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Genesis of the Arctic Ocean Basin

High-altitude aeromagnetic surveys provide new data on the earth's crust in this remote area.

Elizabeth R. King, Isidore Zietz, Leroy R. Alldredge

Aeromagnetic surveys have been systematically made of more than half the Arctic Ocean, and the high-altitude aeromagnetic profiles thus obtained (*1*) reveal significant contrasts in the magnetic character of its several parts. These contrasts suggest that the earth's crust under the Arctic Ocean is complex, and that it resulted from profound geologic changes dating back to Precambrian time.

The Arctic Ocean has the distinction of being the last of the oceans to be discovered. Pack ice blankets its surface, and the entire region was thought to be covered by shallow seas until Nansen's polar expedition of 1899 recorded water depths of oceanic magnitudes. As more soundings were made, it was found that the deep water is confined to a relatively restricted central area that is surrounded by continental shelves which are exceptionally broad off the Eurasian coast (Fig. 1). This deep water is completely blocked off from the deep water of the Pacific and is linked with the Atlantic by a single, narrow trough between Greenland and Spitsbergen. Not until the end of World War II was it discovered that a major submarine mountain range, the Lomonosov Range, extends across the entire basin, dividing it into two parts. The basin on the North American side is further broken up into two flat-floored basins by a lower but much broader submarine feature, the Alpha Rise. Although a considerable part of the basin on the Eurasian side of the Lomonosov Range is also flat-bottomed, there is a large area adjacent to Spitsbergen and Franz Josef Land which has very rugged bottom relief. Much uncertainty still remains concerning the detailed topography under the Arctic Ocean, although the advent in 1957 of nuclear submarines able to obtain continuous bottom profiles has contributed greatly to knowledge of the terrain on the sea floor.

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Nature of the Arctic Ocean Basin

The nature of the Arctic Ocean Basin is a subject of debate, primarily between geologists working on the adjacent continental areas and geophysicists utilizing data from earthquake seismology and various types of geophysical measurements over the basin area itself. For the earth as a whole, seismic refraction measurements, supported by much more abundant gravity data, show that the crust in the continental areas is radically different from that in the oceanic areas. The Mohorovičić discontinuity, which separates the dense, high-velocity rocks of the mantle from the overlying crust, is 20 to 40 kilometers deep under the continents and only about 5 kilometers deep under the floor of the oceans. The continental crust is predominantly silicic material in which there is an increase in density and in seismic velocity with depth, whereas the oceanic crust is composed of more mafic rock under a thin veneer of sedimentary material. Ewing and Press (*2*) state that, with the exception of certain marginal tectonic belts, the earth's crust appears to belong to one of these two distinct types. So far, direct measurements of crustal thickness have not been made in the Arctic Ocean Basin. Until the oceanic or continental nature of this region has been definitely established, valid conclusions about its geologic history and the interrelationships of the surrounding continental blocks cannot be made.

Geology of Surrounding Areas

The known geology of the surrounding areas has led many geologists to conclude that the deep Arctic basins are a later development in a region which was formerly an integral part of the North American and Eurasian continents. A large part of this region comprised the Hyberborean Shield of Shatskiy (*3*) and constituted the nucleus of Eardley's proposed "Ancient Arctica" (*4*), for which he cites a number of arguments that are briefly summarized here.

The Precambrian shields of the Northern Hemisphere, which form the cores of the continents, cluster around the Arctic like fragments of an originally much larger whole. The Canadian Shield and the adjacent Greenland Shield are the largest, and the Baltic Shield and Anabar Shield in the Eurasian sector are more restricted (Fig. 2). The shields are flanked by extensive platform areas which occupy much of the Arctic lowlands and probably continue uninterrupted across the continental shelves, especially north of Scandinavia. Another platform may occupy the Chukchi Shelf, as postulated by Saks and others (*5*). These platforms have a relatively thin cover of Paleozoic sedimentary rocks over the Precambrian crystalline complex and resemble the Central Stable Region of middle North America, indicating that epeiric sea conditions formerly prevailed through this whole region. Eardley (*4*) concludes that the Paleozoic Cordilleran Geosyncline of western North America extended through Alaska, with the volcanic assemblage toward the Pacific and the mainland assemblage bordering the Arctic. Such a setup implies a source of sediments north of the present coast. Positive evidence for such land areas is found in the thick clastic sedi-

