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Petroleum geology of East Siberia

by

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CONTENTS

CONTENTS (continued)

ILLUSTRATIONS

ILLUSTRATIONS (continued)

ILLUSTRATIONS (continued)

TABLES

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ABSTRACT

The unmetamorphosed geologic section of the East Siberian region consists of upper Proterozoic clastic and carbonate sediments; Cambrian evaporites, carbonates, and black shales; Ordovician through Permian clastic and carbonate sediments; Triassic basaltic flows and intrusives; and Jurassic and Cretaceous clastic sediments.

During Early and Middle Cambrian time, a barrier reef extended across the region from southeast to northwest. Salt and anhydrite were deposited in the vast lagoon to the southwest behind this reef, and these evaporites are the principal seals for the oil and gas pools in this part of the basin. Black carbonaceous shale was deposited on the northeast (seaward) side of the reef.

The structure of the sedimentary section is typical of platforms; broad, gentle warps are complicated by smaller highs. Salt tectonics are responsible for much of the structural relief above the Middle Cambrian. An unconformity at the base of the Cambrian evaporites masks structure in the underlying upper Proterozoic, and many of the pools are in stratigraphic traps within the Proterozoic just below the unconformity. The Triassic basaltic flows, present at the surface over about half the platform, are a great deterrent to exploration. Dolerite dikes and sills, which intrude much of the sedimentary section, severely complicate interpretation of seismic data.

The total potentially favorable area of East Siberia for the occurrence of oil and gas is 3,230,000 km^2 (1,235,000 mi^2). This favorable area is equal to more than 40 percent of the conterminous United States.

The region is in the early stages of exploration. Drilling density is only one well per 3,200 km^2. This distribution is uneven, drilling having been concentrated in those areas where discoveries had already been made. Further, exploration seems to have been concentrated along the main rivers, the transportation arteries.

Deposits in the Lena-Tunguska province are in stratigraphic traps in Proterozoic to Cambrian clastic and carbonate sediments sealed by Cambrian salt and in anticlinal structures in areas of salt tectonics. Source beds seem to be Proterozoic. The pools in the Khatanga-Vilyuy province are in anticlines in Triassic, Jurassic, and Cretaceous clastic sedimentary rocks. Source beds are Permian carbonaceous shale.

Most discoveries have been gas; however, several fields have oil rings. The traps appear to have once been filled by oil. Later, regional uplift released pressure and allowed gas dissolved in formation waters and in oil to come out of solution and fill the traps, displacing the oil.

Commercial gas has been produced in the Yenisey-Khatanga and Vilyuy oil-gas regions.

The undiscovered petroleum resources of East Siberia are placed in the range 2.2 to 14.6 BB (billion barrels) recoverable oil and 72 to 278 Tcf (trillion cubic feet) recoverable gas. The mean estimates are 7.3 BB and 158 Tcf. Gas-hydrate deposits in the Lena-Vilyuy province, where permafrost is more than 400 m thick, are estimated to contain 27 Tcf of possibly recoverable gas.

INTRODUCTION

East Siberia is a vast, maturely dissected upland approximately 2,500 km wide in north-south and east-west directions (fig. 1). Total area is about 3.5 million km^2, which is about one-tenth of the total area of the Soviet Union. The term "East Siberia" is a geographic designation. The geologic element that coincides with East Siberia is the "East Siberian platform" or simply the "Siberian platform." The term "Siberian platform" has now been generally adopted in the Soviet literature and is used in this report.

Two oil-gas provinces are recognized in East Siberia: Lena-Tunguska and Khatanga-Vilyuy (fig. 2). In the Lena-Tunguska province the hydrocarbon source rocks are largely in upper Proterozoic-Lower Cambrian sediments, and the plays are in these same rocks. Both oil and gas have been discovered. In the Khatanga-Vilyuy province, the source rocks are upper Paleozoic and Mesozoic, and the plays are Mesozoic; only gas has been discovered here. Although the source rocks and plays of the two provinces are different, their general geology is such that both provinces can be treated as a unit in describing their structure, stratigraphy, and paleogeography. This approach is used in most Soviet works on the region, including the recent definitive treatment by Kontorovich and others (1981).

GEOGRAPHY

Up until the seventeenth century, East Siberia was inhabited by only a few thousand nomads. Russian fur traders and the military swept across this vast region, indeed half again as wide as the entire conterminous United States, during the first half of that century, establishing trading posts all the way to the Pacific Ocean. The region was not extensively colonized, however, until the second half of the nineteenth century (Lydolph, 1970).

Most of East Siberia is the Middle Siberian Plateau, a maturely dissected upland where elevations range from 200 to 1,000 m. Lowlands (less than 200 m elevation) are present in the northeast along the lower course of the Lena River and in the north as the North Siberian Lowland, which is topographically and geologically an extension of the West Siberian Lowland. Both these lowland areas are within the Khatanga-Vilyuy oil-gas province.

The climate of East Siberia is cold and dry. January temperatures range from an average of -40 °C (-40 °F) in the north to -20 °C (-4 °F) in the south. Average July temperatures range from 6 °C (43 °F) in the north to 20 °C (68 °F) in the south. Most of the region receives less than 10 cm (4 in.) of precipitation between November and March and 10 to 30 cm (4 to 12 in.) between April and October. Duration of snow cover is from 185 to 230 days.

The northern part of East Siberia, the area in general to the north of 70° N. latitude, is a barren tundra. This is about one-fifth of the study region. The rest of the region is a taiga where larch, which has a shallow root system and can grow on permafrost, is the predominant tree. Pine, birch, and spruce forests are abundant in the south in areas of less permafrost.

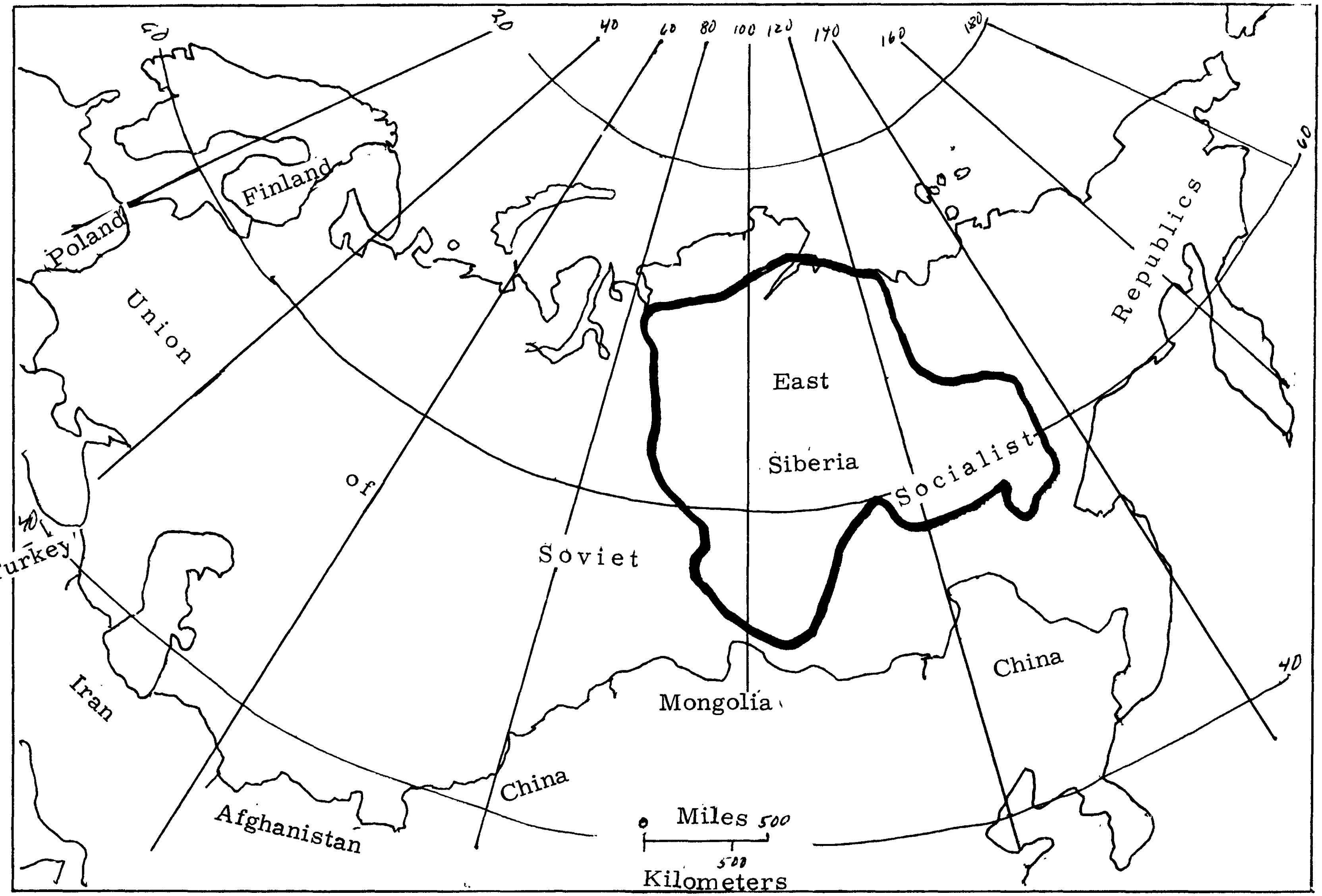


Figure 1. Location map for East Siberia.

