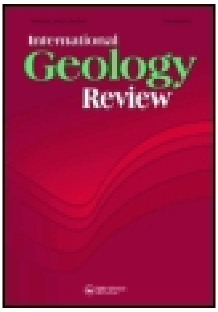

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Chapter 3

DEEP STRUCTURE OF THE WESTERN SECTOR OF THE EURASIAN-ARCTIC CONTINENT-TO-OCEAN TRANSITION ZONE

A. K. Bogolepov, V. A. Zhuravlev, E. V. Shipilov, and *A. Yu. Yunov*

Geophysically, the best studied part of this zone is the crust of the West Arctic, or Pechora-Barents-Kara, cratonic region. Its basement consists of an assemblage of complexes of different ages: Karelian on the northeast flank of the Baltic shield, Karelian or Baikalian on the Pechora platform and the problematic offshore continuations of the Caledonides of Scandinavia and the Hercynides, the early Kimmeridgian of the Ural-Novaya Zemlya zone and Taymyr [68]. Tectonic nodes at the junctions of the heterogeneous basement complexes are the sites of the largest negative structures—inherited-superposed pull-apart basins with thick late Paleozoic-Mesozoic sedimentary fill (the largest in area are the South Barents, North Barents, and South Kara basins) [27, 39, 127, 245, 318] (Fig. 11).

Crustal Structure in the Barents Sea Zone

In the Soviet sector of the Barents Sea zone, interpretation of geological and geophysical data has revealed the following main tectonic elements: the offshore continuation of the Pechora syneclise, the Kola-Kanin homocline, the South Barents basin, the Central Barents uplift, the Nordkap depression, the North Barents basin, the Cis-Novaya Zemlya region of border uplifts, the Svyataya Anna trough, and the Pay Khoy-Novaya Zemlya fold belt. At the boundary between the South Barents basin and the Pechora syneclise there is a long, wide zone where a series of stepped normal faults is developed in the pre-late Paleozoic complex, the Kola-Novaya Zemlya zone.

Each of the tectonic elements listed above has its own structural features and rock associations, reflected in the seismic data and anomalies of the natural physical fields (Fig. 12). As these anomalies are caused to a considerable extent by deep-level heterogeneities in the lithosphere, which show up only in part in the near-surface structures, we cannot expect complete correspondence between the boundaries of the tectonic regions and anomalous zones. Nevertheless, for the Barents sea these boundaries mainly coincide, which indicates a substantial degree of inheritance of the tectonic processes and of the direction of vertical movements.

The anomalies of the natural physical fields indicate the deep structure of the Timan-Pechora region is the same on land and under the Pechora Sea [127].

To the northwest the region is bounded by the Kola-Novaya Zemlya zone, where the northwest-southeast trends of the gravity and magnetic anomalies come to an end or are rotated to the northeast-southwest. The Kola homocline is characterized by complex linear-block structure of the basement and a northeast dip of the sedimentary complex, truncated by erosion in the coastal zone. Here, in a belt a few tens of kilometers wide, a Precambrian crystalline basement is developed, in part overlain by a Riphean subplatform complex that crops out on Kil'din Island and on the Rybach'ye peninsula. The northern boundary of the homocline is arbitrarily drawn along a zone of abrupt increase in thickness of the sedimentary cover. In the central part of the region, physical fields delineate an east-northeast—west-southwest-trending transverse block. Possibly a triple junction of a Riphean rift system is situated here, or else a complex combination of two ancient fault systems. On the continuation of this block to the east-northeast, a series of deep faults of the Kola-Novaya Zemlya zone is traced, along which large collapse structures formed in pre-Late Devonian time on the edge of the incipient proto-South Barents basin.

