few other expeditions dependent on "mammal power" brought back significant scientific data from the central Arctic Ocean Basin during the heroic age of arctic exploration in the 19th and early 20th centuries, but mammal power experienced instant obsolescence with the arrival of aircraft in the Arctic in the 1920s.

The development of reliable lightweight gasoline-or diesel-driven vehicles for over-ice transportation after the Second World War promises a revival of over-ice logistic systems for some types of scientific studies in the central Arctic. Snowmobiles and conventional-tracked vehicles are now commonly used for scientific research and other activities in the fast-ice zone of the arctic ice pack in winter and spring, but more important opportunities lie in operations that can now be conducted beyond the fast-ice zone.

It has been proposed that lightweight gasoline-driven snow vehicles deployed by aircraft may be an efficient means of acquiring on-ice multichannel seismic reflection data in late winter and spring. It is estimated that about 15 to 20 km of profiles could be recorded in this manner per day through use of a snow streamer with geophones and explosive sources. If the DeHaviland Twin Otter aircraft is used for deployment, such surveys could be conducted as far as 500 to 600 km from airfield bases and farther if on-ice fuel dumps are established. Snow vehicles are not practical, however, for independent over-ice travel for useful distances during the late summer and early fall when the smoothing snow cover is minimal, the ice surface is pitted with melt ponds, and there are many open leads between ice floes. In this season, when the ice pack reaches its annual minimum position and icebreakers can penetrate it most easily, air cushion vehicles or amphibious craft that can traverse both open water and rough sea ice may be able to provide logistic support for seismic reflection, seismic refraction, and other geoscience studies from sea ice. Such vehicles, of which the amphibious ARKTOS, developed by Watercraft Offshore Canada, Ltd. of Richmond, British Columbia is an example, would have to be deployed from icebreakers because they are too large for aircraft capable of landing on summer and fall sea ice.

SHIPS

From the first recorded voyage of western man to the Arctic, that of Pytheas of the Greek colony of Massilia in 320 B.C., until the *Jeannette* and the *Fram* were inserted in the main ice pack in the late 19th century, exploration of the Arctic Ocean by ship extended only as far north as the marginal ice zone. Ships contributed little to our knowledge of the solid earth beneath the Arctic Ocean Basin itself until the development of ice-reinforced steel-hulled marine research vessels with diesel propulsion and large icebreakers with diesel and nuclear power plants during and following the Second World War.

Ice-reinforced research vessels operating as far north as the marginal ice zone in late summer and early fall have obtained valuable geophysical and oceanographic data over the continental shelf, slope, and rise at the margins of the Arctic Ocean Basin in the Beaufort Sea and the vicinity of Svalbard and on the outer shelf in the Laptev Sea. Because sea-ice forecasting is an inexact science, however, operations are inefficient when data are sought in areas of the Arctic Ocean that are only occasionally ice free.

The advent of large, powerful diesel-electric-and nuclear-powered icebreakers able to negotiate the main polar ice pack has made it possible to acquire geological, geophysical, and other scientific data in the central Arctic Ocean Basin. The *Polar* class icebreakers in the United States and the *Ermak* class diesel and the *Arktika* class nuclear icebreakers in the USSR allow scientific investigation of the central Arctic Ocean Basin, whereas the earlier vessel classes could work only in the basin margins. Harbingers of this revolution are the cruise of the West German polar research vessel *Polarstern* to 86°22'N in 1987 to conduct multidisciplinary research; the voyages of the *Arktika* and *Sibir* to the North Pole in 1977 and 1987, during which geophysical data were collected; and the cruise of the *Polar Star* to the Northwind Ridge in 1988 to collect geophysical data and cores. As additional experience is acquired in deep penetration of the polar ice pack, and especially when two icebreakers can work together, complex multidisciplinary expeditions will be possible in most areas of the Arctic Ocean. However, icebreaker operations may be difficult or severely curtailed in areas of the Arctic Ocean such as the vicinity of the Queen Elizabeth Islands, where heavy concentrations of pressure-ridged sea ice are commonly found.