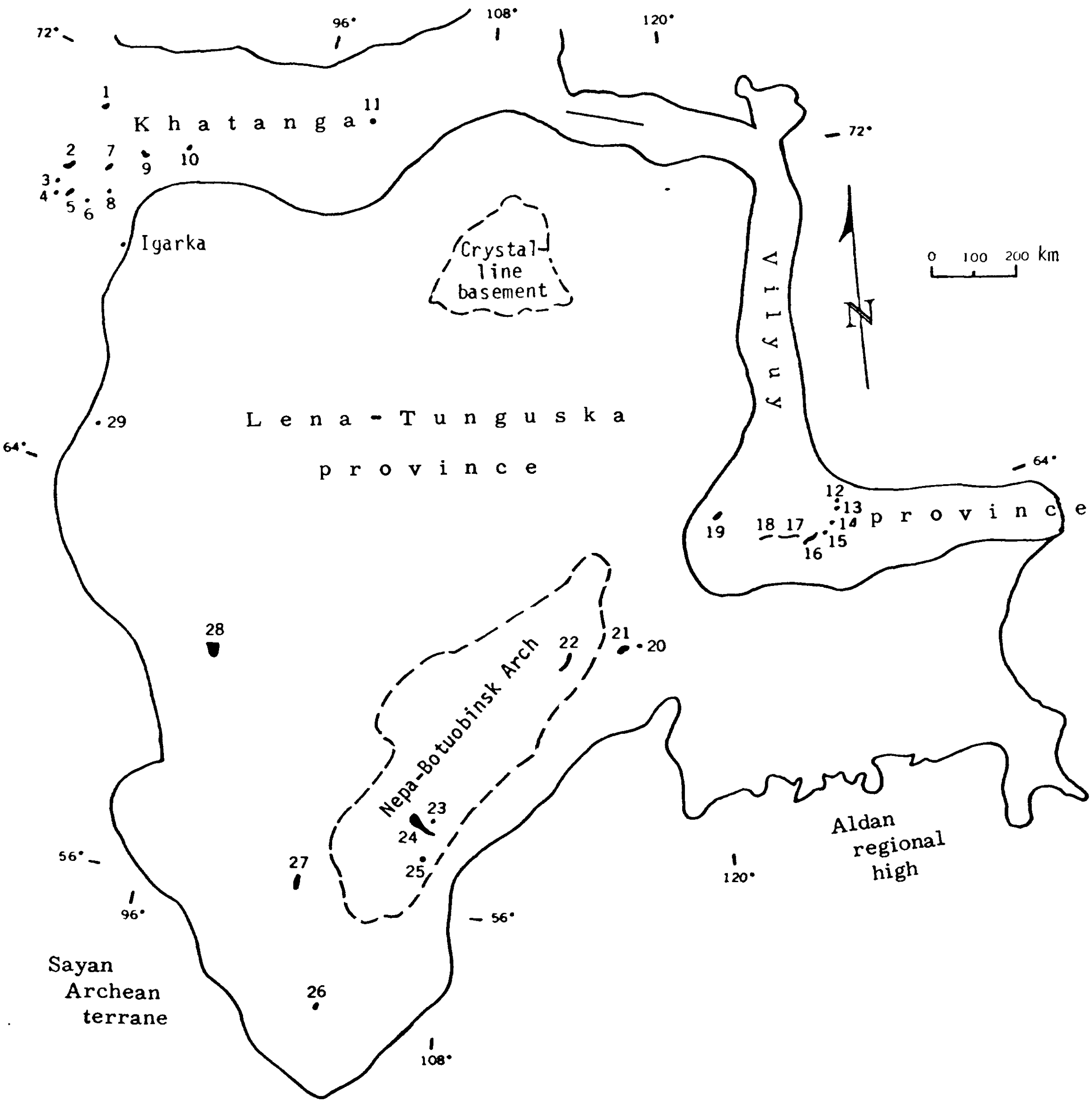


Figure 2. Oil-gas provinces of East Siberian platform, gas and oil fields:

1 - Deryabin
2 - Pelyatkin
3 - Severo-Solenin
4 - Yuzhno-Solenin
5 - Messoyakh
6 - Zimneye
7 - Kazantsev
8 - Nizhnekhet
9 - Ozer
10 - Dzhangod
11 - Balakhnin
12 - Sobo-Khain
13 - Ust-Vilyuy
14 - Nizhnevilyuy
15 - Badaran
16 - Sobolokh-Nedzhelin
17 - Tolon-Mastakh
18 - Srednevilyuy
19 - Srednetyung
20 - Vilyuysko-Dzherbin
21 - Verkhnevilyuchan
22 - Srednebotuobinsk
23 - Ayan
24 - Yaraktino
25 - Markovo
26 - Atov
27 - Brat
28 - Kuyumba
29 - Podkamen

Permafrost is present throughout almost all of East Siberia. It is continuous in the northern half of the region and as much as 650 m (2,000 ft) thick (Suslov, 1961; Cherskiy and others, 1983). In the southern half are islands of thawed ground, which increase in number and size toward the south. Extensive deposits of gas hydrate are associated with this permafrost.

The region is very sparsely inhabited. Population density is less than one person per square kilometer over most of the area. These people are largely the native Evenks and Yakuts. Greater population densities of up to ten per square kilometer are found along the rivers, and these people are largely Russians.

ACKNOWLEDGMENTS

Constructive discussions with Gregory Ulmishek, James A. Peterson, Charles D. Masters, and Jack Rachlin contributed greatly to preparation of this report, as did also the deliberations of the Resource Appraisal Group of the Branch of Oil and Gas Resources of the U.S. Geological Survey (USGS). The source material for the study was published literature that is on deposit in the USGS library at the USGS National Center in Reston, Virginia. The literature available was felt to be quite adequate for synthesizing the geologic history of the region and estimating the undiscovered oil and gas resources.

STRUCTURE

Crustal Thickness

Information on the crust of the Siberian platform is based on extensive magnetic, gravity, and seismic surveys. About 20,000 km of seismic profiles have been run. Nuclear explosions appear to have been used extensively in deep seismic sounding.

Thickness of the granitic crust is 15 to 18 km, and that of the basaltic crust ranges from 20 km in the south to 30 km in the north. Depth to the M-discontinuity ranges from 33 to 48 km (fig. 3).

In general, the crust is thinnest beneath basins in the sedimentary section and thickest beneath regional structural highs. For example, in the Yenisey-Khatanga regional low, the basement has downwarped to depths of 10 to 12 km, and the M-discontinuity stands very high at a depth of only 33 km. In the Vilyuy and Tunguska basins the M-discontinuity also stands high. On the Aldan and Anabar regional highs, however, the M-discontinuity is much deeper. It is below 48 km on the Anabar massif, where crystalline basement is exposed at the surface.

The major structural highs and lows of the Siberian platform thus developed in response to isostatic adjustment of the crust as reflected in the configuration of the M-discontinuity.