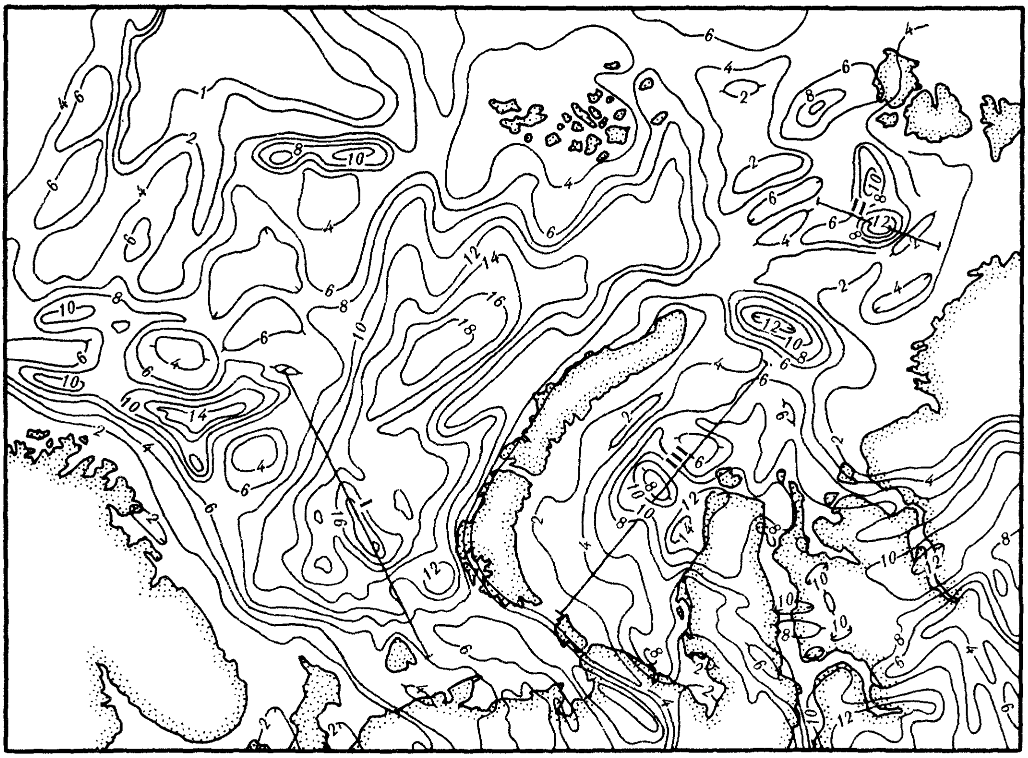
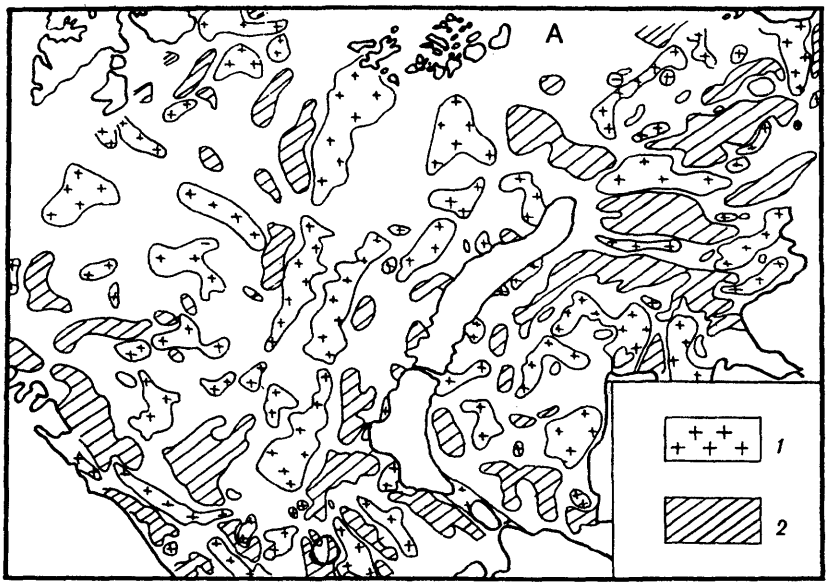


FIGURE 11. Schematic relief of the top of the folded or crystalline basement, regardless of age (contours in km, simplified), and location of seismic profiles (see Figs. 13, 14).

The South Barents basin is clearly distinguished by gravity and magnetic anomalies, which typically have low intensity, large size and chiefly north-northeast—south-southwest orientations. The basin is separated from the region of the Central Barents uplifts on the west by deep fault zones, expressed in the gravity map by high gradients.

Seismic exploration indicate that in pre-Late Devonian time, an uplift formed in the region of the present southeastern edge of the basin; this was deeply eroded, and then collapsed in steps, possibly during Caledonian rifting. The Hercynian phase of tectogenesis was manifested in the region of the present South Barents basin in Late Permian-Triassic time by deep subsidence and clastic sedimentation in a tensional environment. Although subsidence and accumulation of thick piles of sedimentary rocks dominated, the region underwent repeated uplift and erosion, as indicated by regional unconformities, especially pronounced at the level of some seismic reference horizons. The greatest subsidence, compensated by sedimentation in the South Barents basin, occurred in the Permo-Triassic stage of its history.