The advantages that icebreakers bring to arctic solid-earth geoscience are their ability to carry researchers and bulky or heavy equipment to or near areas of specific scientific interest in sea ice, to support a wide variety of scientific investigations concurrently, and to carry helicopters and over-ice vehicles that can conduct collateral research 100 km or more beyond the ship. Gravity, piston, and box coring are now routine from icebreakers, and these ships can be adapted to deploy the longer piston cores and shallow drills that are under development in a number of institutions. Seismic refraction, seismic reflection, gravity field and bathymetric measurements, and sea-ice and oceanographic observations are also routinely conducted from icebreakers. A prime advantage of icebreakers over-ice stations is their ability to move relatively quickly to successive sites or traverses of interest along predetermined tracklines. Drifting stations lack this mobility and can be moved from point to point only by relocation, which is cumbersome and time consuming. Suitable campsites may also not be available in all areas of interest.

Experience on the *Polar Star* in 1988 suggests that under certain conditions, seismic reflection studies can be conducted from icebreakers in multiyear pack ice. These conditions are sea-ice concentrations of about seven-tenths or less, or the presence of open leads or polynas, when only one ship is used for reflection profiling. Further development, especially the use of two ships working in tandem, may allow profiling in higher ice concentrations. Limiting factors are ice floes and pressure ridges too thick to be broken semicontinuously and ice concentrations too high to allow a small area behind the advancing ship to remain free of large pieces of ice during profiling. Conditions that would permit seismic reflection profiling in areas of sea ice are not widespread, but they can be found locally in many areas of the central Arctic in summer. Targets for seismic reflection profiling in the central Arctic can, however, be defined only broadly. The specific location of profiles across features of interest will depend on locating suitable ice conditions from satellite images and airborne reconnaissance. If these restrictions are accommodated, it appears that 6-and even 12-channel seismic reflection surveys employing air gun or water gun sources can be conducted in many areas of the Arctic Ocean from icebreakers.

The only icebreakers capable of operating in the central Arctic Ocean Basin today are the Soviet *Arktika* class nuclear-powered icebreakers, the Soviet *Ermak* class diesel-powered ice-breakers, and the two U.S. *Polar* class vessels. Only the *Arktika* class icebreakers, however, are truly capable of sustained operations in far northern waters. Although highly ice capable, the *Ermak* class icebreakers are fuel limited. The *Polarstern* cannot routinely operate alone at these high latitudes, and it was at the limit of its operational capabilities when it attained 86°22'N in 1987. The Canadian Coast Guard's *St. Laurent* and the U.S. Coast Guard's *Polar* class ships working in pairs might be able to work in parts of the central Arctic, but they are unreliable for sustained solo operations at such high latitudes. The Soviet heavy icebreakers, which can work more or less routinely in the central Arctic Ocean Basin, are employed along the northern sea route and may become available for charter in late summer and early fall of years with mild sea-ice conditions, when they would be largely idle. Employment of one of these ships for a tourist cruise to the North Pole in 1990 and solicitations for passengers for a second cruise in 1991 suggests that Soviet nuclear icebreakers will be available for charter by western scientists seeking research platforms in the Arctic Ocean Basin.

With the cancellation of the Canadian *Polar 8* icebreaker, there will be no existing or prospective North American ship that alone can routinely support scientific work in the central Arctic Ocean Basin. The U.S. Coast Guard is planning a new icebreaker with extensive research facilities, but the proposed design indicates that this ship will be less ice capable than the *Polar* class vessels (4-foot versus 6-foot continuous level icebreaking capability). In 1988, the Polar Research Board issued a report on *"Evaluation of the U.S. Coast Guard's 'Preliminary Design Document' for the Proposed Next Generation of Polar Class Icebreakers"* that provides recommendations on specifications for redesign, including features necessary for supporting geophysical research and for acquiring "...cores and dredge samples from the deep Arctic Basin." (NRC, 1988a). The committee reaffirms these recommendations, particularly because although there are already several U.S. and Canadian icebreakers capable of working in the marginal ice zone, there are none that can work independently in the central Arctic Ocean Basin.