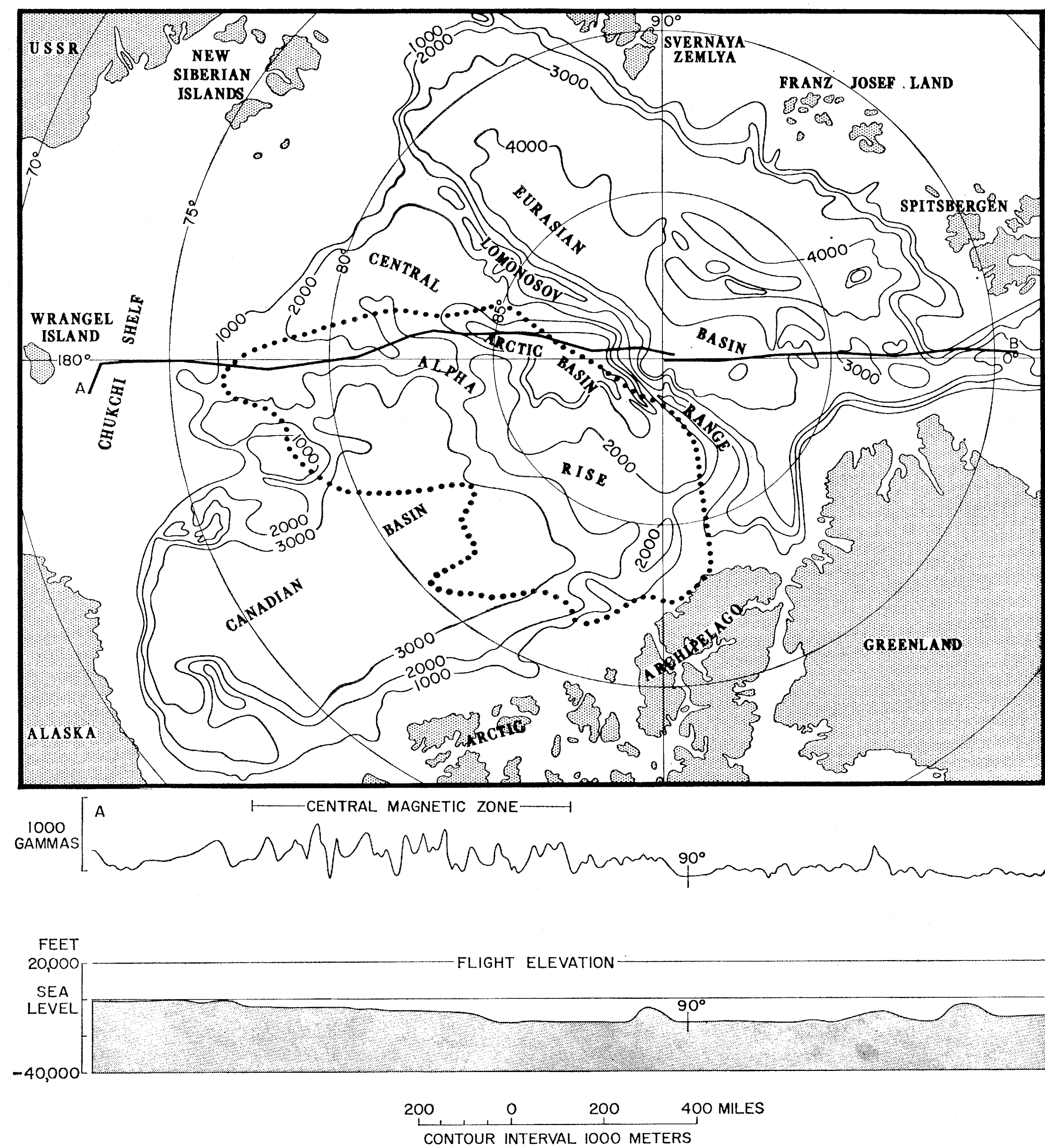


Fig. 1. Topographic map of the Arctic Ocean, with accompanying aeromagnetic profile (heavy solid line). Dotted line shows the areal extent of the Central Magnetic Zone. [Bathymetry after Ostenso (*12*)]

mentary deposits of the Paleozoic and early Mesozoic which form an almost continuous belt from Alaska through the Arctic Archipelago (*6*).

These platform areas were separated by a number of Paleozoic linear orogenic belts which evidently were originally more extensive than the segments which are now found crossing the Arctic margins (Fig. 2). Although the Franklinian geosyncline of the Canadian Arctic Archipelago tends to parallel the coast and may have a continuation across northern Greenland, most of these fold belts strike north onto the continental shelves, where they can be traced through the several island groups and are apparently cut off by the present deep Arctic basins. Most of the Mesozoic tectonic trends are concordant with the Arctic coasts, particularly through Alaska and far eastern Siberia. Where the Verkhoyansk Folding strikes north through the New Siberian Islands, it lines up with the Lomonosov Range, which Soviet geologists believe to be a related tectonic feature (*5*). Eardley (*4*) concluded that, although the breakup of Arctica began in Paleozoic time, the basins acquired their present great depths during the Tertiary, which was distinguished by profound vertical movements that amounted to 7600 meters along the east coast of Greenland and controlled, or at least modified, the present coastlines of many of the islands of the Canadian Arctic Archipelago, adjacent Greenland, and Spitsbergen. In a more recent study, Pushcharovskiy (*7*) postulates that the formation of the deep basins commenced during the second half of the Mesozoic.

