Institute of the Lithosphere
Russian Academy of Sciences

EXPLANATORY NOTES

FOR THE TECTONIC MAP OF THE BARENTS SEA AND THE NORTHERN PART OF EUROPEAN RUSSIA

SCALE 1:2,500,000

Moscow
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Explanatory Notes to Supplement the

TECTONIC MAP OF THE BARENTS SEA AND THE NORTHERN PART OF EUROPEAN RUSSIA

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The Map was compiled in the Institute of the Lithosphere, Russian Academy of Sciences, Moscow, in collaboration with the Research Institute of Marine Geophysics, Murmansk, the Timan-Pechora Department of VNIGRI, Ukhta, and GEON Center, Roskomnedra, Moscow.

The Tectonic Map of the Barents Sea and the Northern Part of European Russia (scale 1:2,500,000) covers the northern part of the Russian Plate and the Urals, and the adjacent shelves of the Barents, Kara and Pechora seas. The accompanying geological profiles show the internal structure of major tectonic units of the region. The challenge to the authors has been to show the relationship between onshore structures and those of the vast Arctic shelf. The Precambrian Russian, Timan-Pechora and Svalbard continental plates as well as the Hercynian Urals foldbelt and the Cimmerian Pai-Khoi - Novaya Zemlya foldbelt along the eastern margin are shown on the map. The Explanatory Notes also contain a description of the internal structure of tectonic units. They describe the age, composition, volume, structure and geophysical characteristics of sediments. The oil and gas potential and main features in the tectonic evolution of the region are given in the concluding chapters.

The Explanatory Notes contains 101 pages, 22 figures, 113 references.

The Tectonic Map is supplemented with profiles on 2 sheets.

CONTENTS

INTRODUCTION

The Tectonic Map of the Barents Sea and the Northern European Russia (scale 1:2,500,000) covers the northeastern part of the Russian plate, the Timan-Pechora plate, northern Urals and adjacent Barents Sea. In the north, the area is bounded by Franz Josef Land, in the west by the Svalbard Archipelago, and in the east comprises the western part of the Kara Sea. The principal challenge was to show the continuation of onshore structures beneath the west Arctic shelf.

Several research centres have contributed much to the map compilation, which is based on voluminous factual material. The data used have been published in individual papers and monographs, and were used for compiling special geological maps published in Russia and Scandinavia during the past 10 years. The map presented can be used for revealing common features of the distribution of hydrocarbon deposits, which are particularly abundant in this region.

The data for the Map and Explanatory Notes was collected by the authors and their colleagues from the Institute of the Lithosphere, Russian Academy of Sciences (RAN); GEON Center, Roskomnedra (Moscow); Research Institute of Marine Geophysics (Murmansk); the Timan-Pechora Branch, the Russian Research Geological Prospecting Institute (Ukhta).

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The authors are grateful also to cartographers from PKO "Kartografiya" and especially to D.I.Zhiv. The map compilation was supported by the State Research Program "World Ocean" from the Ministry of Science and Technology of Russia, the publication of the map and Explanatory Notes was supported in part by the Russian Foundation for Basic Research, Project 95-05-30689.

I. GENERAL TECTONIC ZONING ANG PRINCIPLES APPLIED WHEN COMPILING THE LEGEND

The area covered by the map includes consolidated blocks and fold-nappe belts regenerated in Recent time with finite periods of intensive deformation of different age, from the Karelian (the end of the Early Proterozoic) to the early Cimmerian (the latest Triassic-earliest Jurassic).

The southwestern corner of the Map (Fig. 1) is occupied by the northeastern margin of the East European paleoplatform, comprising the Baltic shield and Mezen syneclise. The Early Precambrian basement of the shield is exposed in the coastal area of the Kola Peninsula and belongs to the Murmansk block. It plunges southeastward under the sedimentary cover of the Mezen syneclise and northeastward into a narrow offshore strip on the margin of the Kola Peninsula. Isopachs show thickness changes of the sedimentary cover. Paleorifts-aulacogens infilled with Riphean deposits are also highlighted.

The northern part of the Map is occupied by the Svalbard plate, where a younger crystalline basement is exposed on Nordaustlandet (Svalbard Archipelago) and is dated as Grenvillian (~1.0 Ga). In the east, the early Cimmerian folded structure of the northern part of the Novaya Zemlya Archipelago developed on this basement. Within the East Barents rift system, the Grenvillian basement is highly faulted and in its axial part it is probably replaced by oceanic or suboceanic crust. This rift system is therefore shown using a special colour. On the adjacent uplifted areas, the depth to basement and the thickness of the sedimentary cover are contoured.

In the central and southern segment of the Map, the Timan-Pechora plate, which has a younger, Late Proterozoic, Baikalian folded basement, adjoins the northeast margin of the Russian plate of the East European platform. This boundary is faulted. The Baikalian fold structures come to the surface in the Timan uplift, on the Kanin Peninsula and in northern parts of Rybachi and Varanger peninsulas.

On the Timan-Pechora plate, the basement is overlain by a sedimentary cover which includes Paleozoic (from Upper Cambrian or Ordovician) and Mesozoic deposits. The thickness of these deposits and the depth to basement are contoured. The northern boundary of the plate lies offshore and is defined by a system of approximately E-W trending strike-slip faults and normal faults.

In the east, the Timan-Pechora plate is bounded by the Late Paleozoic-Hercynian Urals foldbelt and its system of foredeeps. The western and central zones of the Urals foldbelt are

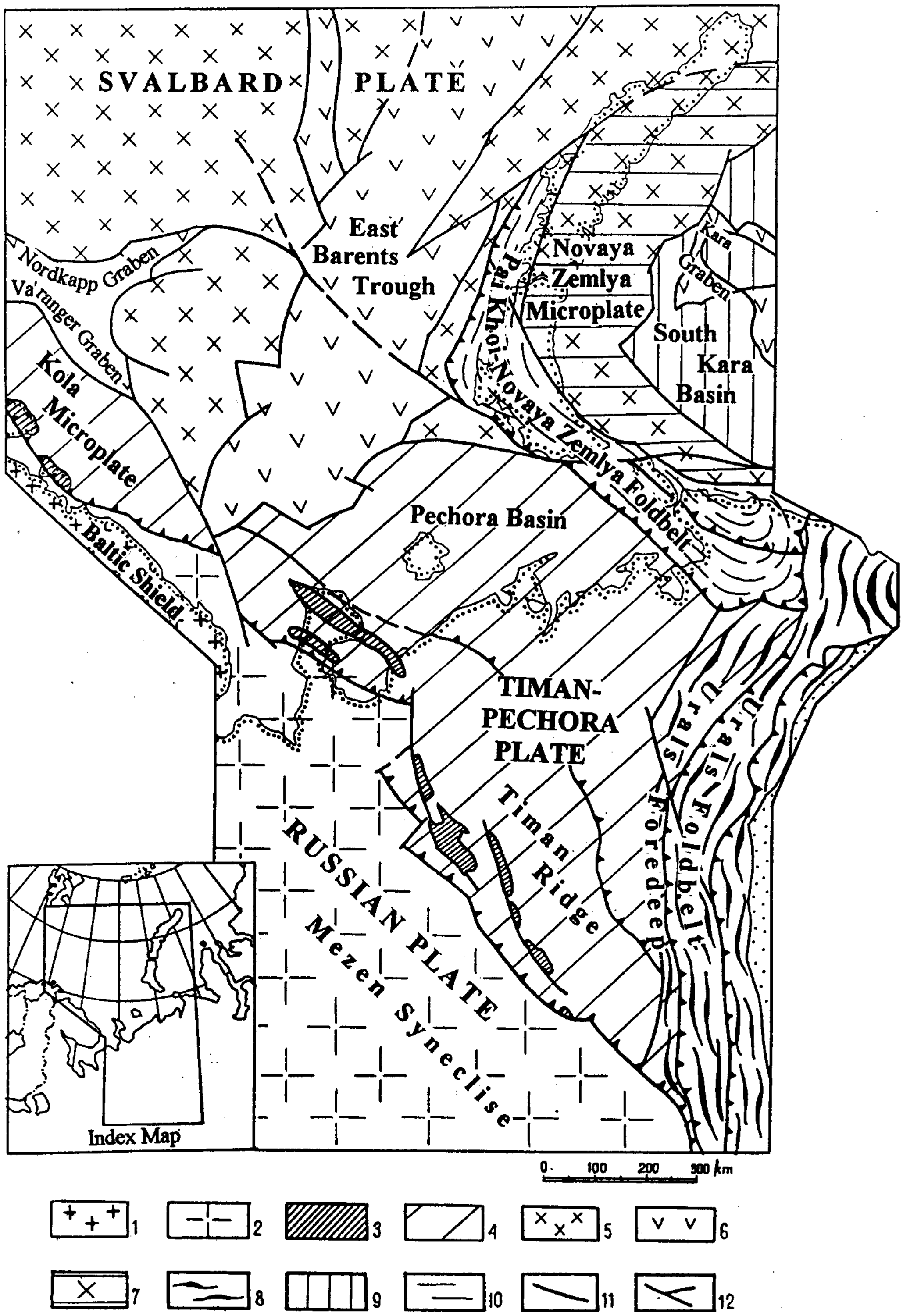

Fig. 1. Tectonic scheme of the northern European Russia and adjacent aquatic areas
1 - basement of the Baltic shield; 2 - Proterozoic basement overlapped by the Russian Plate cover; 3 - Riphean-Vendian fold structures; 4 - epi-Baikalian plates; 5 - epi-Grenvillian plate; 6 - troughs with suboceanic crust; 7 - epi-Grenvillian plate with elements of Cimmerian folding; 8 - Hercynian fold structures; 9 - epi-Hercynian plate; 10 - Early Cimmerian fold structures; 11 - thrusts; 12 - faults

superimposed on the Precambrian basement. Shelf sequences, mainly comprising carbonate, are characteristic of the external zone of the Uralian orogen. Bathyal shale sequences, in places with basic volcanics, as well as flysch are clearly distinguished in the Paleozoic units. Ophiolite associations and stratified zonal plutons composed of ultramafics (dunites, pyroxenites and gabbro) play a significant role in the Urals. In the east, the Uralian structures are overlain by the sedimentary cover of the younger West Siberian plate. In the west, the Uralian foldbelt is bounded by foredeep basins infilled with molasse.

The Pai-Khoi - Novaya Zemlya foldbelt, which includes the Pai-Khoi Ridge, Vaigach Island, South Island and the southeastern part of the North Island of Novaya Zemlya, represents an orographic extension of the Urals Foldbelt. It has a structure similar to the Urals Foldbelt but of different strike adjoining the Urals along a major strike-slip thrust fault. The age of deformation is also somewhat younger (latest Triassic-earliest Jurassic).

The structure of the thick sedimentary cover of the Pechora-Sea basin, which includes Paleozoic and Mesozoic deposits and which is of special importance due to its oil-and-gas prospects, is shown using contours of depth to basement, of depth to top Carboniferous-Lower Permian carbonates on the Timan-Pechora plate (on land), and of depth to top Volgian sediments (offshore). Intraplate basic magmatism is shown using a special symbol. Salt domes are shown within the Nordkapp-Varanger graben system, which has a suboceanic crust. A special symbol designates astroblems: the onshore Kara structure and the hypothetical offshore Mjolnir and Loparian structures, identified by seismic studies.

The western part of the South Kara basin, which is situated to the east of the Novaya Zemlya microplate, is also represented on the map. Within this basin, contours and different colour tints show the depth to acoustic basement, which is assumed to be Paleozoic.

II. STRUCTURES OF THE NORTH EUROPEAN RUSSIA

1. Baltic Shield

The Baltic Shield is represented on the map by the northernmost edge of the Murmansk block and its submarine slope. The Archean supracrustal structures within it have an approximately E-W trend. Fragments and relics of basic rocks (amphibolite facies pyroxene schists) serve as a substrate to repeatedly metamorphosed rocks. In the process of two-stage granitization, these rock complexes are reworked first into plagiomigmatites and then, in the second stage, into plagiomicrocline magmatites. The age of granitization is estimated as 2.8-2.7 Ga in the west of the zone, decreasing to 2.6 Ga in the east. Archean granitization processes were accompanied by formation of dome structures, which were cut in the Proterozoic by a series of arch-like overthrusts associated with the Kolmozero-Voronya shear zone trending NW-SE.

Numerous NE-SW trending dolerite dykes were emplaced during the Riphean. Intensely metamorphosed rocks of the Murmansk block dip north beneath the Riphean sedimentary cover exposed at the surface in the south of the Varanger and Sredny Peninsulas and on Kildin Island.

2. Russian Plate

2.1. Mezen Syneclise

The Mezen syneclise occupies the northern part of the Russian plate, itself part of the East European paleoplatform. It extends in the north into the White Sea, in the west it is bordered by the Baltic Shield, and in the southwest by the Belorus saddle. The Mezen syneclise opens south into the Moscow syneclise without a distinct boundary. Southeast of the Mezen syneclise, the Sysola arch of the Volga-Urals anteclise forms the boundary. In the east the syneclise is bounded by the Riphean fold structures of the Kanin-Timan belt. The sedimentary cover is made up of three major lithological and stratigraphic successions (from top to bottom): Upper Permian-Cenozoic, Carboniferous-Lower Permian, and Upper Proterozoic-Devonian (sections E, F, Sheet 2 of the Tectonic Map).

The Upper Permian-Cenozoic succession is predominantly represented by shallow-water marine sediments, and is composed of siltstones, marls, and more rarely limestones, Upper Permian dolomites and sandstones, and mainly Mesozoic and Quaternary sandy-clayey deposits. Terrigenous deposits dominate the succession overall, and in areas where Mesozoic sediments are lacking, mudstones and marls prevail. The thickness of the unit increases eastwards towards the Timan region to 1000 m, and then decreases abruptly within 50-100 km distance to pinch out on the western slope of the Timan Ridge. In the southern part of the syneclise the unit is 500-700 m thick.

The Carboniferous-Lower Permian succession is represented by Carboniferous dolomites and limestones and Lower Permian terrigenous-anhydrite(halogenic)-carbonate deposits (Asselian-Kungurian age). Rocks crop out in the western part of the syneclise. The succession occurs steeper and is faulted at the boundary with the Kanin-Timan Belt. The thickness generally ranges from 500 to 600 m, but may reach more than 1.0 km in southern areas transitional to the Moscow syneclise.

The Upper Proterozoic-Devonian terrigenous succession comprises Riphean clastic rocks, Vendian sandstones, siltstones, mudstones and clays, and Cambrian, Silurian? and Devonian sandy-clayey deposits. Riphean deposits infill basement grabens; younger deposits are developed throughout the area. The succession is thicker than overlying units, reaching 3.0-3.5 km. Structurally it represents a specific level in the sedimentary cover, which infills and smoothes out negative topographyc forms on the crystalline basement.

The basement of the Mezen syneclise is made up of pre-Riphean highly metamorphosed (mainly amphibolite facies) rocks. Direct geological data indicating the petrographic composition and the tectonic zoning of the basement are limited. Existing schemes are based on qualitative interpretation of the magnetic and gravitational fields and suggest an extension of the Archean and Early Proterozoic elements of the Kola blocks of the Baltic Shield into the region [9; 13; 19; 44; 48; 74; and others]. Velocity and density data provide additional evidence [41].

The velocity (Vr) at top basement varies from 5.8 to 6.6 km/s, and the density varies from 2.72 to 2.97 g/cm^3. On the whole, low density (2.72-2.85 g/cm^3) is consistent with territories where low velocity (5.8-6.1 km/s) prevails, and density values increase (2.85-2.95 g/cm^3) in areas with high velocity (6.2-6.6 km/s). The Mezen syneclise is characterised by 6.0-6.3 km/s velocities typical of granite-gneiss and rock associations metamorphosed at amphibolite facies. In the north and in the nearby Timan area, velocity values of 6.0-6.1 km/s prevail, whereas in the middle course of the Northern Dvina River and in the south of the region, the characteristic values are 6.2-6.3 km/s, which indicate a change of geological formations. Smaller discontinuities with a wide range of velocities (from 5.8 to 6.4 km/s) have a complicated distribution. They are as a rule linear and oriented in a NW-SE direction in the Timan and central areas. In axial regions of the Pinega, Vychegda and Elva rifts, velocities of 5.8-5.9 km/s seem to indicate the break-up in the basement. Similar zones of disjunctive dislocations are thought of as being developed in the Middle Dvina rift and in separate areas of a marginal suture between the syneclise and the Kanin-Timan Foldbelt. High velocity parameters (more than 6.4 km/s) most likely correspond to granulite and charnockite associations, or massifs of magmatic intrusions of basic and ultrabasic composition.

In the northwest of the region, on the interfluve of the lower courses of the Northern Dvina and Mezen rivers, velocity discontinuities have a concentric structure. An external band of the structure is represented by a velocity of 6.2-6.3 km/s and a density of 2.8-2.92 g/cm^3. In some places, there are local decreases in the velocity down to 5.8 km/s and increases up to 6.6 km/s. In the inner part of the concentric structure, in the direction of the axis, the velocity decreases first down to 6.0-6.1 km/s (density 2.76-2.77 g/cm^3) and then drops to 5.8-5.9 km/s (the density increases up to 2.82 g/cm^3) in the centre. The diameter of the concentric structure is 200 km. The fact that ring structures intersect the basement structures is interpreted to indicate that petrographic inhomogenities are younger than the relief formation stage. It seems that dome-like or oval granite-gneiss elements typical of the oldest Precambrian provinces occur in the upper part of the consolidated crust [34; 55]. A wide distribution of ring structures in the White Sea area and on the Baltic Shield suggests their extension below the sedimentary sequence of the Mezen syneclise. The southern part of the Mezen syneclise exhibits a similarity with the Karelian structures.

There are several pronounced features in the basement topography of the region. The western peripheral area submerges up to 1.5-2.0 km from the Baltic Shield side. The northern zone is occupied by a series of major uplifts (2.0-2.5 km). The central area has a depression, the depth of the basement ranging from 2.5 to 4.4 km. The peripheral area represented by a gentle monocline is made up of the Vetryanyi Poyas uplift. Along its eastern boundary, a system of the Onega (within the Onega Peninsula), Middle Dvina (in the middle course of the Northern Dvina River) and Toema (in the south of the syncline) rifts occurs with an amplitude of 1.0-1.5 km. The rifts are detached but seem to belong to a single aulacogen zone extending from northwest to southeast. The Onega and Middle Dvina rifts separate the western monocline from a swell of the major Arkhangelsk uplift located in the north, the apical part of which is less than 1 km high and occurs in the area of the Northern Dvina mouth and the bay of the same name in the White Sea. Southeast of the entrance to the White Sea, the Zolotitsk-Kuloi uplift is distinguished within the Zolotitsa-Kuloi block (Fig. 2), which is made up of smaller horst-like scarps (Zolotitsa, Chubala) separated by conjugated grabens (Keretsk, Padun, Eldoma). The Zolotitsa uplift is separated from the Arkhangelsk uplift by the narrow Keretsk rift. Horst, graben-like and rift structures are oriented in a NW-SE direction. Rifts widen and join in the central area of the deep-seated basement.

The northern elevated zone is made up of the Zolotitsa-Kuloi and Nes uplifts separated by the Ust-Mezen rift. The uplifts are of isometric form and have flat summits with an altitude of about 2.0-2.5 km. The geometry indicates that they originated as a single major rise which was then separated into two salients by a rift structure. The Ust-Mezen rift is oriented NNW-SSE to approximately N-S. In the southeast it extends to the central depression.

The central depression is more than 4.0 km deep, and is formed by the Leshukonskoe-Pinega (western) and Safonovo (eastern) zones, separated by the Mezen-Vashka arch. The Leshukonskoe and Pinega rifts form the western zone. The Leshukonskoe rift is 170 km long along the 4.0 km contour and about 50 km wide, and including two troughs involved and genetically related to it (the Eldoma trough in the north and Pylema trough in the southeast), the the rift extends for more than 250 km. The Kepinsk and Azopol troughs are distinguished in the axial part, which, along with marginal negative relief forms, made up a rift system of the initial evolutionary stage of the depression.

In the south, the Leshukonskoe rift is attached en-echelon to the larger Pinega rift 450 km long and 90 km wide. A series of local grabens can be traced here, the largest of which are the Kurmysh, Ust-Vyiya and Upper-Pinega rifts.

The Safonovo rift zone, comprising the Viryugin, Elva and Safonovo rifts, is distinguished in the east of the region. The Safonovo rift is confined to the Timan part of the syneclise and extends for 200 km in a NW-SE direction. It is replaced to the northeast, en-echelon, across a saddle, by the Virgyun short rift with the basement submerged up to 4.5 km. The Shoina trough should be considered as a seaward extension of the northeastern structures of the rift zone, as should the Pesh depression in the southern part of the Barents Sea [45]. The basement of the Shoina trough in the offshore extension occurs at a depth of 3-5 km. The trough is separated from the onshore part of the syneclise by a saddle situated between the Kanin and Kola peninsulas, the pre-Baikalian basement being at a depth of 1-2 km. The saddle is made up of contiguous uplifts: the Mezen massif and the Ludovatykh massif. The sedimentary cover mapped here is represented by Upper Proterozoic and Devonian-Carboniferous deposits.

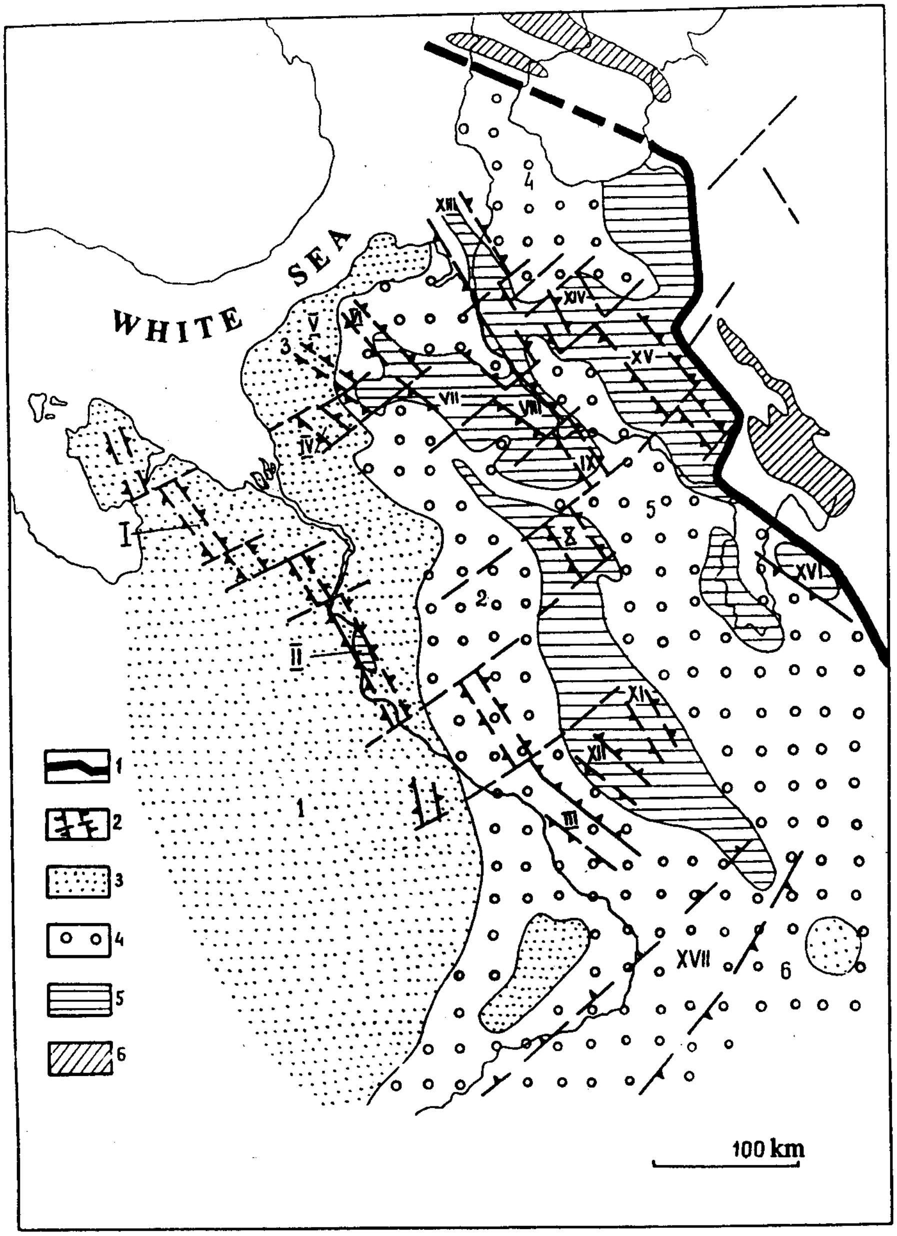

Fig. 2. Tectonic zonation of the crust in the Mezen syneclise [41]

1 - West-Timan marginal suture; 2 - rift grabens and transform faults; 3-5 - regions with different hypsometry of the top of consolidated crust, km: 3 - 0-2; 4 - 2-3.5; 5 - more than 3.5; 6 - exposures of the Riphean rocks on the Timan Ridge and Kanin Peninsula. Roman numerals indicate elements of the Mezen rift system: the Onega-Toema rift zone, rifts: I - Onega, II - Middle Dvina, III - Toema; Leshukonskoe-Pinega rift zone, rifts: IV - Keretsk; V - Padun; VI - Eldoma, VII - Kepin, VIII - Azopol, IX - Pylema; the Pinega rift zone, rifts: X - Kurmysh, XI - Ust Vyia, XII - Upper Pinega, XIII - Ust Mezen; the Safonovo rift zone, rifts: XIV - Viryugin, XV - Safonovo, XVI - Elva. The Central Russian aulacogen - XVII. Arabic numerals indicate interrift megablocks and arches: 1 - the Vetryanyi Poyas, 2 - Arkhangelsk-Eldoma, 3 - Zolotitsa-Kuloi, 4 - Nes, 5 - Mezen-Vashka, 6 - Sysola

North and south of the saddle, the section is increased by the addition of Permian and Lower Triassic deposits, and even Jurassic in more subsided areas.

The Mezen-Vashka megablock has the basement at a depth of 2-3 km. It is represented by a linear high-amplitude horst trending approximately N-S in the northern (Mezen) part. In the southern part, the horst becomes more gentle and is separated by the local Koslan basin (in the lower course of the Mezen River) into two branches: Koinas (eastern) and Vashka (western). The Vychegda rift is distinguished in the southeastern Timan part of the region. It is the deepest structure of the Mezen syncline: the basement surface occurs at a depth of more than 6 km. The Sukhona rift is oriented discordantly (NE-SW) with respect to other structures of the Mezen basin, and is situated in the south of the region. The axial part of the Vychegda rift is assumed to comprise a northeastern extension of the Central Russian aulacogen representing a core structure of the Moscow syneclise.

The tectonic nature of deep crustal horizons is reflected in the topography and in changes in physical parameters of the Moho (M) identified with the crust/mantle boundary. The M-boundary within the syneclise occurs at a depth of 38 km [41]. Against the background of a general rise from 42 km at the boundary of the syneclise with the Baltic Shield to 30 km in the north of the central area (the lower Mezen River), a series of morphological structures of both signs, and of different amplitude and strike is observed (Fig. 3). A zone of downwarping more than 40 km deep is observed in the northwest, near the Zolotitsa salient and the eastern closure of the Arkhangelsk rise of the basement. The downwarping may exceed 42 km in some local depressions. A general downwarping of the mantle surface and the presence of still deeper small topographic structures in combination with horst-like relief of the basement surface in this region is accompanied by kimberlite magmatism. Such features are also observed in the Mirny-Aikhal diamond-bearing region [65] and are considered as one of the deep signs of diamond deposits. An inverse relationship between the basement topographic forms and the Moho indicates an increased thickness of the consolidated part of the crust to more than 38 km.