If the new U.S. Coast Guard icebreaker is not capable of routine work in the high Arctic, the North American scientific community will have to turn to the Soviet icebreaker fleet for support in geoscience research in the central Arctic Ocean Basin. If the Soviet icebreakers are not available to western scientists and if the *Polar* class vessels prove too fragile for sustained high-latitude operations, the United States will be severely limited in its ability to conduct solid-earth geoscience research in this region.

Thus, the scientific interests of the United States in the Arctic Ocean demand that a much more ice-capable vessel (e.g., able to operate routinely in the central Arctic Ocean) be added to the U.S. icebreaker fleet. Previous Polar Research Board reports have recommended procurement of such a vessel based on the requirements of the arctic marine science community (NRC, 1988b). The arctic geoscience community reaffirms this need.

SUBMARINES

Submarine exploration of the Arctic Ocean Basin was first attempted by Sir Hubert Wilkins in 1931, when he cruised a short distance beneath the polar ice pack in Fram Strait in a secondhand diesel-and battery-powered submarine. Deep penetrations of the ice pack, however, awaited the development of nuclear submarines in the 1950s. The U.S. submarine *Nautilus* brought the nuclear age to the Arctic when it sailed north through Fram Strait in 1957, followed by its epochal crossing of the Arctic Ocean from the Bering Strait to the Greenland Sea in 1958. Since then, nuclear submarines of the United States, the Soviet Union, and the United Kingdom have operated extensively in the Arctic Ocean Basin, gathering large quantities of classified bathymetric and sea-ice data and demonstrating the feasibility of routine under-ice operations. The potential usefulness of nuclear submarines for scientific studies of the Arctic Ocean Basin is widely recognized, but the priorities of the Cold War and high operating costs have until now precluded the employment of these vessels for nonmilitary purposes. The apparent end of the Cold War and the renewed interest in the Arctic, however, may be creating opportunities for the use of nuclear submarines for arctic geoscience research.

Bathymetric, gravity, magnetic, and side-scan seabed imaging data can now be collected from nuclear submarines, and it appears likely that high-frequency, shallow-penetration seismic reflection data can also be acquired. Although the engineering and fabrication costs will be high, acquisition of medium-or low-frequency seismic reflection data using sparker, exploder, or water gun sources and single channel or multichannel streamers is probably also feasible from nuclear submarines. Electrical and electromagnetic methods for studying the solid earth are not viable from submarines because of the conductivity of seawater.

Proposals for using nuclear submarines for solid-earth geoscience would, of course, have to consider both their total cost and the relative cost of alternative platforms for particular applications. We lack the data for assessing these costs, but it appears that regional magnetic and gravity fields in the Arctic can be mapped more cheaply with aircraft unless the operating expenses of the submarines were subsidized or shared with other projects. Submarines are uniquely suited, however, for acquiring regional bathymetric, side-scan sonar and probably high-frequency, shallow-penetration seismic reflection data beneath the polar ice pack. Furthermore, there are no alternative platforms for acquiring such data uniformly over the entire Arctic Ocean Basin or even large subregions thereof, although ships may be more cost-effective for research in certain areas of the basin. The first use of submarines for solid-earth geoscience in the Arctic would probably be to gather regional bathymetric, side-scan sonar, and probably high-frequency seismic reflection data. Suitably equipped submarines can also deploy and recover ocean bottom instruments such as ocean-bottom seismometers year-round in the Arctic. Recovering such instruments from surface vessels in sea ice is feasible mainly in summer and fall and commonly requires high-risk under-ice operations by divers.