Underwater Topography

The evidence from underwater topography, although not conclusive, is especially significant because, in the absence of erosion, the topography tends to reflect the mechanism responsible for its origin. The bathymetric data are too meager to give a true picture of the terrain, but the continuous depth profiles obtained by the nuclear submarines provide representative samples of the bottom detail in each of the geomorphic provinces of the Arctic Ocean. According to an analysis of these profiles by Dietz and Shumway (*8*), vertical movements of 750 to 1000 meters are indicated by truncation of the major ridges at various elevations, evidently through planation by wave action when they stood 750 to 1000 meters higher relative to present sea level. Many of the slopes, particularly on the flanks of the Alpha Rise, have steplike rises or escarpments suggestive of block faulting. The Lomonosov Range has slightly convex slopes, which rule out the construction of the ridge by volcanism (*8*). Its relatively simple asymmetric shape is indicative of a tectonic feature such as a fault block or slightly overturned geanticline (*8*, p. 1326), although the latter requires horizontal compression rather than vertical uplift. The flatness of the deep basin floors is due to a considerable accumulation of sedimentary material, which implies that the basins are well-established features. The combined areal

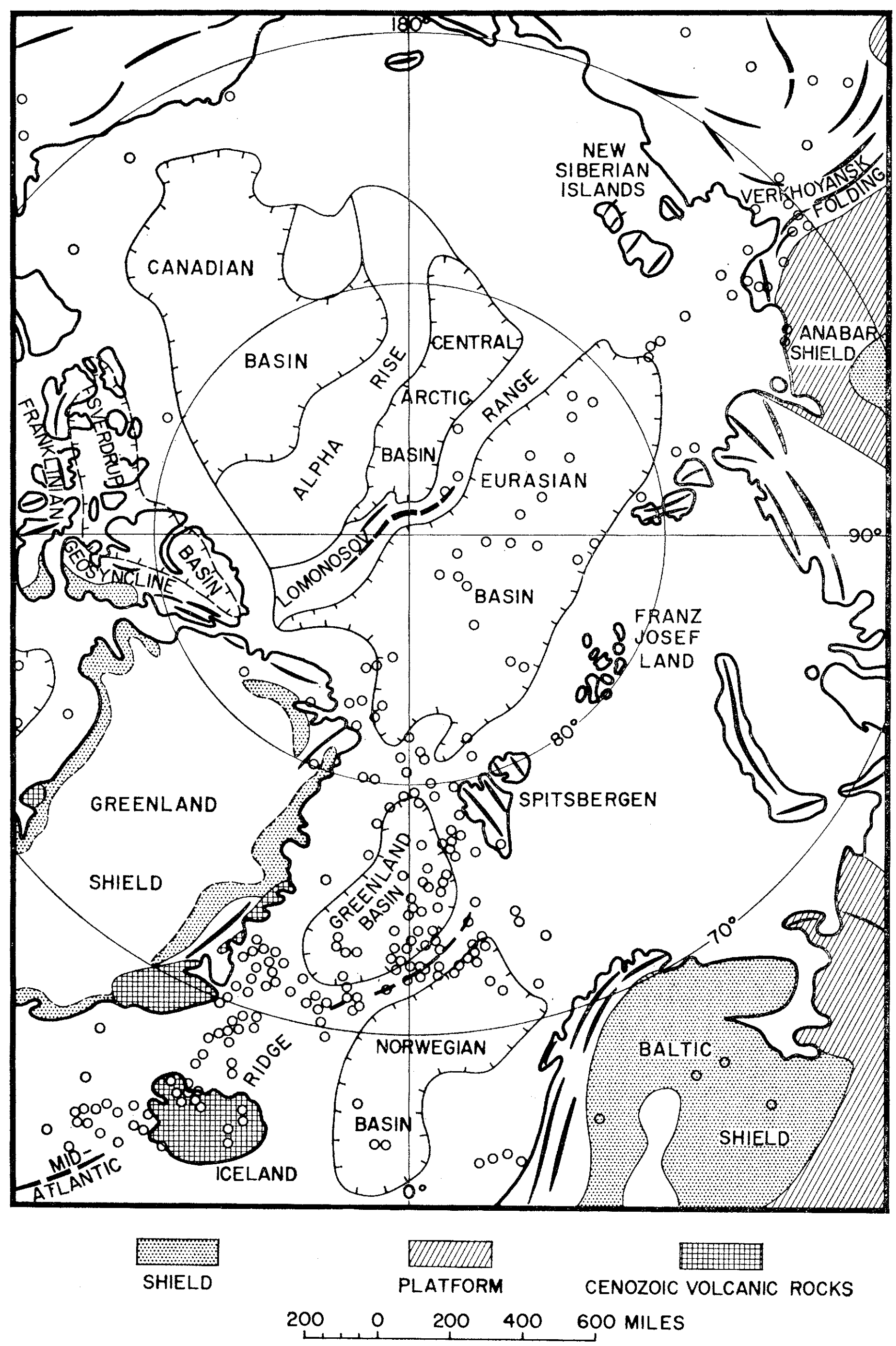


Fig. 2. Generalized tectonic map of the Arctic Ocean and surrounding land areas, showing shields and platforms, principal tectonic trends (black spindles), areas of extensive Cenozoic volcanic rocks, the Sverdrup basin of Mesozoic sedimentary rocks, and deep basins and submarine ridges of the present sea floor. The open circles are epicenters [after Linden (*23*)].