A more elevated occurrence of the M-boundary (less than 30 km) is observed in the lower course of the Mezen River basin. The apical part of the elevation falls within the Ust Mezen rift. To the southeast, there is an area with contours about 34 km, which coincides spatially with the Safonovo rift zone in the basement. In all these cases, a decrease in the thickness of the consolidated crust (down to 28-30 km and less) occurs with an inverse relationship between the depth of the basement and the mantle surface, which is characteristic of rift structures. A similar crustal type is observed in the Central Dvina rift. A local rise of the M-

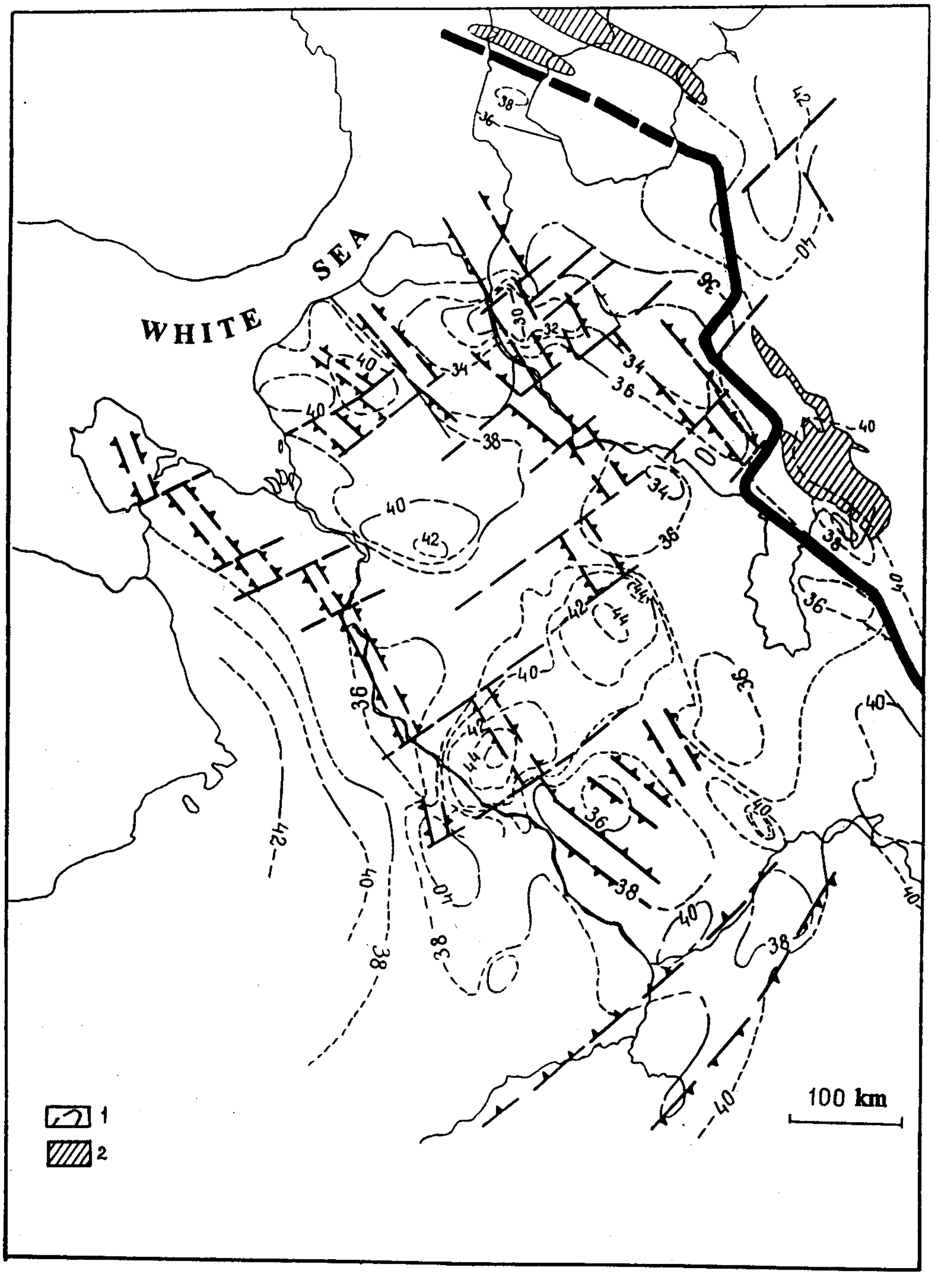

Fig. 3. Depth of the Moho boundary within the Mezen syneclise [41]
1 - contours; 2 - exposures of the basement of the Timan-Pechora plate onto the surface

boundary up to 35 km results in the thinning of the consolidated crust down to 32 km. In the vicinity of the Safonovo rift, in the northeast of the syneclise, the M-boundary undergoes no contrary rise but dips uniformly in the direction of Timan, sinking from 38 to 40 km. Rifts are not reflected by the M-boundary. A dome-like uplift to less than 36 km is distinguished below the southern edge of the Pylema rift and extends over the Mezen-Vagin arch. As a result, a complicated relationship occurs between topography and the lower surface of the crust, varying from inverse to direct.

An extensive depression of the M-boundary (as defined by the 40 km contour) extends in a northeasternward direction on the interfluve of the upper reaches of Northern Dvina and Mezen rivers. Two smaller local depressions of isometric form are distingushed within the area. The depth of the M-boundary is 46 km in the western depression, and 42-44 km in the northeastern depression. The western depression does not correspond to the topography of the basement surface, whereas the northeastern depression has a close to direct relationship. Further south, several local uplifts up to 36 km are revealed. The extreme western rise corresponds to the Toema and Upper Pinega rifts, the central rise is confined to the Mezen-Vashka uplift, and the eastern rise to the Elva rift. In the south of the syneclise, in the area of the Central Russian aulacogen, the mantle surface occurs in the basement at a depth of 38 km dipping down to 40 km under the Sysola arch and belonging to the Volga-Urals anteclise here.

The data cited above indicate several types of relationships of key boundaries in the crust of the Mezen syneclise, which are caused by different mechanisms of interaction between deep and subsurface processes. A more stable relationship is characteristic of rift zones. It is expressed by a counter displacement of the top and bottom of the crust, and by a considerable crustal thinning (by more than 3-5 km). Preservation of features characteristic of rifting, which occurred in the Riphean-early Vendian, until the present time indicates its intensity and the substantial effect that it had on the crust.

Velocity discontinuities at the mantle surface in the syneclise range from 7.9 to 8.4 km/s, and even more. A persistent northwestern zonation of discontinuities is evident. A vast field (up to 300 km across) of "average" velocities equal to 8.2 km stands out in the central region. The area of "average" velocities narrows down to 50-60 km to attain a linear form trending in a northwestward direction. Linear zones 200-300 km long and 50-70 km wide of reduced velocities appear southwest and northeast of the area of thinning, up to 7.9 and 8.0 km/s respectively indicating a low density e of the mantle. The territory is bounded on the west and east by areas with a velocity of more than 8.4 km/s. The western high-velocity zone is located below the Onega-Tom rift zone. The eastern zone comprises graben structures of the basement of the Leshukonskoe-Pinega and Safonovo rift zones. The confinement of high-velocity zones to rift structures suggests a relationship between them and restites of magmatic subcrustal paleorift "pillows". The anisotropy of properties is revealed below the Middle Dvina rift, which manifests itself as a variation of velocities in the NW-SE (about 8.2 km/s) and NE-SW (up to 8.4 km/s) directions. The spreading and strike-slip faultingt nature of the anisotropy is most probable [43].

The tectonics of consolidated crust of the Mezen region is characterized by elements of regional lateral and vertical stresses and displacements. Structures indicating subhorizontal transformations, e.g. intracrustal nappes, slices, zones of tectonic stratification and thinning out, are developed in the Earth's crust and were formed over an extended period. Growth of the consolidated crust occurred during plate (terrane) tectonic events [42]. In the Riphean-Vendian, rift zones and intervening blocks represented the principal tectonic elements [6; 41]. Rift zones were characterized by the rise of the M-boundary and the resultant thinning of the consolidated crust. The rise of the M-boundary proceeded either in specific local areas directly below grabens (the Middle Dvina rift and others) or on a regional scale. In the latter case, a concentration of several rift elements or the connection of several rift zones (the Ust-Mezen, Viryug, Toema, Upper Pinega and other rifts) took place. Boundary velocities decrease on the basement surface in graben zones that indicates rock disintegration due to tectonic processes. Destruction processes and penetration of mantle magmatic masses has resulted in intrusions and basification zones developed at the base of the crust [42]. Central areas of most of the rift structures are not magnetic or only slightly magnetic. Some grabens contain magnetic bodies in their flanks that intersect the crust from the basement to the M-boundary. It is likely in these cases that mantle magnetic rocks penetrate into marginal zones of rift structures. In the upper mantle, areas of high boundary velocity (as a rule more than 8.4 km/s) and density (3.4-3.45 g/cm^3) occur, which can be interpreted as restites of synrift subcrustal magmatic chambers containing remaining heavy components, corresponding to rift structures.

Rift zones comprise systems of graben-like troughs of NW-SE or approximately N-S trend in the basement (Fig. 3). Grabens are of linear form, generally 20-30 km wide (the extreme parameters from 10 to more than 40 km) and from tens of kilometres to more than 100 km long. The subsidence of the axial part with respect to the rift shoulders amounts to 1.5-2.0 km. Grabens are infilled with Late Proterozoic (Riphean?-Vendian) terrigenous rocks. The Onega-Toema, Leshukonskoe-Pinega, Ust-Mezen and Safonovo rift zones can be distinguished. Rift elements are connected through transcurrent faults mainly of approximately E-W trend. Transcurrent faults are subparallel and are integrated into systems of arched lineaments, conforming to the concentric zonation with a centre located in the Kola microplate of the Baltic shield. It is not improbable that their formation was predetermined by an arched paleostructure of the shield with a concentric arrangement of stresses. Rifting predetermined the formation of major Late Proterozoic-Early Phanerozoic linear depressions of the syneclise, e.g. the Leshukonskoe, Pinega and Safonovo rift zones. The accumulation of a great variety of magmatic rocks in the middle part of the crust, which affected the isostatic equilibrium of the lithosphere, was a contributory factor in the postrift subsidence of the territory. The Sukhona rift-related trough was the product of an alternative tectonic system. Formed above the northeastern extension of the Central Russian aulacogen, the trough strikes discordantly with respect to rift zones of the Mezen syneclise. The Sukhona structure has no effect on physical parameters of the basement surface but is characterized by a reduced velocity in the consolidated crust (down to 6.4-6.5 km/s versus 6.6 km/s in surrounding areas) and exhibits anisotropy of velocities up to 0.2 km/s in subcrustal horizons of the mantle caused by fault deformations through the lithosphere [41].

The Timan foretroughs of the Safonovo rift zone occupy a special place among negative elements of the Mezen region. The lack of a pronounced rise of the mantle surface and moreover a gentle monoclinal sinking of the mantle in the direction of the Timan Ridge create the effect of inclination of the Proterozoic basement below the Baikalian structure. The rift-related nature of these troughs is not detectable or it is largely overprinted by subsequent tectonic transformations. Interrift areas are made up of crustal blocks differing in size, thickness, hypsometry of key surfaces, internal structure of the crust, its physical parameters and reflection in potential fields. Among major interrift structures are the Vetryany Poyas, Arkhangelsk-Eldoma, Zolotitsa-Kuloi, Nes, Mezen-Vashka and Sysola megablocks. The Vetryany Poyas megablock most likely represents the southeastern extension of the Baltic Shield under the sedimentary cover of the Mezen syneclise. The northern part of the Arkhangelsk-Eldoma megablock, the Zolotitsa-Kuloi and the Nes megablocks have a reduced thickness of the consolidated crust (34-38 km), and correlate with the White Sea megablock of the Kola Peninsula on the basis that they contain structural and petrographic heterogeneities arranged concentrically in their upper parts. The upper surface of the southeastern part of the Arkhangelsk-Eldoma megablock and the Mezen-Vashka megablock subsided to 2-3.5 km, the Mezen-Vashka megablock having the smallest thickness (32-34 km) among interrift structures. The Sysola arch 38-39 km thick is distinguished in the southeast of the region and belongs to the Volga-Urals crustal structures. A distinctive feature of the arch is the average velocity (6.7

km/s) in the consolidated crust. Such a high velocity is not characteristic of the Mezen blocks and is registered only on local areas in the northern part of the Zolotitsa-Kuloi megablock.

A suture fault between the Mezen syneclise and the Timan fold structure is characterized by a knee-like structure (in plan) that is caused by connection of two orthogonal systems of disjunctive dislocations of NW-SE and NE-SW trend. Dislocations of the first system conform to the general structure of Timan and are related to its development as a linear tectonic feature. Faults with a NE-SW trend show a spatial correlation with transcurrent elements of the Mezen rift system. This situation indicates the active influence of the Pre-Timan area of the East European craton on the evolution of the adjacent fold area.

3. Timan-Pechora Plate

3.1. The Structure of the Timan-Pechora Plate

The epi-Baikalian Timan-Pechora plate is situated in the extreme northeast of European Russia, and in the general framework of East European sedimentary basins it enlarges the epi-Karelian margin of the Russian plate. The Timan-Pechora plate is bounded by the West Timan marginal suture in the west, whereas in the east it is bordered by the frontal folds of the Urals and Pai-Khoi, in the cores of which preorogenic Paleozoic carbonate formations are exposed. Most of these anticlines are located in the hanging walls of the West Urals and West Pai-Khoi overthrusts. In the south, the West Timan suture adjoins the West Urals overthrust to create the so-called Urals-Timan junction [76]. A less confident northern boundary of the Timan-Pechora plate with the Svalbard plate is drawn along the E-W trending Kurentsovo scarp situated in the north of the Pechora Sea basin, or the North Pechora monocline. Tectonic elements lose their morphological features within this structure.

The basement of the Timan-Pechora plate is composed of Late Proterozoic sedimentary and metamorphic rocks with effusive and intrusive bodies. On the basis of the complex interpretation of gravity and magnetic lineations, seismic data and data obtained from deep sea drilling cores, two megablocks can be distinguished in the basement -- the southwestern Timan megablock and northeastern Bolshezemelsky megablock [25; 12; 21; 5]. The megablocks have different geophysical anomaly characteristics and the composition of volcanogenic and metamorphic formations indicate that they originated in different geodynamic environments. The boundary between these blocks is established along the Pechora and Ilych-Chiksha faults, which cross the Timan-Pechora plate diagonally line from the Urals to the Pechora sea basin, and can be traced with confidence using gravity and magnetic lineations.

According to geophysical data, the Timan-Pechora plate basement comprises metamorphic rocks of low and intermediate metamorphic grade (greenschist, epidote-amphibolite in local zones, and amphibolite facies) intruded by a great variety of magmatic rocks [16; 39; 5]. Most researchers consider this basement to have been consolidated during Riphean-Early Cambrian time. However, pre-Riphean crystalline masses are assumed in the Bolshezemelsky megablock area [7; 74]. Data on the velocity and density parameters of consolidated basement units obtained through complex geological and geophysical analysis make it possible to refine some problems of basement zoning.

In the western part of the region comprising the Timan Range and the Izhma-Pechora basin, velocities equal to 5.9-6.0 km/s, locally down to 5.8 km/s, prevail in top basement. The areas are characterized by a relatively low density (2.71-2.78 g/cm^3) of consolidated units, but in some places amounting to 2.84 and even 2.92 g/cm^3. The anomalous magnetic field of the territory manifests itself as a regional negative background indicating nonmagnetic or slightly magnetic properties of the main rock mass. These features lend strength to the suggestion that Riphean metamorphic schists of low-rank metamorphism are developed in the basement, which are similar to those widespread within the exposed Timan "Stones", with individual massifs of basic and ultrabasic rocks.

In the east, a "schist" area is bounded by a linear zone (more than 400 km long and 50-100 km wide) of contrasting and heightened values of physical parameters. Velocities of more than 6.4 km/s prevail in the southern part of the zone, whereas an alternation of local fields with velocities from 5.8 to 6.4 km/s is observed in the northern part. The density ranges from 2.82 to 2.88 g/cm^3. A variety of petrographic units can be assumed for this zone, including weakly to highly metamorphosed complexes, as well as igneous rocks from silicic to ultrabasic composition. According to Belyakova and Stepanenko [5], magmatic associations penetrated by drill holes correspond to the Charkayu-Palyu rear zone and to the Pechora-Ilych-Chiksha frontal zone of a paleo-island arc structure.

In the central part of the plate, comprising most of the Pechora-Kolva trough and Bolshezemelsky arch, velocities amount to 6.2-6.3 km/s, whereas densities varies from 2.82 to 2.9 g/cm^3, locally reaching 2.95 g/cm^3. Such parameters are characteristic of crystalline sequences of intermediate and high-rank metamorphism, which indicates the development of major pre-Riphean crustal massifs in the Bolshezemelsky region of the plate.

In the eastern part of the Bolshezemelsky arch and in depressions of the Urals foredeep, the observed velocities (more than 6.4 km/s) and densities (2.96-3.1 g/cm^3) may indicate the wide development of basic rocks. This interpretation allows paleoblocks of oceanic or suboceanic crust to be identified in these regions.

The internal structure of the Timan megablock is characterized by the NW-SE "Timan" zonation. Its western, narrow, zone is composed of weakly metamorphosed Riphean terrigenous formations, with local platform-type intrusions. The thickness of the Riphean formations is 4-6 km, increasing up to 12-15 km in an eastward direction, behind the Central Timan fault. Carbonate (reef-related) rocks are widespread here, especially within the Central Timan fault, along with terrigenous rocks. Rocks of this eastern larger area are strongly dislocated and metamorphosed to greenschist facies. Magmatic rocks are represented by gabbro-diabases on the Kanin Peninsula and in Central Timan, post-folding binary granites and granodiorites in a strip adjoining the Ilych-Chiksha fault, and orogenic and post-orogenic alkaline gabbroids, granites and syenites confined to the West Timan fault [5].

A special place in the extreme west of the Timan-Pechora plate is occupied by the Timan Ridge, the Baikalian component of which is made up of Riphean formations of the Riphean passive margin (Fig. 4). The position of the Timan Ridge between tectonic sutures (West Timan, Central Timan and East Timan sutures) that separated two areas in the Riphean with different geodynamic environments (the Russian plate and Timan-Urals ocean) is also reflected in the subsequent Paleozoic and Mesozoic tectonic activity.

Magmatic and volcanosedimentary rocks are widespread throughout a strip of the Pechora and Ilych-Chiksha faults. Basic volcanics, amphibole-biotite granitoids and diorites are penetrated by boreholes in western areas of the zone. Gabbro, gabbro-diorites, gabbro-diabases, diorites and plagiogranites, i.e. rocks with initial basaltic magma are characteristic of the eastern areas. Granites are subordinate in all areas of the zone, and they contain a high proportion of basic components as compared with the granite association of the Timan megablock. Effusive calc-alkaline rocks are widely developed. The composition of magmatic associations listed above indicates that their formation in the Late Proterozoic was related to the geodynamic environment typical of island arcs.

Exposures of the Riphean basement rocks extend beyond the limits of the Timan-Pechora plate: Upper Riphean associations occur in the northern half of the Varanger Peninsula and sequences are exposed on the Rybachy Peninsula in the extreme south of the Kola microplate. In the south, the Riphean-Vendian complexes of Varanger and Rybachy peninsulas are separated by a complicated zone of tectonic nappes (Trollfjord-Komagelv) [94; 107], which is replaced to the west by the Kola-Kanin fault. In the northern part of the Varanger Peninsula, the Upper Riphean mainly comprises shale-sandstone formations of the Barents Group, up to 9-11 km thick, overlain by Vendian sandstone-shaly deposits up to 4.5-5.0 km thick [112]. On the Rybachy Peninsula, the Upper Riphean turbidite sandstones and conglomerates of the Eina Group are overlain by thin sandstones and shales of the Bargun Group. The total thickness of the deposits (3-3.5 km) is considerably less than that on Varanger. Using stromatolites, these complexes can be correlated with sequences on the Kanin Peninsula [106]. There are good grounds to believe that Riphean-Vendian rocks form the base of the Kola microplate and extend northward beneath the Barents Sea.

The core from most boreholes penetrating Upper Proterozoic rocks on the Bolshezemelsky megablock contains predominantly acidic volcanics and tuffs. Intrusive rocks

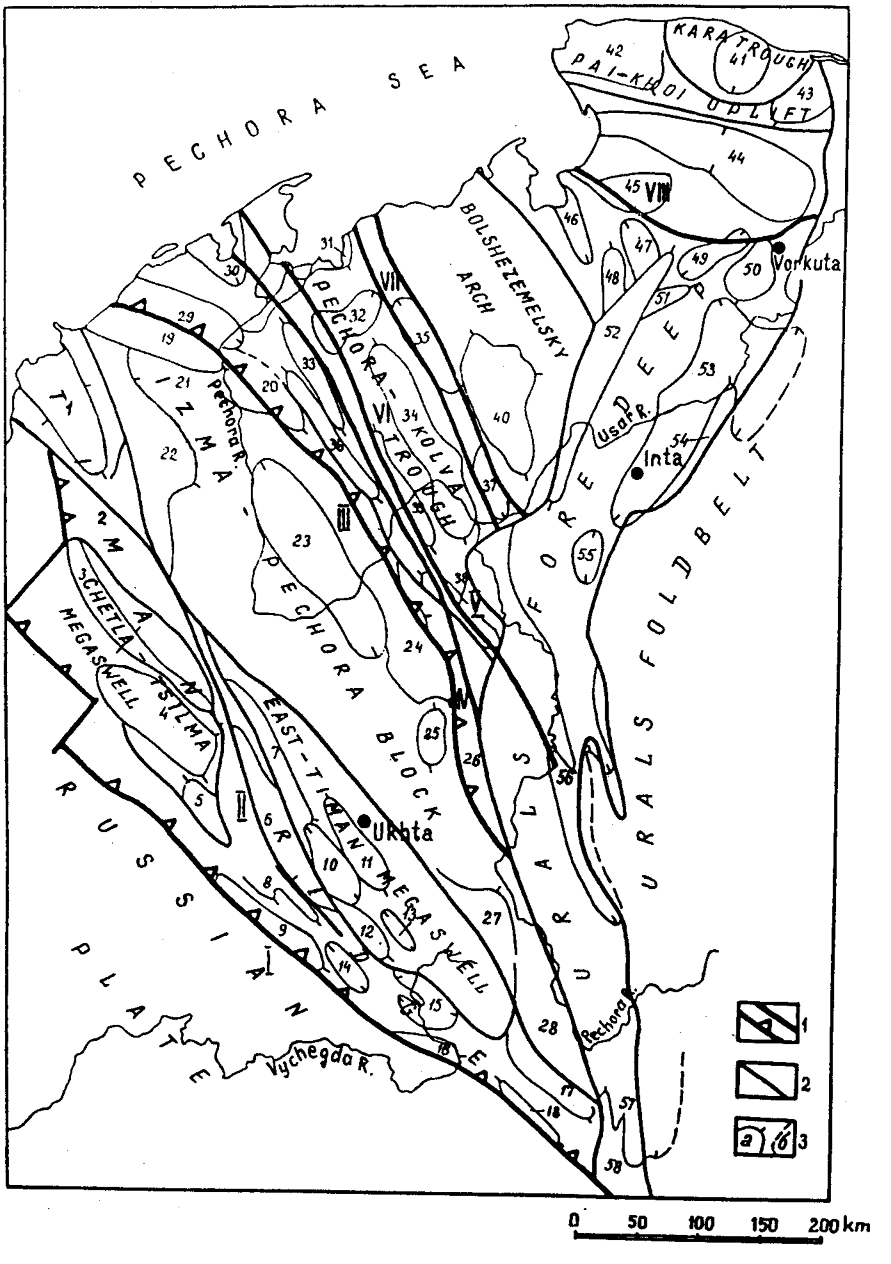

Fig. 4. Tectonic structures of the Timan-Pechorapa plate (the basement surface). Compiled by V.G.Getsen, V.A.Dedeev, I.V.Zaporozhtseva, N.A.Malyshev, N.I.Timonin, and G.D.Udot (1984)

Boundaries of structures: 1 - superorder (megastructures); 2 - first-order (major); 3 - second order (intermediate) (a - in platform cover, b - under allochthonous overthrust sheets of front folds of the western slope of the Urals). First-order structures: A - Timan megablock; B - Bolshezemelsky megablock. Major ruptured dislocations and structural sutures: I - West Timan suture; II - Central Timan fault, III - Pechora fault system; IV - Ilych-Chiksha fault system; V - Pechorogorsky fault; VI - Shakin-Yuryakha fault; VII - Kolva fault system; VIII - Vashutkin-Talotin thrust. Second-order structures: 1 - North-Timan swell, 2 - Kosma junction, 3 - Tsylma swell, 4 - Chetla uplift, 5 - Obdyr swell, 6 - Upper Vym depression, 7 - Vym swell, 8 - Ropchin uplift, 9 - Sindor sweel, 10 - Toba depression, 11 - Ukhta swell, 12 - Ochparma swell, 13 - Upper Volsk depression, 14 - Nivsher depression, 15 - Volsk depression, 16 - Dzhezhim-Parma swell, 17 - Nema scarp, 18 - Ksenofontovo swell, 19 - Seduyakha swell, 20 - Ust Sula uplift, 21 - Soima Bay, 22 - Tobysh scarp, 23 - Ersin depression, 24 - Kipiev ulift, 25 - Lemju-Irael uplift, 26 - Michayu-Pashnin uplift, 27 - Omra-Soiva scarp, 28 - Dzhebol monocline, 29 - Oksino depression, 30 - Kolokolkov Bay, 31 - Ust Pechora (Nosovaya) uplift, 32 - Nerutin depression, 33 - Vydshor swell, 34 - Laya swell, 35 - Kharyagin depression, 36 - Lebed uplift, 37 - Lower Usa depression, 38 - Lyzha scarp, 39 - Yuryakha swell, 40 - Sandivei-Bagan uplift, 41 - Ust Kara depression, 42 - Amderma uplift, 43 - Edunei Cape, 44 - Pai- Khoi depression, 45 - Talotin swell, 46 - Maloyu depression, 47 - Upper Adzva depression, 48 - Adzva uplift, 49 - North Rogov depression, 50 - Yarva uplift, 51 - Upper Rogov uplift, 52 - Chernyshov uplift, 53 - Usa depression, 54 - Lemva uplift, 55 - Kosyu depression, 56 - Synya-Ilych depression, 57 - Kolva-Vyshera bay, 58 - Polyudov transverse uplift are represented by binary granites, diabases and granitoids. Their composition ranges from earlier basic varieties to later acidic [5]. On the Bolshezemelsky megablock, terrigenous (Vendian-Cambrian) red beds with an admixture of tuffaceous material, bodies and flows of acidic effusive rocks are also widespread. They occupy the highest part of the pre-Ordovician section, and represent the products of washout and redeposition of Riphean volcanics and can be considered as a molasse formation of the Baikalian orogeny. A considerable mass of basic rocks is interpreted to occur at lower stratigraphic levels of the section (1 km beneath its surface) on the basis of geophysical data. The internal zoning of the eastern part of the Bolshezemelsky megablock, with the exception of the Pechora and Ilych-Chiksha fracture zones (Fig. 4), does not strictly follow the "Timan" orientation. Areas of slightly metamorphosed volcanosedimentary associations with a reduced volume of volcanics of K-type alkalinity are found here. Complex intrusions of granodiorite-granitic and tonalite-plagiogranitic associations are common. These areas of pre-Riphean consolidation slightly affected by basite magma are surrounded by zones with active effusive and intrusive magmatism.

The consolidation of the Upper Proterozoic complex of the Timan-Pechora plate as a consequence of the Baikalian folding was extremely heterogeneous. A high rigidity appears to have been typical of most of the Timan megablock basement, formed under passive margin conditions of the East European craton on Karelide continental crust and characterized by intrusion of major Vendian-Cambrian granite batholiths. In the Bolshezemelsky megablock, formed on the active margin with a transitional-type crust, the rigidity was restricted to areas where relicts of continental crust survived and volcanoplutonic processes culminated in acid magmatism. Thus, the intrusion of granites and the origin of granite-gneiss domes enhanced in the Late Riphean-Vendian resulted in further granitization and an expansion of areas with a thickened granite-gneiss layer.

Some areas of the Timan-Pechora plate with a thinner crust appeared to be predisposed to tension, which caused the formation of rifts and high penetrability for intrusion of basic magmatic rocks. Such a paleogeodynamic situation occurred along the Pechora and Ilych-Chiksha fault system and east of it, in the Denisovo strip of gravimagnetic lineations, which is thought to have represented an island arc, a subduction zone and an incipient ocean during the Middle-Late Riphean. Fault-fold deformations of the Baikalian orogeny resulted in the closure of this basin and formation of a volcanoplutonic belt controlled by the Pechora and Ilych-Chiksha faults in the west and by the Kolva faults in the east. A second island arc zone is

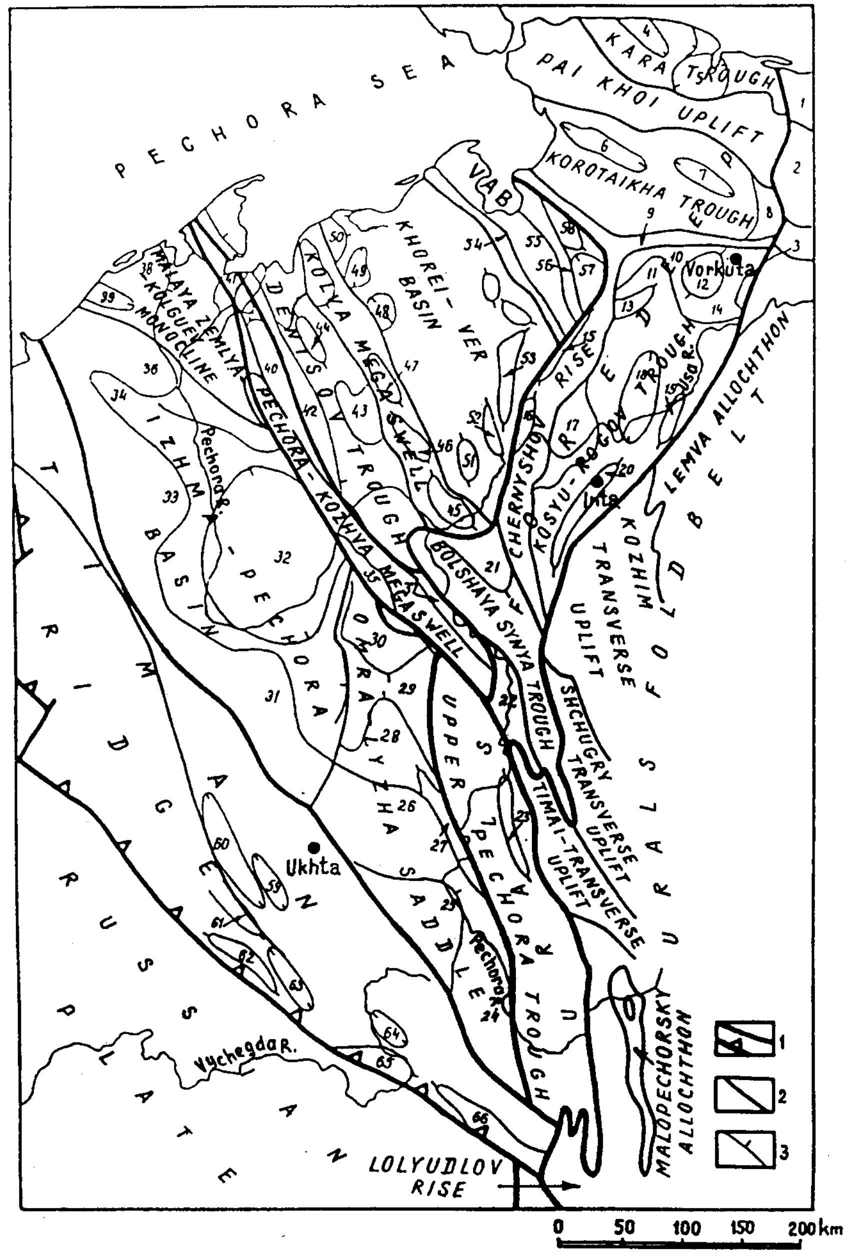

Fig. 5. Tectonic structures of the Timan-Pechora plate (the surface of Lower Permian deposits). Compiled by V.G.Getsen, V.A.Dedeev, I.V.Zaporozhtseva, N.I.Timonin, G.D.Udit, and V.V.Yudin (1984)

Boundaries of structures: 1 - superorder (megastructures), 2 - first-order (major), 3 - second-order (intermediate). First-order structures within the Polar Urals: 1 - Baidaratskaya transverse depression, 2 - Ochenyrd transverse uplift, 3 - Upper Usa transverse depression. Second-order structures: 4 - Tabju depression, 5 - Kara impact structure, 6 - Lower Yangarei depression, 7 - Ponutin depression, 8 - Upper Syrjaga scarp, 9 - Chernov uplift, 10 - Padma scarp, 11 - North Rogov depression, 12 - Yarvozh uplift, 13 - Upper Rogov rampart, 14 - Vorkuta uplift, 15 - Khosedayu swell, 16 - Usinsk-Ushor swell, 17 - Kochma scarp, 18 - Abez depression, 19 - Lemva swell, 20 - Inta structural zone, 21 - Nitchemyu-Synya uplift, 22 - Middle Pechora uplift, 23 - Vuktyl swell, 24 - Dzhebol monocline, 25 - Omra-Soiva scarp, 26 - Velju-Tebuk scarp, 27 - Michayu-Pashnin structural zone,, 28 - Lemju-Irael scarp, 29 - Sotchemju junction, 30 - Luza scarp, 31 - Izhma scarp, 32 - Brykalan depression, 33 - Tobysh scarp, 34 - Soima Bay, 35 - Mutnomaterikovy swell, 36 - Seduyakha swell, 37 - Pechergorodsk structural zone, 38 - Sengei scarp, 39 - Oksino depression, 40 - Pyata depression, 41 - Korovin depression, 42 - Shapkin-Yuryakha swell, 42a - Nosovaya uplift, 43 - Mishva scarp, 44 - Laya swell, 45 - Usa swell, 46 - Vozei swell, 47 - Kharyagin swell, 48 - Upper Shapkin depression, 49 - Chernaya depression, 50 - Vangurei Cape, 51 - Vagai uplift, 52 - Middle Makarikha swell, 53 - Salyukin swell, 54 - Sorokin swell, 55 - Maloyu depression, 56 - Gamburtsev swell, 57 - Upper Adzva basin, 58 - Zenchenko swell, 59 - Tobysh depression, 60 - Upper Vym depression, 61 - Ropchin uplift, 62 - Sindor swell, 63 - Nivsher depression, 64 - Volsk depression, 65 - Dzhezhim-Parma swell, 66 - Ksenofontovo uplift, VAB - Varandei-Adzva block located in the Polar Urals (Fig. 5). An oceanic-type basin probably existed east of this zone, in the northeast of the Timan-Pechora plate.