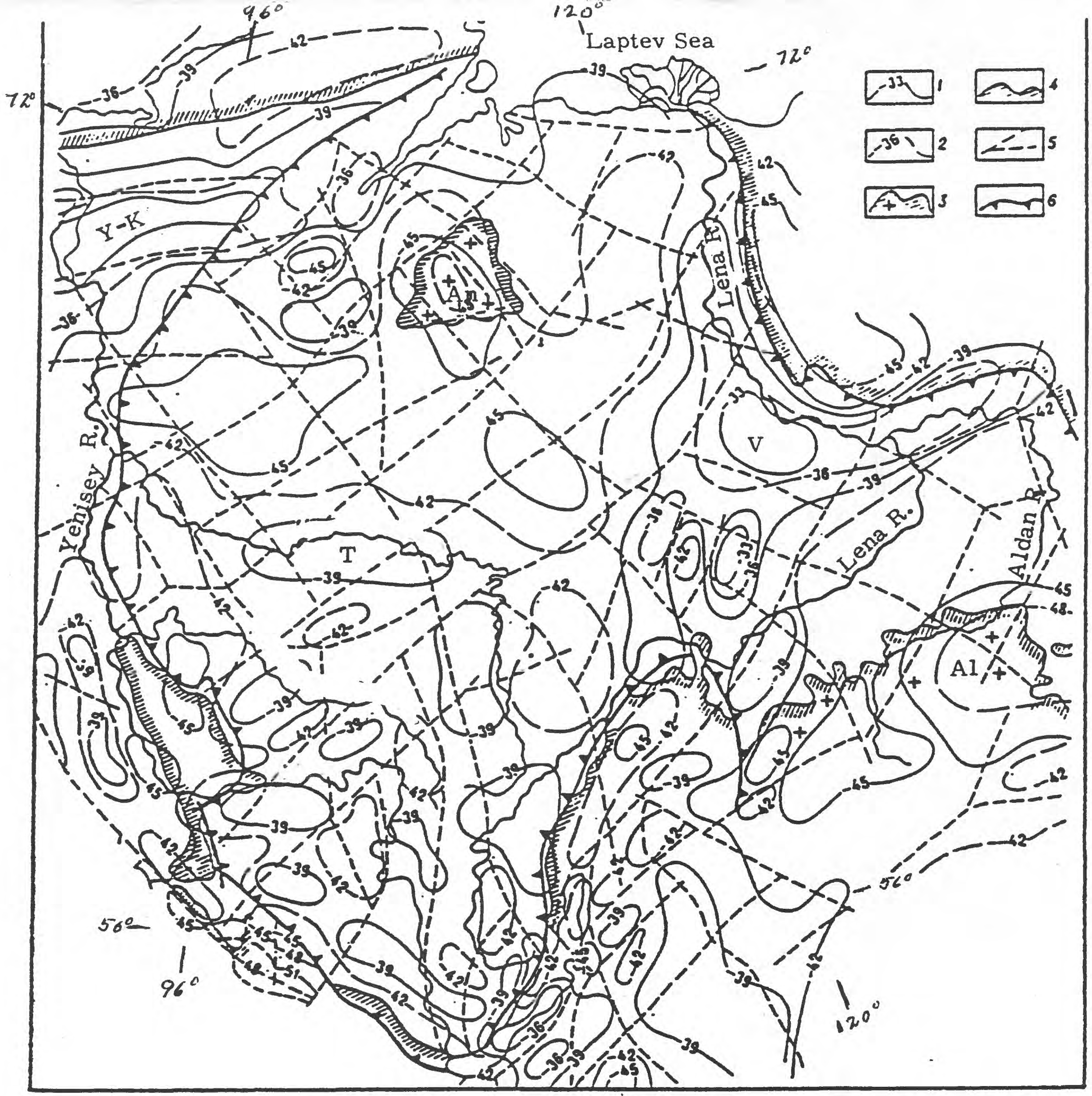


Figure 3.--Map of relief of Mohorovicic surface of East Siberia (after Kontorovich and others, 1981, p. 149). Structural contours on M-discontinuity, km: 1 - principal; 2 - auxiliary; 3 - crystalline basement exposed at surface; 4 - folded frame of platform; 5 - faults bounding crustal blocks; 6 - present margin of ancient Siberian craton.

Y-K - Yenisey-Khatanga regional low
V - Vilyuy Basin
T - Tunguska Basin
Al - Aldan regional high
An - Anabar regional high

Structure of Basement

The folded basement of the Siberian platform formed during a time of nearly three billion years, beginning in the Middle Archean (3.3 b.y.) and reaching completion in the Late Proterozoic (0.7 b.y.). Two large structural subdivisions are recognized: the Aldan-Anabar and the Tunguska (fig. 4). This basement is covered everywhere by sedimentary rocks except on the Anabar and Aldan arches and in some places along the margins of the East Siberian platform.

Aldan-Anabar Structural Subdivision

The Aldan-Anabar structural subdivision consists of the Iyengr massif, Aldan and Anabar fold systems of early Archean age, the Batomg fold system of late Archean age, and the early Karelide Olekmin and Olenek fold systems. These fold systems are separated from one another by faults.

Iyengr massif.--The Iyengr massif is located in the eastern part of East Siberia and is elongate in a north-northeast direction (fig. 4). The Iyengr series here consists of schists and gneisses of the granulite and amphibolite facies. The massif is cut by faults into several blocks. A few mafic and ultramafic bodies are present within the massif. The terrane is more than 3,300 m.y. old.

Aldan fold system.--The Aldan fold system is a northwest trending fold system in the southeast part of East Siberia. The predominant rock types are granulitic gneisses and schists, and several mafic and ultramafic bodies are present. The age of this fold belt is greater than 3,300 m.y.

Anabar fold system.--The Anabar fold system extends as a wide belt from the Laptev Sea on the north almost to Lake Baykal in the south. Hypersthene-plagioclase gneisses and schists of granulite facies are the predominant rock types. A series of closely spaced mafic and ultramafic bodies occur along its contact with the Tunguska structural subdivision on the west. The Anabar fold system is Early Archean and older than 3,300 m.y.

Batomg fold system.--The Batomg fold system is in the eastern part of the East Siberian platform. It is composed of charnockites, anorthosites, plagioclase gneisses, amphibolites, marbles, metadiorites, and metagabbros. It is Late Archean in age, older than 2,600 m.y.

Olekmin fold system.--The Olekmin fold system in the southern part of East Siberia consists of Early Archean, Late Archean, and Early Proterozoic structural units. The Early Archean rocks are plagiogranites and charnockites. The Late Archean units are biotite gneisses and schists. The Early Proterozoic rocks are volcanic and clastic complexes and granites. Their age is placed at greater than 1,900 to 2,000 m.y.

Olenek fold system.--The Olenek fold system is in the northeast part of the East Siberian platform. It is composed of metasediments intruded by silicic and basic bodies. Its age is greater than 2,000 m.y.