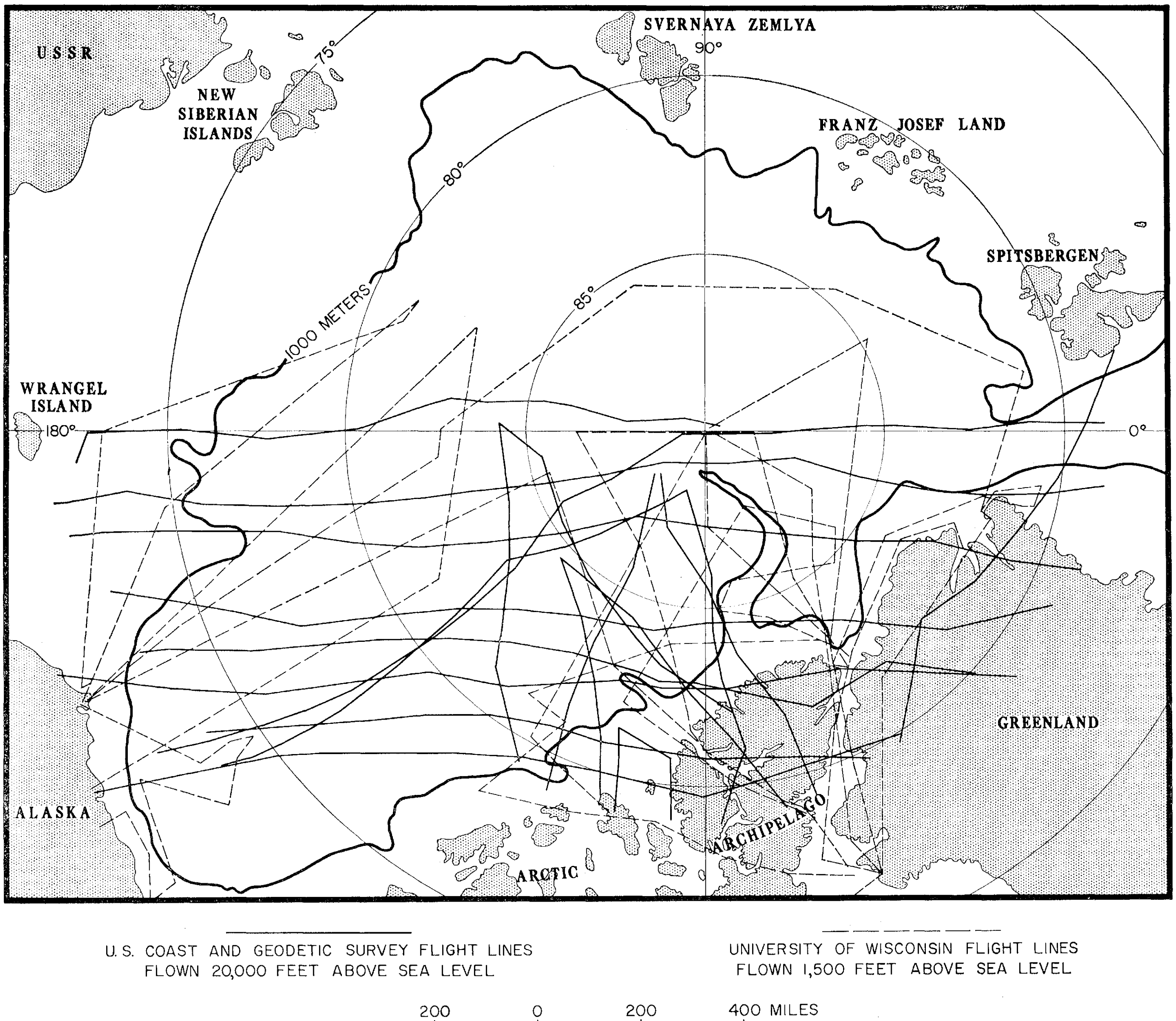


Fig. 3. Location of aeromagnetic profiles over the Arctic Ocean.

extent of the basins is limited and is roughly comparable to the area of the Mediterranean or Caribbean seas.