Deep subsidence of the South Barents basin in the Triassic, which was preceded by conditions of tension, promoted an increase in permeability of the crust to magmas. Positive linear gravity anomalies in the northern part of the South Barents basin and on the Ludlovian saddle correspond to the border fault zones along which mafic magmas probably were emplaced in Triassic time; this is confirmed by modelling densities in the section, and by the agreement between the depth of the magnetic active horizon and the anomalous seismic horizons of series A in the Triassic sequence [127].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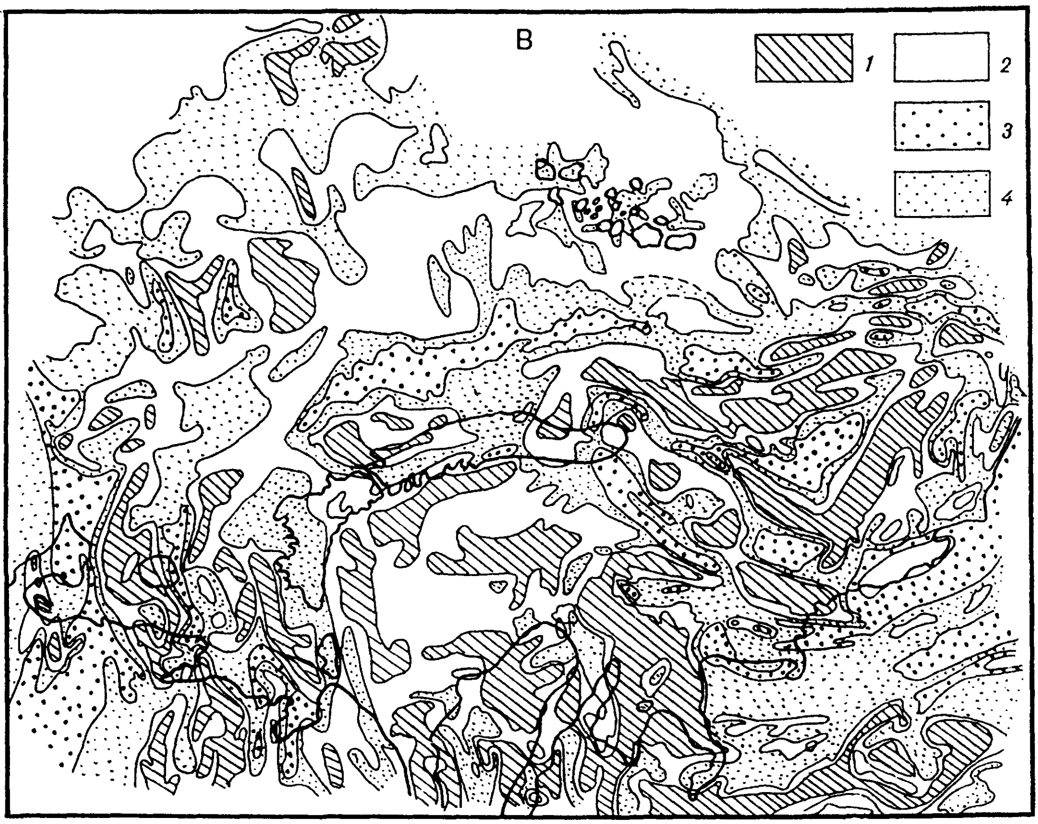
1
2


B
1
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4

Correlation-refraction at the margins of the basin shows a wave guide at depths of 4 to 5 km, within Middle-Upper Triassic strata, expressed as a down-section velocity inversion (from 4.7-4.8 to 4.15 km/s), which indicates abrupt vertical lithologic and physical heterogeneity. The genesis of the horizons of series A, which tend to be near the paleorift zone of the eastern part of the Barents Sea, in our opinion, should be considered a manifestation of global tectonomagmatic activation, including the early Cimmerian tectogenesis of Novaya Zemlya, the Mesozoic trap magmatism of Franz Josef Land and the Triassic taphrogenesis in the South Kara basin. This process was synchronous with the epoch of trap magmatism on the Siberian platform.

In the western part of the South Barents basin, the region of the Central Barents uplift is delineated, elongated roughly north-south and consisting of a number of large arch uplifts—the Fedynskiy, Central Barents, and Persey, separated by saddles at the level of the top of the upper Paleozoic deposits.

The eastern closure of the Nordkap depression extends in the form of two branches, extending eastward and northeastward from the south and northwest of the rimming Fedynskiy arch uplift. Within the graben-like depression, salt domes intrude the sequence of upper Paleozoic-Mesozoic formations, the thickness of which is estimated to be 6 to 9 km. The salt is presumably Late Devonian to Early Permian in age. Both branches of the depression have large negative gravity anomalies. The basement in the depression has sunk 12-15 km (see Fig. 12). Another large salt basin is found in the Ol'ga depression, in the junction zone between of the Svalbard platform and the Central Barents uplifts [39].

The North Barents basin has a quiet, mainly positive, low-gradient field, resembling that of the South Barents basin. It is bounded on the west and east by zones of high gradients. The marginal parts of the basin are asymmetrical; its eastern edge is steeper and complicated by a series of deep faults. On the northeast it meets the Svyataya Anna trough across a saddle, expressed as an arcuate belt of positive gravity anomalies that may be traced from the northern end of Novaya Zemlya to Franz Josef Land.