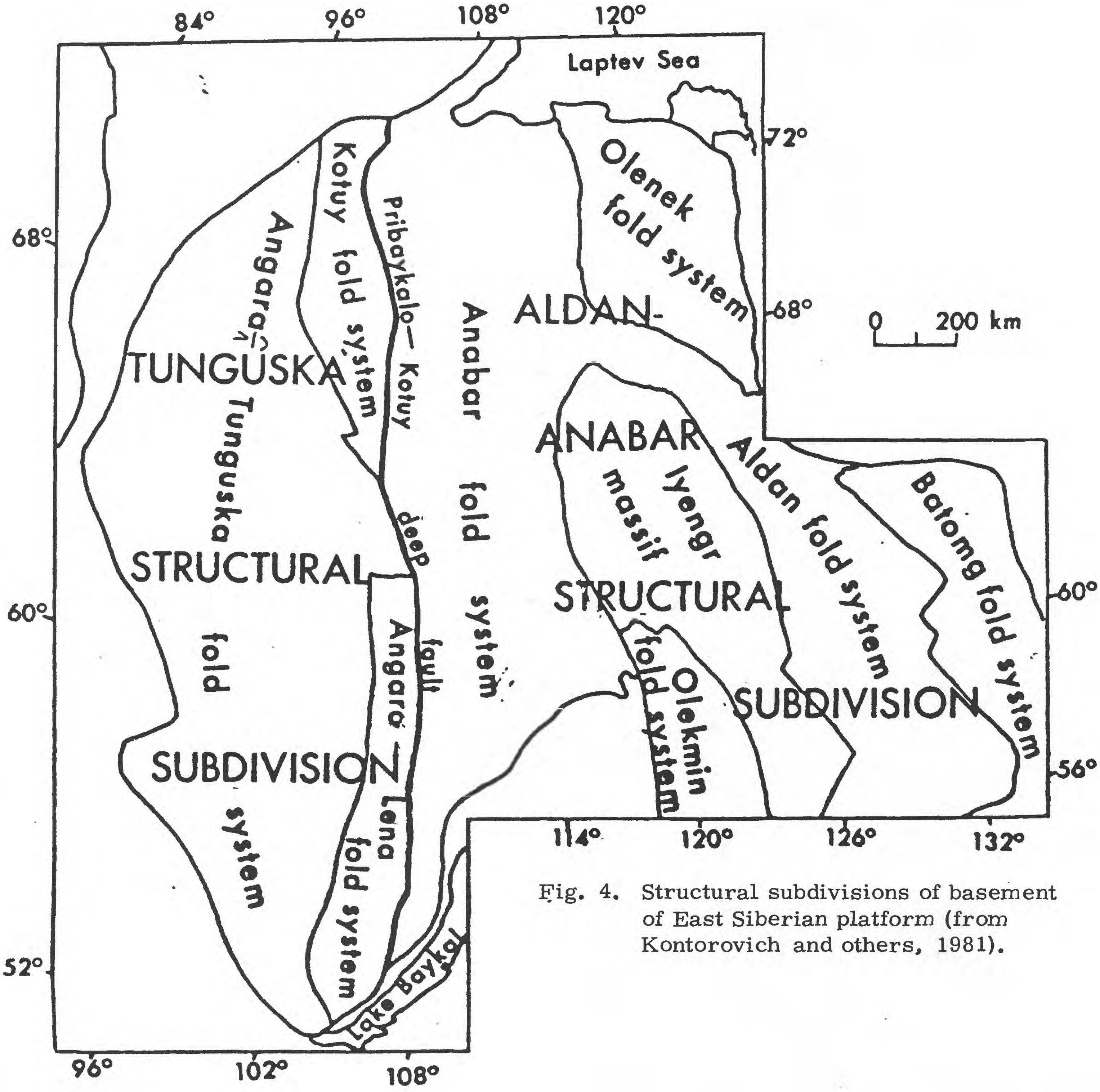


Fig. 4. Structural subdivisions of basement of East Siberian platform (from Kontorovich and others, 1981).

Tungusska Structural Subdivision

The Tunguska structural subdivision extends over the western third of the Siberian platform. It is separated from the Aldan-Anabar structural subdivision by the Pribaykalo-Kotuy deep fault, along which are closely spaced mafic and ultramafic bodies. Within the Tunguska structural subdivision are the Angara-Tunguska, Angara-Lena, and Kotuy fold systems.

Angara-Tunguska fold system.--The Angara-Tunguska fold system consists of terranes of both Early and Late Archean age. The early Archean rocks are biotite, hornblende, and pyroxene gneisses; granites and migmatites are widespread. The rocks are alternating gneisses, schists, marbles, and amphibolites. The age of this fold belt is greater than 2,600 m.y.

Angara-Lena and Kotuy fold systems.--These two systems are late Karelide features, older than 1,700 m.y. Granites and migmatites are abundant in these terranes.

Relief of Basement Surface

The surface of the basement of the Siberian platform is a contact between the highly metamorphosed pre-Riphean basement complex and the sedimentary-volcanic cover. The morphological elements of this surface formed as a result of protracted epeirogenic oscillations of the Earth's crust accompanied by multistage block tectonics. Three broad regions are recognized: Tunguska regional low, Irkutsk amphitheater, and Aldan-Anabar province (fig. 5) (Kontorovich and others, 1981, p. 168).

In the Tunguska regional low, depth to basement is 4 to 5 km and in places 6 to 7 km. The basement surface is relatively smooth, and the highs and lows have a general northwest trend. Closure on these forms is generally 1.0 to 1.5 km.

The Irkutsk amphitheater contains a northeast-trending high in the east (Nepa-Botuobinsk regional high) and a region of deep subsidence on the west (Kansko-Taseyev depression). The crest of the Nepa-Botuobinsk regional high is at -1.5 km, and it closes on the -2.25-km structural contour. The deepest part of the Kansko-Taseyev depression is at -7 km.

The Aldan-Anabar province of relatively high occurrence of the basement surface is divided by the Vilyuy depression and by a shallower downwarp into three large highs, the Anabar, Olenek, and Aldan. Basement is exposed on the Anabar high in the north and on the Aldan high in the southeast (see also fig. 6A).

Structure of Sedimentary Cover

The Siberian platform is divided broadly into two parts: the pre-Mesozoic part and the Mesozoic marginal depressions. In the pre-Mesozoic part, the Paleozoic and Proterozoic sections are generally more than 2 km thick and

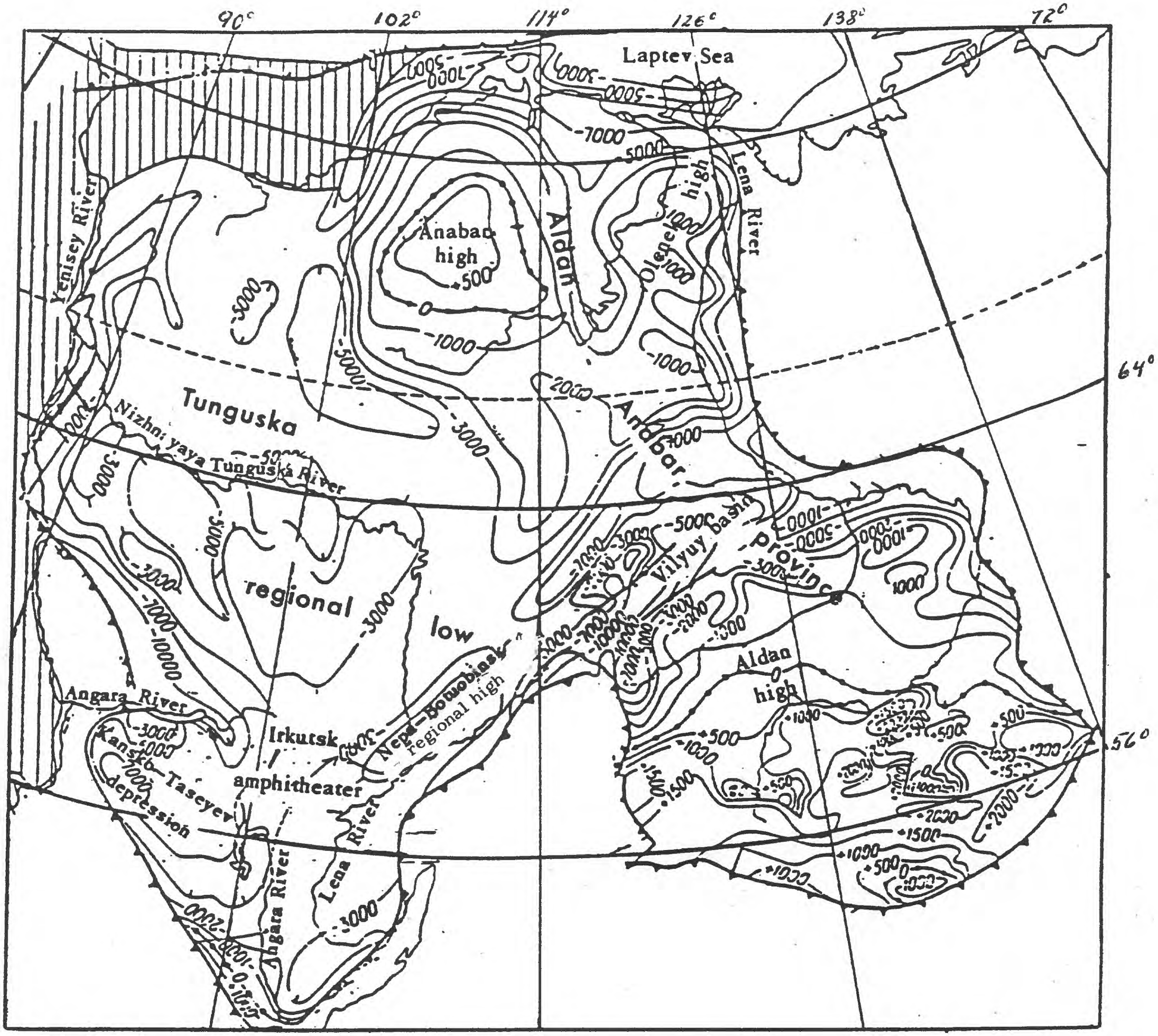


Figure 5.--Structure contours in meters on surface of basement of Siberian platform (from Provodnikov, 1975, p. 50).

reach 8 to 12 km; rarely are more than a few hundred meters of Mesozoic deposits found except for Triassic dolerites. In the Mesozoic marginal depressions, thickness of Mesozoic clastic deposits is up to 7 km. The large "super-order" structures (fig. 6A, I-XII) are described here briefly. First-order structures are identified on the map (fig. 6A, 1-58), and many of these are referred to in other parts of this report. Several first-order structures along the western margin of the platform are not within the boundaries of the super-order structures. Figure 6B shows two cross sections.