Seismic Evidence

A considerable array of evidence collected from analyses of earthquake records indicates that the deep-basin areas have an oceanic or intermediate crust. It has been found from a study of earthquake data that a short-period surface wave, the Lg phase, is transmitted through continental crust but not through oceanic crust (*2*). Using this as a criterion, Oliver *et al.* concluded that the Arctic Ocean Basin was oceanic because it did not transmit the Lg phase (*9*). Rayleigh waves and Love waves both have dispersion curves which vary with the thickness of the crust. Dispersion of Rayleigh waves transmitted through the Arctic shows considerable scatter, but the points fall between the theoretical curves for typical oceanic and typical continental crust (*9*). More recently, Hunkins (*10*) calculated from the Love-wave dispersion that the crust is 6 to 15 kilometers thick along a path crossing all the major ridges and basins.

Gravity Data

Similar results have been obtained from gravity data. The published data are few, particularly for the deep basins; they consist of data obtained at the U.S. drift stations (*11*) and of measurements obtained during landings on the sea ice by scientists of the United States and Canada. In the deep-basin areas the free-air gravity anomaly appears to be near zero except for local variations, and over the Alpha Rise and the edge of the continental shelf it tends to be positive. The best available data are from the area off the coast of Alaska (*12*). They indicate a thinning of the crust from about 35 kilometers under the Brooks Range to 17 kilometers in an area 700 kilometers north of the coast; the calculations were based on reasonable density values for crust and mantle and on the assumption that no significant lateral density contrasts are present. A seaward shallowing of the Mohorovičić discontinuity is also indicated by gravity data across the continental shelf northwest of the Canadian Arctic Archipelago (*13*). Gravity observations by the U.S.S.R., made on hundreds of sea-ice landings all over the Arctic Ocean, unfortunately have not been released, but presumably they form the basis of several crustal-thickness maps published by Demenitskaya (*14*). These maps were derived from an empirical relationship between Bouguer gravity values and seismic determinations of the Mohorovičić discontinuity based on a world-wide compilation of available data. In the Arctic this relationship gives a thickness of 2 to 7 kilometers under the deep basins and of 15 to 25 kilometers for the intervening ridges, but there are no seismic determinations against which these values can be checked. Woollard (*15*) has developed a similar empirical formula which gives slightly greater crustal thicknesses for both ridges and basins (*12*, p. 74).

Magnetic Data

This apparent conflict of the geophysical interpretation with the inferred geologic relationships has thrown considerable doubt on the concept of an original land mass or region of shallow seas (*16*). The high-altitude aeromagnetic profiles (Fig. 3) have been analyzed in an attempt to resolve some of these contradictions. The profiles were obtained at 6000 meters (20,000 ft) above sea level, and they show regional magnetic patterns very clearly. In addition, a considerable number of low-level profiles have been obtained, at 450 meters (1500 ft) above sea level, by workers from the University of Wisconsin (*12*); several of these low-level profiles extend farther into the Eurasian Basin and considerably enhance the coverage of the high-level group (Fig. 3).

The most significant magnetic contrast is observed between profiles recorded on either side of the Lomonosov Range. Over the Eurasian Basin, with a few exceptions, the profiles are nearly flat or have only minor fluctuations, but over most, if not all, of the Central Arctic Basin and the Alpha Rise, and over more than half the Canadian Basin, there is a large region of closely spaced, high-amplitude anomalies, some of them of as much as 1000 gammas (one gamma is a unit of magnetic intensity equal to 10^{-5} oersted). This region, which we call the Central Magnetic Zone, is set off for the most part by well-defined boundaries (Fig. 1). The demarcation between this zone and the surrounding areas is particularly sharp on the continental shelf off the Canadian Arctic Archipelago and over the Chukchi Cap north of Wrangel Island, suggesting fault control. Several block-shaped anomalies over the flanks of the Alpha Rise have widths comparable to that of the block faulting inferred from block-shaped topography recorded on the ocean-bottom profiles along the Rise. This indicates that faulting may have an influence on the magnetic profiles here. Obviously the substratum beneath the North American sector is completely different from that of the Eurasian sector. Significantly, profiles over the Central Magnetic Zone also show no resemblance to oceanic magnetic profiles over the Atlantic and Pacific, even for the more magnetic areas such as the Bermuda Rise (*17*) and the California offshore area (*18*). These true oceanic profiles all look much alike, except over isolated features such as seamounts, and over regions of probable thick sedimentary accumulation near the continental margins. Typical profiles for the Atlantic and Pacific oceans are shown in Fig. 4, to illustrate the contrast between these profiles and a representative low-altitude profile across the Central Magnetic Zone, for which the distance from detector to ocean floor was comparable. A low-altitude profile over the Eurasian Basin