In the structure and thickness (reaching 15-18 km) of its sedimentary section, the North Barents basin is rather similar to the South Barents, differing in the quieter wave field, which indicates a relatively uniform sedimentary sequence, as well as in the higher stratigraphic position of the disharmonic reflecting horizons developed in the northern part of the South Barents basin.

The Svyataya Anna basin has a negative gravity field with anomalies whose axes trend predominantly north-south. On the south, the basin is separated from the South Kara syneclise by the North mega-arch, which here corresponds to a narrow arcuate zone of positive gravity anomalies. It connects the northwestern part of the Taymyr peninsula and the Cape Zhelaniya uplift and extends to the eastern islands of Franz Josef Land. The eastern edge of the Svyataya Anna basin truncates a region with east-west-trending high-gradient magnetic and gravity anomalies, extending in the direction of the northern part of the Taymyr peninsula and the Severnaya Zemlya archipelago. On the north, between the islands of Vize, Ushakov and Franz Josef Land, the basin opens out via the Svyataya Anna trench into the Arctic Ocean basin. The thickness of the upper Paleozoic-Mesozoic deposits in the basin is comparable to that in the South and North Barents basins.

In the region of the Cis-Novaya Zemlya marginal uplifts there is a complex system of strike slip-thrust faults on the side of the Novaya Zemlya orogen.

FIGURE 12. Geophysical fields of the Barents and Kara seas. A) Local gravity anomalies (1-positive, 2-negative); B) magnetic anomalies: 1, 2) positive anomalies (1-high amplitude, 2-low amplitude), 3, 4-negative anomalies (3-high amplitude, 4-low amplitude).

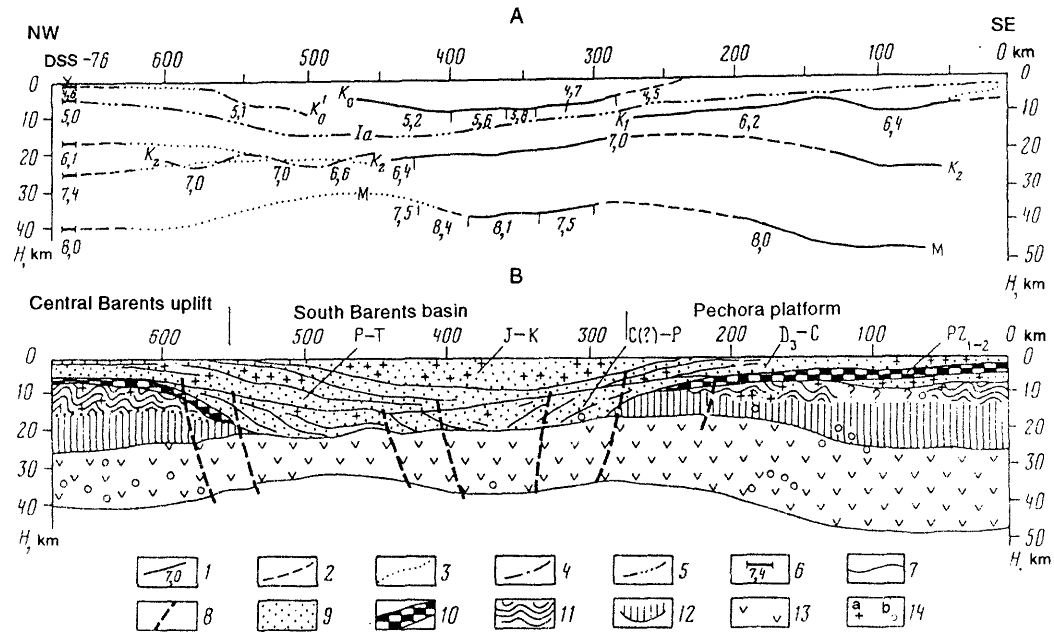


FIGURE 13. Seismic section and geologic section based thereon, of the crust of the South Barents basin along DSS profile 82 (profile I of Fig. 11). 1-6) Seismic boundaries with boundary velocity (in km/s) according to: 1-3) DSS (1-reliable, 2-uncertain, 3-tentative), 4) correlation-refraction, 5) reflection, 6) refracting boundaries along DSS profile 76 at intersection with DSS-82; 7) boundaries of geologic complexes; 8) abyssal faults; 9, 10) complexes of sedimentary cover: 9) clastic, 10) carbonate; 11) folded basement; 12) granitic-metamorphic layer; 13) lower high-velocity ("basaltic") layer; 14) upper (a) and lower (b) surfaces of magnetic bodies. Seismic boundaries K_0 and K'_0) top of young basement, K_1) top of consolidated crust and upper basement, K_2) top of high-velocity layer (~7 km/s). M) Mohorovičić discontinuity—base of crust.