The geodynamic environments mentioned above, which resulted in formation of the folded basement of the Timan-Pechora plate, are reflected in the structure of its major pre-Ordovician structural elements and on their subsequent tectonic activity during the course of the geologic evolution of the region.

A relative tectonic stability was characteristic of territories with the pre-Baikalian continental crust and acidic plutons. These territories comprise the Izhma-Pechora block (microplate) occupying most of the western Timan-Pechora plate, and the Bolshezemelsky megablock, with a superimposed basin infilled by Vendian-Cambrian molasse. Territories of high penetrability of the pre-Baikalian basement with widespread basite formations were characterized by an incomplete tectogenesis, as no intense acidic magmatism of the final stages of the orogeny has been found there. This predetermined these zones to a high tectonic activity in the post-Baikalian stage of the tectogenesis. The inherited regime of downwarping resulted in the formation of fault-related depressions in the early stages of Paleozoic tectogenesis, and inversion megaswells and swells in the late stages (Shapkin-Yuryakha, Kolva, Sorokin, and others). A block of the Pechora-Kolva deep located west of the Bolshezemelsky arch, and probably a zone of the Adzva basin east of it, as well as blocks in the Urals foredeep belong to such mobile structures of the Baikalian basement of the Timan-Pechora plate.

Megablocks and their constituent blocks, which originated during the course of the Baikalian folding, retained their characteristic features in the modern structure of the Timan-Pechora plate as tectonic elements of corresponding orders. A general subsidence of the basement under the sedimentary cover to a depth of 10-12 km occurs between the Timan Ridge, where it is exposed at the surface, and western structural zones of the Urals and Pai-Khoi, as well as in the direction of the Pechora Sea basin.

The modern structure of the Timan Ridge corresponds by the basement surface to the outline of the West Timan marginal uplift in the Baikalides. The ridge is made up of fold-thrust and fold-horst dislocations related to a certain extent to deep-seated faults of NW-SE trend. Dislocations of the ridge along with complicated disjunctive dislocations intersect the faults at an acute angle. The West Timan fault comprises the Ksenofontovo, Dzezhim-Parma, Sindor and Obdyr swells ranging in size from 25 x 70 to 50 x 230 km, with an amplitude from 0.3 to 0.8 km (Fig. 4).

In the central part of the Timan ridge, the West Timan suture and the entire zone of slightly metamorphosed Riphean rocks are overlain by a tectonic slice, which belongs to the central Timan overthrust. The Chetlas uplift, in the crest of which the Riphean rocks are exposed, is situated in this area. The uplift is 100 km long and 40 km wide, with an amplitude of 0.5 km. {In the south, the Obdyr anticline with Riphean rocks exposed in the crest adjoins the uplift along the fault. Further south, the basement is depressed to a depth of 0.9-1.2 km in the crest of the Sindor swell, located en-echelon, and appears at the surface in the crest of the Dzhezhim-Parma swell.

In the northern part of the Timan Ridge, the North Timan swell is associated with the Central Timan tectonic suture. In the central part of the Timan Ridge, the impact of the suture can be traced in the eastern part of the Chetlas uplift, composed of Riphean metamorphosed rocks, and manifests itself on the surface as narrow disjunctive folds in the Tsilma swell, also with exposures of Riphean rocks. Further south, the West Timan suture is adjoined by the Vym and Ochparma swells at an acute angle. These structures represent a narrow anticlinal zone, which is displaced along the thrust southwestward for 4-5 km so that the Riphean rocks exposed in the fold cores overlie the Permian and Carboniferous deposits occurring in the autochthon. The vertical amplitude of the dislocation is 2 km.

The northernmost Kanin-North Timan swell is situated between two branches of the East Timan fault. Riphean rocks are exposed in its crest. The swell with its seaward extension is 400 km long and has an amplitude of up to 1 km. The Ukhta swell is also situated in the East Timan fault zone. However, it is the least dislocated, major structure of the Timan Ridge, and has brachianticlinal form. Its crest and western flank are cut by small-amplitude upthrusts and faults. The depth of the basement varies from 0.2 km in the crest to 1.0 km on the flanks. Swells of the Timan Ridge are separated by synclines with gentle western flanks and steep eastern flanks cut off by rupture dislocations. The basement is depressed in synclines up to 2 km.

The Izhma-Pechora block (microplate) of the basement represents a major monocline dipping in an eastward direction from Timan to the Pechora and Ilych-Chiksha fault zone. The monocline is separated from the Timan Ridge by faults with an amplitude of 0.8-0.5 km. The depth of the basement on the west of the monocline is 0.5-1.5 km, increasing to the east to 1.7-3.5 km. There are several salients and promontories oriented to the east and southeast, which occur against a general background of dip in a northeastward and eastward direction. In the east of the Izhma-Pechora block (microplate), along the Pechora fault zone, the major Malozemelskaya structural zone can be traced with a hinge dipping southeastwards. The structural zone comprises the elevated Seduyakh swell in the north, and salients and promontories with small swells in the southeast. The northeastern flanks of local structures of the Malozemelskaya zone are bounded by faults of the Pechora deep-seated fault zone. Southwestern flanks are dislocated by small-amplitude disjunctions, which often form a branching system that complicates the crest parts of structures in the marginal uplift. The Ersin basin comprising the Brykalan depression and several troughs represents a synclinal structure adjacent to the Seduyakh swell within the Izhma-Pechora block (microplate).

A system of structural sutures separating the Timan and Bolshezemelsky megablocks is represented on the N-S trending Ilych-Chiksha segment by elongated (up to 300 km long) and narrow (5-10 km wide) scarps bounded by faults (amplitude 0.1-0.8 km), gradually plunging in the direction of the Upper Pechora basin of the Urals foredeep. The Pechora part of the system, which is also composed of fault scarps in the southeast, branches further northwestward into three individual faults: the western Charkayu-Pylema, the central Lebedin, and the eastern Shapkin-Yuryakha.

The Malozemelskaya-Kolguev monocline occurs between the Charkayu-Pylema and Shapkin-Yuryakha faults in the northwestern sector of the Bolshezemelsky massif. The surface of the basement, which plunges northward and northeastward (from 2-2.5 km to 5-10 km), is cut in the onshore part by two disjunctive structures striking northwestward. The structures represent small-amplitude horsts, one side of the elevated blocks of which appears to be submerged below the "shoulder" level. Dissected relief of the basement surface probably remains in the offshore part of the monocline.

The most significant structure of the Bolshezemelsky massif is the Pechora-Kolva block, which spans a considerable part of the volcanoplutonic belt of the internal part of the Baikalian basement. With reference to the basement surface, the Pechora-Kolva block can be shown to comprise the complicated Denisov trough in its central part, structural scarps in the Pechora deep-seated fault, and the Kolva megaswell along the fault of the same name. The scarps of the Pechora fault, which plunge gently in the direction of the Denisov trough, are represented by narrow fault zones with swells and basins, brachianticlines and synclines. In the geological past, prior to inversion movements and formation of the adjacent Permian-Triassic troughs, grabens originated along the scarps.

The most extended (about 400 km long) Lyzha-Kyrtael scarp is bounded by the Vydshor and Podcherem-Kamensk faults in the west and the Shapkin-Yuryakha and Pechorogorodsk-Perebor faults in the east and northeast. The Nyaltayus anticline is the most elevated area of the escarpment (up to 4 km). The basement surface plunges in a northwestward and southeastward direction. The major Pyata syncline (20x100 km), in which the basement occurs at 6 km depth, is situated in the northwestern part of the scarp. In the southeast, the basement plunges from 5.2 km in the crest of the Lyzha-Kyrtael structures to 10 km in the Ust-Shchugor syncline. The Mutnomaterikovaya scarp is located en-echelon further northwest and subsided up to 6.5 km. Narrow high-amplitude (up to 1.0 km) anticlinal folds are a characteristic feature of this scarp.

The Denisov trough includes the Shapkin-Yuryakha fault swell and the Lodmin-Komandishor disjunctive swell. The trough extends along the fault of the same name and consists of synclines separated by narrow pinches. The crest of the swell is complicated by a graben, which consists of transverse depressions and bridges oriented NE-SW and separated by faults. Its eastern slope is cut off by the Kolva megablock. The Nos uplift bounds the Shapkin-Yuryakha swell to the north. The depth of the basement in the crest of the uplift is 4 km, ranging from 5 km in the swell structures to 7.0 km in synclines of the trough.

The Kolva megaswell extends along the Kolva fault for more than 300 km and consists of the Usa, Kharyaga, Yareiyu-Khylchuyu disjunctive structures, with a basement depth of 7.5-4.0 km and the Vozeya and North Kharyaga bridges elevated for 1-5 km. Besides the faults of northwestern strike, which determine the general configuration of the megaswell, there are faults of other orientations. The structure of the megaswell becomes more complicated where it crosses the E-W trending Nos uplift. In addition to a general depression, a peculiar "wedge" with an actively dislocated basement surface occurs here. Another "tectonic wedge" with a local rise of the basement adjoins the eastern shoulder of the graben. In offshore part, the Pechora-Kolva trough attains a more uniform structure and opens in the form of a trough toward the Kurentsovo scarp north of the Nos uplift [1].

The Bolshezemelsky arch of the basement gently dips in an eastward and northeastward direction. It comprises several major structural elements.

The Bolshezemelsky arch represents the most elevated surface of the basement. It is 100 km wide and 230 km long, the amplitude is 1.0 km, and the depth of the basement at its crest is 4 km. The arch is asymmetrical because the western slope is cut off by the Kolva megaswell. The gentle eastern and northeastern slopes are complicated by structural promontories and embayments oriented northeastward and southward. The crest and adjacent slopes are cut by small-amplitude faults, which form a close network of northwestern and northeastern strikes. Local uplifts of the basement are recognized on the arch crest and in its structural promontories.

The Sadayaga uplift is situated north of the Bolshezemelsky arch and is separated from it by a shallow saddle. The majority of the uplift lies offshore in the Pechora Sea. Like the Bolshezemelsky arch, the uplift trends close to E-W, and the depth of the basement at its crest is about 5.0 km. The Gulyaev saddle separating the Chernorechensky depression from the northern part of the Varandei-Adzva swell is located between the Sadayaga uplift and the Pomor scarp, the major northernmost structure of the block. The southwestern base of the Pomor scarp adjoins a seaward extension of the Kolva deep-seated fault. The basement of this part of the scarp, which has an isoclinal form, occurs at a depth of 5-5.5 km. With the subsidence, the strike of the scarp hinge changes to the northwestern or "Timan" direction. When approaching the Kurentsovo scarp, the Pomor scarp outline disappears at a depth of 7-9 km.

The Upper Adzva basin has the form of an asymmetric fault trough striking northwestward. Its gentle southwestern slope has a open, disjunctive fold (the Sorokin swell), structural uplifts, embayments and scarps. These structures are widely developed at the edge of the trough bounded by faults of the Chernyshev uplift. Near the Vashutkin-Talotin fault, on which a basement slice is elevated representing the northeastern slope of the trough, its axial zone extends to a depth of 7-9 km. The basement surface is represented here by disjunctive synclines and anticlines.

The basement in the Pai-Khoi and Urals foredeeps is also separated into a series of blocks, each corresponding to depressions of present-day boundaries. The basement of the Karatikha basin in the Pai-Khoi foredeep represents a monocline trending in a northwestward direction and plunging under the Paleozoic-Mesozoic structure. The southwestern part of the monocline is elevated in the system of faults: the Vashutkin-Talotin fault and that of the Chernyshov uplift. The faults separate the monocline from the Upper Adzva basin and the Kosyu-Rogov trough located south of it. The basement occurs at a depth of 10 km. Among structures of the monocline ,only the Pursamyl uplift is distinguished.

The Kosyu-Rogov trough represents a structural element of the Urals foredeep. It extends northeastwards unlike the Korotaikha basin, being wedge-shaped (110 x 330 km) and opening to the north where it is bounded by transverse structures: the Padimei scarp, Yarvozh uplift, and Yunjagin anticline. The part of the basin with deepest basement (up to 11 km), which has an isometric form, is overthrust by sheets of the Lemvan allochthon of the Polar Urals. The western slope of the Kosyu-Rogov trough is separated from the Khorei-Ver and Varandei-Adzva blocks by faults of the Chernyshov uplift, and submerged relative to them by 1-2 km. This slope is cut by a series of faults near the Chernyshov uplift, the faults having a northwestward strike similar to that of the Upper Adzva block.

The structural and formational characteristics of the basement of the Bolshaya Synya trough indicates its affiliation with the Pechora-Kolva block. At the present-day, the basement surface in the trough occurs forms a deeper (up to 11 km) southeastern extension of the Shapkin-Yuryakha swell and gentle dislocations of the Kolva megaswell, i.e. belongs to the Denisov trough. The Bolshaya Synya trough is situated between the southern branch of faults of the Chernyshov uplift, the Urals fold-thrust structures, and the faults of the Lyzha-Kyrtael scarp. The trough measures 50 by 290 km. The southeastern part of the trough is cut off by an upthrust. This part is slightly elevated representing a symmetrical syncline striking in the same direction as the Urals.

The extension of the Lyzha-Kyrtael structure buried under the sedimentary cover of the Urals foredeep separates the Bolshaya Synya and Upper Pechora troughs.

The Upper Pechora trough is situated in the south of the western Urals region. It measures 60 by 400 km, and has a N-S strike. Its gentle western slope is separated from the Izhma-Pechora block (microplate) by the Ilych-Chiksha fault system. The NE trending faults feathering this system complicate the structure of the western slope. The eastern slope is more steep, complicated by upthrusts which form elongated scarps bulging up one after another to a watershed area in the Polar Urals. The depth of the basement in the axial part of the Upper Pechora trough is 9 km. Its southern edge is complicated by faults of the Urals-Timan junction and attenuated Ilych-Chiksha fault system.

The present-day structure of the sedimentary cover of the Timan-Pechora plate resulted from a stage-by-stage tectonic evolution, which is synchronous with the evolution of the Urals geosyncline for which three main cycles are distinguished: (1) the Caledonian cycle, which was unfinished, and restricted to the initial stage only; (2) the Hercynian cycle, which was completed; (3) the Mesozoic-(Cimmerian)-Cenozoic cycle, which is still in progress. The successive change of tectonic regimes is marked in the sedimentary cover by structural levels and sublevels, separated by angular and nondepositional unconformities.

Deposits of the Caledonian cycle composing only one structural level are represented by a basal terrigenous lower-middle Ordovician formation replaced by upper Ordovician, Silurian and lower Devonian carbonates. Lower Devonian terrigenous deposits are developed only in the northwest of the region. Formations of the Hercynian cycle form a more complete succession, the structural levels of which allow three stages of geotectonic evolution to be distinguished.

The lower level comprises mainly middle Devonian-lower Frasnian terrigenous deposits and middle Frasnian-Tournaisian terrigenous-carbonate deposits with reefs. The middle level starts with lower-middle Visean carboniferous-terrigenous deposits, but the majority, up to and including the Upper Carboniferous, is composed of carbonate deposits. The upper level is diverse. In the Urals part of the region, it is made up of orogenic formations represented by flysch, green molasse, rock salt and potasium-magnesium salts, coal-bearing sequences, red-beds and continental molasse. On the r est of the plate, the flyschoid and green molasse gives way laterally to carbonates, rock salt to anhydrites, and coal-bearing sequences to red beds. Middle Jurassic-Cretaceous and Neogene-Quaternary structural levels are made up of terrigenous rocks of the Mesozoic-Cenozoic cycle.

On the basis of the general character of dislocations and formational features within the structural levels of the Caledonian-Hercynian tectogenesis, as well as with due regard to the internal structure of the basement and the present-day morphology of its surface, the Timan-Pechora plate can be subdivided into major tectonic elements as follows: the Timan Ridge, Izhma-Pechora basin, Malozemelskaya-Kolguev monocline, Pechora-Kolva aulacogen, Khorei-Ver basin, Varandei-Adzva block, Urals and Pai-Khoi foredeeps (Fig. 5). Deposits of the Mesozoic-Cenozoic cycle occur above a stratigraphic hiatus and angular unconformity, and rest on different structural and formational units of the Hercynides. They form two upper structural levels of the platform sedimentary cover which belong to the Pechora superimposed syneclise.

3.2. Urals Foredeep

The Urals foredeep includes (from south to north) the Upper Pechora, Bolshaya Synya, and Kosyu-Rogov basins separated respectively by the Middle Pechora transverse uplift and southern structures of the Chernyshev uplift. The main part of the Bolshaya Synya basin appears to be superimposed onto structures of the Pechora-Kolva aulacogen: the southeastern pericline of the Kolva megaswell and the Denisov trough; this explains its northwestern "Timan" strike. In general, the structural and formational character of basins is characterized by an active, widening progressively northwards, deflection of morphologically variable pre-orogenic areas of pericratonic subsidence of the Timan-Pechora epi-Baikalian plate, with accumulation of Permian and Triassic molasse formations 6-7 km thick, and subsequent compressive deformations during the final Late Triassic-Early Jurassic orogenic stage of the Hercynian tectogenesis.

Compressive deformations had the least effect on the folding of external zones (western slopes) of the Kosyu-Rogov and Upper Pechora basins, whose morphology is close to the platform-type and dislocations often belong to structural elements extending to adjacent areas of the platform. Central zones of basins are characterized by anticlines, both separated and combined into systems of dislocations, often complicated by upthrusts and overthrusts. Overthrusts sometimes complicate only molasse sequences and do not affect the pre-orogenic (carbonate) base of the trough. Fold-nappe and fold-imbricate structures along with tectonic slabs belong to eastern (internal) zones of basins. Fold-nappe dislocations are characterized by folds which are thrust over each other successively. Fold-imbricate structures representing allochthonous slabs broken into separate slices which are in turn made up of anticlinal folds formed along overthrusts, are developed near transverse uplifts: southern structures of the Chernyshev ridge, and Middle Pechora uplift, are examples. The lateral displacement of these structures of the eastern zone measures 10-25 km. Tectonic slabs represent a third variety of deformations in the eastern zones. They consist of extended narrow anticlines, developed along the frontal overthrust, and conjugated deep and wide synclines (the Vuktyl slab of the Upper Pechora basin, the Uldor-Kyrta and other slabs of the southern part of the Bolshaya Synya basin). With depth, overthrusts become more gentle in an eastward direction. In all dislocations studied, the displacement planes are confined to Ordovician halogenic rocks, Silurian-Lower Devonian, Middle-Upper Devonian, Tournaisian, lower-middle Visean carbonate clayey sequences.

The Korotaikha basin belongs to a foredeep in the area where the Urals and Novaya Zemlya-Pai Khoi fold systems meet. The Korotaikha basin is separated from the Kosyu-Rogov basin by the Vorkuta transverse uplift, with horst-like structures on the edges (the Upper Rogov structure and Chernov ridge). Tectonic slabs are traced in the Korotaikha slab up to and including its western slope. However, the carbonate base of the western and central zones of the basin is dislocated by gentle folds, and tectonic slabs (except the Vashutkina-Talotin slab) are composed here of Permian and Triassic orogenic formations. Carboniferous, Devonian and possibly Silurian carbonate pre-orogenic formations only make up slabs of the Pai-Khoi-Urals area. Basalt sheets are found at the base of the Triassic formation.

The suture fault-fold structural system of the Chernyshov ridge is distinguished as an independent element of the Urals foredeep. It formed in pre-Middle Jurassic time above the linear faults bounding the external (western) slope of the Kosyu-Rogov basin. Blocks of the ridge, which are composed of pre-orogenic carbonate formations, are brought along overthrusts in the direction of the Kosyu-Rogov basins to a greater extend, and towards the Khorei-Ver basins to a lesser extent. Disjunctive synclines are infilled between blocks by Triassic rocks with thin basaltic sheets at the base.

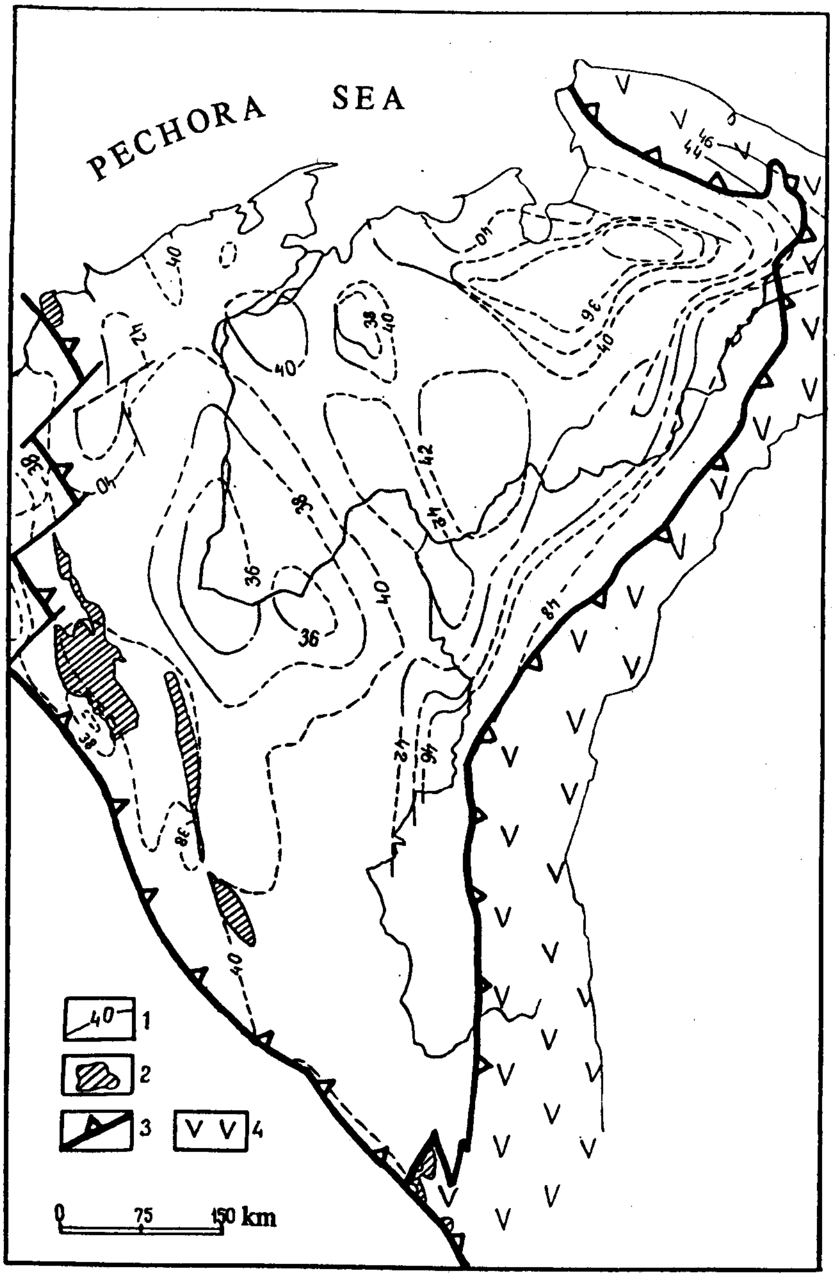

Fig. 6. Relief of the Moho boundary within the Timan-Pechora plate [40]
1 - contours, km; 2 - basement exposures on the surface; 3 - plate boundaries; 4 - Urals and Pai Khoi foldbelts

3.3. Geophysical Structure of the Crust

Tectonic transformations of the crust are reflected in the structure and distribution of physical discontinuities along the M-boundary. Using the hypsometry of the boundary between the crust and mantle, the Timan-Pechora plate is reliably subdivided into several individual areas (Fig. 6): the Timan (38-42 km), Izhma-Pechora (36-39 km), Denisov--Khorei-Ver (40-44 km), Moreju-Korotaikha (34-38 km), and Urals--Pai-Khoi (42-48 km). A spatial relationship between these areas and major morphostructural elements of the basement is apparent that indicates their genetic dependence and affiliation to specific blocks of the crust. Unlike morphological features, the distribution of velocity parameters along the M-boundary does not follow the structural divisibility of the overlying part of the lithosphere. Both low-velocity (7.9 km/s) and high-velocity (8.4 km/s) assemblages are developed below the Timan crustal block. Below the Izhma-Pechora block, a gradual increase in subcrustal velocities occurs in a southward direction from 8.2 km/s through the area with 8.3 km/s to 8.4 km/s. In the Denisov--Khorei-Ver region, the velocity of 8.2-8.3 km/s is registered, being 8.4 km/s at some areas (along the profile Chernaya River-Khorei-Ver River-Usa River).

There is a definite relationship between low-velocity parameters (8.0 km/s) and the structural divisibility of the crust. Low velocities are characteristic of the northwestward trending strip below the contact zone of the Izhma-Pechora and Denisov-Khorei-Ver block and in the northeastern peripheral area of the plate corresponding to the Urals-Pai-Khoi trough. Areas of deep subsidence of the basement surface and high-velocity areas in its upper part coincide spatially with these regions. Active tectonic processes are quite conspicuous in the whole crust.

The principal features of the deep structure and tectonic zonation of the crust in the Timan-Pechora basin are reflected in its divisibility into blocks and in the character of interaction of crustal blocks [101; 40]. The Timan, Izhma-Pechora, Denisov--Khorei-Ver, Maloju, Karataikha, Kosyu-Rogov, and Upper Pechora blocks are distinguished (Fig. 7).

The blocks differ in topography, physical properties of the basement, mantle depth, thickness of the consolidated part of the crust, and its velocity parameters (Fig. 6, 7).