A regional bathymetric, side-scan sonar and high-frequency seismic reflection survey from a submarine would improve understanding of the physiography and shallow structure and stratigraphy of the Arctic Ocean Basin. An even greater advance in knowledge of the earth's crust beneath the Arctic Ocean would follow, however, from a regional submarine seismic reflection survey. Installing and operating such a system would certainly be expensive, but in the committee's view, based on the analysis of current and planned facilities, the scientific reward would be worth the cost and technological risk. A submarine seismic reflection survey would in a relatively short period, provide detailed knowledge of the structure and seismic stratigraphy of the Arctic Ocean Basin and its margins. It would create a data set from which the geologic framework and tectonic history of the entire Arctic Ocean Basin could be inferred. Also, it would define the optimum sites for further geological sampling to determine the paleoclimatic and paleoceanographic history of the region. In addition, it would provide the data to evaluate the nonrenewable resource potential of perennially ice-covered areas of the Arctic Ocean Basin and of its continental shelves.

The committee believes that within a few years, submarines will become the mainstay of geophysical data acquisition in the Arctic, and it strongly recommends that a national program to acquire multisensor geophysical data beneath the arctic ice pack be considered. The suggested program would create a special niche for the United States in arctic solid-earth geoscience and produce major breakthroughs in scientific knowledge as well as economic returns to the United States.

DEEP SUBMERSIBLES

Manned deep-diving submersibles have led to advances in understanding of mid-ocean ridges, oceanic hydrothermal systems, submarine erosion and depositional systems, and many other features of the world ocean. Their application to Arctic Ocean Basin solid-earth geoscience does not appear imminent, however, because of the prohibitive logistic difficulties and substantial risks in operating such vehicles beneath the polar ice pack. Moreover, many of the topics such vehicles would study are usually defined at a more mature stage of scientific exploration than now exists in the Arctic Ocean Basin. Unmanned deep-diving submersibles would remove some of the risk and expense associated with manned submersibles, but they are nevertheless costly. Therefore, the committee believes that regional geophysical studies and subseabed sampling, both utilizing other facilities, have a higher priority.

BUOYS

Buoys that transmit data via satellites are important systems for gathering oceanographic and meteorological data in the Arctic Ocean, and they may be important for collecting and studying fine-grained particulate and organic matter in the water column. Such data are important for determining sedimentation in the Arctic Ocean and therefore can contribute to evaluation of the underlying sediment column. As with submersibles, however, the committee believes that sediment buoys have a lower priority than the acquisition of regional geophysical data and subseabottom rock and sediment samples.

SUBSEABED SAMPLING

Four piston cores and a dredge haul from drifting ice stations and three piston cores from icebreakers have recovered pre-Pliocene sediments or rocks from slopes on Alpha and Northwind Ridges in the Amerasia Basin. In addition, more than 600 samples of Plio-Pleistocene and Quaternary sediment have been recovered by random sampling of ridges and basin plains by piston cores lowered from drifting ice stations and icebreakers in the Amerasia Basin. Study of these samples constitutes only the first step toward understanding the stratigraphy and environmental history of the Amerasia Basin, but it suggests that a fairly complete lithostratigraphic and biostratigraphic history of the basin from its origin in Cretaceous time to the present can be pieced together from suitably placed piston cores.

Piston coring with 10-m core barrels is now routine from ice stations and icebreakers. Experience on *Polar Star* in 1988 and 1989 showed that as many as five piston cores per day, with lengths to 28 feet, can be collected routinely in 1,000 to 4,000 m of water covered by high concentrations of multiyear pack ice with no loss of equipment. More time was spent identifying and occupying sample sites than in coring operations. Improvements under development at a number of institutions, including longer core barrels, air-pressure devices to drive core barrels into the bottom sediment, and water lubrication systems to facilitate the injection and extraction of piston corers in the subbottom may permit even longer cores to be recovered routinely. Lightweight rotary drills and piston coring systems that may be deployable on ice floes from aircraft as small as the ubiquitous DeHaviland Twin Otter are also under development.