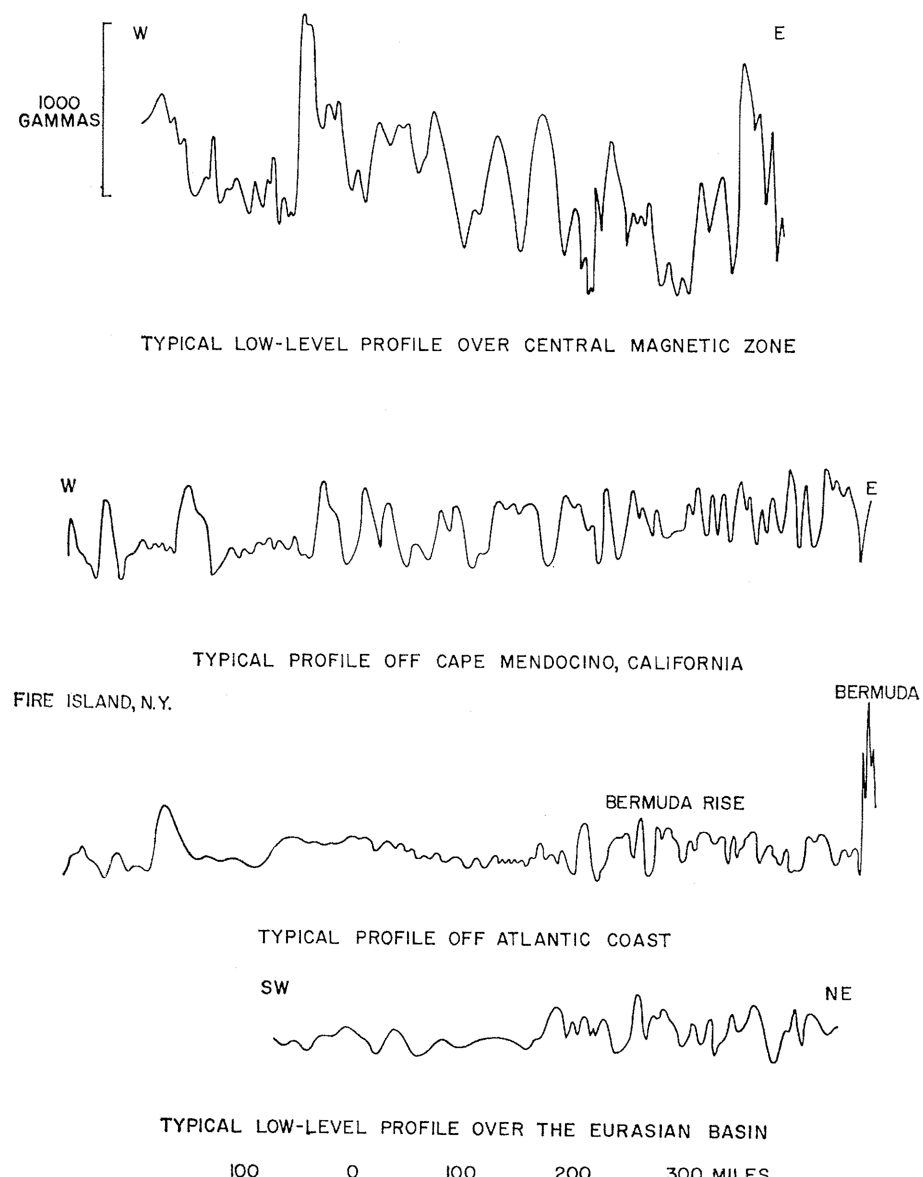


Fig. 4. Comparison of the two main types of aeromagnetic profile on either side of the Lomonosov Range with typical profiles over major ocean areas.

is also given, to show that this basin does bear a close resemblance to truly oceanic areas.

In the Central Magnetic Zone many of the anomalies have amplitudes several times those of the typical oceanic anomalies. They also tend to be grouped into a series of larger features and to be much more irregular in their heights and frequency of occurrence than anomalies observed over the ocean areas. These same distinctive characteristics are observed on profiles obtained over the highly magnetic Precambrian rocks of the Canadian Shield (*19*) or over their buried equivalent to the south in the Central Stable Region of the United States (*20*). Although most of the magnetic data for these regions have been recorded at lower elevations, when representative profiles are arranged according to increasing altitude from top to bottom, their underlying similarity is clear (Fig. 5), and the Arctic profiles might be mistaken for the shield profiles obtained at a higher elevation. This similarity strongly suggests that the Central Magnetic Zone is a large region where the lithologic units have dimensions and magnetizations closely resembling those of shield and platform areas. Several of the high-altitude profiles of the Central Magnetic Zone which extend south across the Canadian Shield permit a direct comparison of the two areas that is even more conclusive (Fig. 6). Both areas have magnetic