The Sadayaga uplift, in which the basement rises up to 6.2-6.5 km with a local depression in the axial part, occurs in the north-central area of the Maloju block. According to magnetometric modelling results along the deep seismic sounding profile, a magnetoactive body extending up to the base of the crust is confined to this uplift. The body is taken to be of mantle nature, the result of penetration of magnetic magmatic basic rock masses. The lower

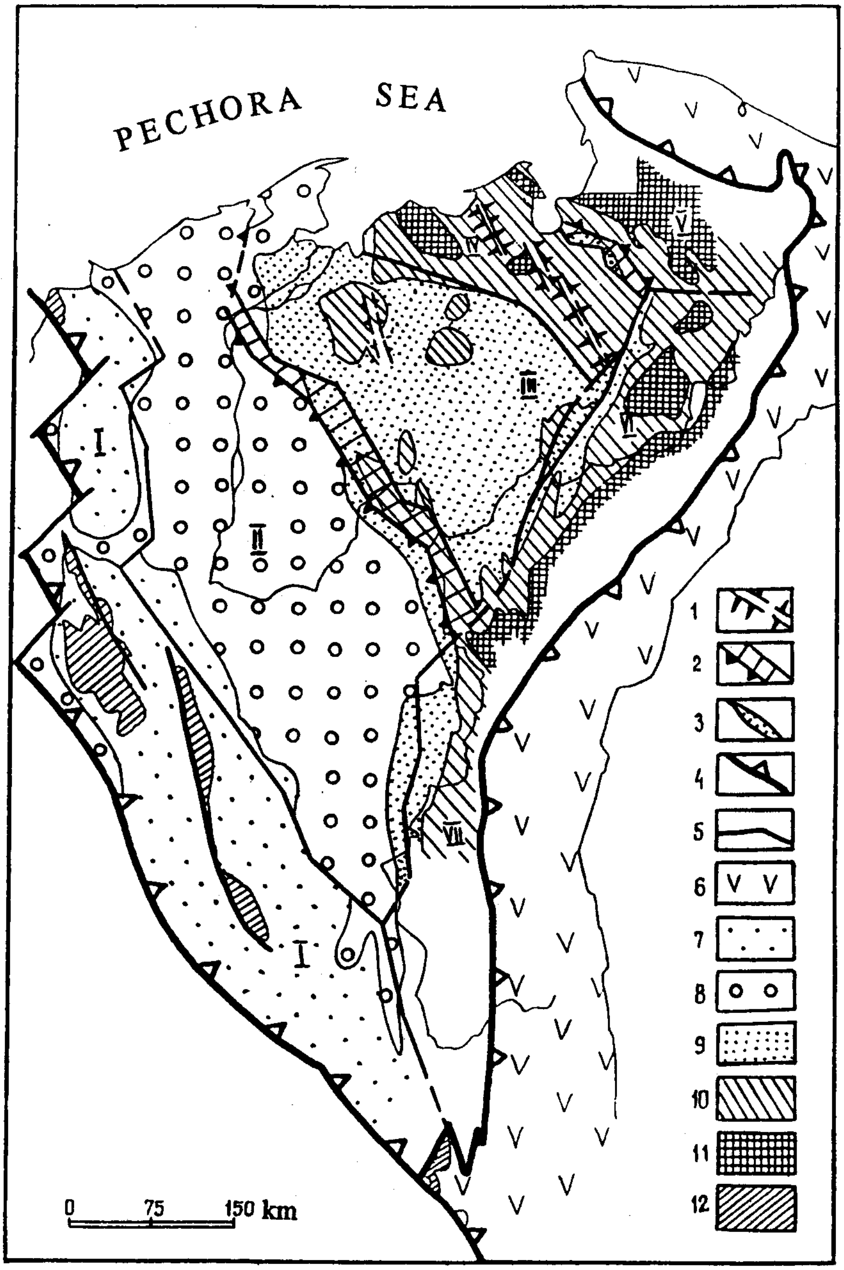

Fig. 7. Zonation of the Timan-Pechora plate basement [40]

1 - paleospreading axes; 2 - paleosubduction (collision) zones; 3 - zone of echelon structures of Chernyshov Ridge (transform zone); 4 - Main Uralian and West Timan marginal sutures (thrusts); 5 - faults; 6 - Urals foldbelt; 7-12 - consolidated crust areas with different depth of its top (km): 7 - >2; 8 - 2-4; 9 - 4-6; 10 - 6-8; 11 - <8; 12 - basement exposures on the surface. I-VII - crustal blocks (microplates): I - Timan, II - *Izhma*-Pechora, III - Denisov--Khorei-Ver, IV - Maloyu, V - Korotaikha, VI - Kosyu-Rȯgov, VII - Upper Pechora

parts of the crust below the Sadayaga uplift are affected by high-velocity igneous rocks causing the increase in seismic velocities up to 7.4 km/s versus 6.6-6.8 km/s in surrounding areas. The magnetic field above the magmatic chamber and adjacent territory is of linear character similar to magnetic lineations in the oceans. Based on the material presented, the Maloju block can be interpreted to be a relict of the axial zone of spreading with a structure like a rift valley contained within it [40].

4. Hercynian Urals Foldbelt

4.1. General Structural Pattern

The northern part of the Urals foldbelt is represented on the map, and is conventionally subdivided into the Northern, Sub-Polar, and Polar Urals. Structures of the foldbelt extend for more than 1500 km along the eastern edge of the Russian and Timan-Pechora plates. The N-S trend of the Urals structures changes in its northern part to a NE-SW trend.

A clear transverse zonation is characteristic of the Urals, and manifests itself in the linear distribution of sedimentary, volcanogenic, and intrusive-magmatic complexes, comprising three, elongate, approximately N-S zones (Fig. 8). The Western (West Uralian) zone comprises carbonate sequences of epicontinental and shelf basin origin occurring on the continental basement of the platform margin. The Axial (Ural-Taus) zone is made up of uplifts of continental basement. The Eastern zone comprises volcanogenic arc complexes which are replaced in the Polar Urals by major ophiolitic allochthons.

The sedimentary cover of the younger West Siberian platform overlies part of the Eastern zone, especially its East-Tagil strip. A zone of elongated basins containing a thick sedimentary cover succession of the Russian and Timan-Pechora plates, extends along the western edge of the Urals foldbelt, forming the Urals foredeep. In the northern part of the Polar Urals, the NNE-SSW trending structures are cut by structures of the Early Cimmerian Pai Khoi-Novaya Zemlya fold system along the fault-thrust zone of the Main West Uralian fault.

The Western, Axial and Eastern structural zones are bounded by major tectonic thrusts (Fig. 8). The most important, the Main Uralian thrust, represents a suture of the Uralian paleoocean. Elongated bodies of serpentinitic melange and large ophiolitic sheets are confined to the overthrust. The conventional division of the Urals into mio- and eugeosynclinal zones is placed along this fault.

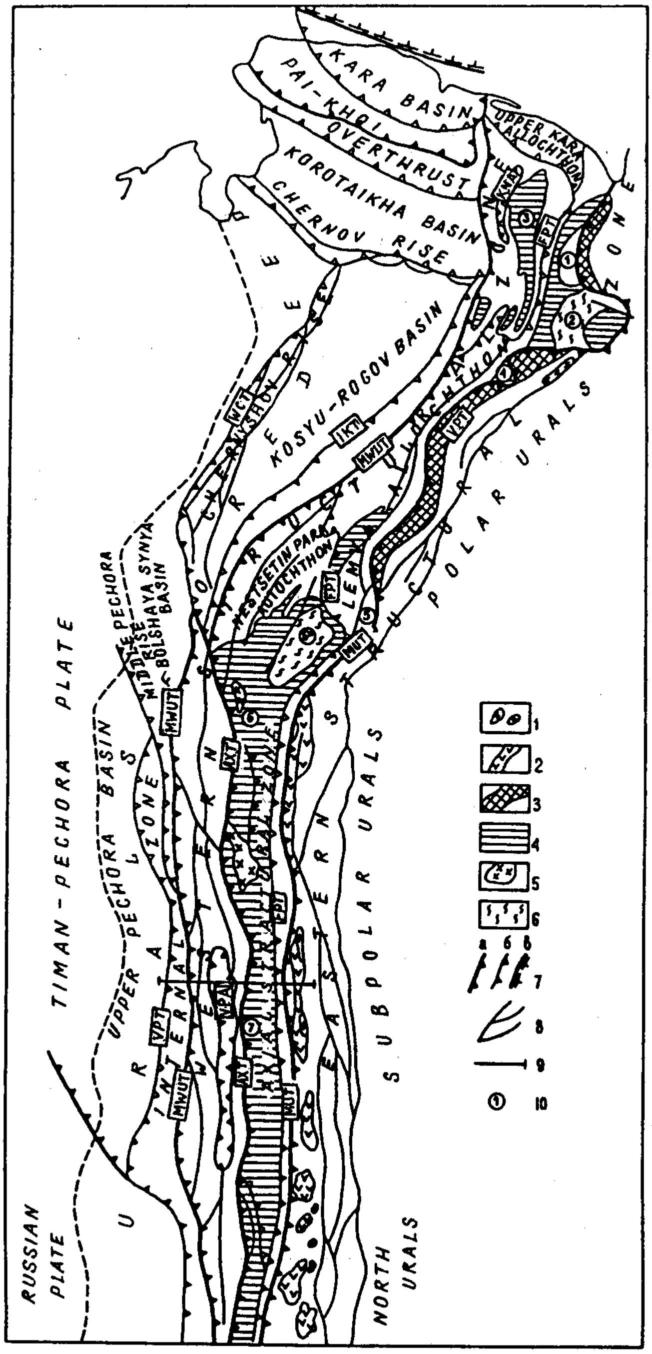

Fig. 8. Tectonic structures of the North and Polar Urals [86]

Thrusts: MUT - Main Uralian; MWUT - Main West Uralian; AXT - Axial; FRT - Frontal; VPT - Vuktyl-Polyudov; WCT - West Chernyshov; IKT - Inta-Khanovei.

1 - Paleozoic granites; 2 - Alaskan-Uralian-type massifs; 3 - ophiolites; 4 - Riphean-Vendian rocks; 5 - Riphean granitoids; 6 - uplifts of Lower-Middle Proterozoic rocks; 7 - thrusts: (a) - principal, (b) - others, (c) - aquatic; 8 - other faults; 9 - A-A' profile; 10 - numerals on the map mark uplifts of the pre-Ordovician basement: 1 - Marunkeu, 2 - Kharbei, 3 - Ochenyrd, 4 - Kharamatalou, 5 - Nerkayu, 6 - Kozhim, 6a - Khobei, 7 - Vogul. Slaty allochthons: UPA - Upper Pechora allochthon, KNA - Kara-Nyarma allochthon, VOA - Voikar ophiolite allochthon

Along the eastern edge of the Western structural zone, the internal (Eletsk) zone of flyschoid rocks can be traced. Along the eastern edge of the Axial zone, the very narrow Salatim zone composed of bathyal shales stretches throughout the entire Urals foldbelt.

Inhomogenity along as well as across the Ural foldbelt is characteristic. The most distinctive feature is the different structure of the Eastern structural zone in the Subpolar and Polar Urals regions: only arc complexes are developed in the North and Subpolar Urals, whereas ophiolite allochthons dominate in the Polar Urals sector. Structural zonation along the foldbelt is less pronounced. It is determined by alternating uplifts and depressions, which trend NW-SE in the Subpolar Urals and approximately E-W in the Polar Urals. Major, slightly folded doubly-plunging structures exposed by erosion, are typical of uplifts. Depressions are characterized by complexly dislocated, rootless, intensely folded flyschoid and shaly allochthons (Upper Kara, Kara-Nyarma, Lemva, Malopechorsky, and others).

The structure of the Urals foldbelt represents in general a collisional fold system of monovergent folds and envelopes of tectonic sheets thrust westwards, in which structural units from different geodynamic settings of passive and continental margins, marginal seas and island arcs are juxtaposed and accreted in tectonic zones.

4.2. Precambrian Metamorphic Complexes

Basement rock complexes are overlain by sedimentary sequences of the Western zone, and are autochthonous with respect to overthrusts and ophiolitic allochthons of the Polar Urals. The basement is widely exposed in a narrow horst-like structure of the Axial zone emplaced along the high-amplitude Axial overthrust.

Extensive outcrops of basement rocks are observed in uplifts and tectonic windows located in the northern part of the Polar Urals. Basement rock complexes are represented by dislocated and metamorphosed Lower, Middle, Upper Riphean and Vendian deposits. Lower Proterozoic and Riphean rocks are exposed in major uplifts: the Khobei cupola of the Nikolaishor Formation gneisses in the Kozhim uplift, the Kharbei gneiss uplift in the Khanmei tectonic window of the Polar Urals, and a nappe of intensely metamorphosed rocks and eclogites of the Marun-Keu Ridge, which are as old as 1.8-1.65 Ma west of Sum-Keu [71].

In the Axial structural zone, Lower Proterozoic sequences are overlain by dislocated Upper Riphean, Vendian and Lower Cambrian deposits metamorphosed to amphibole-greenschist facies. Isoclinal folds are widely exposed in transverse uplifts. A major fan-shaped anticlinorium is formed in the area of wide distribution of Precambrian rocks (in the Kozhim transverse uplift); the vertical bedding of metamorphic rocks dominates in the axial part, which changes to overturned northeast-dipping bedding in the west, and overturned northwest-dipping bedding in the east.

A narrow (12-30 km) strip of Riphean-Vendian rocks of the Axial zone is sharply displaced upwards along the Axial overthrust. The amplitude exceeds 2-3 km with respect to the present-day depth of the basement occurrence of the Western zone and the basement surface cut by the Axial overthrust. Such a horst structure bounded by faults probably appeared during rifting, which evolved along the edge of the Timan-Pechora plate in Vendian-Cambrian time (650-530 Ma ago) [49; 2; 85].

Upper Riphean and Vendian sequences are metamorphosed to amphibolite-greenschist and greenschist facies, which were then overprinted by the dynamothermal metamorphism of Middle Paleozoic collisional processes. The formation of small Kozhim-type granite massifs (320, 270, 240 Ma) is related to this stage [72].

4.3. Bathyal Paleozoic Complexes

Bathyal complexes are developed in major transverse depressions of the Western structural zone. In the Polar Urals, deep-water metamorphosed sediments form the rootless thrust structure of the Lemva allochthon. The structure is made up of numerous tectonic sheets and slivers thrust northwestwards and composed mainly of condensed sequences of carbonate-siliceous, siliceous-clayey and siltstone shales. Some slivers comprise packets of formations in the following age ranges: Ca_3-O_3, S-D, S-C, C-D. In the north, sequences ranging in age from Ordovician to Silurian are represented in the Kara-Nyarma allochthon.

The Upper Pechora shale allochthon composed of folded Ordovician-to-Devonian units is situated in the southern part of the Western zone, in the basins of Unya and Malaya Pechora Rivers.

The very narrow (from 2-5 to 12 km) zone of the Salatim allochthon located between the Frontal and Main Uralian overthrusts extends for more than 1000 km along the front of the overthrust of the Eastern structural zone (Fig. 9). The zone is made up of complexly dislocated, folded, uniform, middle-upper Ordovician clayey-siliceous, coaly shales, siltstones and pelitic tuffites [53]. Aphyric basalts and basic volcanics are similar to oceanic tholeiites. The Salatim belt of tectonized dunite-harzburgite with gabbro and eclogite-like rocks is distinguished within the zone [11]. Thus, individual metamorphosed fragments of ophiolites, probably of ocean margin-type, occur in the Salatim allochthon.

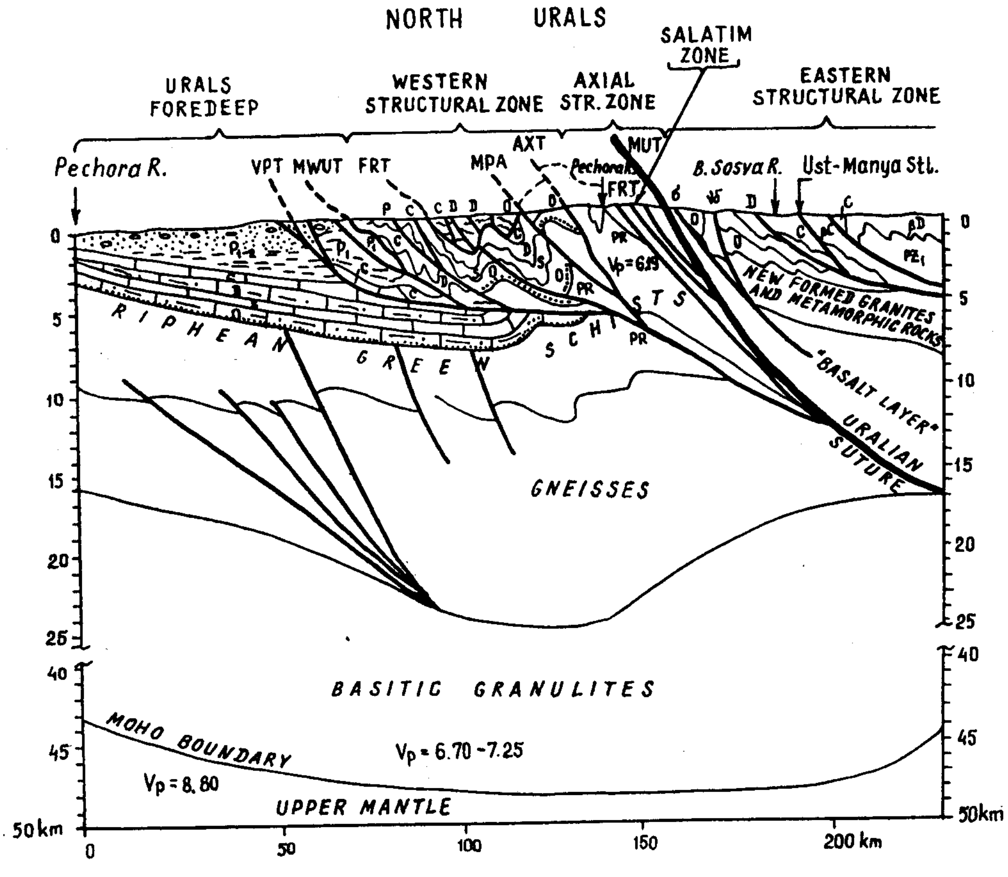

Fig. 9. Geological-geophysical section of North Urals and adjacent areas [83; 84]
MUT - Main Uralian thrust (suture); AXT - Axial thrust; FRT - Frontal thrust; MWUT - Main West Uralian thrust; VPT - Vuktyl-Polyudov (Main pri-Uralian) thrust; MPA - Malopechersky allochthon

4.4. Island Arc and Oceanic Complexes of the Eastern Structural Zone

The Eastern, or Tagil, structural zone comprises two major lithodynamic units: the arc complexes of the Tagil allochthon situated in the North and Subpolar Urals, and the marginal-sea ophiolite complex of the Voikar allochthon located in the Polar Urals. Oceanic-type ophiolites are not found in the Urals. Thus, the rocks of the Eastern zone reflect the dynamics of the tectonic development of the marginal-sea and island-arc evolutionary stages of the Urals paleoocean. The Tagil allochthon consists of two zones corresponding to two island arcs: the West Tagil and East Tagil zones, of which the Western and Eastern overthrust sheets were formed.

The West Tagil overthrust, known as the North Sosva-Shchekur sheet of the Tagil allochthon, extends along the North and Subpolar Urals for more than 500 km, with a width of 10-40 km and a thickness of 7-9 km (according to seismic data).

Volcano-sedimentary units (O_3-C_1) are represented by spilitized tholeiitic basalts, plagioporphyry, keratophyres, andesite-basalts and andesites of the calc-alkaline series in the O_3-C_1 time interval , and by tuffaceous volcanomictic clastic sediments and reef-related limestones in the S_2-D_2 time interval. The deposits are folded into narrow linear, N-S trending folds and slivers of different order, dipping westwards, and which are bounded by overthrusts, upthrusts and faults.

A chain of massifs of the dunite-clynopyroxenite-gabbro formation (platinum-bearing formation) extends directly along the Main Uralian overthrust among the lower and middle Silurian volcanics. The massifs are characterized by a roughly zonal concentric structure and by the presence of specific pipe-like dunite bodies. These rocks are known elsewhere as massifs of the Alaska-Urals type. The West Tagil island arc was formed in the latest Llandoverian-earliest Wenlockian. Despite the magmatic character of rocks composing the platinum-bearing massifs, the contacts with enclosing rocks are as a rule tectonic, and the enclosing rocks are metamorphosed and tectonized [24]. Greenstone metamorphic transformation of volcanics, plagiogranite and later granite magmatism allow us to interpret the complex of the West-Tagil zone as a mature island arc. Complexes of the East Tagil overthrust are buried under the cover of the West Siberian plate.

The Shchuchya overthrust is situated in the northernmost part of the Polar Urals ending the zone of Paleozoic arc formations. The Shchuchya synform, 80 by 100 km in size, is of isometric form. The nappe is generally 4-6 km thick, in places being up to 8 km [84]. It is

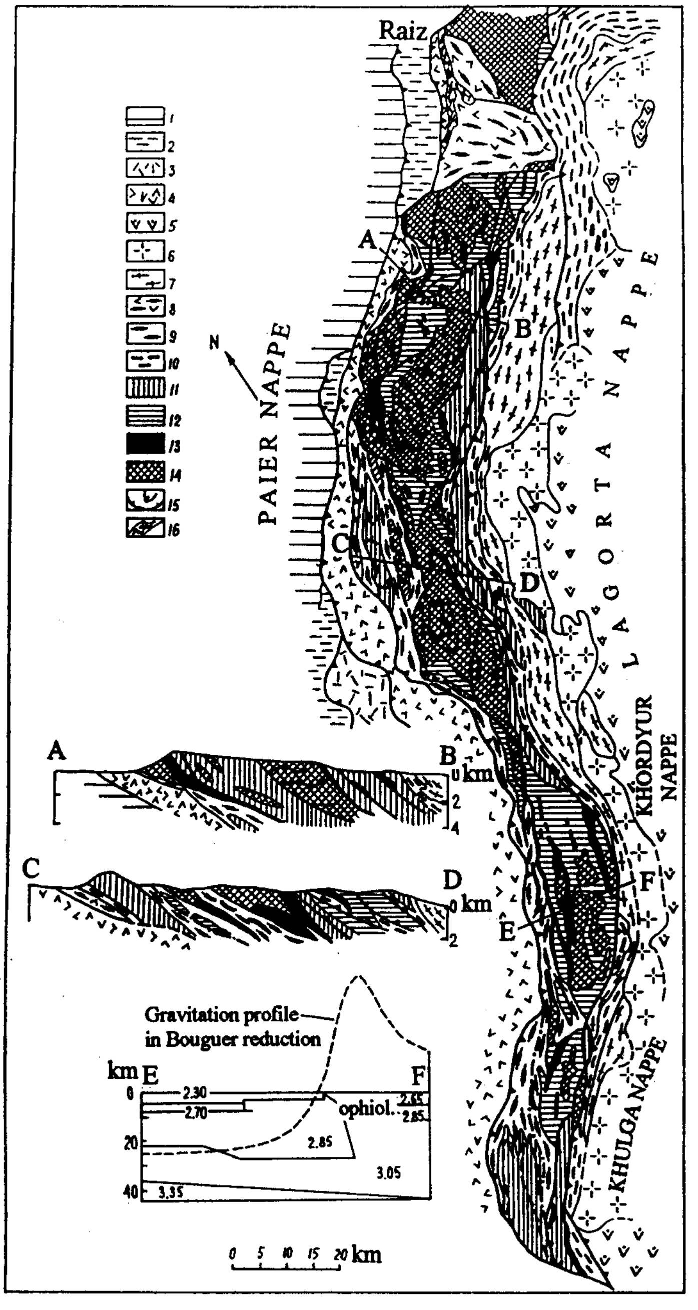

Fig. 10. The structural map of the Voikar ophiolite allochthon, Polar Urals [52; 54]

Ordovician-Devonian deposits: 1 - carbonate formations of a platform shelf overlain by Carboniferous-Permian graywackes and flysch; 2 - cherty-shale formations of a marginal sea; 3 - tuffaceous-terrigenous formations of an island arc outer zone; 4 - volcanoterrigenous formations of an island arc central zone (the Tagil-type section). Silurian-Devonian deposits: 5 - volcanogenic formations of an island arc inner zone (the East Tagil-type section); 6 - diorites. Ophiolites and related metamorphic rocks: 7 - tonalites, 8 - tuffaceous-terrigenous sequences of the epidote-amphibolite facies; 9 - garnet and garnet-zoesite amphibolites, glaucophane shists; 10 - plagioclase amphibolites; 11 - gabbro-diabases, gabbro-norites, and garnet granulites; 12 - wehrlites, clinopyroxenites, and olivine-antigorite rocks; 13 - dunites; 14 - harzburgites; 15 - striation of harzburgites; 16 - serpentinitic melange

Section D-E represents the geophysical profile across the Khordyur nappe. Numerals indicate the rock density thrust onto the Riphean-Vendian continental basement and adjoins the rear part of the ophiolite allochthon sheet of the Syumkeu massif. Tectonic structures of the overthrust are represented by slivers separated by high-amplitude thrusts. Asymmetric folds of different order, which strike in a northeasterly and easterly direction, are developed in slivers.

4.5. Ophiolites of the Eastern Structural Zone

Ophiolite association rocks are widely developed within the Polar Urals sector of the Eastern structural zone. This makes the structure of this part of the zone radically different from that of the Tagil allochthon situated south of it. A belt of ophiolitic allochthons extends along the Main Uralian overthrust for more than 450 km, and consists of three ophiolite massifs (from south to north): the Voikar-Synya, Rai-Iz, and Syumkeu.

The Voikar allochthon comprises the Voikar-Synya massif, one of the largest ophiolite complexes in the world. The allochthon, 250 km long and from 5 to 25 km wide, is comparable to the similar ophiolite complex of Oman. It is bounded by the Main Urals fault on the northwest. A packet of ophiolite sheets is thrust over the Salatim complex, whereas in the northern part of the allochthon they are emplaced onto the structures of the Lemva allochthon and the Proterozoic continental basement. Three major ophiolite nappes are distinguished in the Voikar-Synya peridotite massif of the Voikar allochthon (Fig. 10) [52; 54]. The lower, Khulga, nappe lying in the southwestern part of the allochthon is made up mainly of garnet and zoisite amphibolites and schists. The Khordyur and Paier nappes located in the middle and northern parts of the massif are composed of dunites, lherzolites, metamorphosed hartzburgites, gabbro and diabases.

The Rai-Iz massif, situated along strike from the Paier nappe, and northeast of it, represents a gently dipping, deformed, ultrabasic slab at the northeastern edge of the nappe, from which it is separated by a salient of continental basement forming the Kharmatolou uplift. The upper Lagorta nappe is thrust over the ophiolite nappes on the southeast and is composed of amphibolites, tonalites, granodiorites and the Voikar-type (East Tagil type) arc volcanics [52].

The Khulga nappe is thrust onto the structures of the Salatim allochthon, and the rocks it contains have been subjected to gradual stages of deep, high-temperature plastic deformations and crushing of massive gabbro-norites and rocks of the sheeted dyke complexes in the granulite and amphibolite facies. According to geophysical data, the total thickness of the nappe is 3-4 km.

The Khordyur and Paier nappes have a similar structure and composition. The nappes are mainly made up of lenticular bodies (20-60 x 10-18 km) of tectonized and massive harzburgites, lherzolites, dunites and metamorphosed harzburgites [52]. According to geophysical data, the thickness of the nappes varies from 0.5 to 6.0 km. Ultrabasic sheets are overlain in the southeast by rocks of the sheeted complex with MORB-type gabbros. Gabbroids are tectonized over vast areas and transformed into actinolite-tremolite-anorthite rocks and blastomylonites. Plagiogranitization was intense. The metamorphic rock complex is cut by sheeted dyke clusters. Using the Sm-Nd ratio, the massif rocks (gabbro, harzburgites, diabases) are dated at 373±61 Ma, and were formed during the interval 434-312 Ma.

Along the northwestern edge of the structure, a zone (up to 12 km wide) of intensely metamorphosed rocks of the Tagil type dunite-clinopyroxene-gabbro series occurs at the base of the nappes, which are transformed into en echelon lenses and zones of tectonites, blastomylonites, plagioclase-garnet amphibolites and eclogite-like rocks. The series represents fragments of the West Tagil zone. Rock units of the West Tagil zone were dismembered, folded, and tectonized during the course of thrusting of large, hot mass of the Voikar allochthon. With the subsequent overthrusting, the rocks in effect became "welded" to the nappe front, and moved onto sequences of the Salatim and Lemva complexes as a single body [53].

The Lagorta nappe, the uppermost in the Voikar allochthon, composes its southeastern part. A sequence of amphibolitic blastomylonites, tectonic blocks of ultrabasics, gabbro and diabases occurs at the nappe base and is folded into isoclinal flow folds overturned northeastwards. Tonalite massifs overlie the sequence. Tonalite veins penetrating the nappe rocks for hundreds of metres are developed where the tonalites are in contact with sequences of the Khordyur and Paier nappes. Thus, tonalites were the last to form in the ophiolite association. Tonalites are dated by the K-Ar method at 440-420 Ma, which allows the time of ophiolite formation to be constrained. The upper part of the nappe is composed of granodiorites overlain by arc volcanics of the Voikar (Shchuchya) type represented by andesite-basalts, tholeiitic basalts and tephroid sequences.

The Syumkeu ophiolite allochthon is situated on the northernmost edge of the Eastern structural zone. The nappe represents a recumbent fold, overturned eastwards , with a reduced upper limb. The harzburgite core occurs in the thinned eastern part. The front part of the thrust sheet, 0.5 km thick, is composed of folded serpentinite schists with relicts of olivine-antigorite rocks. Garnet and zoisite amphibolites and gabbro-amphibolites, similar to amphibolites at the base of the Voikar allochthon, are developed in the basal part of the nappe along its eastern edge. The sheet is thrust over metamorphic complexes of the Proterozoic basement. In the east, it is bounded by a sheet of the Shchuchya metavolcanics. It should be pointed out that the presence of ultrabasic relicts and klippes (Maslo Mount, Yarkeu Mount, and others) suggests that the Voikar, Raiz and Syumkeu massifs were parts of a single huge ophiolite nappe, the northern part of which was emplaced far onto the edge of the continent, with the rocks being affected by the most intense tectonic processes. The intensity of tectonic processes at the thrust front can be judged not only from the scale of detachments but also from the fact that the Murunkey deep-seated slab, composed of gneisses, amphibolites and eclogites, was detached from the Uraltaus basement zone and moved.

Geophysical study of the Voikar allochthon suggests that thick and extended ultrabasic sheets (in contrast to rootless ophiolite allochthons) have their roots deep in the upper mantle (Fig. 10). Sheets containing roots of the Voikar-Synya massif can be traced down to a depth of 15-25 km, where they connect with a layer which has the geophysical characteristics of the upper mantle [54]. A similar situation is established for the Ivrea zone in the Alps [103]. As the ophiolite nappe was moved along the Main Uralian overthrust, it is just along this overthrust in the mantle the oceanic complexes together with underlying differentially depleted ultrabasics were detached.