Field experience suggests that the ratio of Cretaceous and Tertiary to Quaternary cores in the Arctic would increase significantly if piston core sites were chosen on ridge crests and slopes on the basis of bathymetric criteria or seismic reflection profiles, if ships or air-mobile coring stations were placed over specific stratigraphic targets, and if the improved coring devices now under development were able to obtain deeper subbottom penetrations. High-resolution seismic reflection data would be invaluable for achieving deeper stratigraphic penetration by identifying sampling sites where Quaternary sediment, which almost everywhere mantles bedrock in the Arctic Ocean Basin, is thin. Given careful site selection and improved coring equipment, we believe that most of the stratigraphic section in the ridge systems of the Arctic Ocean Basin can be sampled in sufficient detail to construct a stratigraphic framework for the region.

The stratigraphic record obtained by piston cores can be supplemented by dredging from ice stations and by drilling with lightweight coring systems placed on the seabed. Dredging from an ice station has recovered the only sample of the volcanic rocks inferred to underlie Alpha Ridge, but the near ubiquitous mantle of Quaternary deposits nevertheless places older sediment and rock beyond the reach of dredges almost everywhere in the basin. Dredging from ships in pack ice is time consuming and difficult and would ordinarily be tried only where high-resolution seismic reflection data indicate that hard rocks crop out at the seabed.

Coring with tethered lightweight rotary drills placed on the seabed is a technology with considerable promise that is under development in Finland, Canada, and the United States. These systems have yet to be proven reliable and practical, however, and they may be better suited for sampling hard rock than soft sediment. When their development reaches the stage at which they can be used routinely from ice stations and icebreakers, they will provide an important tool for piecing together a pre-Quaternary stratigraphy of the Arctic Ocean Basin.

A number of proposals for deep drilling in the Arctic Ocean Basin have been made in recent years. Their objectives have ranged from Quaternary stratigraphy of the continental shelves to continuous sampling of the entire sedimentary column in the basin. Thanks to the infrastructure that was created for petroleum exploration in the Beaufort, Chukchi, and Barents Seas, coring of Quaternary and deeper targets on arctic shelves from specialized drill ships or bottom-founded platforms can be contracted from commercial companies experienced in both the European and North American Arctic. Contract drilling from shorefast and bottomfast ice on arctic shelves—especially the shallow inner shelves—is available in the Beaufort and Chukchi Seas and perhaps in the Barents and Kara Seas. Although these services are costly, they are available on relatively short notice. The real technological challenge in arctic drilling is the acquisition of continuous deep cores from off-shelf, deep-water sites.

Cost-effective off-shelf core drilling within areas of perennial sea ice must overcome a number of natural conditions that appear to be beyond the capability of current technology. Even with icebreaker support, existing drill ships—including the Ocean Drilling Program's JOIDES *Resolution*—are not sufficiently ice strengthened to maneuver safely within the main polar ice pack. Sedimentary fill in the Canada and Makarov Basins ranges from 6 to 12 km or more, and its upper part is inferred to consist of Late Cenozoic turbidites that are of secondary interest for determining the environmental history of these basins. Drilling such targets in deep water is at the limits of petroleum industry technology in areas free of sea ice, and it is enormously costly. The semicontinuous movement of the mainly wind-driven ice pack will not permit such deep bores to be drilled, especially because continuous coring would be required, without some method of holding position against the drift of the ice pack. Such methods have been developed for shallow areas of arctic shelves, but none is in prospect for the deep-water areas of the basin.

Because there are more than 600 cores in the Plio-Pleistocene and Quaternary section of the Arctic Ocean Basin, principal targets for future stratigraphic coring are the Cretaceous and Tertiary beds that lie at shallow depth beneath the crests and slopes of the submarine ridges of the basin. The first phase of sampling should be by piston coring, dredging, and possibly shallow coring with tethered drills deployed on the seabed. Coring sites should be pre-selected from high-resolution seismic reflection or bathymetric profiles or side-scan sonar images, and the coring should be conducted from icebreakers or ice stations deployed by aircraft, which can be positioned over selected sites. After a preliminary stratigraphy and more precise targets have been defined by these methods, a more sophisticated program of coring to somewhat greater depths might be instigated. A realistic program might attempt a series of 50 to 100-m core holes from a specially modified icebreaker that could occupy preselected sample sites at a late stage of a coring program. A large, randomly drifting commercial drilling platform has been proposed recently to obtain cores from the Arctic Ocean Basin. Such platforms are costly (estimated cost about $40 million per year) and have essentially no prospect of acquiring a comprehensive suite of pre-Quaternary samples from the Arctic Ocean Basin.