The Admiralty zone of uplifts is a large complex structure, commensurate in size with the adjacent Novaya Zemlya region, from which it is separated by deep faults. The zone extends for 400 km in a northwest-southeast direction and has a fold-block structure. Along the west flank of these uplifts there is a gradient zone, separating them from the relatively quiet anomaly field of the North Barents basin.

The depth to the Mohorovičić discontinuity in the Barents Sea ranges from 32 to 40-45 km (Fig. 13). In the South Barents basin, several uplifts are noted in the relief of the Moho, rising to 28-32 km depths. On the periphery of the sea, beneath Novaya Zemlya, the Franz Josef Islands and Spitsbergen, the base of the crust descends to 35 km. The boundary velocities on one of the largest uplifts of the Moho are about 8.0 km/s. On the periphery of the uplifts of the Moho, the velocities increase to 8.1-8.2 km/s. This is observed in particular on the DSS profile on the Baltic shield side, where boundary velocities of 8.1-8.3 km/s were recorded [318]. Beneath the Franz Josef Land archipelago, velocities in the upper mantle are about 8.1 km/s [245]. On the whole, the relative decreases in depth to the M discontinuity in the South Barents and, apparently, in the North Barents basins are 8-10 km.

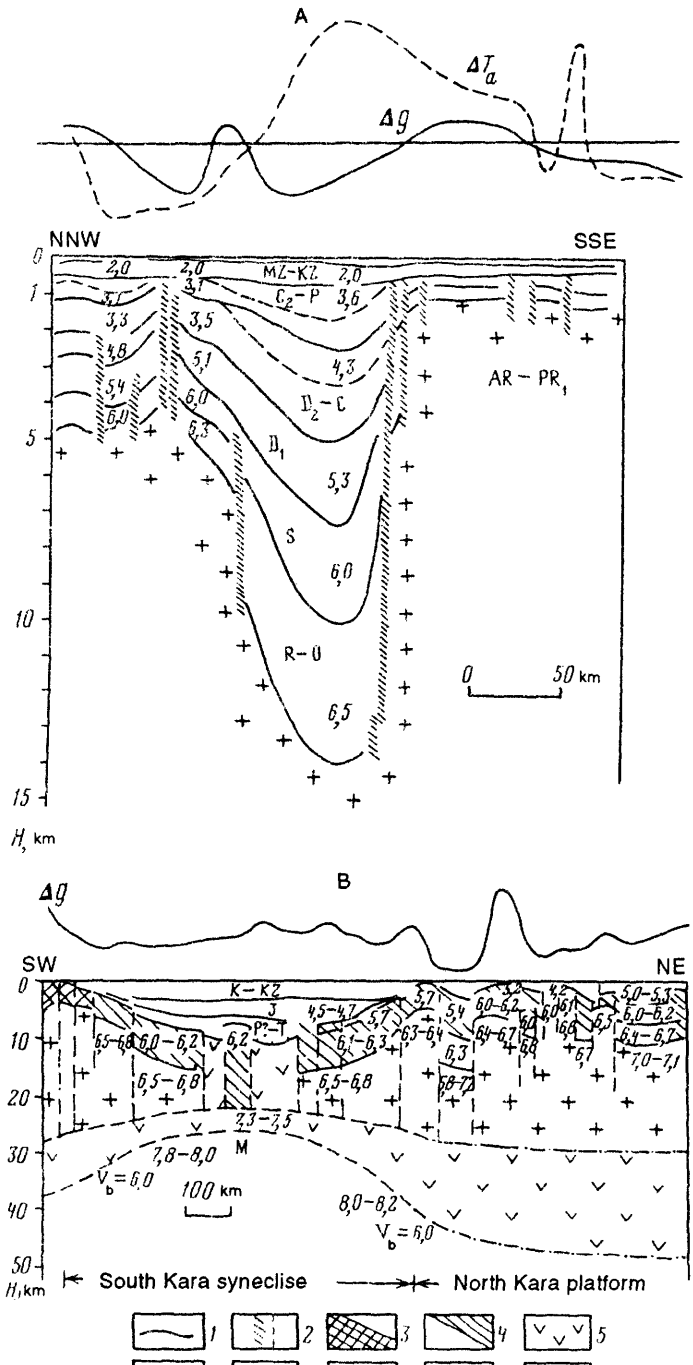
As is seen from Figure 13, the consolidated part of the crust in the South Barents basin is sharply reduced in thickness—from 35-40 km beneath the Central Barents uplift and Pechora plate to 15-20 km in the center of the basin. The so-called "granitic" layer, with seismic velocities of 6.2-6.4 km/s, is missing from the section here.