4.6. Carbonate Sequences of the Western Structural Zone

The Western structural zone is situated along the eastern edge of the platform autochthon. The tectonic sheets of which it is composed are thrust over sedimentary units of the Urals foredeep. In the west, the zone is bounded by the Main West Uralian overthrust. In the east, the occurrence of carbonate units is limited by the Axial thrust in the Subpolar Urals {and} the Frontal overthrust in the Polar Urals, which separates the Lemva bathyal rocks from carbonate flysch sequences. Sandstones, gravelstones and siltstones are developed in the lower part of the Ordovician, and are replaced by an Upper Ordovician-Silurian limestone-dolomite sequence. The upper sequence (Middle Devonian-Upper Carboniferous) begins with the Elets-type terrigenous deposits passing into Upper Devonian-Middle Carboniferous and Carboniferous-Permian argillaceous limestones and a continuous carbonate flysch sequence. Carbonate flysch deposits dated to the Ordovician-Devonian and Lower Carboniferous-Permian are developed in the Subpolar Urals. Sedimentary units are cut by thrusts and upthrusts into series of tectonic slivers, envelopes of which are thrust to the west. The total thickness of the folded sedimentary cover of the Western zone in this part of the Urals reaches more than 4-5 km in some areas (on the basis of the basement surface contours).

The structure of the Urals foredeep was discussed above, in Section 3.2, where the eastern edge of the Timan-Pechora plate was described. We concentrate on its main features. A continuous chain of elongated basins, which were formed as a result of considerable downwarping of the continental basement and exceed twice or thrice the average depth of the basement occurrence on the plate, extends along the edge of the Pechora and Russian plates. The basins are separated by uplifts of an upthrust nature. The western boundary of the Urals foredeep is conventionally placed along the strip of carbonate molasse. In the east, the structure is bounded by the Main West Uralian thrust. In the Outer zone of the foredeep, the sedimentary cover of the platform, from the Ordovician to Upper Permian and Triassic sequences, plunges under thrust structures of the Inner zone of the foredeep and the Western zone of the Urals. A narrow Inner zone lies along the eastern edge of the foredeep. In the Subpolar Urals, it extends from the Middle Pechora uplift to the southern edge of the map. Gently folded units of Carboniferous and Lower Permian carbonate molasse are thrust along the Vuktyl-Polyudov thrust (VPT, see Fig. 8) onto gently dipping sequences of the Urals foredeep. In the Polar Urals, tectonic sheets are made up of Permian flysch, with subordinate Carboniferous deposits at the base. The sheets were faulted along the Inta-Khanovei thrust.

Three major basins are distinguished in the foredeep: the Kosyu-Rogov basin is separated by the Chernyshov Rise in the north; to the south, the Bolshaya Synya and Upper Pechora basins are separated by the Pechora-Kozhva megaswell. In the south, at the Polyudov uplift, the foredeep structures are affected by a major thrust of the Timan Ridge. In the north, a layer-by-layer N-S detachment structure can be identified in the Kosyu-Rogov basin. The basin cover (like that of the Korotaikha basin) has been displaced, representing a tectonic sheet shifted layer-by-layer along incompetent Upper Ordovician salt sequences [81; 87]. A complicated rootless system of tectonic slivers developed as a result of thrusting.

4.7. Principal Evolutionary Stages

The Subpolar and Polar Urals region represents a fold-and-thrust collisional system that developed as a result of continuous Cambrian to Permian-Triassic evolution and interaction of the Paleozoic Urals ocean structures and the passive continental margin of the Timan-Pechora and Russian plates. During the accretion and westerly directed overthrusting, the oceanic, marginal-sea and island-arc complexes, as well as shelf seas and carbonate molasse assemblages of the passive margin were transported, accreted and transformed into a system of nappes successively transported west to form the Eastern, Axial and Western structural zones of the Urals.

Palinspastic reconstructions of the Urals paleocean were made mainly on the basis of information from the South and Central Urals [29; 27]. The reconstruction of the Subpolar Urals [84] was carried out for the D_2-T_1 time-interval and ignores earlier periods. An intriguing reconstruction of the Silurian island arcs of the North Urals has been carried out by Yazeva and Bochkarev (1995). The model of the Polar Urals evolution suggested by Saveliev and Samygin (1979) mainly concerns the formation of the Voikar allochthon, taking no account of the role of the Salatim basin and a back arc}.

The history of the region can be reliably restored from the Cambrian-Early Ordovician, when the formation of the continental margin has been completed, and volcanic arcs have been built up in the eastern part of the ocean in the Silurian. Marginal-sea structures in the Subpolar and Polar Urals were formed by different processes, which resulted in the radically different geological structure of the Eastern zone in these two regions. In the Polar Urals, the Voikar uplift originated in the Ordovician, from which a huge tectonic sheet of ultrabasics of the ophiolite allochthon had been formed by the Silurian. West of the uplift, the West Tagil volcanic arc arose in the Ordovician, the northern part of which pinched out in this region. A decrease in the extent of the West Tagil island arc complex predetermined the possibility of its transformation and consumption by the front of the advancing Voikar allochthon (Fig. 11). The Voikar uplift was absent in the North and Subpolar Urals, and a spreading zone marked by the intrusion of small ultrabasic bodies lies along the extension of this structure. Units of the West Tagil island arc are represented by volcanics and intrusions (Fig. 11-II). On the passive margin, the Salatim marginal sea of the Polar Urals was separated from the ocean by the Kharbei-Nerkayu uplift (continental basement) since the Early Ordovician. In the Subpolar Urals, the Salatim basin was not separated from the ocean by the basement uplifts, but the continental basement of the basin was destroyed owing to stretching in a zone of

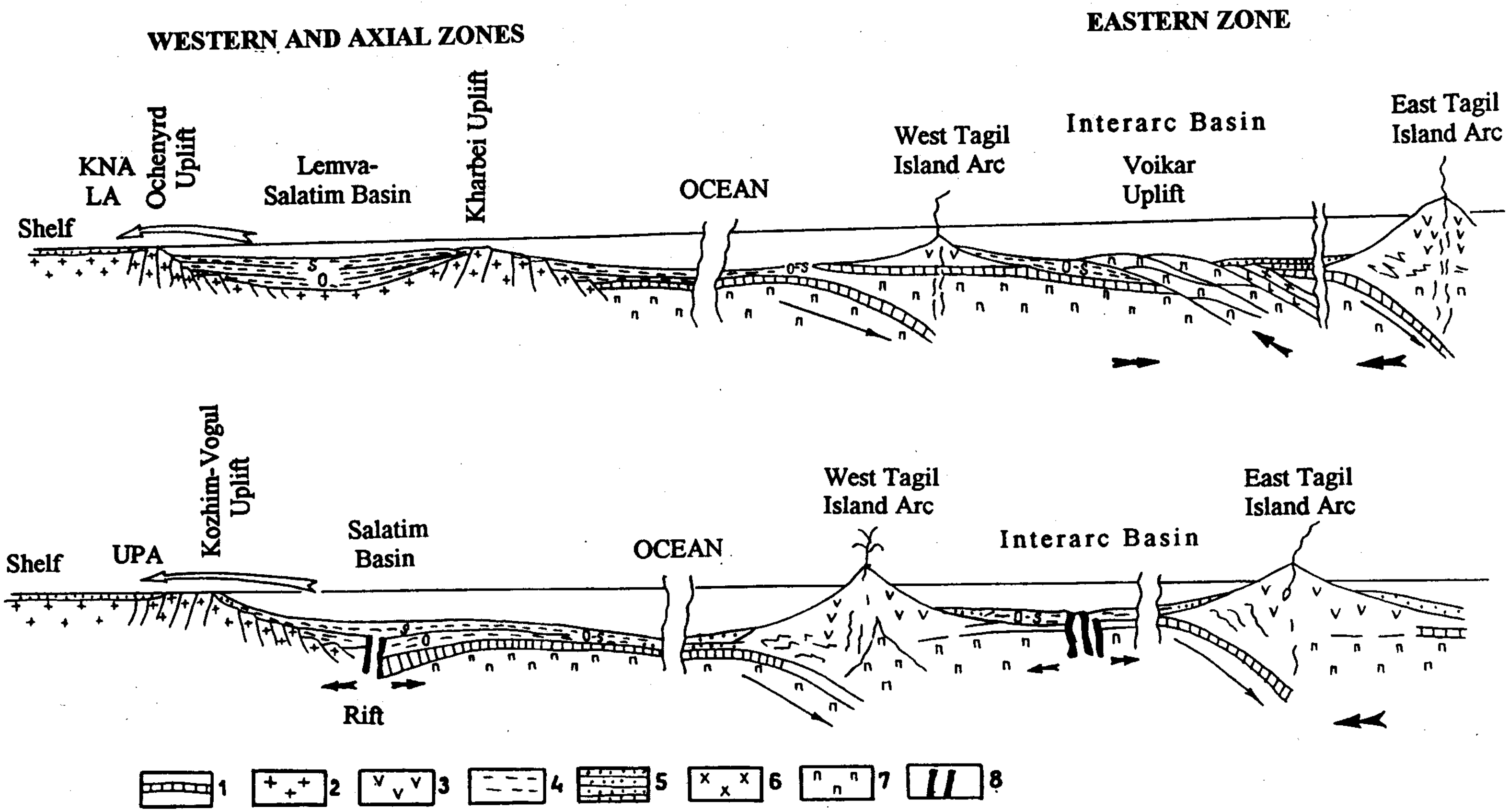

Fig. 11. Palinspastic reconstruction of the Urals ocean and continental margin for the Late Silurian (430-420 Ma)

I - Polar Urals; II - North and Polar Urals. Arrows show the direction of accretion of shale allochthons: Kara-Nyarma (KNA), Lemva (LA), Upper Pechora (UPA). Symbols: 1 - oceanic crust, 2 - continental crust, 3 - island arc complexes, 4 - bathyal sediments, 5 - shelf sediments, 6 - tonalites, 7 - mantle peridotites, 8 - peridotites of rifts and spreading zones diffuse spreading. The Salatim basin was deep enough for condensed siliceous bathyal deposits to accumulate (Fig. 11, I-II), from which shale allochthons developed in the Carboniferous.

Radical changes in the geodynamic setting occurred in the oceanic sector. In the Early Silurian, the Voikar volcanic uplift was transformed into a tectonic ophiolite sheet, in which a laminated complex developed in its eastern part and tonalites penetrated about 440-420 Ma ago. The northern part of the West Tagil island arc formed west of the Voikar uplift, whereas to the east, volcanics of the East Tagil island arc were generated. Between the arcs, an interarc basin evolved, in which the Voikar ophiolite sheet developed. Southwards, in the Subpolar Urals, thick and extended island arcs (West Tagil and East Tagil) appeared. A spreading zone with embedded peridotites were formed in the interarc basin. Differentiation and crystallization of basaltic magmas began in the West Tagil zone in the Silurian; massifs of the Alaska-Urals type were formed in intermediate magma chambers.

Shelf and bathyal sediments accumulated on the continental margin. In the southern Salatim sea, a spreading zone developed, which was absent in the Lemva zone of the Polar Urals. During the course of increasing compression, tectonic blocks moved laterally further west, the movement being irregular.

The size of the ocean and backarc basins decreased during Silurian-Middle Devonian time. In the Middle Devonian, the Voikar allochthon overlapped the complexes of the West Tagil zone which completed its volcanic activity. The complexes were then metamorphosed and attached to amphibolites of the allochthon base. An island arc developed behind this allochthon. The West Tagil and East Tagil island arcs joined in the Subpolar Urals during Eifelian time. In the Polar Urals, the Voiar allochthon joined the East Tagil island arc in the Late Devonian. In the Middle-Late Devonian, the motion of the envelope of ophiolite allochthons and island arcs resulted in the formation of the Salatim dislocation zone. The thrusting of sheets over the continental margin and exposure of their frontal parts to erosion took place from the end of the Visean to the Late Carboniferous. In the Middle Carboniferous, thrusting in a westward direction resulted in the formation of shale allochthons (Kara-Nyarma, Lemva, Upper Pechora).

The final stage of the tectonic evolution of the Urals fold-and-thrust system occurred in the Late Carboniferous-Early Permian. The platform edge submerged due to thrusting of huge masses over the continent margin. The process of carbonate accumulation and formation of flyschoid and molasse units occurred during the Permian. The motion of rigid tectonic sheets in a westwasd direction resulted in delamination of the cover of the Kosyu-Rogov basin and in the formation of the rootless structure of the Chernyshov Rise.

The formation of the Urals foredeep was completed in the Late Permian, and since that time the Urals system has represented a consolidated platform.

5. Early Cimmerian Pai-Khoi - Novaya Zemlya Foldbelt

This complicated foldbelt is situated between sedimentary basins that occupy the Barents and Kara shelves. The structural pattern of the Early Cimmerian system is determined by an arch-like configuration of complex folded and disjunctive structures bounding the Kara Sea basin. as well as by the fact that sedimentary units affected by the Early Cimmerian tectogenesis were formed on different basement belonging to two major plates of different age. Two major uplifts are distinguished in the southern and northern parts of the Novaya Zemlya Archipelago: the Southern Novaya Zemlya and Northern Novaya Zemlya antiforms, which are separated by the Karmakul trough. The Pakhtus and Litken antiforms represent smaller-scale structures (Fig. 12).

Late Riphean-Vendian rocks, whose folds were formed by the late Baikalian tectogenesis, lie at the base of the southern part. The northern part comprises a single late Riphean-Early Mesozoic succession probably resting directly on the Early Proterozoic (?)- Early Riphean crystalline basement of the Svalbard plate. Successions also have a different structural style in southern and northern parts of Novaya Zemlya.

Data on the tectonics and geology of Novaya Zemlya are derived from studies conducted by E.A.Korago, G.N.Kovaleva, V.F.Il'ina and others [66; 37].

5.1. Basement Complexes

Exposures of Riphean and Vendian folded basement units are present locally on Novaya Zemlya. Lower Proterozoic-Lower Riphean rocks are represented on the Northern Island of Novaya Zemlya, where they compose the basement exposures of the eastern edge of the Svalbard plate.

The Upper Riphean-Vendian-Cambrian metamorphic complex is best represented on Pai-Khoi, on Vaigach Island, in the southern part of the Southern Island of Novaya Zemlya, in the Kara Strait and on the Rusakov Peninsula. Late Baikalian flyschoid shales and siltstones on the northwestern coast of Pai-Khoi and the Kara Strait are separated from the Early Cimmerian succession by a sharp discontinuity and disconformity. Upper Proterozoic rocks

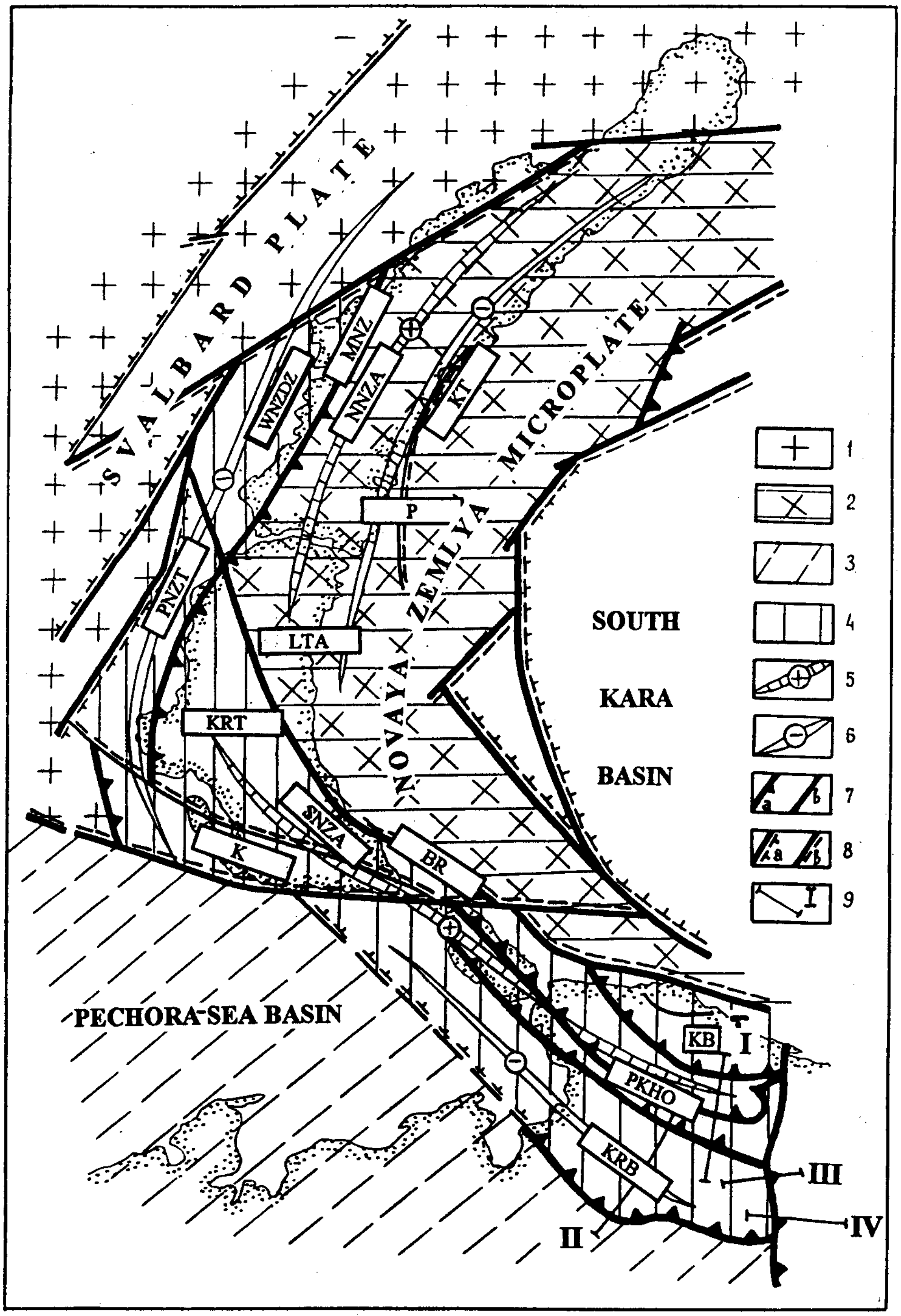

Fig. 12. Tectonic scheme of the Pai-Khoi - Novaya Zemlya region [67]

1 - Svalbard plate; 2 - same, affected by the Early Cimmerian tectogenesis; 3 - Timan-Pechora plate; 4 - Early Cimmerian Pai-Khoi - Novaya Zemlya foldbelt; 5, 6 - axes of major structures: 5 - positive, 6 - negative; 7, 8 - tectonic dislocations: 7 - on land (a - main thrusts, b - faults), 8 - in sea (a - thrusts, b - faults); 9 - section lines (see Figs. 13, 14)

Names of structures: NNZA - North Novaya Zemlya antiform, SNZA - South Novaya Zemlya antiform; PKHO - Pai-Khoi overthrust, KRT - Karmakul trough, WNZDZ - West Novaya Zemlya dislocation zone, PNZT - Pre-Novaya Zemlya trough, KT - Kara trough, LTA - Litken antiform, KRB - Korotaikha basin, KB - Kara basin; thrusts: MNZ - Main Novaya Zemlya, BR - Baidaratsky, P - Pakhtusovsky, K - Kalodkin underwent two-stages of folding, and are characterized by complicated dislocations created by the interference patterns of folds of approximately E-W trend (Late Baikalian tectogenesis) with those of NW-SE trend (coinciding with the orientation of the Paleozoic folding). Microfossils in metaterrigenous sediments characterize, according to L.I.Ilchenko, two distinct units - Late Riphean and Vendian.

Thin sills and dykes of diabase and lamprophyre are developed in the south of the Novaya Zemlya Archipelago. The K-Ar age of gabbro-diabases and Konga-diabases ranges from 392±28 to 445±22 Ma, which corresponds to the O_4-D_1 time interval. Similar metadiabases are penetrated by granitoids in which zircons yield U-Pb ages of 680±50 and 730±50 Ma in the Mityushikha Bay (southwest of Southern Island).

A large exposure of Precambrian deposits up to 100 km long, extending from the Russkaya Gavan Bay to Inostrantsev Bay, is observed on the northwestern coast of Northern Island. Sequences are represented by weakly metamorphosed (up to phyllites) sandy-clay deposits containing Late Riphean-Vendian microfossils, and are overlain by layers with remains of Cambrian trilobites. The boundary between the Proterozoic and Paleozoic is concordant and gradational. Upper Cambrian flyschoid and schist formations along with overlying Cambrian-Silurian graptolite-bearing sequences form a single structural unit containing Upper Proterozoic-Middle Ordovician flyschoid deep-water successions and Upper Ordovician-Silurian flyschoid-molassoid calcareous-clayey successions. This unit seems to have been deposited in a trough with steep slopes enhancing the gravitational turbidity flows.

Despite the apparent similarities, Upper Precambrian units in the southern and northern parts of Novaya Zemlya show structural differences that suggest they had different provenances. The most essential distinction is a sharp unconformity between the Ordovician and Proterozoic sequences in the south (the Cambrian being absent from the section), and their different composition; by contrast, uninterrupted Upper Proterozoic-Cambrian sections with similar composition occur in the north. The distinctions mentioned are fundamental because they allow two types of Precambrian basement to be distinguished within the Barents and Kara seas.

Two Proterozoic blocks of different age - the southern, Late Riphean-Vendian (Late Baikalian), and northern, Early Proterozoic-Early Riphean (Grenvillian) - can be distinguished in the archipelago. The Baidaratsky deep-seated fault separates them. The main distinctive feature of the blocks is that the southern block underwent folding and inversion between the Vendian and Ordovician, whereas the northern block is characterized by continuous development of an aulacogen from the Late Riphean to Early Paleozoic.

On the Tectonic Map, a strip of the Early Cimmerian folding extends in a northwestern direction through Pai-Khoi, Vaigach and the southern part of the archipelago, and overlaps the Baikalian structures of the Pechora plate. The middle and northern parts of Novaya Zemlya are underlain by the Middle Proterozoic Svalbard (Barents-Sea) plate, which was affected by the Cimmerian folding.

5.2. Early Cimmerian Structures

Deposits ranging in age from the Proterozoic to Early Triassic compose the Early Cimmerian fold system. In the southern part of the region, the tectogenesis involved Ordovician to Lower Triassic rock units, whereas in the northern part it involved Proterozoic to Upper Permian rocks. Three major uplifts are distinguished within the region located en-echelon and separated by transverse troughs: the Pai-Khoi, Vaigach-South-Novaya Zemlya, and North-Novaya Zemlya. Associated synclinorium zones lie east and west of the uplifts.

The Pai-Khoi uplift-overthrust is made up of envelopes of complexly dislocated folds striking northwestwards. It is composed of Ordovician-Permian sequences. The central part of the Pai-Khoi uplift (Fig. 13) comprises bathyal shale units of the Pai-Khoi shale allochthon similar to the Lemva formations of the Polar Urals. Condensed sections in tectonic slivers include sequences from the uppermost Cambrian and Ordovician to Devonian.

Along the Main Pai-Khoi thrust, the allochthons have been transported southwestwards over Permian-Carboniferous flysch and carbonate shelf sequences composing the pre-Pai-Khoi allochthonous structural zone. The Pai-Khoi uplift is bounded on the northeast and southwest by basins infilled with Permian and Triassic carbonate molasse. Carboniferous-Permian tectonic slabs of the Kara basin are thrust onto the Pai-Khoi allochthon on its northern side. In the southwest, the pre-Pai-Khoi structural zone is thrust onto the Carboniferous-Triassic molasse of the Korotaikha foredeep.

The emplacement of the Pai-Khoi nappe in a southwestward direction resulted in the detachment of the Silurian-Permian sedimentary cover of the Korotaikha basin (Fig. 13-II). As in the Kosyu-Rogov basin of the Urals, the detachment occurred along incompetent salt rocks at the Ordovician-Silurian boundary, and the Silurian-Lower Carboniferous sequences are exposed at the surface in the Chernov Rise.

The Early Cimmerian Pai-Khoi fold-thrust system is characterized by a northwest strike and consistent northeast dip of tectonic dislocations. Nappes and slivers of the Uralian structures in the extreme north strike to the north and dip to the east. The Uralian and Pai-

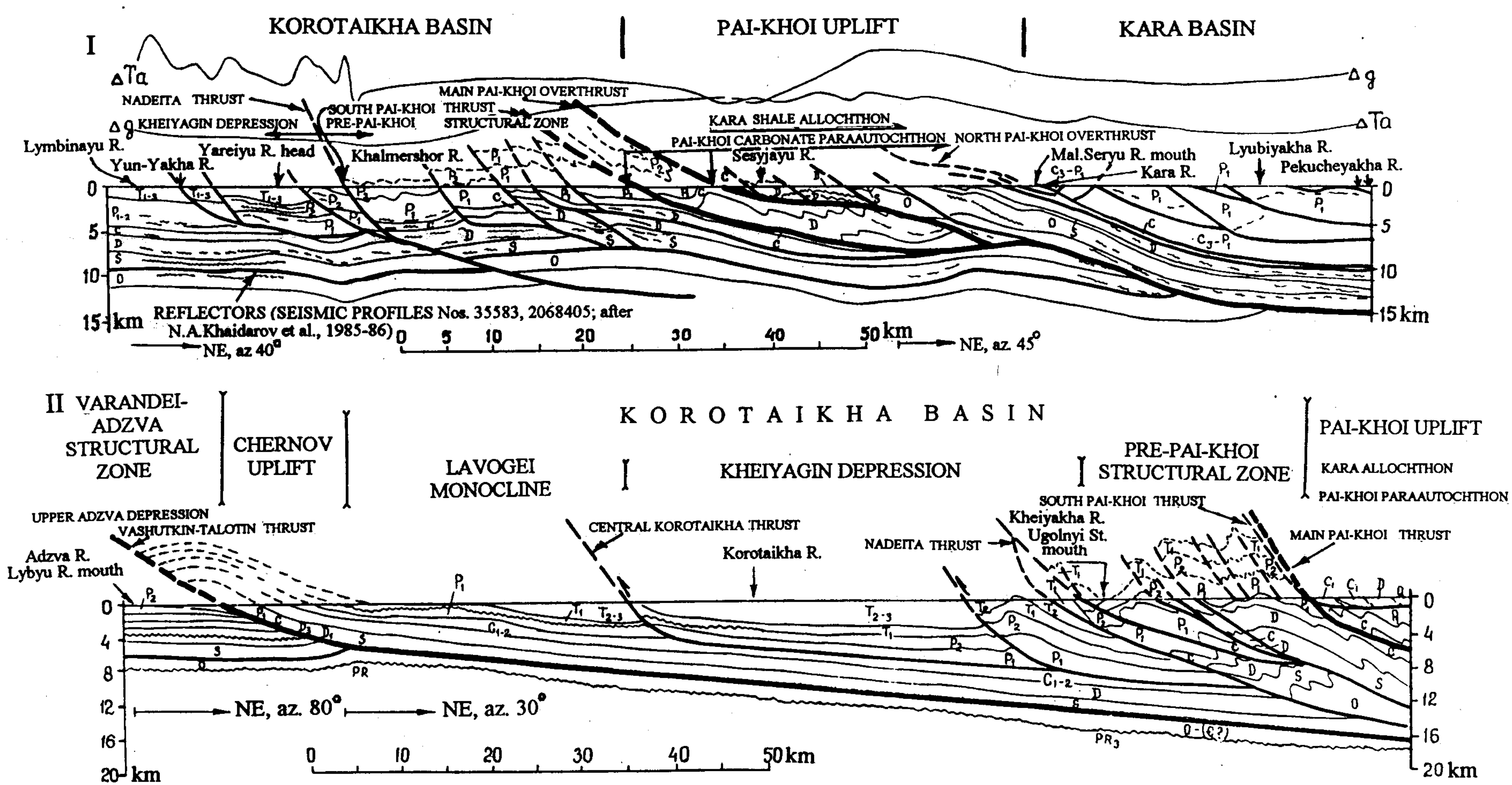

Fig. 13. Geological and geophysical sections across the Pai-Khoi uplift (Line I) and the Korotaikha basin (Line II), after V.V.Yudin (see Fig. 12 for section lines)

Khoi structures are contiguous along the Main West Uralian thrust, and further north along the South Pai-Khoi thrust. Uralian trends are cut along these structures. The displacer of the Main West Uralian thrust, which bounds the east side of the Korotaikha basin, dips eastwards (Fig. 14). During the Early Cimmerian tectogenesis, sequences of the Pai-Khoi and Korotaikha basin were detached and displaced to the south, the displacement proceeding along the Main West Uralian thrust.

The South Novaya Zemlya antiform extends for 300 km from Vaigach island to the southern and western parts of the Southern Island, where the rock units comprising the antiform gently dip into the transverse zone of the Karmakul trough. In the northeast, the uplift is cut by the deep-seated Baidaratsky fault (Fig. 12).

Two zones are distinguished in {the structure}: the northeastern (Kara) and southwestern (Barents) [38]. The first zone is represented mainly by carbonate-siliceous-clayey bathyal deposits ranging from the Middle Carboniferous to Middle Permian. The second zone is composed predominantly by shallow-water carbonate and flysch deposits. A peculiar feature of the structure is that faults have subvertical displacement planes, and thrust sheets are developed only in areas of disharmonic folding. Isoclinal folds are widespread, which probably compensated the lateral displacements indicated by thrusting along the Kara zone to the west.

The North Novaya Zemlya antiform occupies the northern part of the South Island and the North Island of Novaya Zemlya, extending for 500-600 km. The majority of the uplift is hidden under thick secular glaciers.

An abrupt {rise} (up to 40-50 degrees) of fold hinges takes place north of the Karmakul trough, and Proterozoic-Lower-Middle Paleozoic rocks are exposed at the surface. The inner structure of the antiform is inhomogeneous: zones of intense compression with isoclinal folding alternate with zones of more gentle upright folds. Wide suture zones (10-15 km) are formed along major faults and extend along the boundary between the North-Novaya Zemlya antiform and the Kara basin. In the middle part, the uplift is made up of fan-shaped tectonic blocks. In the west and northwest, the uplift is thrust onto units of the Barents Sea. The northern edge of the island is made up of folded Cambrian-Ordovician molasse deposits. The middle part of the Island is covered by a glacier.