Structures of the Pre-Mesozoic Part of the Siberian Platform

The Anabar regional high (anteclise) has an area of 760,000 km^2; it is equant in shape and 1,000 to 1,100 km wide (fig. 6A, I). From the Anabar and Olenek highs (see also fig. 5), the basement subsides to levels of -2.5 to -3.0 km on the margins. The structurally lowest level is at -5.0 km in the Sukhan depression between the Anabar and Olenek highs. The sedimentary section is predominantly clastic and carbonate rocks of Riphean and early Paleozoic age.

The Baykit regional high (fig. 6A, II) is an elongate feature in the southwest part of the Siberian platform along the Podkamennaya-Tunguska River. Its area is about 120,000 km^2. It is separated from the Yenisey Range on the west by the very narrow Turin megadownwarp. The sedimentary cover here is largely Riphean and lower Paleozoic clastic and carbonate rocks; Cambrian salt is also present. Upper Paleozoic and Triassic deposits 0.5 to 1.0 km thick are present in the north part of the area.

The Nepa-Botuobinsk regional high (fig. 6A, III) is a northeast-elongated arch that has an area of about 220,000 km^2. Basement is at -1.2 km at the crest and -2.5 to -3.0 km on the flanks. The section is largely salt-bearing clastic and carbonate sediments of early Paleozoic age. Proterozoic clastics of Vendian age are present on the flanks. Clastic coal-bearing rocks of late Paleozoic and Jurassic age and some Triassic volcanics occur on the northwest and north flanks.

The Aldan regional high (fig. 6A, IV) covers a rectangular area of more than 650,000 km^2 in the southeast part of the platform. Its long dimension is about 1,000 km. Crystalline basement is exposed across most of the southern half. The sedimentary section is largely lower Paleozoic clastic and carbonate rocks. A thin cover of Jurassic deposits is present on the north.

The Tunguska regional low (syneclise) (fig. 6A, V) covers an area of more than one million km^2 in the western part of the Siberian platform. It is expressed only in the upper Paleozoic and Triassic rocks, the thickness of which ranges from 1.0 km in the south to 3.0 km in the northwest. In the north the Tunguska regional low overlaps completely the Kurey regional low, and on the south it covers parts of the Baykit and Nepa-Botuobinsk regional highs and the Sayan-Yenisey regional low. These overlapped structures are expressed only on pre-upper Paleozoic horizons.

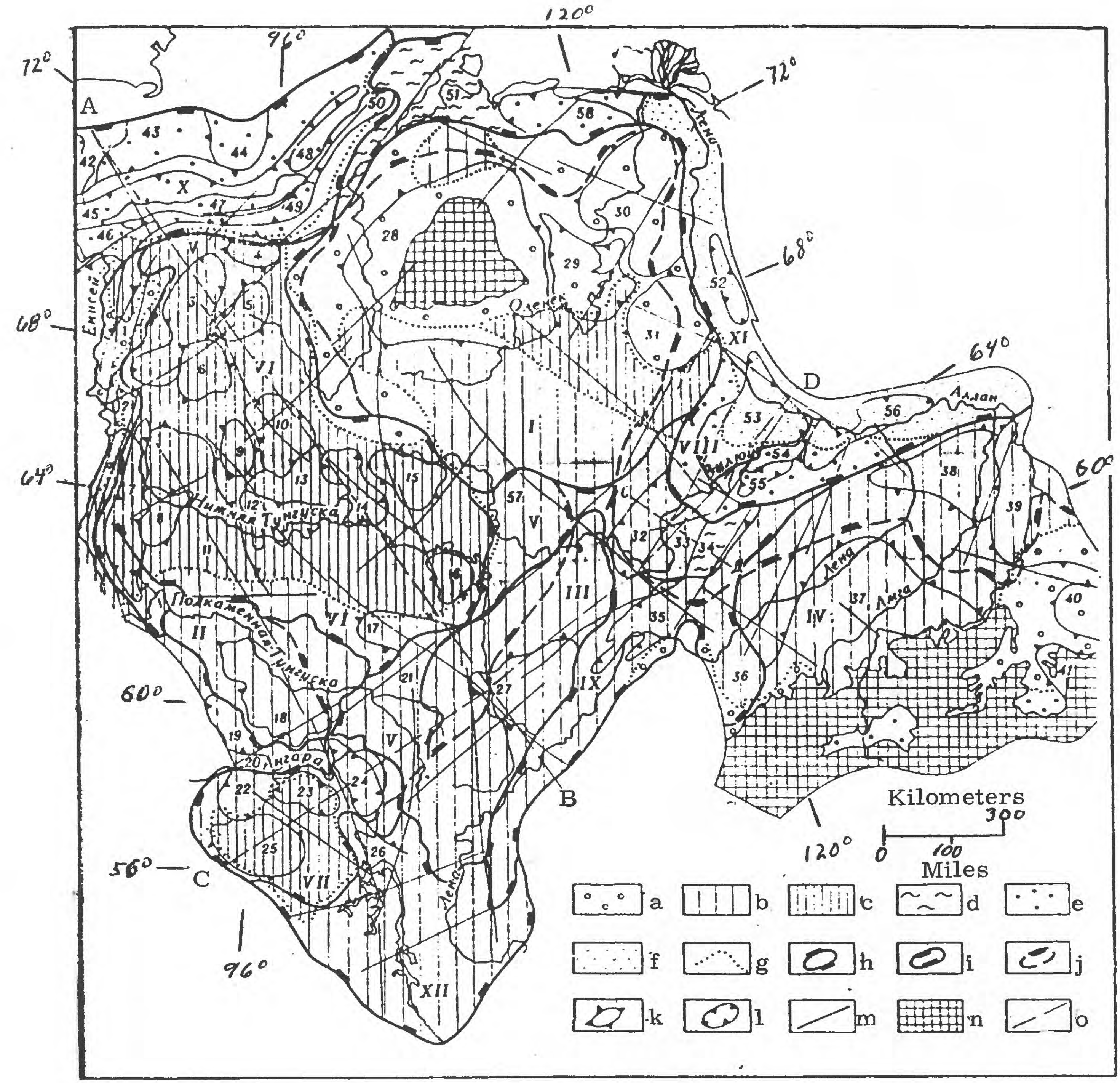


Figure 6A.--Tectonic map of sedimentary volcanic cover of the Siberian platform (from Kontorovich and others, 1981, p. 175).

Main stages of formation of cover: a - Riphean, b - Vendian-Middle Cambrian, c - Vendian-Ordovician, d - early-middle Paleozoic, e - late Paleozoic-Mesozoic, f - Late Cretaceous; g - boundaries of regions of different main stages of formation of cover. Very large structures: h - positive, i - negative, j - superimposed marginal zones of negative structures. Large structures: k - positive, l - negative; m - very large faults; n - basement exposed at surface; o - lines of profile.