The "basaltic" layer has velocities of 6.8-7.5 km/s. According to correlation-reflection data, the minimum depths to its K_2 surface, with a boundary velocity of 6.7 km/s, are 17-20 km. Its deepening to 22-26 km is observed in the profiles, toward the Baltic shield and Pechora platform. On the periphery of the South Barents basin the thickness of the "basaltic" layer is about 20 km, but immediately below the basin it is reduced to 8-10 km. Apparently in the places where it is deeper , the basement has been considerably modified by destructive processes, accompanied by tectonomagmatic reworking of the continental crust. A systematic decrease in thickness of the consolidated crust is observed in both the South and North Barents basins.

The Crust under the Kara Sea

In the Kara Sea, the heterogeneous North Kara platform and the South Kara syneclise, separated by the North mega-arch which extends from the western part of the Taymyr peninsula to the northern end of Novaya Zemlya, are distinguished by a combination of geological and geophysical data. In the magnetic and gravity fields, the North Kara platform has the form of an oval structure as much as 800 km in diameter, with distinct concentric zoning (see Fig. 12). The northern part of this large annular structure is truncated by the continental slope of the Arctic Ocean. The peripheral part of the megastructure includes the land area of the Severnaya Zemlya archipelago, the northern Taymyr and the northern block of Novaya Zemlya, and continues toward the eastern islands of the Franz Josef Land archipelago along the Barents-Kara saddle. Toward the northwest there is a systematic increase in the size of the anomalies and decrease in their gradients, reflecting general deepening of the basement surface in that direction, from 0 to 12-14 km. The local anomaly field reflects the structure of the crystalline basement, cut into blocks with vertical displacements of up to 5-7 km. Large linear magnetic anomalies reflect the structure and composition of the basement rocks. Positive linear anomalies are confined to zones of increased magmatic permeability of the crust, concentrated toward basins. Negative magnetic and positive gravity anomalies correspond to basement uplifts. According to correlation-refraction data, the basement shows a wide scatter of boundary velocities—from 5.7-6.0 to 6.7-7.1 km/s (see Fig. 14).

In the central part of the North Kara platform, large negative gravity anomalies are observed, corresponding to a depressed (to 15-17 km) part of the basement surface. Analysis of the geophysical field potentials provides grounds for extending the Precambrian structure of the Taymyr-Severnaya Zemlya region over a considerable part of the North Kara shelf, which allows us to consider the North Kara platform to be an isolated megablock with a mainly Precambrian basement. Its central part is depressed, and the marginal zones uplifted. The main structural elements of the North Kara platform are systematically grouped in accordance with the concentric zoning of the largest tectonic sutures and change their strike as they are traced from west to east, from northwest-southeast through east-west to northeast-southwest near the Severnaya Zemlya archipelago. In the depressions the thicknesses of the sedimentary sequence reach 6-8 km on the average, on the uplifts they decrease to 4-2 km. The upper Mesozoic part of the section of the North Kara platform is subdivided stratigraphically by analogy with the sedimentary section of the Barents platform, where ages have been determined by drilling. In the sedimentary section of the largest basins, two structural levels can be distinguished (Fig. 14). The lower apparently consists of carbonates, evaporites and clastic formations, the age of which is tentatively taken to be Riphean to middle-to-late Paleozoic. The upper structural level, up to 2 km thick, presumably is Triassic-Cenozoic in age; it has low formation velocities (2.0-2.8 km/s) and an average density of 2.27 g/cm^3. The Triassic-Jurassic stage transgressively overlies deposits of various ages. In


A
ΔTa
Δg
NNW
SSE
MZ-KZ
C2-P
D2-C
D1
S
R-O
AR-PR1
0 50 km
H, km
B
Δg
SW
NE
K-KZ
J
M
100 km
South Kara syneclise
North Kara platform

the uplifts, deposits of that age possibly are absent; in the basins their thickness reaches 1 km. The Cretaceous-Cenozoic deposits veneer older formations, and are at most 1 km thick.

The South Kara syneclise, which is the northern part of the West Siberian platform, is separated from the North Kara syneclise by the North mega-arch, and is bounded on the south by the Pay Khoy-Novaya Zemlya orogen (see Fig. 12). The gravity and magnetic fields of the South Kara syneclise are complex. In general, the magnetic field has a relatively high level and high gradients. On the rim of the syneclise, along the Pay Khoy-Novaya Zemlya orogen and the North mega-arch, negative gravity anomalies are observed. The North mega-arch and southern part of the Pay Khoy-Novaya Zemlya orogen are distinguished by a relatively high-level gravity field and a chiefly negative magnetic field.