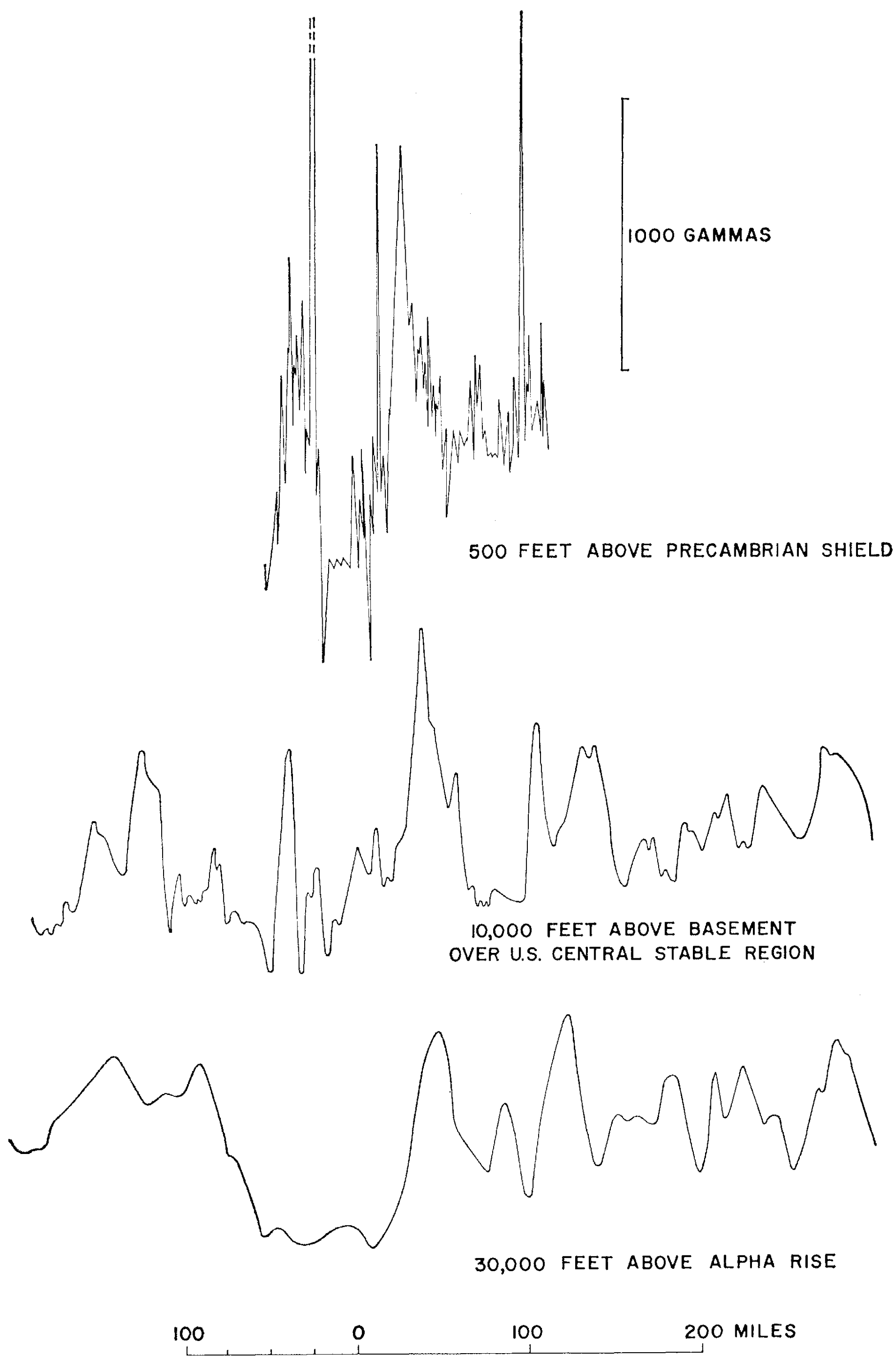
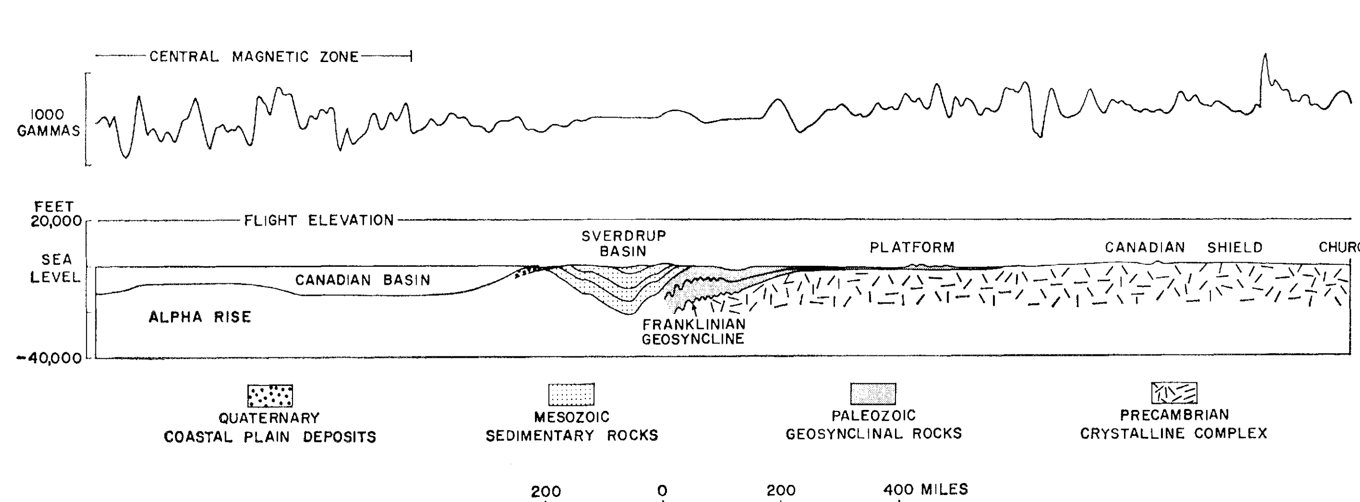