I, Anabar regional high; II, Baykit regional high; III, Nepa-Botuobinsk regional high; IV, Aldan regional high; V, Tunguska regional low; VI, Kurey regional low; VII, Sayan-Yemisey regional low; VIII, Vilyuy basin, IX, Cis-Patom regional downwarp; X, Yenisey-Khatanga regional downwarp; XI, Cis-Verkhoyansk foreland downwarp; and XII, Angara-Lena structural step.

Structures: 1 - Khantay-Rybnin mega-arch, 2 - Kurey-Baklanikhin mega-arch, 3 - Lam-Khantay megadownwarp, 4 - Ledyan arch, 5 - Ayan arch, 6 - Anam arch, 7 - Nizhnetunguska megadownwarp, 8 - Suringdakon arch, 9 - Yukteliy arch, 10 - Verkhnekochechum depression, 11 - Bakhtin megahigh, 12 - Turin depression, 13 - Kochechum arch, 14 - Korvunchan depression, 15 - Turun arch, 16 - Ilimpey arch, 17 - Chun high, 18 - Kamov arch, 19 - Terin megadownwarp, 20 - Angara zone of folds, 21 - Katanga saddle, 22 - Boguchano-Manzin high, 23 - Mursko-Chun depression, 24 - Kat depression, 25 - Dolgomostov depression, 26 - Bratsk high, 27 - Nepa arch, 28 - Anabar mega-arch, 29 - Sukhan depression, 30 - Olenek arch, 31 - Mun arch, 32 - Ygyattin depression, 33 - Suntar arch, 34 - Kempendyay depression, 35 - Nyuy-Dzherbin depression, 36 - Berezov depression, 37 - Tolbin megahigh, 38 - Yakutsk arch, 39 - Aldan-Maysk depression, 40 - Omnin arch, 41 - Idyumo-Khaykan high, 42 - Taymyr high, 43 - Pyasin hemi-depression, 44 - Yangodo-Gorbit high, 45 - Central Taymyr megadownwarp, 46 - Tanamo-Malokhet mega-arch, 47 - Rassokhin mega-arch, 48 - Balakhnin mega-arch, 49 - Dudyptin-Boganid megadownwarp, 50 - Zhdanikhin megadownwarp, 51 - Khatanga saddle, 52 - Mengkeren megadownwarp, 53 - Linden depression, 54 - Khapchagay mega-arch, 55 - Yuzhno-Khapchagay megadownwarp, 56 - Lungkhin-Kelin megadownwarp, 57 - Syugdzher saddle, 58 - Lena-Anabar megadownwarp.

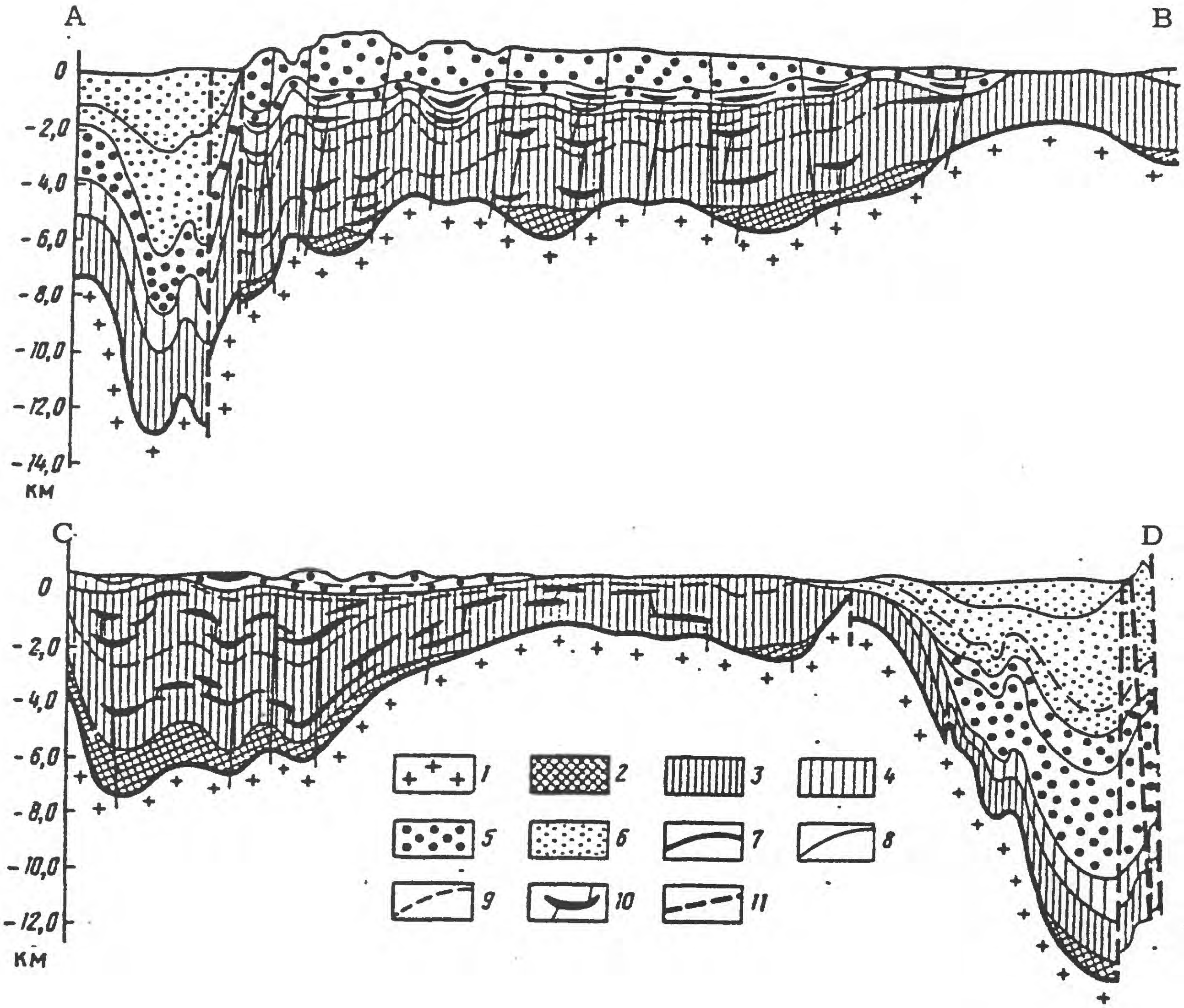


Figure 6B--Structure of platform cover along profiles A-B and C-D (fig. 6A) (from Kontorovich and others, 1981).

1 - Crystalline basement; structural stages of platform cover: 2 - Riphean, 3 - lower Paleozoic, 4 - middle Paleozoic, 5 - upper Paleozoic and Triassic, 6 - Jurassic-Lower Cretaceous and Upper Cretaceous-Paleogene; boundaries: 7 - basement and cover, 8 - structural stages, 9 - structural substages; 10 - magmatic bodies (thin, steeply dipping lines are dikes); 11 - main faults.

The Angara-Lena structural step (fig. 6A, XII) in the southern-most part of the Siberian platform has an area of about 200,000 km^2. The basement surface is but little differentiated, its position ranging from -2.0 km to -3.0 km. The sedimentary section consists largely of Riphean-Vendian clastic deposits and Cambrian salt-bearing clastic and carbonate deposits. Thin Ordovician, Silurian, and Jurassic sediments are also present.

Structures of the Mesozoic Marginal Depressions

The Yenisey-Khatanga regional downwarp (fig. 6A, X) extends for about 1,200 km along the north margin of the Siberian platform; it is 200 to 400 km wide. On the west it opens out into the West Siberian platform and is a geologic continuation of this feature.

Depth to basement is 8 to 12 km in the central part of the downwarp and 5 to 6 km on the north and south flanks. Lower and middle Paleozoic carbonate and clastic deposits are 1 to 5 km thick. The upper Paleozoic section consists largely of sandy-clayey and coal-bearing rocks, which are 2 to 4 km thick. Jurassic and Cretaceous rocks, largely Lower Cretaceous, compose more than half the section. These are marine sandy-clayey rocks, and their thickness is 5 to 9 km.

The Cis-Verkhoyansk foreland downwarp (fig. 6A, XI) separates the Mesozoic Verkhoyansk fold system from the Siberian platform. The boundary with this fold system is a series of overthrust faults.