The gravity field of the central part of the syneclise is relatively high-level. As a rule, hgih-amplitude positive magnetic anomalies match linear positive gravity anomalies. This circumstance was caused by deep reworking of the crust in narrow rift zones, with mafic magmatism; this is confirmed by seismic exploration, density modeling, and calculation of the depths to the top of the magnetic masses [245, 318]. In the South Kara syneclise, the basement surface can be correlated with a refracting horizon having boundary velocities of 6.0-6.2 km/s, which lies at depths of 6-9 km in the southern and 10-12 km in the central part, or else with a boundary with V_b of 6.5-6.8 km/s at depths of 7-9 and 13-16 km/s in the respective areas.

Identification of the basement surface is especially complicated in the regions immediately adjacent to the Novaya Zemlya orogen, toward which both the above-mentioned boundaries rise abruptly. Here the refracting boundaries may be related both to the front of folding and metamorphism and to dipping disjunctive boundaries [379]. Reverse fault-thrust structures, indicating horizontal displacement of masses toward the west, are known both in southern Novaya Zemlya and in the Novaya Zemlya zone of the Barents Sea. Higher than the above-mentioned refracting boundaries, horizon A is distinguished by common-depth-point reflection data; some investigators identify it with the surface of the Hercynian basement. The low V_b (5.0-5.2 km/s) of the refracting horizon corresponding to horizon A and the not-so-high calculated density of the underlying rocks (2.65 g/cm^3) would not contradict interpretation as the top of the metamorphic basement. Probably in the South Kara region near Novaya Zemlya this surface can be correlated either with the buried Paleozoic sequence or with the front of folding. Density modeling suggests that the boundary with V_b = 6.0-6.2 km/s can be taken as the top of the Riphean-lower Paleozoic sequence. If so, the refracting boundary with V_b = 6.5-6.8 km/s may correspond to the top of the Archean-lower Proterozoic crystalline basement. In the central part of the syneclise, this boundary is not recorded. The lower complex with V_b = 6.0-6.2 km/s thickness and the mantle or crust-mantle boundaries rise in this zone; this may indicate that the syneclise was superposed on a Riphean aulacogen (see Fig. 14).

Thus, the age of the heterogeneous basement in the South Kara syneclise is pre-Paleozoic. Four structural levels can be distinguished in the sedimentary section: Riphean-early Paleozoic aulacogenic (?), middle-late Paleozoic paracratonic, Permo-Triassic taphrogenic, and Jurassic-Cenozoic platformal.

FIGURE 14. Geologic-geophysical sections of the crust: A) CDP profile of the North Kara platform (profile II of Fig. 11), B) correlation-refraction profile of the South Kara basin (profile III of Fig. 11). 1) Reflecting and refracting marker horizons; 2) abyssal faults; 3) folded complexes of Novaya Zemlya; 4) Riphean-Paleozoic complex; 5) crystalline basement; 6) "basaltic" crustal layer; 7, 8) seismic velocities, 7) boundary, 8) effective; 9, 10) crustal discontinuities: 9) from seismic data, 10) presumed. Geophysical profiles: ΔT_a) averaged magnetic anomalies; Δg) Bouguer gravity anomalies.

In deeply depressed zones the platform complex may also include Upper Triassic deposits. The boundaries of the taphrogenic complex may shift in time and space.

On the periphery of the South Kara syneclise, a complex system of structural terraces or benches is developed, rimming the Pay Khoy-Novaya Zemlya orogenic region and North mega-arch (see Fig. 12). The benches are subparallel to the orogenic region and mega-arch, in plan forming an annular structure comparable in size to the North Kara oval.

In the central part of the syneclise, in graben-like depressions, the platform and taphrogenic sequences reach a total thickness of 12-15 km, but on uplifts they are reduced to 7-6 km.

Deep seismic sounding shows a series of refracting boundaries in the West Siberian platform, characterizing the layering of the crust and upper mantle [139]. Boundary F, with a boundary velocity of 5.2-6.1 km/s, may correspond to the top of the pre-Mesozoic basement, consisting of heterogeneous pre-Jurassic formations; boundary K_0, with a boundary velocity of about 6.0-6.2 km/s, corresponds to the top of the consolidated basement; boundaries K_1 and K_2, with boundary velocities of 6.5-6.6 and 7.1-7.4 km/s, characterize intracrustal layering [27, 139, 245, 318]. The seismic velocities and thicknesses of the layers of consolidated crust that are distinguished in the South Kara syneclise are in fairly good agreement with the data given above.

In some correlation-refraction soundings in the marginal parts of the South Kara syneclise, the Moho surface lies at a depth of 32-35 km and has boundary velocities of 8.0-8.2 km/s (see fig. 14). Beneath the depressed central part of the syneclise the upper mantle rises to depths of 26-28 km and boundary velocities decrease to 7.8-8.0 km/s. The K_2 boundary, with V_b = 7.3-7.5 km/s, lies at depths of 22-25 km. Here the thickness of this layer is half that in the marginal parts of the syneclise (reduced from 10 to 5 km), due to a rise of the M discontinuity.