The formation of the West Novaya Zemlya dislocation zone in the Barents Sea and the Kara basin is associated with the emplacement of the North Novaya Zemlya antiform to the west and northwest.

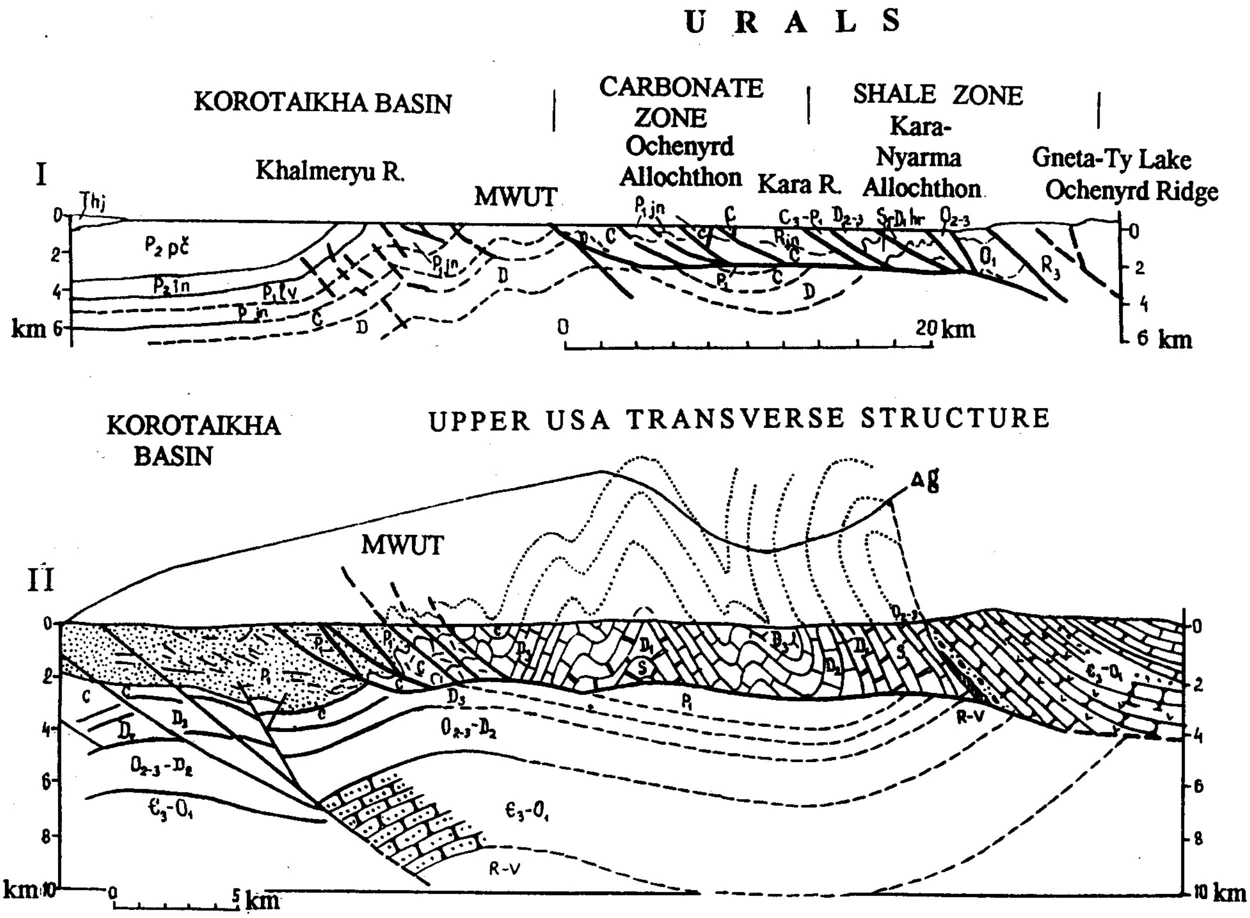

Fig. 14. Geological and geophysical sections of the collision zone of the Korotaikha basin and the Urals structures (see Fig. 12 for section lines), after L.N.Belyakov (1987)

5.3. Stages of Formation

Differences in the formation of the Precambrian complexes discussed above affected the evolution of the region in the Paleozoic. An uplifted peneplain existed in the south of the archipelago during the Cambrian. Cambrian units are absent here, being either eroded or undeposited; the Ordovician molasse is also absent or poorly developed. At this time, a trough, which was formed in the latest Riphean-Vendian and filled in with molassoid and rhythmic flyschoid formations until the end of the Silurian, continued to evolve in the north of the region.

In the Ordovician-Silurian, thick sequences of shallow-water carbonate and terrigenous-carbonate shelf deposits accumulated in the southern part of the region, which extended from the southern part of Novaya Zemlya through Vaigach Island into the Pre-Pai-Khoi structural zone. Carbonate shelf sedimentation in the southwest of Novaya Zemlya persisted to the Mid-Late Carboniferous (Fig. 15).

In the Middle Devonian, paleobasins separated into two zones with different depositional environments. A deep trough of the Kara structural zone was formed in the east and centre of the region, in which bathyal carbonate-siliceous-clayey sediments accumulated. An area of shallow-water carbonate sedimentation still remained in the southwest and west. The development of this depositional zonation was accompanied by Middle Devonian-early Frasnian magmatism, with petrochemical features typical of modern oceanic tholeiites synchronous with rifting processes in the Timan-Pechora region, Pai-Khoi and the Barents Sea area.

During the second half of the Carboniferous and during the Permian, thin littoral carbonate-terrigenous sequences formed in the north of Novaya Zemlya. Throughout the rest of the territory, sedimentation had acquired a deep-water character by the end of the Carboniferous. In the Late Permian, the deep-water trough was infilled with clastic material derived from the Urals orogen. The development of the trough was complete by the Mid-Triassic. At the Triassic-Jurassic boundary, the region underwent folding and piling up accompanied by intrusion of granitoids dated by the K-Ar method at 210-180 Ma [66].

Structures of the Pai-Khoi-Novaya Zemlya region are younger than in the Urals. The Early Cimmerian age attributed to the folding is based on the fact that all sequences from Upper Proterozoic to Lower Triassic have been dislocated. Upper Paleozoic sediments accumulated in the deep-water trough, where shale units are replaced upsection by thick sequences of flyschoid sediments. Triassic sediments are represented by variegated molassoid

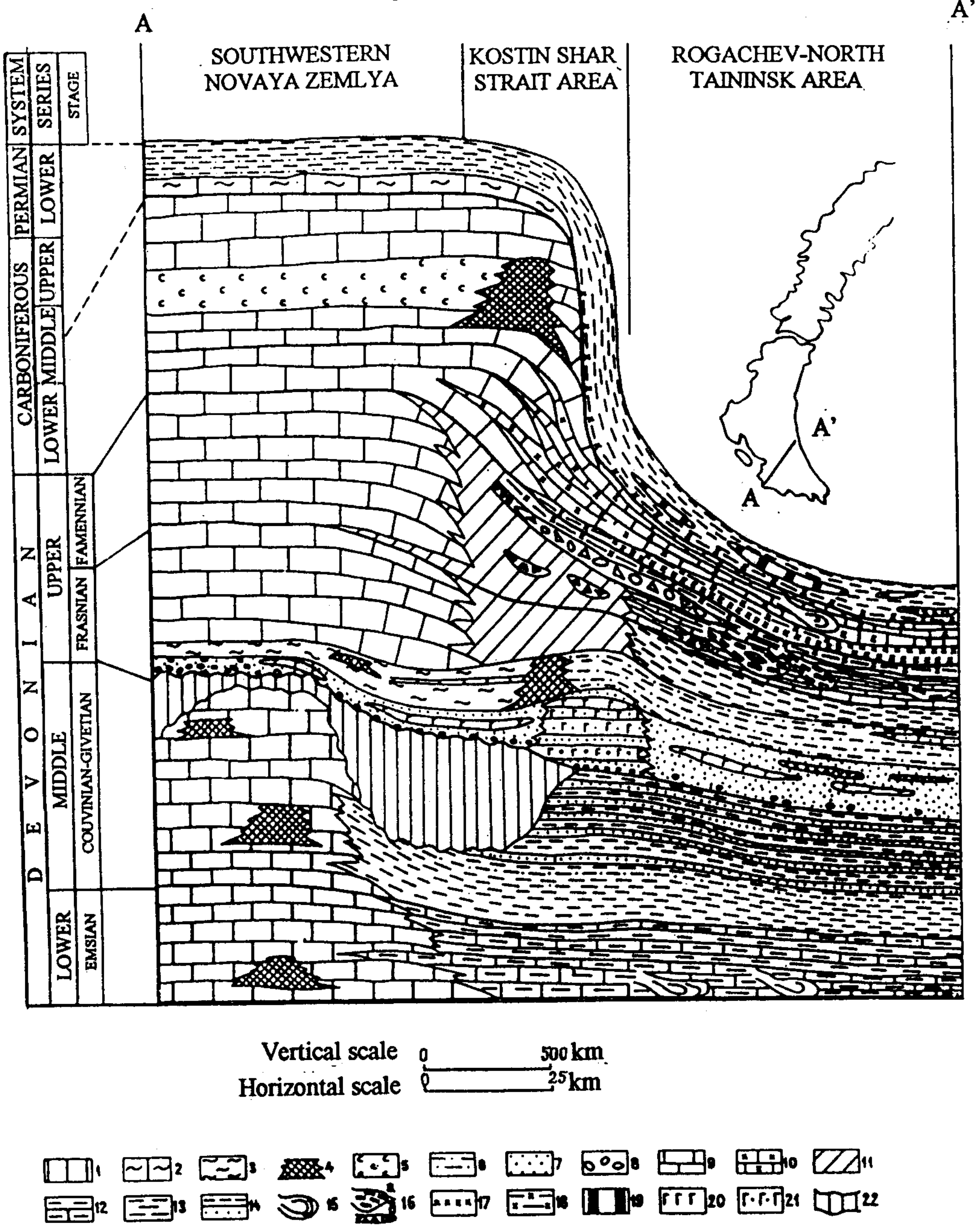

Fig. 15. Paleofacies and lithological profile of Paleozoic deposits of southern Novaya Zemlya, after N.N.Sobolev, Profile A-A' [66]

1 - complex of reef plateau facies; 2 - predominantly bioclastic, oozy and oozy-grainy limestones; 3 - calcareous mudstones with intecalations of brachiopod limestones; 4 - separate organogenic edifices; 5 - gypsum; 6 - siltstones; 7 - quartz sandstones; 8 - conglomerates; 9 - pelitomorphic limestones; 10 - siliceous limestones with radiolarians; 11 - mudstones and pelitomorphic limestones (goniatite facies); 12 - dacryoconarid limestones with intercalations of black mudstones; 13 - black mudstones; 14 - mudstones rhythmically alternating with quartz sandstones; 15 - landslides; 16 - debris flow deposits: a - carbonate stratified breccia, b - carbonate unsorted boulder-pebble conglobreccia in association with calcarenites; 17 - phthanites; 18 - siliceous radiolarian shales; 19 - carbonate and siliceous-carbonate manganese ores; volcanogenic complexes: 20 - basalts, 21 - basalt tuffs; 22 - amplitude of pre-Frasnian erosion

rocks that indicate shallow-water conditions and the infilling of the trough. Granites of Early Jurassic age are known from the North Island of Novaya Zemlya. Tectonic movements in Pai-Khoi and the Timan-Pechora region also took place at the Triassic-Jurassic boundary. As a result of the Early Cimmerian tectogenesis, the present day fold structure of Novaya Zemlya was established, which bounds the region of extension in the south of the Kara basin. Formation of the East Barents rift zone assisted in the underthrust of blocks of the Svalbard plate beneath the structures of Novaya Zemlya.

6. Impact Structures

The Kara depression, which has long been known in the northern part of Pai-Khoi in the Kara River valley, represents an impact structure 50 km in diameter [75]. The structure is dated to the Late Cretaceous. The Kara meteorite crater shows up as a depression with a sluggish relief (the amplitude is 40-60 m) within the Pai-Khoi foothills. The inner structure of the Kara crater has been established mainly on the basis of geophysical data. A gravitational horseshoe-shaped minimum is established above the northeastern part of the crater. The field is complicated in the centre by the positive maximum corresponding to the central uplift. The edges of the crater are marked by a zone of high gravitational field gradient, which is associated with the steep slopes of the crater cone. The steep slopes and horizontal bottom, with a gentle inclination to the centre at an angle of 5-10°, have been established using two intersecting seismic profiles. Radial ridges are observed on the bottom. The crater depth varies from 0.6-0.8 km in the southern part to 2.0-2.5 km in the northern part, which might be associated with a fault in the north.

The central uplift, 10-11 km in diameter, and slightly displaced to the southwest, represents in plan a polyhedron with re-entrant angles. In the centre of the crater, a borehole penetrated Precambrian rocks at a depth of 0.5 km, which occur outside the crater at a depth of 3-3.5 km. A dome with 1.8 km amplitude has been established in fissure rocks below the central uplift at a depth of 4 km, where seismic horizons are clearly traced. These rocks were uplifted from a depth of about 6 km. Assuming a gradual damping of the anticline downwards, its depth should be 8-9 km. Thus, with 50 km width, the depth of dislocations in the meteorite structure is equal to 1/5D.

Allogene breccias of different types (klippen, megabreccias, boulder and gravel breccias), suevites and tagamites are described among impact rocks. The position of impact rocks in the crater is not symmetrical. A sequence of allogene breccias, hundreds of metres thick, occurs in the southern elevated part of the crater. Suevites with irregular bodies of tagamites overlain by a thick sequence of allogene breccias with tagamites occur in the northern and northeastern parts of the crater bottom. The asymmetry in the crater rock occurrence seems to be related to the fact that the southern part of the crater was uplifted by a fault at the instant of meteorite impact.

In addition to the Kara impact structure, two more craters of the same type are distinguished within the Barents Sea: the Mjolnir and Loparian structures, both presumably of Jurassic-Cretaceous age [98]. The first is located in the west of the region whereas the second occurs in the southern part of the South Barents basin.

III. STRUCTURES OF THE BARENTS SEA FLOOR

The structure of the Barents Sea floor from 77°N to the south and from 30°E to the west is presented on the tectonic map. Spitsbergen, Franz Josef Land and the continental slope area between 77°N and 82°N are not included in the map. The map covers the western part of the Kara Sea and the Pechora Sea. The seafloor of the Arctic shelf has little relief. The deepest areas are about 350 m bsl (Fig. 16).

The Barents and Kara sea areas have been extensively covered by aeromagnetic and gravimetric surveys, as well as cut by seismoacoustic and seismic profiles of different resolution (Fig. 17). In addition, a series of deep trial boreholes have been drilled on the seafloor.

On the basis of special geological and geophysical investigations, the following structures were distinguished within the seafloor. The Svalbard plate occupies a vast area of the Barents Sea floor and Novaya Zemlya. It is cut in the central part by the approximately N-S trending East Barents trough. In the south, the plate is bounded by the Nordkapp and Varanger grabens, south of which the Kola microplate is situated. The southern edge of the East Barents trough separates the Kola microplate in the west from the Timan-Pechora plate of the same age in the east. The Pechora-Sea basin, the northernmost structure of the Timan-Pechora plate lies offshore. In the east, the Pai-Khoi foldbelt separates the Novaya Zemlya microplate, which was affected by Cimmerian tectonic movements, from the Svalbard plate. Further east on the Arctic shelf, the South Kara basin represents a trough with a suboceanic-type crust.

The structures of the seafloor are described from west to east.

7. The Structure of the Russian Plate Shelf

The structure of the offshore margin of the Kola Peninsula has been revealed in a series of common depth point (CDP) seismic profiles [45], in refraction correlation (RC) profiles [56; 57], and in some deep seismic sounding (DSS) records [1; 15] crossing the Kola shelf. According to these data, a surface with boundary velocities more than 6.0 km, which corresponds to the Archean-Lower Proterozoic (Karelian) basement, can be identified at a depth of 1.5-5.0 km. The surface is downthrown by the coastal fault zone by 0.5-2.0 km relative to the modern topographic surface of exposures of coeval rocks on the Kola Peninsula. Taking into account the prolonged denudation of the Baltic shield, the real

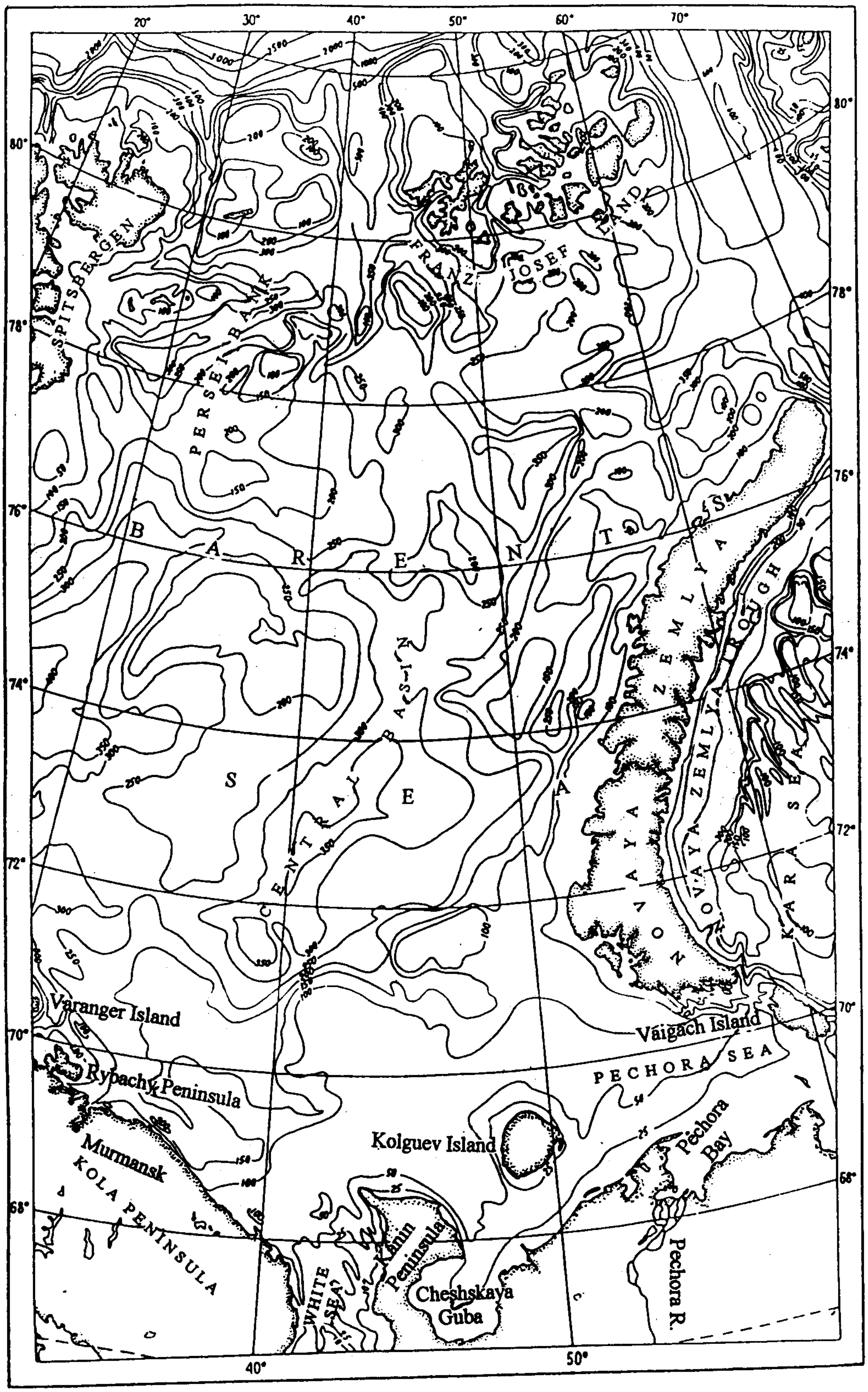

Fig. 16. Bathymetric map of the southern Barents Sea (after [89] and others)

displacement on faults separating the basement surface on land and offshore could be considerably greater.

In the sea, the basement surface is inclined in a southward direction towards the Kola Peninsula and plunges, as a series of steep narrow scarps separated into transverse blocks, to the north and northeast in the direction of the Norkapp and Varanger grabens of the South Barents basin. The basement surface is overlain by a dislocated sequence of Upper Proterozoic terrigenous deposits, which crop out on the seafloor, on Varanger and Rybachiy peninsulas, and on Kildin Island. The total thickness of the deposits may exceed 3-4 km. In the north and northwest, the Upper Proterozoic cover of the megablock is overlain almost perpendicular to the strike by nappes of the Scandinavian Caledonides.

Sedimentary sequences, younger than Proterozoic, represented by Devonian-Permian deposits, are developed as a narrow strip along the outer edge of the megablock and belong to the plate structure of the Barents-Pechora platform area.

The Shoina trough in which basement subsided to a depth of 3-5 km in the offshore extension, should probably be considered as an offshore extension of structures of the eastern zone of the Mezen syneclise (the Safonovo trough, Pesha basin). The trough is separated from the onshore part of the syneclise by a connecting strip situated between the Kanin and Kola peninsulas in which the pre-Baikalian basement occurs at a depth of 1-2 km.

The connecting strip is made up of contiguous uplifts: the Mezen massif and the Ludovatykh ridges. The sedimentary cover mapped here is represented mainly by Upper Proterozoic and Devonian-Carboniferous deposits. In the direction of the Shoina and Safonovo troughs, north and south of the connecting strip, the section increases at the expense of Permian and Lower Triassic deposits, and Jurassic deposits in more downwarped areas.

Judging from the age of deposits in the upper part of the section and the morphology of structural elements, the connecting strip was also affected by Late Hercynian and even Early Kimmerian geodynamic events, which resulted from the constriction of the northern part of the syneclise. The constriction is associated with the compressional environment between rigid blocks of the Baltic Shield and Timan-Pechora plate, which occurred probably during the late Permian-Triassic or later, due to displacement in a westward direction along approximately E-W trending coastal faults of the Pechora-Sea basin.

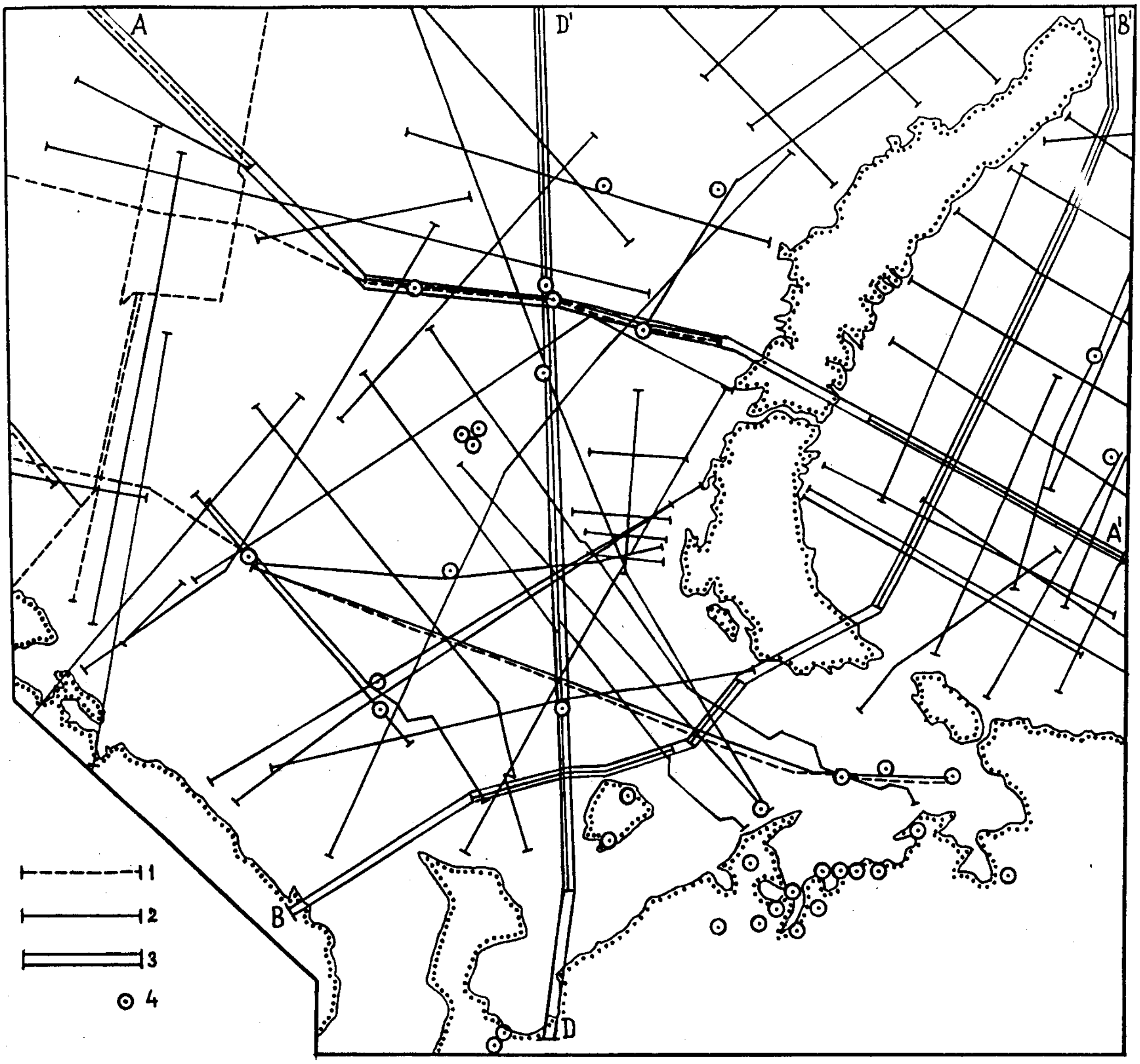

Fig. 17. Geological and geophysical data used for shelves of the Barents and Kara seas
1 - composite seismogeological sections (after Sigmond, 1992; Johanson et al., 1992); 2 - seismic, seismogeological sections, and sections through profiles of the deep seismic sounding and complex refraction method, geomagnetic and geodensity modelling of the earth crust (modified after M.L.Verba et al; V.E.Volk et al., R.M.Demenitskaya et al., Yu.P.Ershov et al., B.V.Senin, E.V.Shipilov, R.H.Gabrielsen et al.); 3 - profiles AA', BB', DD' (see Sheet 2, Tectonic Map); 4 - boreholes

8. Svalbard Plate

The Svalbard plate occupies the whole territory of the Barents Sea from Spitsbergen in the west to the Kara Sea in the east. The geological structure and the age of rocks of the plate were established using sections on Spitsbergen and Novaya Zemlya.

The structure of the basement surface relief was determined by analysis of changes in the depth of the crystalline basement, the structure of the sedimentary cover, and reflections of tectonic dislocation zones in geomorphological features on the seafloor.

The basement surface in the Barents Sea was determined mainly using geophysical data, principally deep seismic sounding data and the modelling of the crustal structure using magnetic and gravimetric survey data. Deep sea drilling data, which would provide direct evidence of the structure and composition of the basement, are rare. All data are supplemented by a small number (about 100-120) of sections obtained by deep drilling on the shelf and islands, as well as on island exposures.

The massive development of Mesozoic (Triassic-Lower Cretaceous) terrigenous deposits, which almost everywhere compose the upper part of the platform cover and are in places overlain only by Upper Cenozoic or, rarely, Upper Cretaceous-Cenozoic layers, indicates the geological unity of the platform area.

In the southern part of the Barents Sea, the Svalbard plate is contiguous, across a deep-seated strike-slip fault trending NE-SW, with a zone of Baikalide Riphean-Vendian rocks representing the extension of the Timan-Pechora plate. In the east, the Svalbard plate is bordered by the South Kara basin and Cimmerian structures of the southern part of Novaya Zemlya.

The Svalbard plate is composed of large blocks bounded by fault systems - strike-slip- and upthrow-faults, as well as thrusts which separate areas of uplift and subsidence.

The paleostructure of the Svalbard plate was affected by later tectonic processes related to the development of the Paleozoic nappe-thrust system of the Urals and the Cimmerian block-thrust orogenic system of the Pai-Khoi-Novaya Zemlya foldbelt. Their effect resulted in formation of the Pai-Khoi-Vaigach and East Barents troughs; the Cimmerian tectogenesis affected the northern part of Novaya Zemlya.

Fault deformations on the plate boundaries caused the opening of the Nordkapp and Varanger grabens.