The downwarp is more than 1,000 km long and about 150 km wide. It is divided into a northern (north-south-trending) segment and an eastern (east-west-trending) segment by a large basement high at the site of the change in trend.

In the northern segment of the downwarp, Permian and Mesozoic sediments are 1 to 6 km thick. Area of the segment is 133,000 km^2. In the eastern segment, Paleozoic sediments are thicker, and some Riphean deposits are found. Also, up to 1,000 m of Neogene sediments are present. Total thickness is 5 to 12 km. The eastern segment covers 62,000 km^2.

The Vilyuy basin (fig. 6A, VIII) in the eastern part of the Siberian platform is divided into three large tectonic elements: outer (western), transitional, and inner (eastern) zones. (These zones are not designated in figure 6.)

In the outer zone, Lower and Middle Jurassic continental deposits dip gently toward the central regions of the basin. In the transitional zone, Permian and older Paleozoic sediments, as well as thicker Mesozoic deposits, are present. In the inner zone, the section is 8 to 10 km thick and consists largely of Permian and Mesozoic deposits. Lower and middle Paleozoic deposits here are 2 to 3 km thick and generally at depths greater than 7 km. Total area of the Vilyuy basin is 310,000 km^2.

STRATIGRAPHY AND PALEOGEOGRAPHY

Introduction

The sedimentary cover of the Siberian platform was deposited during a time span of well over a billion years. In spite of the late Precambrian age of the older of these sediments, they have not been metamorphosed, and commercial oil and gas have been found within the oldest (Riphean carbonates at Kuyumba). Total thickness of the sedimentary cover is up to 12 km. East Siberia is a frontier exploration region, and much new information is now appearing in the literature on the stratigraphy as exploration drilling moves out into areas where drilling density is low.

Since the time span of deposition of the sedimentary cover was so long, the environment of deposition changed markedly from time to time. In general, however, land areas were on the south and west and open sea to the north and east.

The ages of the stratigraphic units present in the sedimentary section of the Siberian platform are Riphean and Vendian of the Late Proterozoic, Cambrian, Ordovician, Silurian, Devonian, Early Carboniferous, Middle and Late Carboniferous, Permian, Triassic, Jurassic, Cretaceous, and Neogene.

Riphean Series

The Riphean Series and the overlying Vendian Series constitute the upper Proterozoic of the Siberian platform. The lower Riphean is not widespread and is not considered here. The middle and upper Riphean have been studied extensively in outcrop and in core and are exploration targets (Trunov, 1975, p. 21-41).

At the beginning of the middle Riphean about 1,350 m.y. ago, the Siberian platform was a broad, low continent with seas along all its margins. Shelf seas encroached onto the platform on the north and east. A geosynclinal basin was present on the west, south, and southeast (fig. 7).

Thick clastic sediments, carbonates, and volcanics were deposited in the outer (toward the Siberian platform) miogeosynclinal part of the geosynclinal basin. The source area was the platform as well as volcanic islands along the boundary between the miogeosynclinal and eugeosynclinal zones.

In the shelf seas of the north and east were deposited thin, shallow-water sandstones and dolomites; these are typical platform deposits - algal dolomites and quartz sandstones that thin with distance from the source.

The paleogeography at the beginning of the late Riphean was the same as that of the middle Riphean; however, uplift in the eugeosynclinal areas off to the south and west resulted in the detritus being derived largely from these new high areas. The Siberian platform itself remained low. Orogenic uplift in these geosynclinal areas in the last half of the late Riphean led to a shift of the seaways toward the platform (fig. 8). The shelf seas on the north and east receded.

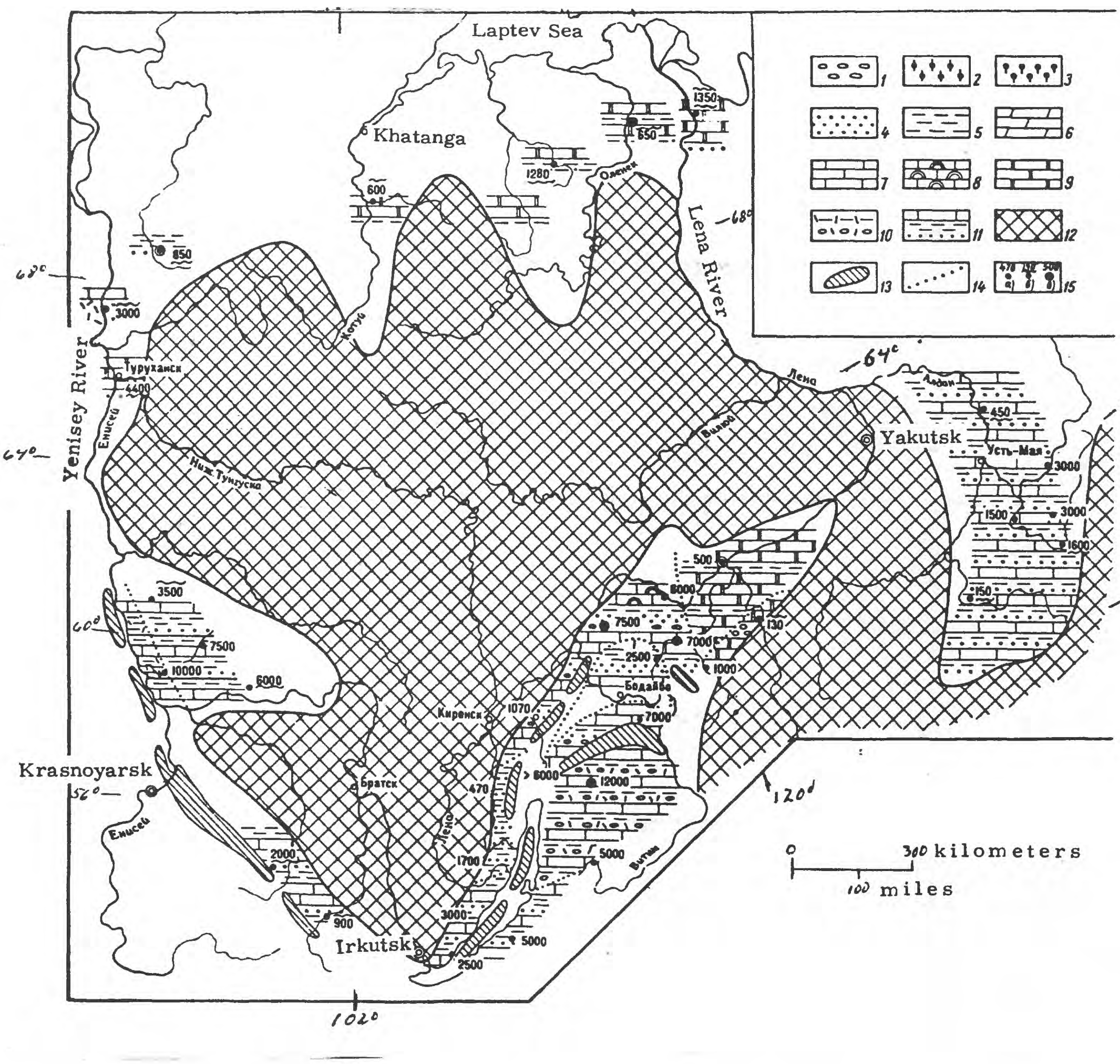


Figure 7.--Lithologic-paleogeographic map of the Siberian platform for the middle and first half of the late Riphean (from Trunov, 1975).

1, gravels; 2, polymict sands; 3, arkosic sands; 4, quartz sands; 5, clays, silts; 6, marls; 7, limestones; 8, algal limestones; 9, dolomites; 10, silty-clayey and coarse-clastic rocks with beds of silicic effusives; 11, schematic section for this entire stratigraphic unit; 12, stable land area; 13, land area periodically covered by the sea; 14, boundaries of lithofacies complexes; 15, thickness in meters of sedimentary sections (a - complete, b - incomplete due to absence of upper or lower part, c - thickness of a well section).