Differences in the deep structure in the central and northern parts of the syneclise are clearly expressed in sections compiled from CDP reflection and refraction-correlation surveys (see Fig. 14). The thickness of the consolidated crust in the central part of the syneclise is about 15 km, compared to some 25 km on the periphery. This reduction occurs as a result of a decrease in the thickness of each crustal layer situated between the K_1, K_2 and M boundaries. The thickness of the upper layer of the consolidated crust, possibly corresponding to upper Proterozoic-lower Paleozoic units, also is halved—from 7 to 3-4 km. In individual segments of the seismic profiles, the boundaries with velocities of 6.0-6.2 to 6.5 km/s cannot be traced and are superseded by higher-velocity horizons, which we identify with basaltoid trap bodies (V_b = 6.7-7.0 km/s). The borders of these zones are marked in the magnetic field by a sharp reduction in the amplitude of local anomalies. The depth to the top of the crystalline basement (V_b = 6.5-7.1 km/s) reaches 12-15 km in these zones.

In describing the layering of the consolidated crust, it should be mentioned especially that the lower intracrustal boundary K_2 is conformable with the Moho discontinuity, and the upper one, K_1, is conformable with the F boundary and discordant with the two lower ones. On the whole, the consolidated crust in the central part of the syneclise is about 10 km thinner and amounts to about 15 km, which can be explained by destruction of the "basaltic" and "granitic" layers during their reworking and contamination by anomalous upper mantle.

* * *

Thus the deep structure of the West Arctic continent-ocean transition zone has several characteristics that enable us to consider it the tectonotype for the marginal shelf platforms of the Arctic basin. The main patterns of its structure are the following.

The centers of deposition of the largest basins (the South and North Barents Sea, North and South Kara) are about equidistant from one another (600-800 km), and the lines joining them, which mark the axes of maximum subsidence, form a triple-junction zone, typical of the rift systems of the continents.

The reduction in crustal thickness to 32-25 km in the transition zone, with relief of the M discontinuity differentiated into isolated domes beneath the central parts of the basins; the anomalous nature of the geophysical parameters of the consolidated crust and upper mantle; the vagueness of the transition from the sedimentary cover to the basement, whose nature is unclear in the most depressed parts of the basins; the extensive development of high-amplitude normal faults on their margins; and the marked block-fault subdivision of the base of the sedimentary cover as a whole, all indicate considerable destruction of continental crust during the formation of the deep depressions in the transition zone itself.

Chapter 4

THE CAUCASUS: INTEGRATED GEOPHYSICAL INVESTIGATIONS OF THE LITHOSPHERE

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Two main tectonic units constitute the territory of the Caucasus—the young Scythian craton on the north and the Alpine fold belt on the south.

The Hercynian-Cimmerian Scythian craton occupies the entire lowland part of the region—Ciscaucasia and the northern foothills of the Greater Caucasus. The Precambrian granitic-metamorphic basement is exposed on the north flank of the Greater Caucasus and has been penetrated by wells in several areas in Ciscaucasia. The younger folded basement consists chiefly of Devonian to Carboniferous clastic turbidite-flyschoid deposits, intruded by Hercynian granitoids. These are unconformably overlain by Permian to Triassic shallow-water shelf or continental molasse deposits. The typical platform cover, exposed in the north flank zone, consists of carbonate-evaporite-lagoonal-coal-bearing shelf deposits, Jurassic, Cretaceous, and Paleocene-Eocene in age. This is overlain by Alpine shallow-marine and continental molasse of Oligocene (Maykop group), Neogene and Quaternary age, especially thick accumulations of which fill the foreland depression.

The southern edge of the Scythian craton was involved in Alpine tectogenesis, and as a result there is no clear boundary between it and the Alpine fold belt of the Greater Caucasus.

The Alpine belt of the Caucasus is fairly inhomogeneous; within it there are developed both intensively deformed units, consisting chiefly of sedimentary associations of great thickness (Greater Caucasus) and ophiolites (Sevan zone of the Lesser Caucasus), and slightly folded zones with thin sections, chiefly shallow-water deposits (Transcaucasia, southern Armenia-Nakhichevan).

The northernmost tectonic unit of the Greater Caucasus is the Front Range zone. The granitic-metamorphic basement of this zone is Hercynian in age. It is overlain by Silurian-Devonian-Lower Carboniferous turbidite shales, volcanics and limestones. Resting on these are allochthonous slabs of ophiolite, unconformably overlying coal-bearing late Viséan to Middle and Upper Carboniferous molasse and Permian and Triassic redbed molasse (with volcanics).

In the Main Range zone, separated from the Front Range by a system of regional faults, the granitic-metamorphic basement also is Hercynian. Small patches of upper Paleozoic, lying