7

Research Priorities

Establishing priorities for solid-earth research in the Arctic requires a weighting of three factors: intrinsic importance of the work for arctic and world science, scientific and technological feasibility, and the status of necessary or desirable prerequisite research. In addition, there should be a place in an arctic geoscience program for some high-risk research of unspecified rank seeking new approaches or trying new techniques for which generally accepted guidelines or precedents do not exist, and there should be a place for "little" as well as "big" science. It is therefore unrealistic to place in priority order the proposed research solely on the basis of perceived relative importance. The committee suggests that the research proposed in this report be undertaken in general accordance with its position in the following matrix, which recognizes that some studies are prerequisite to others and that, in the Arctic, logistics commonly govern what is possible and when. This approach will yield an integrated program of studies that will most efficiently and cost-effectively advance understanding of the solid earth in the Arctic Ocean Basin.

TABLE 1: Matrix for evaluating the priority of research needs in the arctic solid-earth geosciences.

		Technologic Feasibility	
Character of Research	Now	Soon (2 to 5 years)	Uncertain (>5 years)
Necessary prerequisite to other research	1A	2A	3A
Not necessary prerequisite to other research	1B	2B	3B
Higher risk (no clear guidelines)	1C	2C	3C
		Prerequisite required	Prerequisite required

Projects that are technologically feasible now (column 1) should be undertaken before those that are thought to require further development or at least additional testing and seasoning (column 2). Columns 2 and 3 include research that has a prerequisite in column 1. Projects requiring technology that is unproven (column 3) would, of course, be scheduled provisionally as well as last. Within each vertical column, those projects that are necessary or highly desirable prerequisites to other studies (row A) should be scheduled before those that, although technologically feasible, do not provide background data necessary for other studies (row B). The higher-risk studies (row C) can be scheduled concurrently with the projects in rows A and B, depending on perceived scientific promise and available funds. For each study identified in the matrix, reduction and interpretation as well as acquisition of the required data are intended. Order within categories is arbitrary. Note that more specific recommendations on sequencing research on the ridges and subbasins of the Amerasia Basin are presented in Tectonic Problems in the Amerasia Basin in Chapter 5.

Research in Category 1A

- Establishment of a standardized network of modern digital seismograph stations entirely around the circum-arctic rim
- Regional magnetic and gravity mapping of the entire Arctic Ocean Basin from submarines or aircraft
- Seabed side-scan sonar imaging and bathymetric mapping of the entire Arctic Ocean Basin from submarines

Research in Category 1B

- Paleomagnetic analysis of arctic tectonic problems from outcrops on the circum-arctic rim
- Comparative analysis of trans-arctic geologic structure and stratigraphy
- Analysis of paleoenvironmental history as recorded in circum-arctic nonmarine and paralic sediments
- Sedimentation studies requiring samples from shallow cores (piston, gravity, box), high-resolution seismic reflection profiles, and continental shelf drilling
- Gas hydrate studies requiring multichannel seismic reflection and refraction data and samples from cores or shallow drill holes on outer shelves or upper slopes in seasonally sea-ice-free or light sea-ice areas
- Paleobiogeographic and paleoecologic research requiring samples from onshore outcrops or from shallow cores and drill holes on the continental shelf
- Ice-rafted sediment studies that require satellite imagery and samples from sea-ice and shallow subseabed cores

Research in Category 1C

- Paleoenvironmental indicator research requiring samples from onshore outcrops, shallow cores, or drill holes on the continental shelf

Research in Category 2A

- Seismic reflection and seismic refraction studies of Arctic Ocean Basin ridges and subbasins (prerequisite to coring and drilling)
- Geophysical studies along continental margin transects (prerequisite to coring and drilling)