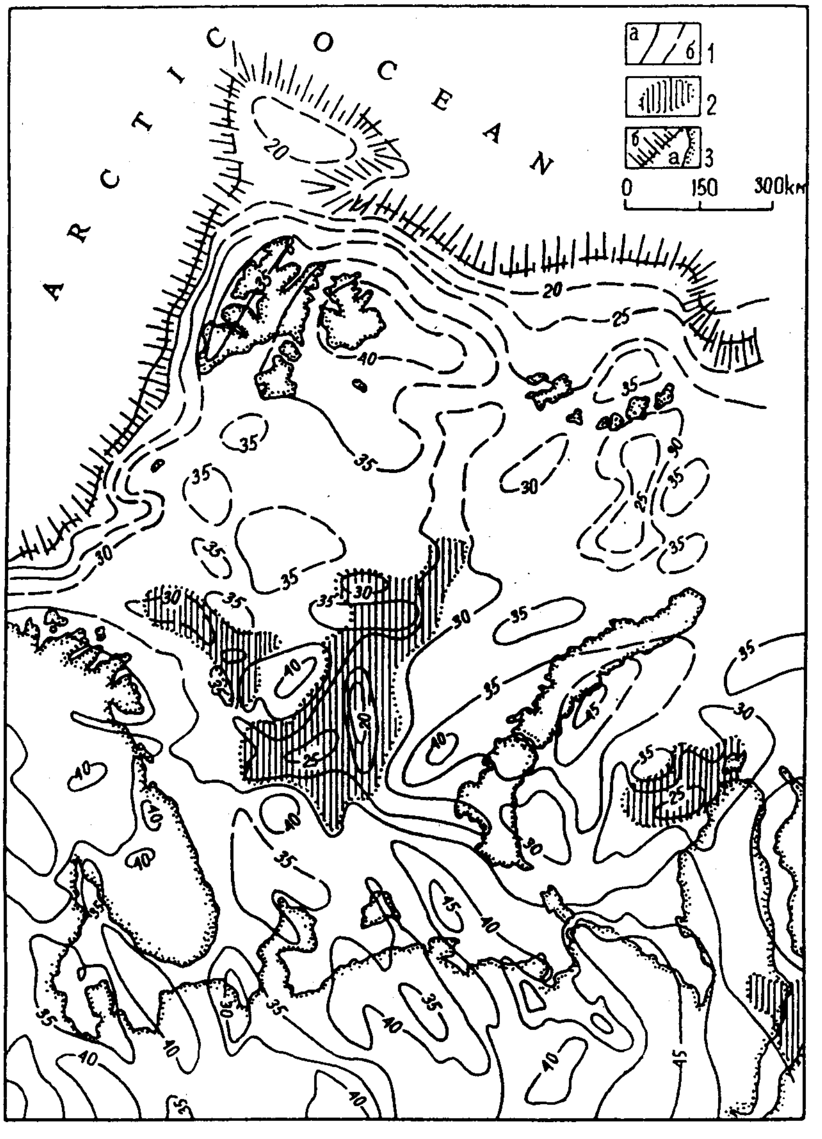

Fig. 18. Thickness of the earth crust in the Barents and Kara seas
1 - isolines of the depth of the crust foot, km: a - on the basis of DSS, CRM, CDPM; b - on the basis of the geomagnetic and geodensity modelling; 2 - areas of anomalous suboceanic ("granite-free") crust by seismic and magnetometric data; 3 - boundary of continental shelf area

8.1. Internal Structure of the Plate

According to seismic studies as well as geomagnetic and density modelling, the Svalbard plate is characterized by a thinned continental and subcontinental crust 25-35 km thick, which is considerably thinner than average continental crust (35-45 km). The crustal thickness increases up to 35-40 km on islands as well as on uplifts (Finnmark, Persej, Gardar) (Fig. 18).

A thinned (20-25 km) and geophysically anomalous "granite-free" suboceanic crust is developed in troughs and rifts [77].

The heat flow is higher than on the continental margin, increasing up to 80-90 mW/m^2 in troughs with areas of geophysically anomalous crust.

Determination of the tectonic age of sediment-covered basement rock units in the shelf area was based on the analysis of the basement surface morphology, correlation with the studied areas on land, the study of the structure and age of lower parts of the section by seismic and drilling data, chronology of events by absolute age determinations for rocks in the basement exposures or in boreholes, and on the detection of tectonic zones below the sedimentary cover by morphological, magnetic and gravimetric data.

According to available data, the Svalbard plate basement is composed mainly of Pre-Baikalian complexes, which are exposed in the east of Spitsbergen, on Bear and Bely islands, on North East Land and Novaya Zemlya. In the southern and western marginal zones of the plate, the basement was affected by Grenvillian movements, with a clear hiatus and unconformity at the boundary between the Late Riphean and Vendian, and by Caledonian movements in the extreme west and southwest, in the vicinity of foldbelts of Spitsbergen and northern Scandinavia. A belt, in which a paleobasement affected by Middle-Late Proterozoic movements was supposed to have evolved, is situated between the Pre-Baikalian blocks (Persej massif and Finnmark uplift), and corresponds to the Central Barents zone of uplifts.

Well-studied sections of the Svalbard plate [37] (Fig. 19), for which age determinations have been carried out, are located in the northern part of Novaya Zemlya.

The oldest assemblages are represented by Lower Proterozoic-Lower Riphean rocks metamorphosed to epidote-amphibolite facies in the North Sulmenev Bay on the western coast of Northern Island. Marbles, schists and amphibolites are intruded by granites. Metasediments contain Upper Proterozoic acritarchs. The U-Pb dating for zircons yielded 1550±80 and 1490±100 Ma for amphibolites and schists, and 1300±90 Ma for granites intruding schists. At the same time, the K-Ar dating for amphibole and biotite yielded 645±50 and 584±27 Ma, which probably reflect the age of the latest metamorphism.

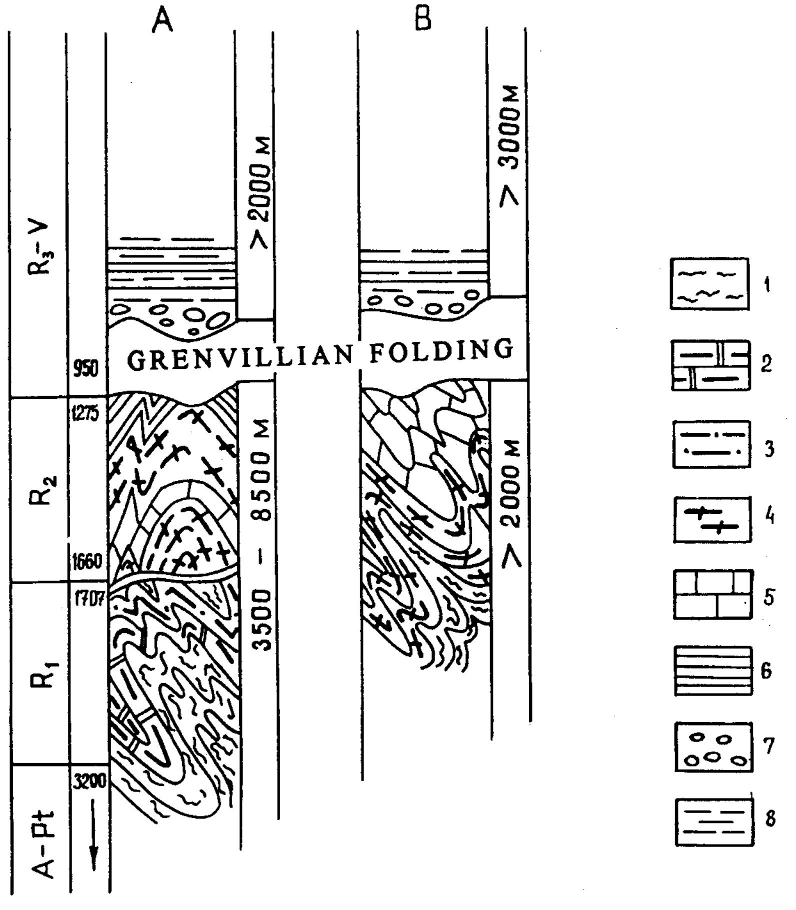

Fig. 19. Correlation of sections of the Precambrian basement of the Svalbard plate

A - northeastern Spitsbergen (after Krasilnikov, 1973; Ohta, 1992); B - western North Island of Novaya Zemlya, the Sev.Sulmeneva Guba [66]

1 - gneisses and schists; 2 - marbles and calciphyres; 3 - quartzites; 4 - biotite and two-mica schists; 5 - marbelized dolomites and marbles; 6 - carbonaceous and graphite-bearing shales; 7 - conglomerates; 8 - chlorite-sericite shales

The stratigraphic range of the sedimentary cover is rather variable. It is represented more completely in troughs where, according to seismic data, Upper Proterozoic-Cambrian to Cretaceous and Paleogene deposits may be present. The oldest Proterozoic-Silurian part of the section may make up from a third to a half of the total thickness of sediments infilling the troughs. However, areas of more complete section cover a smaller part of the plate compared with regions that have reduced sections.

Such regions comprise basement blocks uplifted to varying degrees, on which deposits are observed up to 4.5-7.0 km depth, ranging from the Devonian or probably Upper Silurian occurring directly on the eroded surface of the pre-Baikalian basement to the Triassic-Lower Jurassic making up the upper part of the sedimentary sequence, with the exception of a thin (5-50 m) cover of Quaternary and Pliocene-Quaternary deposits of different genesis unconformably overlying the Jurassic-Triassic units in these areas.

Owing to the lack of deep boreholes in the inner parts of the plate, it is impossible to characterize the composition of its sedimentary cover in detail. Nonetheless, some boreholes drilled in its marginal areas in the north, west and south [46; 97], in combination with seismic material, do give an insight into the problem.

Cambrian-Silurian deposits developed mainly in troughs and probably on the deeply subsided blocks of the western part of the plate are of carbonate or terrigenous-carbonate composition. Southern sections differ in their greater content of terrigenous material and the more pronounced unconformity between the Cambrian and Ordovician deposits, which corresponds to the Finnmark tectonic phase.

The overlying Upper Silurian-Devonian deposits are developed both in troughs and uplifts. They constitute the Old Red Formation known in Spitsbergen, which is represented by terrigenous, often coarse-clastic rocks. The lower boundary of the formation is related to the main Caledonian unconformity, which in different parts of the plate may take up the interval from the Mid-Silurian to Early Devonian. The top of the deposits are marked by the Svalbard unconformity corresponding approximately to the Devonian/Carboniferous boundary, but slightly shifted in places down- or upsection - into the upper parts of the Devonian or lower parts of the Carboniferous (Fig. 20).

Above this unconformity, up to the Permian-Triassic boundary, a sequence occurs that is again mainly composed of carbonate rocks as well as evaporites characteristic of Carboniferous and Permian deposits [10]. A key seismic horizon, one of the most commonly encountered in the Barents Sea, is associated with the top of Paleozoic, mainly Permian, carbonates.

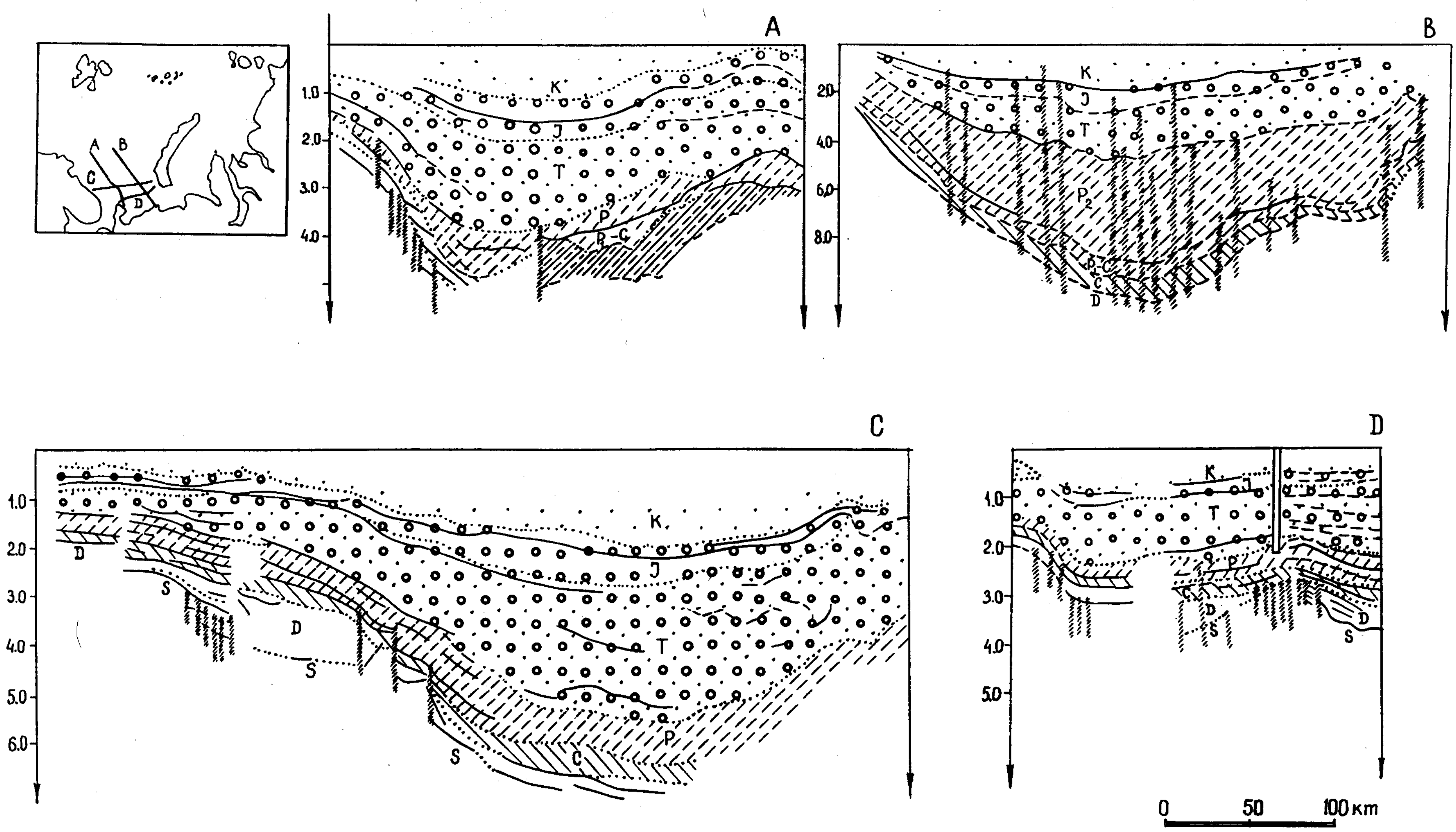

Fig. 20. Examples of seismogeological sections across the southern Barents Sea

The Triassic-Jurassic terrigenous sequence is separated from the Upper Paleozoic terrigenous-carbonate sequence by an unconformity corresponding to the Late Hercynian phase of tectonic activity. It is represented by continental and marine deposits of various compositions and origins, and contains abundant intraformational hiatuses, which indicates a great diversity of depositional environments during the Early and Middle Mesozoic. A characteristic feature of the sequence is the presence of bituminous clayey rocks, which are present in the Triassic but are most widespread in Upper Jurassic units (from the Oxfordian to Tithonian stage). Erosional surfaces and the second of the most common key seismic horizons are related to the top of the Jurassic deposits throughout the region. The morphology of the horizon is shown on the tectonic map.

The most elevated blocks of the plate do not contain the upper parts of the section, and the sequence can be represented by Triassic and Lower Jurassic (more rarely Middle Jurassic) rocks.

Lower Cretaceous terrigenous deposits overlying the erosional surfaces as well as carbonate-terrigenous deposits in the western part of the plate are grouped in the troughs as a rule with Middle-Upper Jurassic deposits to form peculiar syncline units overlying the troughs (or rifts). In the northern parts of the plate, volcanogenic and volcanosedimentary basic rocks are assigned to the Lower Cretaceous.

Upper Cretaceous and Paleogene terrigenous deposits make up a separate unit, which has limited distribution on the plate, occurring only within the Nordkapp and Varanger grabens and at its western periphery. Thus, the deposits should be considered not as components of the platform cover of the plate, where uplifting and erosion dominated at this time, but as components of the cover of its marginal zones facing oceans, the Baltic shield and East Barents trough.

The Persej massif, uplifts of the Central Barents zone, Finnmark uplift, as well as East Edjin and Nordkapp grabens serve as examples characterising the most significant structural elements of the plate.

The Persej massif is situated in the northern part of the plate. Its core is made up of Precambrian metamorphic rocks, the top of which occurs at a depth of 4.5-5.5 km. The massif is expressed in the seafloor topography as a bank of the same name, and in the geological structure as exposures of Permian and Triassic rocks. The sedimentary cover is represented by deposits ranging from the Devonian to Jurassic.

The East Edjin graben represents a complicated structure expressed differently at different structural levels. It is represented in the relief of the basement surface by a narrow trench trending NE-SW and approximately E-W in the east. A supposed Precambrian basement occurs here at a depth of 10-11 km. A deep (350-400 m) trough in the seafloor topography connecting the Bear and Persej trenches corresponds to the graben. However, only the eastern part of the graben is clearly expressed in the geological structure of the seafloor and in the structure of upper levels (Triassic and Jurassic) of the section. In contrast, its western part is represented in the upper parts of the section by a saddle, with fracture zones bounding the north and northwest of the Central zone of uplifts related to it. The sedimentary cover is represented here by Upper Proterozoic-Lower Paleozoic deposits varying in thickness from 0.5 to 5.0 km, and by a Middle Devonian-Lower Cretaceous sequence with a total thickness of 8-10 km. Judging by the thickness variations of individual units, the depocentre location changed repeatedly.

The Central Barents zone of uplifts trending approximately E-W is situated south of 76°N. The zone was named after its key structure - the uplift of the Central Bank described by H.Rennewick et al. in 1982 [95]. It represents an extended system of uplifted blocks of complicated configuration, the Precambrian rock surface occurring at a depth of 4-6 km. The system can be considered as a relict of the Precambrian orogenic (horst?) zone that emerged as a result of collision of two cratons, the Baltic and Arctic, in the Late Proterozoic, which comprised the Persej and North East Land massifs [108]. The sedimentary cover comprises deposits ranging from the Devonian to Triassic. As in the East Edjin graben, the western fragments of the zone are characterized by inconsistency in their structural expression at the level of the basement surface and overlying levels of the sedimentary cover. Thus, one can observe that the axis of the zone of uplifts has a NE-SW trend in the basement (from Loppa Bank to Central Bank), an approximately E-W trend in Permian-Mesozoic deposits and in the geological structure of the seafloor (from Gardar Bank to Central Bank), and again a NE-SW trend in the seafloor relief. It is believed that this phenomenon typical of the southwestern part of the plate is caused by repeated phases of tectonic activity, which affected this region from the Caledonian to the last Cenozoic phase of subsidence.

In this connection, the "transitional" structural elements like the Bjarmeland scarp or "platform" distinguished by Norwegian geologists seem to form on the southern flank of the zone of uplifts.

The Finnmark uplift, sometimes referred to as East Finnmark (after the province in the north of Norway), represents a complicated barrier domain, which separates the sedimentary basins of the western and eastern sectors in the south of the Barents Sea. As was mentioned above, the basement of the uplift occurring at a depth of 4-5 km is made up of a major pre-

Baikalian block, the most elevated part of which is distinguished as the Fedynsky uplift. In the seafloor relief, the uplift is expressed by the exposure of Triassic rocks among Jurassic-Cretaceous deposits. The sedimentary cover deposits vary from Middle Paleozoic to Triassic in the central part of the uplift, and from the Lower Paleozoic and possibly Vendian to Jurassic-Cretaceous on its slopes.

The Admiralty horst represents an extreme southwestern element in the belt of blocky uplifts of the Pre-Baikalian basement, which extends through the northern edge of Novaya Zemlya towards northwestern Taimyr. The stratigraphic range of the sedimentary cover deposits varies from Paleozoic (Ordovician-Silurian?) to Triassic, and from the Jurassic to Lower Cretaceous in the marginal parts. The total thickness of deposits varies from 5-6 km on the crests of some uplifts to 7-8 km in local depressions.

The Gusinaya Zemlya block situated between the Admiralty horst and orogenic structures of Novaya Zemlya is distinguished by convention only, because, as pointed out above, this zone has not been adequately studied. The block represents an area of deep (up to 12-14 km) subsidence of the basement. Judging from the dips of horizons in Middle Paleozoic deposits on the eastern edges of some seismic profiles, the block surface seems to be tilted under Novaya Zemlya. Differentiation of the structure on lower parts of the section indicates that this surface can be broken into blocks perpendicular to the strike of the zone. The overlying section occurring at a depth of 0-12 km comprises deposits from the Lower Paleozoic to Upper Cretaceous, the Jurassic sequence being contained in upthrow-thrust or nappe structures related to thrust displacements of blocks of the Novaya Zemlya belt in a westerly direction.

8.2. Troughs and Grabens with Suboceanic-Type Crust

The East Barents trough distinguished in 1985-1986 [46; 56, 57; 60] as a single independent structural element represents a crustal structural unit of a type rare for North Eurasia. Its peculiar feature lies in the fact that with considerable length (more than 1500 km) and width (300-600 km) the trough is characterized by great subsidence (up to 14-18 km) of the base of the sedimentary cover throughout the area, and the occurrence of spots of anomalous crust (Fig. 18) and upper mantle. The trough can be subdivided into a series of smaller basins: the South, North, and East Barents, in which the basement depth decreases from south to north, from 18-20 km in the first basin to 16-18 km in the second and 12-13 km in the third. It should be pointed out that at a depth of more than 14-16 km the basement-cover boundary becomes difficult to resolve: first, features of "normal" folded or crystalline basement are recognized in refraction correlation profiles and by other seismic data; second, sedimentary units appear to lie directly on the surface of "lower crust"; third, any attempt to establish a seismic boundary between lower parts of the section and the underlying consolidated crust failed, and its possible extension is established by the results of magnetic and geodensity modelling.

The basins are separated by the Ludlov and Albanov-Gorbov saddles expressed in the basement surface relief. Their position and morphology at the level of the basement do not correspond to saddles, which were primarily identified in the structure of the upper part of the section [15], mainly in Jurassic deposits.

There is no way of reliably determining a tectonic age for the basement because it was affected by several phases of rifting [59; 79; 111; 110]. However, by some indirect features, for instance, on the basis of morphological similarity of some of its elements with structures of adjacent areas and by the age of overlying lower units of the sedimentary cover, we can suggest that the time of the basement formation in the South Barents basin (as far north as the Ludlov saddle) differs from the time of its formation further north. In the South Barents basin the basement is most probably Baikalian and extends the belt of Baikalides of the Timan-Pechora plate that were highly affected by subsequent tectonic events. North of the Ludlov saddle the basement is most probably made up of the Pre-Baikalian crust broken into small blocks and intruded by magmatic bodies.

The trough is infilled mainly with Upper Paleozoic and Mesozoic sequences (see sections on Sheet 2 of the Tectonic Map). Cretaceous-Cenozoic layers are only present within these basins, the thickest Cenozoic section being located in the Franz-Victoria and St.Ann grabens beyond the limits of the discussed region.

The sedimentary cover section has been studied by drilling on separate uplifts to a depth of 4.5 km, and reliably traced by seismic methods to a depth of 12-14 km. Fragments of reflectors are found at even greater depth, 16-17 km.

The main part of the section (about 6-8 km) comprises the Upper Permian-Triassic terrigenous deposits. They occur on thin (up to 1 km) Permian-Carboniferous carbonates, below which the thickness of Devonian carbonate and terrigenous-carbonate deposits is assumed to increase gradually towards the central part of the trough. On the trough slopes the thickness of these deposits generally decreases; however, there are narrow local troughs, or "pockets", which are filled with Devonian rocks of great thickness.

The total thickness of Jurassic-Lower Cretaceous terrigenous deposits is about 2-2.5 km. Seismic data demonstrate that the Ludlov saddle separating the South- and North-Barents basins is best expressed only in these deposits. The saddle is represented here by a complicated series of anticlines and synclines generally of approximately E-W trend, which is oriented obliquely to the trough and bounded by the trough slopes.

Like the basement, the lower parts of the section, from the lowest Paleozoic up to Triassic inclusive, are broken into blocks. Upsection, many faults are transformed into small-amplitude or amplitude-free (fissure) dislocations, which are poorly distinguished on time sections.

A characteristic feature of the sedimentary cover structure is abundant magmatic bodies [58; 78]. The magmatic activity, which is one of the typical feature of rifting stages in the trough history, is related to so-called "anomalous seismic horizons", which are established in deposits of the East Barents trough by seismic methods [78; 80; 110].

The Lower-Middle Devonian succession is the oldest unit in which such horizons have been established. In time sections, the horizons are expressed as "bright spots" related to faults, and in plan are confined to offshore extensions of tectonic zones of Timan and Novaya Zemlya.

The Permian-Triassic succession is most enriched in "anomalous horizons", which are combined as horizons of Group A (A - within Permian deposits; A_1, A_2, A_3 - within Triassic deposits). On the margins of basins, some of these horizons, for instance A_2, are associated with seismic boundaries, which reflect hiatuses and unconformities in the sedimentary section. The greatest number of anomalous horizons of this group is established on the Ludlov saddle [36].

In the Jurassic terrigenous succession, the "anomalous horizons" are observed in its lower parts and occur within the Ludlov saddle and North Barents basin.

In the Lower Cretaceous terrigenous succession, the "anomalous horizons" are traced in separate areas in the North Barents basin, and are also associated with fault zones.

In the anomalous magnetic field, "anomalous horizons" are characterized by high values, as well as by excess density from gravimetric data.

Overall, a strip of "anomalous horizons" bounded by trough boundaries becomes younger from south to north, which is confirmed by a higher stratigraphic and hypsometric position of these horizons right up to the exposure on the surface as flood basalts in Franz Josef Land. This peculiar feature, as well as the structure and geophysical characteristics of the horizons, led to the suggestion that they were magmatic. This suggestion was confirmed by deep drilling data [36]. Fragments of diabase associated with horizons of Group A and similar in composition to dyke complexes of Franz Josef Land were found in the drilling mud from

Borehole Ludlovskaya-1. The K-Ar dating (159-139 Ma) also shows synchronism with flood basalts of the archipelago.

The Nordkapp graben, first described in 1975 by K.Hintz and I.Weber, is situated between the Central Barents zone of uplifts and nappe-fold and block structures of the Scandinavian Caledonides. The basement occurs here at a depth ranging from 5-6 km on the trough shoulders to 13-16 km in the central part (see the Tectonic Map). The original age of the basement in the axial zone of the trough is undeterminable due to later compression and rifting occurring during several phases, probably since the Middle Paleozoic (Devonian?) [46; 58; 74; 111]. In the trough slopes, the age of the basement may vary from Caledonian and Baikalian in the western part of the trough, west of 29°E and the Thor-Iversen fault identified by Norwegian geologists [95], to the Karelian and Late Baikalian (Gothian-Grenvillian?) in its northeastern part. The stratigraphic range of the sedimentary cover also varies from Paleozoic to Paleogene in the axial part of the graben (in its eastern part) to the Devonian-Paleogene in the western part, and from the Devonian to Lower Cretaceous on the slope scarps which make up the shoulders of the trough. Evaporite units forming a field of salt diapirs restricted to the graben are associated with Carboniferous-Permian and, probably, Devonian terrigenous-carbonate deposits [10]. The crust in the graben is of "granite-free" or suboceanic type.

The Varanger graben corresponds in the basement structure to the West Kola saddle distinguished earlier in the upper part of the sedimentary cover [15]. At depth, the graben separates the Finnmark uplift and Kola megaplate. The depth of the basement, which is represented by Karelides affected in the Baikalian and later orogenic phases, is 8-9 km in the eastern part of the graben, reaching 12-14 km in its western part. In 1981, H.Rennewick distinguished here the Tiddle Bank basin (graben) or Varanger [95]. Refraction correlation data and the results of deep seismic sounding through the Kola shelf suggest that the sedimentary cover of the graben comprises deposits from the Paleozoic through Cretaceous inclusive. The Paleozoic deposits are dislocated, and in this instance may represent a stratigraphically thicker (at the expense of Lower Paleozoic strata) and older (by the time of dislocation) analogue of dislocated paleocover exposed on the Varanger and Rybachy peninsulas.

9. Structures of the Timan-Pechora Plate Within the Barents Sea

The Pechora basin represents an offshore extension of the Timan-Pechora plate, which is displaced to the west along a series of strike-slip faults located along the shore. Its extreme northern element is the Kurentsov scarp described by S.K.Prokudin in 1984 [60]. In the south, the basin is bounded by a series of left-lateral strike-slip faults with a total amplitude of 70-100 km. These faults can be traced intermittently westwards from the Khaipudyr Bay south of Kolguev Island towards the Kanin Ridge using seismic data and by the shifting and branching of axes of magnetic lineations and axes of comb-shaped folds in the sedimentary cover. Structures of the basement and sedimentary cover are also characterized by an abrupt damping of vertical amplitudes when crossing this boundary from south to north, and by a "dispersal" of linear structural zones so that offshore analogues of one or other structural zone on land are difficult to establish.

To a lesser degree this feature refers to the eastern regions of the basin, especially to the offshore extension of the Varandei-Adzva block and associated troughs and uplifts in the sedimentary cover. This block, the most well-expressed structure, can be traced far offshore. However, its axis also experiences a series of offsets in a westward direction when crossing fault zones.

On the north and northwest side, the basin is bounded by a complicated fold-fault zone [59]. United in the western part, where the total displacement amounts to about 4-6 km, the zone subdivides east of 47 deg.E into two branches. The northern branch with a vertical displacement of 3-5 km stretches northwestwards in the direction of Mityushikha Bay on the North Island of Novaya Zemlya to be hidden beneath its frontal thrusts. The southern branch, which has a vertical displacement of 1.5-2 km and according to seismic and geological data contains a left-lateral-fault component, extends in the direction of the southern edge of Novaya Zemlya where it is also concealed in part by thrust structures.

Both branches are reflected in the bottom topography of the Barents and Pechora seas. The northern branch is expressed in a wide scarp 100-150 m high, whereas the southern branch is expressed as a linear depression 70-80 m deep with a narrow valley incised into the seafloor.

The Kurentsov scarp, V-shaped in plan, is situated between the two branches. The scarp occupies an intermediate position between structures of the Timan-Pechora plate and East Barents trough, and because of this it could change its tectonic affiliation (to the plate or the trough) at different stages of the regional history depending on the predominant stress field.

In terms of the time of formation of the northern and southern boundaries of the plate, the Pechora-Barents zone, judging from the Devonian sequences increasing in thickness from south to north with relatively stable thicknesses of overlying Carboniferous deposits, could have emerged or revived as a boundary element at the end of the Caledonian cycle and possibly faded at the Devonian/Carboniferous boundary, i.e. in the Svalbard tectonic phase. However, it can be seen in seismic records that Permian and Triassic deposits increase in thickness from south to north above the zone, and above the associated faults and high-amplitude anticlines appear to pinch out in the Jurassic deposits (Fig. 20). This indicates a higher tectonic activity of the zone during the Cimmerian cycle.