Fig. 5 (left). Comparison of aeromagnetic profiles over continental cores with a profile over the Alpha Rise. Fig. 6 (below). Single aeromagnetic profile over the Central Magnetic Zone of the Arctic Ocean and the Canadian Shield, showing the similarity of the magnetic characteristics of the two regions. [Geology after Martin (*24*)]



anomalies, of similar amplitudes, separated by a nearly flat segment of profile over the intervening sedimentary zone formed by the combined thickness of the Mesozoic Sverdrup Basin and the Paleozoic Franklinian geosyncline. Thus the magnetic data provide convincing evidence that the floor of the Arctic Ocean on the North American side of the Lomonosov Range is formed by a large sunken block, or blocks, of continental material, a large part probably consisting of a Precambrian complex similar to that of the present shield areas.

The magnetic data show that the Eurasian Basin is underlain by material very different from a continental crystalline complex, and that magnetically the basin has a much greater similarity to typical deep-sea areas than to continents. A zone of earthquake epicenters along the axis of this basin appears to be the northerly extension of an epicenter zone associated with the mid-Atlantic Ridge. Therefore a mid-oceanic ridge has been postulated along the trough between Greenland and Spitsbergen and through the Eurasian Basin in the region of rugged bottom topography (*21*). Such ridges are characteristically associated with high-amplitude magnetic anomalies, but there is no indication of such anomalies in the magnetic data for the Eurasian Basin. Soviet geologists reject the mid-ocean-ridge concept in favor of an actively subsiding geosynclinal trough receiving sediment from the Siberian mainland (*5*), but such a theory does not account for the extensive area of jagged bottom topography. This area is associated with a magnetic pattern of short-period ripples and resembles the Bermuda Rise and similar areas much more closely than it resembles regions of sedimentary accumulation, which usually have much flatter magnetic profiles.

Conclusions

Although the geologic-magnetic evidence that at least one part of the Arctic basin is underlain by continental rocks apparently conflicts with the seismologic-gravity evidence that the deep-water areas have an oceanic crust, the data are not irreconcilable. It should be emphasized that all the geophysical interpretations are based on empirical methods or on arbitrary initial assumptions about densities and layering. Thus, transmission of the Lg phase is a criterion which may not be valid for a structurally complex situation. Dispersion analyses are based on comparisons with theoretical curves, and errors may be introduced in correcting for nonoceanic segments of the wave path. There is a considerable spread in the results of calculations based on various empirical formulas relating Bouguer gravity values to crustal thickness. Although the free-air gravity anomaly is close to zero in the deep-water areas, indicating higher-density material somewhere in the column of underlying rock, this requirement can be satisfied by density distributions other than that of a thin crust over dense mantle material.

The seismological results can be largely accounted for if the Eurasian Basin is a genuine oceanic basin with a thin crust. Most of the earthquake paths used for both the Lg studies and the Rayleigh- and Love-wave dispersion studies cross this basin, which may not transmit the Lg phase. An estimate of crustal thickness derived from the dispersion analyses may be an average value rather than the actual thickness for either of the basins taken separately.

The formation of deep basins by subsidence of a crustal segment implies a mechanism for overcoming the initial isostatic conditions, because a sunken block of crustal material will displace a large volume of denser mantle material. Removal of crustal material from the base of the block by subcrustal flowage (*22*) or by assimilation, or addition of heavier material to the crustal rocks, are some of the possible devices. It is possible that crustal thinning may also be accomplished by tensional stresses, perhaps as a result of convection currents in the mantle, of global expansion, or of some form of continental drift that produces widening intercontinental rifts.

The abundant evidence of vertical movement, particularly the block faulting along the Alpha Rise, supports the possibility that tensional stresses operating through a series of normal faults have been an important factor in the formation of the deep-basin areas on the North American side of the Lomonosov Range. The range itself, if it is a compressional tectonic feature, may predate this tensional phase, but it is significant that it forms the boundary between these two crustal segments. The Eurasian Basin, from all the evidence available, may be an original oceanic feature, or it may be an enlarged rift of relatively recent origin which is still expanding between the Eurasian continent and the Lomonosov Range, as suggested by the active seismic zone along its axis.

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