Research in Category 2B

- All projects (or parts thereof) requiring coring, dredging, and shallow drilling in the Arctic Ocean Basin beyond the continental shelf, including parts of the proposed studies of Arctic

Ocean Basin ridges, subbasins, and continental margins; parts of the proposed arctic ice-rafted sediment, sedimentation, paleobiogeographic and paleoecologic, and gas hydrate and offshore permafrost studies, and the magnetostratigraphy of arctic cores; and all the stratigraphic and paleoenvironmental projects that require samples from the subseabed beyond the continental shelf

- Deep crustal refraction experiments
- Heat flow measurements

Research in Category 2C

- Paleoenvironmental indicator studies requiring samples from cores and shallow drill holes beyond the continental shelf
- Search for evidence of possible solar-terrestrial interactions in the sedimentary record in the Arctic

Research in Category 3B

- All projects that require samples from drilling deeper than about 100-m subseabed at sites beyond the continental shelf, including some of the proposed gas hydrate studies, and all proposals that look toward eventual stratigraphic and paleoenvironmental deep drilling in the Arctic Ocean Basin beyond the continental shelf

8

Special Concerns

INTERNATIONAL COOPERATION

A comprehensive arctic solid-earth geoscience program requires a substantial measure of international cooperation among the United States, Canada, and the USSR. The establishment of the International Arctic Science Committee in 1990, with representation from all arctic countries and from non-arctic countries engaged in arctic research, is unprecedented in providing for coordination and cooperation in all fields of science in the Arctic. Cooperation could encompass such diverse activities as the establishment of a circum-arctic seismograph network with standard instruments accessible to all interested investigators, scientific exchange programs, collaborative research, and access by qualified scientists to the territories of all arctic nations for bona fide research. It would also envision the availability of the research platforms of all arctic nations to all scientists on a commercial basis. The recent announcement that Soviet icebreakers would be available for commercial ventures in the Arctic Ocean is especially welcome because it opens the possibility that western scientists will for the first time have access to mobile platforms from which scientific research can be conducted in virtually any part of the Arctic Ocean Basin.

BIBLIOGRAPHIC AND TRANSLATION PROGRAMS

The standard geological literature is the primary repository of the written and graphic record of geoscience data and interpretations, including the Arctic, but many of the primary sources, especially in the USSR, are not known or readily available in the West. An organized effort to identify these sources and to include them in a carefully indexed international bibliography of arctic geoscience would be an important contribution to all investigators. The bibliographic program should include a translation program for rendering into English, Russian, and one or more of the Scandinavian languages research material judged to be of wide interest to the arctic geoscience community.

RESEARCH DIRECTORY

The size of the arctic geoscience community in the West is such that active investigators are generally acquainted, either personally or through the literature, with most other members of the community. Such acquaintanceship is less common, however, with investigators in the Soviet Union. An international directory of scientists working in the arctic solid-earth geosciences and of the research projects they are pursuing would be a useful reference that would enhance international communication (and perhaps international cooperation) in the field.

A directory of proposed and active arctic geoscience research would also provide a mechanism by which geoscientists contemplating such research could learn about other research efforts with which they might share facilities and platforms. The potential savings from such coordination and logistic collaboration are substantial and would make many otherwise underfunded projects feasible. The mechanism would especially benefit "little science," which because of the commonly high costs of fieldwork in the Arctic, is especially disadvantaged. Indeed, such collaboration may be the only way that a balanced and healthy program of "little" and "big" geoscience can be brought to the Arctic Ocean Basin.

SMALL MEETINGS

International scientific cooperation among active investigators in arctic solid-earth geoscience would be fostered if the research results were exchanged in small meetings of moderately restricted topical focus. Such meetings would be more successful in bringing together working scientists from all of the arctic nations than large, high-prestige multidisciplinary conferences. The meetings would most likely gain the participation of younger scientists and active investigators in the USSR if a number of them were held at provincial research centers as well as at Moscow and Leningrad.

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