The time of development of the southern boundary of the basin is an open question. If we take into account that amplitudes of comb-like folds of the platform cover on the onshore part of the plate decrease on the shelf, we may assume that the basin was slightly isolated at the end of the Hercynian cycle and in the Early Cimmerian phase when these zones were probably formed. Some seismic records show an increase in the thickness of Jurassic deposits north of this boundary, which indicates the possible differentiation of movements with respect to it at the end of the Cimmerian cycle as well. This is also confirmed by the analysis of the composition and thickness of Lower, Middle and Upper Jurassic deposits [108]. Thus we can state that the southern boundary of the offshore part of the Timan-Pechora plate was probably formed a little later than its northern boundary. In the west, the basin is bounded by the Korgin block adjoining the Kanin ridge in the east and northeast. In the east the basin is bounded by structures of the outer zones of the Pai-Khoi-Novaya Zemlya foldbelt.

The surface of the Baikalian basement in the Pechora-Sea basin occurs at a depth of 5.5-6.5 km, 0.5-1 km deeper than on the adjacent land. The most characteristic features of its structure are gentle arch-like zones alternating with wide depressions, which, in contrast to N-S trending zones of the onshore part of the plate, have a NW-SE trend here and are locally approximately E-W trending.

The sedimentary cover deposits range from Ordovician to Lower Cretaceous. North and northeast of Kolguev Island, the lower parts of the section in deep troughs may comprise Upper Cambrian deposits whereas the upper parts of the plate cover may be Upper Cretaceous deposits. The analysis of seismic data shows [23] that Lower Paleozoic deposits are in places deeply eroded, and Upper Devonian deposits occur on rocks of different age, from Proterozoic to Lower-Middle Devonian.

The Kola microplate is considered as the western extension of the Pechora-Sea and Kanin structures. In the northeast, the microplate is bounded by faults of the Varanger zone. In the south, it is separated from onshore structures of the folded rim of the Baltic shield by the Tromse-Finnmark, Mosei [94] and Kola-Kanin [58] zones of faults and strike-slip faults, with total displacements ranging from 3-5 to 8-9 km. The zones are grouped in an extended fault belt, which can be persistently traced for more than 1200 km along the northern coast of Europe from the Tromse basin to the northern submerging edge of the Kanin ridge

Geomorphologically, the belt is marked by a series of scarps in the seafloor relief, which separate the outer and inner shelf, and in the geological structure of the seafloor by the southern boundaries of small Late Cretaceous-Cenozoic basins extending along the belt.

On land, fragments of the microplate make up the Rybachy Peninsula, the northern part of Varanger Peninsula (see Fig. 1), where they are represented by Late Riphean metamorphosed sandstones and red quartzites of the Barents rock group [90].

IV. STRUCTURES OF THE KARA SEA FLOOR

10. Novaya Zemlya Microplate

The region comprises the eastern zone of the northern Novaya Zemlya foldbelt and the microplate occupying the western part of the Kara Sea. On the east the region is bounded by faults of the South Kara basin.

The region is assumed to have a Late Proterozoic basement occurring at a depth of 1-6 km, which was affected by the Cimmerian tectogenesis in the Pai-Khoi-Novaya Zemlya foldbelt and adjacent areas.

Judging from the geological structure of the eastern coast of the archipelago and some seismic data, the stratigraphic range of the sedimentary cover comprises deposits from the Carboniferous (or most likely Upper Devonian) to the Jurassic. Pre-Permian deposits make up a discontinuous cover, being localized in grabens or gentle synclines between comb-like folds whose cores are composed of Ordovician-Devonian rocks.

The Karmakul trough of Novaya Zemlya, which separates its southern and northern anticlinoria, should probably be included as part of this microplate. The total thickness of Upper Devonian(?)-Permian deposits composing the trough may reach 6 km. The Upper Devonian and Permian deposits are assumed to comprise bodies of a volcanic nature.

Thrusting and strike-slip faulting of the upper part of the crust during the Cimmerian cycle related to rifting in the South Kara basin played a great role in formation of dislocations and the general structural pattern of the microplate and Novaya Zemlya.

11. South Kara Basin

The South Kara Basin occupies the southeastern part of the Kara Sea. The basin is separated by a series of arch-like faults from the Svalbard plate in the northwest, west and southwest.

The presumably pre-Late Devonian basement, probably containg Uralian structures, is buried to a depth of 5-7 km. In the central part, the basement is cut by narrow grabens, in which subsidence to a depth of more than 11-14 km has occurred. An "anomalous" suboceanic crust is apparent in these grabens (Fig. 18). It is not improbable that the extension in the Kara basin contributed to formation of thrust structures on Novaya Zemlya in the Mesozoic [58; 110].

Deposits of the sedimentary cover are presumed to range from the Devonian to Paleogene. Only the uppermost part of the section (Cretaceous-Paleogene) has been drilled. Upper(?) Permian, Triassic and Jurassic deposits are the thickest in the section. According to seismostratigraphic data, basaltic intrusions are developed in the Permian-Triassic succession in the central part of the South Kara basin [80]. As in the East Barents trough, the basement and the lower part of the sedimentary cover section were repeatedly affected by faulting and thermo-volcanic processes related to rifting [58; 59].

V. CONCLUSION

12. Oil and Gas Potential

Actual oil and gas potential of the Barents Sea (Fig. 21) is established in its southernmost, extensively studied areas and is related to grabens in the south and extreme southwest of the Svalbard plate, the East Barents trough and Pechora-Sea basin [109].

A group of well-known gas fields (Albatros, Alke, Askelad, Snevit) is located beyond the region, in the extreme southwest of the Svalbard plate, on the tectonic boundary of the Tromse and Hammerfest grabens, the latter extends the Nordkapp graben along strike. These fields are related to Upper Triassic and Lower-Middle Jurassic deposits. The Snevit field also contains oil and gas condensate. Reserves of oil and gas condensate are estimated to be more than 5 million tons, whereas gas reserves are more than 80 billion m^3. A small noncommercial oil accumulation was discovered by Norwegian geologists in Block 7128 located on the southern boundary of the Nordkapp graben (the Finnmark scarp or "platform") in Upper Permian or Lower Triassic sandstones.

Six gas and gas condensate fields were discovered in the East Barents trough by Murmansk marine seismic and drilling departments of the Ministry of Fuel and Power Engineering of Russia, as well as by the former Ministry of Geology: the Murmansk and North Kildin gas fields confined to the southern and southwestern marginal zones of the South Barents basin; the Stockman and Ludlov gas and gas condensate fields [80] situated in the northern part of the South Barents basin near the Ludlov saddle and associated with Middle and Upper Jurassic deposits; the Stockman field, with gas reserves about 3 trillion m^3, is unique; the Ledovoe gas condensate field related to the Ludlov saddle and containing gas and gas condensate accumulations in Middle and Upper Jurassic deposits as well as gas accumulations in Lower Cretaceous deposits; the Lunin gas field (or show) in Lower Cretaceous deposits of the North Barents basin, in the zone where the basin joins the Admiralty horst.

Oil and gas condensate fields are characteristic of the Pechora-Sea basin. Five fields have been discovered here: the Peschanozerskoe and Izhma-Tara fields were located in Triassic deposits on Kolguev Island. South of the island, the Pomor gas condensate field was discovered approximately at the same stratigraphic level, which tends by its tectonic setting to the southern boundary of the offshore part of the Timan-Pechora plate. The North Gulyaev

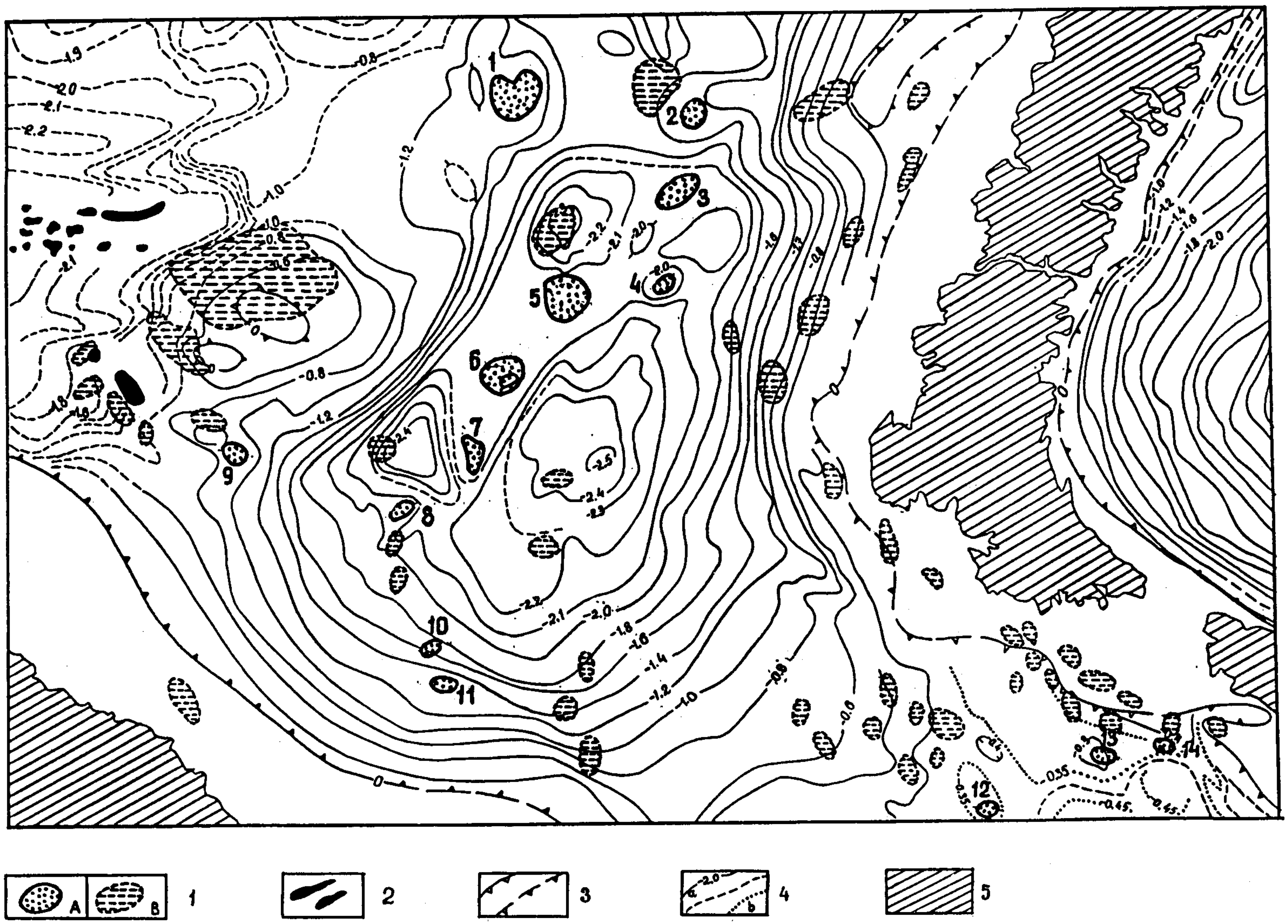

Fig. 21. Scheme of local structures and hydrocarbon deposits in the Pechora Sea and southern Barents Sea

1 - structures with oil and gas fields: a - workable, b - hypothetical; 2 - salt domes; 3 - boundary of Meso-Cenozoic deposits; 3 - contours of Upper Mesozoic and Cenozoic deposits: a - proved, b - probable; 5 - land

Hydrocarbon deposits: 1 - Fersman, 2 - Ludlov, 3 - Ice, 4 - Britvin, 5 - Shtockman, 6 - Teriber, 7 - North Nadezhda, 8 - Nadezhda, 9 - North Kildin, 10 - North Murmansk, 11 - Murmansk, 12 - Pomory, 13 - North Gulyaev, 14 - Fracture and Prirazlomnoe oil fields located in the southeast of the basin belong to a special group. These fields should be considered in connection with Late Hercynian and Early Cimmerian faulting and thrusting processes in the sedimentary cover of the eastern part of the plate, caused by westward emplacement of block structures, of the Pai-Khoi-Novaya Zemlya orogen. According to recent geophysical and drilling data, the estimated reserves in the Permian carbonate of the Prirazlomnoe oil field are likely to grow due to new areas involved, as well as to the increase in the exploration level of oil pools in Silurian deposits.

When comparing the general characteristics of oil and gas fields of the Timan-Pechora plate and the Barents Sea province (Fig. 22), one can identify a change in the stratigraphic range of the proved productivity, which varies from the Devonian (possibly Silurian)-Triassic in the onshore part of the Timan-Pechora plate to the Permian-Triassic in the Pechora-Sea basin (with the exception of the zone adjacent to Novaya Zemlya - Pre-Novaya Zemlya zone). Hydrocarbon accumulations are found in the Triassic deposits at the boundary with the South Barents basin and in the Jurassic-Lower Cretaceous deposits in the East Barents trough. Simultaneously, in the same direction, a change in the dominant composition of hydrocarbons takes place from oil on the Timan-Pechora plate to gas condensate within the trough.

The stratigraphic range of oil and gas potential in the onshore Timan-Pechora province includes Upper Ordovician to Triassic deposits, the Middle- and Upper Devonian as well as Lower Carboniferous deposits playing the leading role. Tens of multilayer pools including practically all types of rocks - reservoirs and traps - known in petroleum geology are found here. Sandstones and carbonates (limestones and dolomites) serve as reservoirs. Caps are represented by clays, more rarely by evaporites. Pools are predominantly of the anticlinal type, both dome-like and linear anticlines are observed, the latter mainly in aulacogens and near the Urals and Pai-Khoi. The dome-like anticlines are often faulted and upthrown, and the linear anticlines are thrust (a classic example is the Vuktyl pool). Thus, tectonically screened pools are often observed along with arched pools. In addition to structural pools, stratigraphic-type traps are widely developed related to shearing or pinching out of reservoir units, and in lithologic-type traps associated with replacement of reservoir units by poorly permeable rocks, in particular, high porous limestones by clayey varieties, or with sandy bodies of bar, deltaic or similar nature. Cleaved clayey limestones, the so-called Domanik (Upper Devonian, Frasnian), represent a special type of reservoir. The other specific type of pools are confined to reef bodies and other bioherms, in particular to Upper Devonian-Tournaisian barrier reefs. In some cases, traps were formed as a result of a combination of tectonic, stratigraphic or lithological screening.

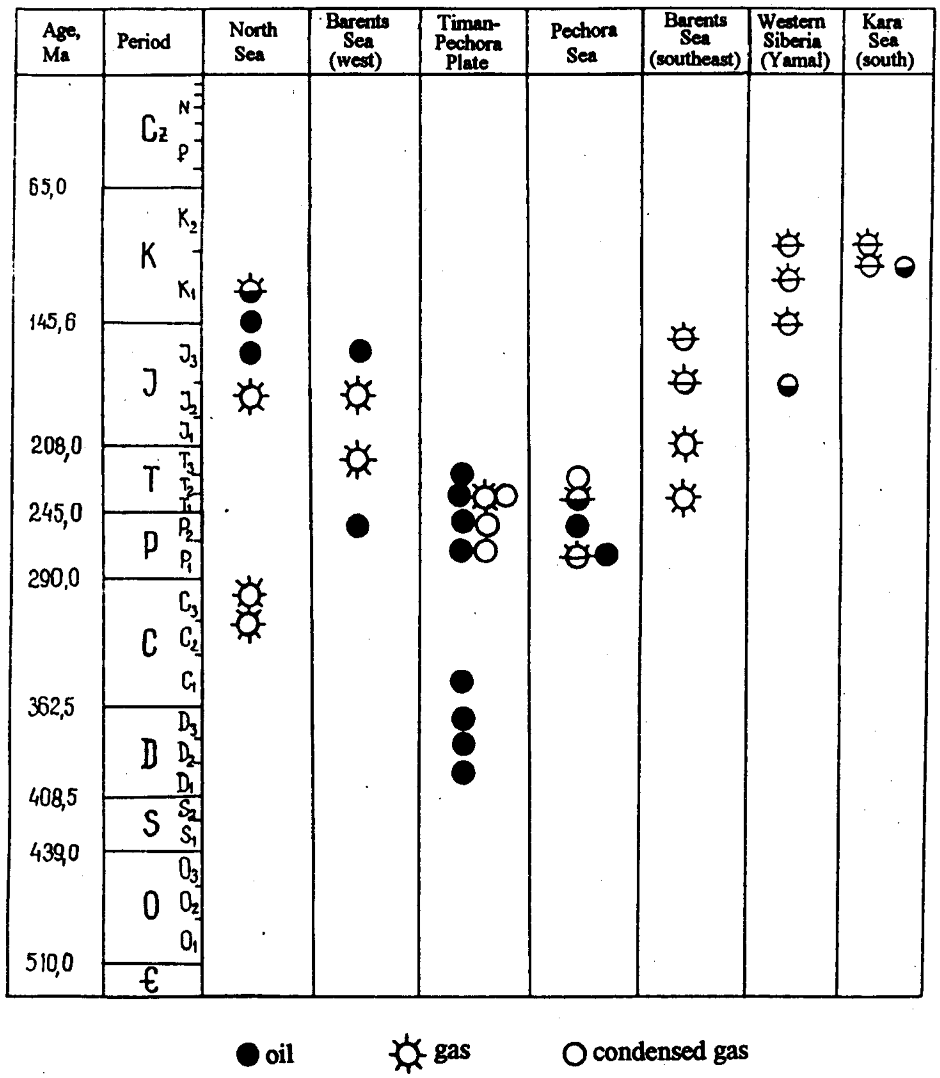

Fig. 22. Distribution of oil and gas potential throughout stratigraphic ranges of the sedimentary cover in the Barents-Pechora region and adjacent areas

Oil pools are most abundant in the Timan-Pechora province. In addition, gas pools with or without an oil fringe, and pools of gas condensate have also been discovered. The oil quality is variable in terms of paraffin and sulfur contents.

Two tendencies are characteristic of the Timan-Pechora province: the age of productive horizons become younger from south to north and the structure of pools becomes more complicated in aulacogens and towards Pai-Khoi and the Urals.

13. Principal Stages of the Tectonic History of the Region

The Archean Stage. Three principal elements are distinguished in the northern part of the Baltic shield, which have NW-SE trend and continue with the same orientation to the southeast beneath the cover of the Mezen syneclise, which is confirmed by the above-mentioned geophysical data. The three blocks (terranes) are designated as the Murmansk, Central Kola, and Lapland-White Sea (the Lapland-White Sea block being of a more pronounced linear character and thus called a belt), and are made up of Late Archean structures, not more than 3.0 Ga old, affected to some extent in the Early Proterozoic. The Archean complex of the Central Kola block contains greenstone belts, whereas their fragments are known in the Lapland-White Sea block. The age of the main metamorphism and granitization, which were followed by basic intrusions, is 2.55-2.45 Ga.

The formation of the continental crust composing this part of the Baltic shield may be thought of as having been completed by the beginning of the Early Proterozoic, and during the Protrozoic the crust was only reworked.

The Early Proterozoic Stage. The Murmansk block was less affected in this zone, whereas the most faulted was the Laplandian-Belomorian belt. A major Imandra-Varguz riftogenic structure (protoaulacogen) was formed in the southern part of the Central Kola block in the Early Proterozoic. The structure is infilled with a sequence of basic, ultrabasic and to a lesser extent intermediate and acid lavas, as well as clastic and carbonate rocks. At the end of the Early Proterozoic, the sequences infilling the rift zones were subjected to compressive deformations, with steep thrusting, and to metamorphism of the greenschist and epidote-amphibolite grades. Within the rift system and on the rest of the Central Kola block, basic dyke suites were formed in the Early Proterozoic during the process of rifting of the Archean crust, as well as numerous intrusive bodies, which can be subdivided by their composition and age into three groups: (1) mafic-ultramafic, (2) intermediate and acid, (3) alkaline. These plutons were formed mainly at the beginning of the eon, 2.4-2.3 Ga ago, the first group also being known in the Laplandian-Belomorian belt.

The Early Proterozoic processes were most intensive within the Laplandian zone of the Laplandian-Belomorian belt. Granulite metamorphism occurred here and a nappe-thrust structure was formed as a result of collision between the Kola and Karelian megablocks in the second half of the Early Proterozoic, 1.94-1.90 Ga ago. At the end of the Early Proterozoic, the northeastern part of the Baltic shield and its continuation below the Mezen syneclise cover reached the craton stage. The area affected by this process also included a northerly extension, judging from exposures of the metamorphosed supracrystalline complex and granites in Ny Friesland (Spitsbergen) [96] and on the North Island of Novaya Zemlya [37]. The radiometric dating of these structures yielded 1.75 Ga for the first region and about 1.5 Ga for the second region, i.e. younger than the craton stage in the northeast of the East European platform. The metamorphism and granitization in the Barents Sea area was preceded by the accumulation of a thick sequence of terrigenous and carbonate sediments, as well as effusion of basic rocks now transformed into amphibolites. To put it another way, the Barents Sea area remained mobile in the second half of the Early Proterozoic, and continued to be so in the Middle Proterozoic as well (see below).

The Middle Proterozoic (Early and Middle Riphean) Stage. The Kola megablock retained its stable and uplifted position during the Early and a part of the Middle Riphean. In the second half (?) of the Middle Riphean, its margins started gradual submerging, with accumulation of typical platform clastic sediments; the process lasted into the Late Riphean. Curiously, it has been found that the configuration of the Kola uplift corresponds almost exactly to the present shape of the peninsula. Rift-aulacogens of NW-SE trend originated within the ensuing Mezen syneclise; in the southeast, the end of the rifts adjoined the Sukhona edge of the Central Russian rift system of NE-SW trend. Parallel to the Mezen system, but northeast of it, the Timan system probably developed. On this basis, the passive margin of the European continent (Baltica) facing the incipient Asian paleoocean was formed in the Middle Riphean (at the end of it?). The margin extended to the present day Pre-Pechora fault zone. Judging from the character of migmatites widely developed here, a volcanic arc was initiated along this fault zone, the main period of the arc evolution occurring during the Late Riphean and Vendian. The origin of this arc was most probably related to a subduction zone inclined below it on the northeast side. East of the arc, the geodynamic setting has defied clear interpretation. A microcontinent may occur here in the area of the Bolshezemelskaya tundra, and a spreading axis is assumed to exist in the Varandei-Adzva zone according to geophysical data. It is significant that the structure of the eastern part of the Timan-Pechora plate probably extended to the Polar and Subpolar Urals; in the Subpolar Urals the rocks of another volcanic arc are found. The volcanic arcs and the microcontinent had to be separated by marginal-sea-type basins with oceanic-type crust, relicts of which some researchers assume to exist in the Urals.

The future Svalbard plate, at least its western part exposed on Nordaustlandet (Svalbard) where the folded basement is intruded by granites, also evolved under a regime of high mobility in the Early (?) and Middle Riphean. Most probably, the accretional complex of an active continental margin is exposed here. The area of the margin uplifted above sea-level comprises Ny Friesland, where the Early-Middle Riphean hiatus is revealed; the same picture is observed on the North Island of Novaya Zemlya.

The Svalbard plate became a craton by the end of the Middle Proterozoic. The basement of the plate is incorporated into the Grenvillian foldbelt extending to this area from North America throughout Greenland and Scandinavia. Events of this epoch do not show up in the southern (in modern coordinates) half of the region discussed, and the change-over from the Middle to Late Proterozoic proceded gradually with the exception of separate areas of the continental margin.

The Late Proterozoic (Late Riphean and Early Vendian) Stage. The environment within the Timan-Pechora plate and northern segments of the Urals suffered no radical changes. A barrier reef originated at the boundary between the inner and outer shelf within the modern Timan Ridge. The development of volcanic arcs was still in progress in the east. In the early Late Riphean, volcanogenic molasse accumulated on the Svalbard plate above the uppermost Riphean thick carbonate and Lower Vendian tillite sequence which replaced with an unconformity the terrigenous units lying below. Upper Riphean and Vendian terrigenous deposits are developed on the North Island of Novaya Zemlya; in both regions the great thickness of deposits indicates pronounced subsidence.

The filling of aulacogens in the Mezen syneclise and the accumulation of relatively thin clastic sediments and then tillites on uplifts and along the periphery of the Kola megablock of the Baltic shield were in progress.

The Late Vendian-Early Cambrian Stage. While a gradual subsidence continued on the Svalbard plate, important events related to the Baikalian orogeny took place in the Timan-Pechora area and at the boundary with the Urals and Pai-Khoi. The orogeny was most probably caused by the collision of island arcs and microcontinents of the northern part of the Paleoasian ocean and probably Siberia with the northeastern edge of Baltica. The orogeny resulted in the formation of the Timan foredeep infilled with Vendian variegated molasse, and volcanogenic molasse in the east of the future Pechora plate and the adjacent Urals. The Riphean (and Lower Vendian?) rocks underwent fold-thrust deformations. The deformations were most intensive in the Urals where thrust sheets also appeared to spread onto the former passive margin of Baltica. A frontal thrust of the Timan Baikalides is traced along the southwestern slope of the Timan Ridge, and extends to the Kanin Peninsula to be exposed again between Rybachy and Sredny peninsulas and on the Varanger Peninsula in Norway.

The Early and Middle Paleozoic (Ordovician-Early Carboniferous) Stage. In the Ordovician, the Timan-Pechora area became the northern part of the passive margin of the East European continent, east of which the Urals ocean basin opened. Inner shelf deposits are mainly developed on the Pechora plate, whereas outer shelf sediments are present within the Urals foredeeps and the external zone of the Urals system, the NE-SW trend of the northern segment of which does not coincide with the NW-SE trend of the Baikalian basement structures. Shelf facies pass to the east and southeast into bathyal, predominantly siliceous-shaly rocks accumulated on the continental slope or rise. They were also deposited on the floor of the narrow Salatim deep-water basin, separated from the open ocean by a marginal uplift of the pre-Ordovician basement. Rocks of the ophiolite association occurring in the south of the basin indicate the local occurrence of spreading. Volcanic arcs were initiated in the Ordovician in the main Urals basin, the eastern zone of the Subpolar and Polar Urals corresponding to its marginal part. The arcs were still developing during the Silurian and Devonian.

The Middle and Late Devonian not only represent the time of important events within the Timan-Pechora plate but also in the adjacent Svalbard plate. This was an epoch of intense rifting processes that affected all earlier consolidated elements of the continental crust, Caledonides of Scandinavia and Spitsbergen included. The South Barents and East Barents rift systems were most probably formed and the Pechora-Kolva aulacogen, which emerged earlier on the Timan-Pechora plate, intensively developed at this time. The three rift systems make up a triple junction in the central part of the Barents Sea. Rifting on the Timan-Pechora plate, especially in its western Timan region was accompanied by basalt volcanism. The Khibiny and Lovozero major plutons dated at 378-362 Ma, as well as carbonatite intrusions and dykes of alkaline rock s are formed in the Kola megablock. Diamond-bearing kimberlite pipes emerged in the Mezen syneclise at this time.

The Late Paleozoic and Triassic Stage. The principal events of this time occurred in the Urals mobile belt. The Siberian continent advancing from the east collided with the East

European continent, and as a result the Urals ocean basin closed to form an orogen with a complicated nappe-fold structure and mountainous relief. A zone of foredeeps was formed along the orogen front, which includes within the limits of the map the Kosyu-Rogov, Synya and Upper Pechora basins. The basins are infilled with molasse sequences: coal-bearing deposits in the first and second basins and salt deposits in the third basin. The molasse sequences later also underwent folding and thrusting which extended to the platform edge of the Kosyu-Rogov basin and brought the pre-molasse basement onto the surface along the Chernyshov uplift. The Uralian deformations affected the eastern parts of the Timan-Pechora plate as well. These processes were active probably until the Middle Triassic.

Meanwhile, marine or even deep-water sedimentation was still in progress in the Pai-Khoi-Novaya Zemlya system. A steady subsidence with accumulation of shelf, mainly carbonate, deposits of moderate thickness also proceeded on the Timan-Pechora and Svalbard plates, i.e. practically in the whole Pechora-Barents sea basins. Analogous sediments but of lesser thickness accumulated in the Mezen syneclise in inner shelf environments.

In the Triassic, the subsidence of the Barents basin became more intense and the thickness of sediments reached several kilometres. At the same time, the Mezen syneclise and the main part of the Timan-Pechora plate became emergent, and a vast area of erosion appeared south of the Barents basin, as a result of which sedimentation in the basins became exclusively terrigenous: the Paleozoic terrigenous-carbonate succession was replaced by the Mesozoic terrigenous succession.

The Jurassic-Cretaceous and Paleogene Stage. The Pai-Khoi-Novaya Zemlya system became a zone of intensive tectonic activity at the end of the Triassic, with folding and thrusting. A foredeep, the Korotaikha basin, emerged in front of this system, whereas the Chernov uplift similar to the Chernyshov uplift appeared on its western edge. Deformations related to the thrusting of the Pai-Khoi-Novaya Zemlya system over the Svalbard plate resulted in compressional deformation on the eastern edge of the Svalbard plate; the same is true for the Pechora plate margin adjacent to the Chernov ridge. Deformations even affected the Lower Cretaceous deposits in places.

The Timan-Pechora plate experienced a slight subsidence during the Jurassic and Early Cretaceous, which reached 1000 m depth only in its coastal and offshore parts. In the Late Cretaceous and Paleogene, the onshore part of the plate became almost completely emergent; minor continental-marine sedimentation continued only in the coastal part and offshore.

A quite different picture was characteristic for the Barents sedimentary basin, where considerable subsidence was still in progress and marine sandy-clayey sediments of great thickness accumulated. Basic magmatism occurs mainly in the form of sills. North of the map area, sheets of Lower Cretaceous basalt on Franz Josef Land are assigned to this magmatism.

The Kara astrobleme, one of the largest impact structures on the Earth, was formed at the Cretaceous/Paleogene boundary.

The Neogene-Quaternary Stage. The main part of the region represented a low relief land area at this terminal evolutionary stage. However, the Timan Ridge was uplifted in the late Pliocene to form its present day mountainous topography. Uplifts were more intensive in the Polar Urals and especially in the Subpolar Urals, extending to the Pai-Khoi and Novaya Zemlya as well.

At the end of the Pliocene, a marine transgression advanced into the Barents Sea area and inundated the northern part of the continental Pechora plate.

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