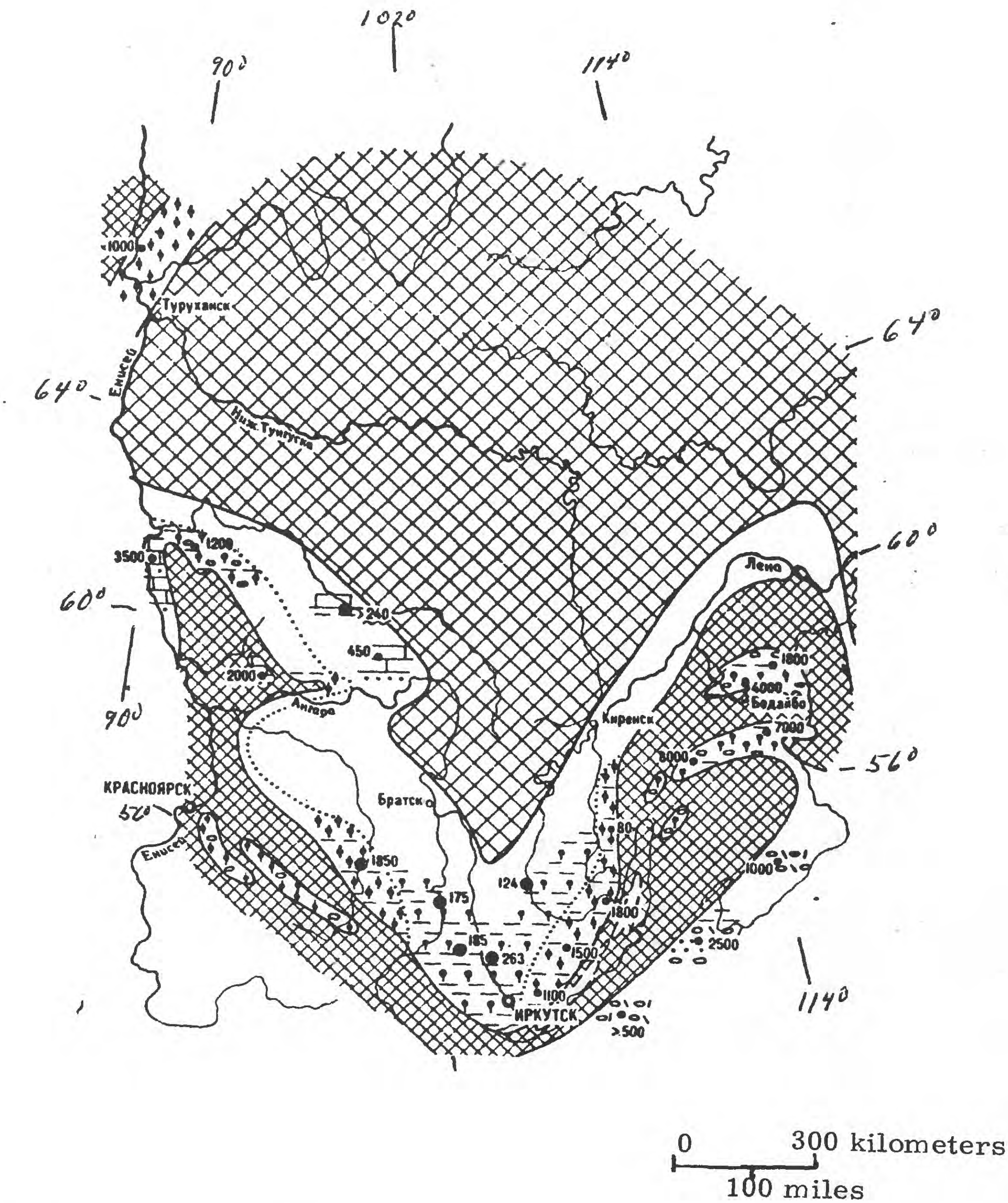


Figure 8.--Lithologic-paleogeographic map of Siberian platform for second half of late Riphean time. Symbols same as in figure 7.

The Riphean section of the Kamov arch in the western part of the Siberian platform is described here because it has had significant study. Commercial oil and gas are present here in middle Riphean dolomites in the Kuyumba field (fig. 9). At the base of the middle Riphean section is the Krasnogor Formation, which consists of 160 m of silty shale. Above this is about 620 m of dolomite of the Dzhur Formation. The overlying Shuntar Formation consists of dark gray to black carbonaceous shale, dolomite, marl, and limestone. The limestones are commonly algal. Thickness is 240 m here, but elsewhere it is up to 600 m. The Krasnogor, Dzhur, and Shuntar Formations are the lower part of the Tungusik Series representing the middle Riphean in the region.

The Serogo-Klyucha Formation is a 200-m unit of gray to black limestones. Its thickness is as much as 650 m in other parts of the region. It overlies the middle Riphean concordantly. Next in the section is the Dadyktin Formation, which is a dark shale in the lower part and algal dolomite in the upper. Thickness is 520 m. The Serogo-Klyucha and Dadyktin Formations are the upper part of the Tungusik Series representing the upper Riphean in the region.

Vendian Series

A long erosional interval followed the Baykalian orogeny in late Riphean time (fig. 9). Renewed deposition in Vendian time was during the interval from 680 to 570 m.y. ago. The base of the Vendian is no problem; it is drawn at the pronounced post-Baykalide unconformity, although in the geosynclinal area adjacent to the platform on the south a continuous Riphean-Vendian section may be present in some places. The top of the Vendian, however, is a much debated matter and has been placed variously at the top of the Ushakov Formation, the top of the lower Moty Formation, the top of the upper Moty, and at the top of the Osin horizon (Kontorovich and others, 1981, p. 35). In this report, the base of the Cambrian, that is, the top of the Vendian, is placed at the base of the middle Moty Formation (figs. 9 and 13).

The Vendian stage began with downwarping of the Siberian platform and broad transgression of the sea along its margins (fig 10). Only in the second half of the stage was almost the entire platform covered. The most extensively studied areas are the Aldan regional high and the Angara-Lena structural step.

On the Aldan regional high (IV in fig. 6A), the Vendian is represented by the Yudoma Formation, which correlates well with the type locality of the Vendian of European Russia (Kirkinskaya and Polyakova, 1975, p. 43). The formation here consists largely of massive dolomite. The basal beds are sandstones and sandy dolomite. Thickness of the Yudoma is 120 to 280 m. Radiometric ages on glauconite from this unit are 580 to 685 m.y.

On the Angara-Lena structural step (XII in fig. 6A) in the region of the Atov and Bratsk highs, the Vendian consists of the Ushakovka Formation and the overlying lower Moty Formation.

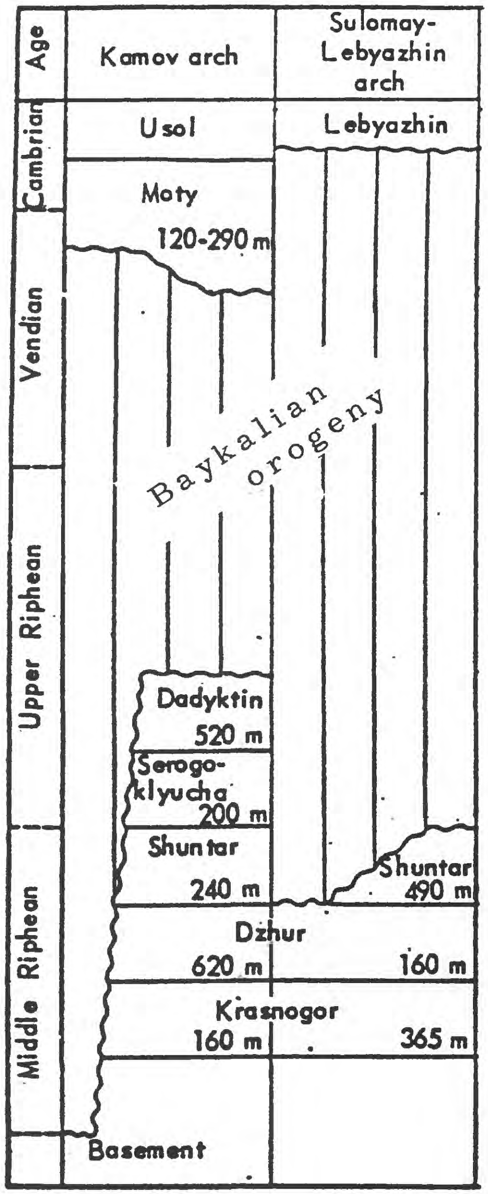
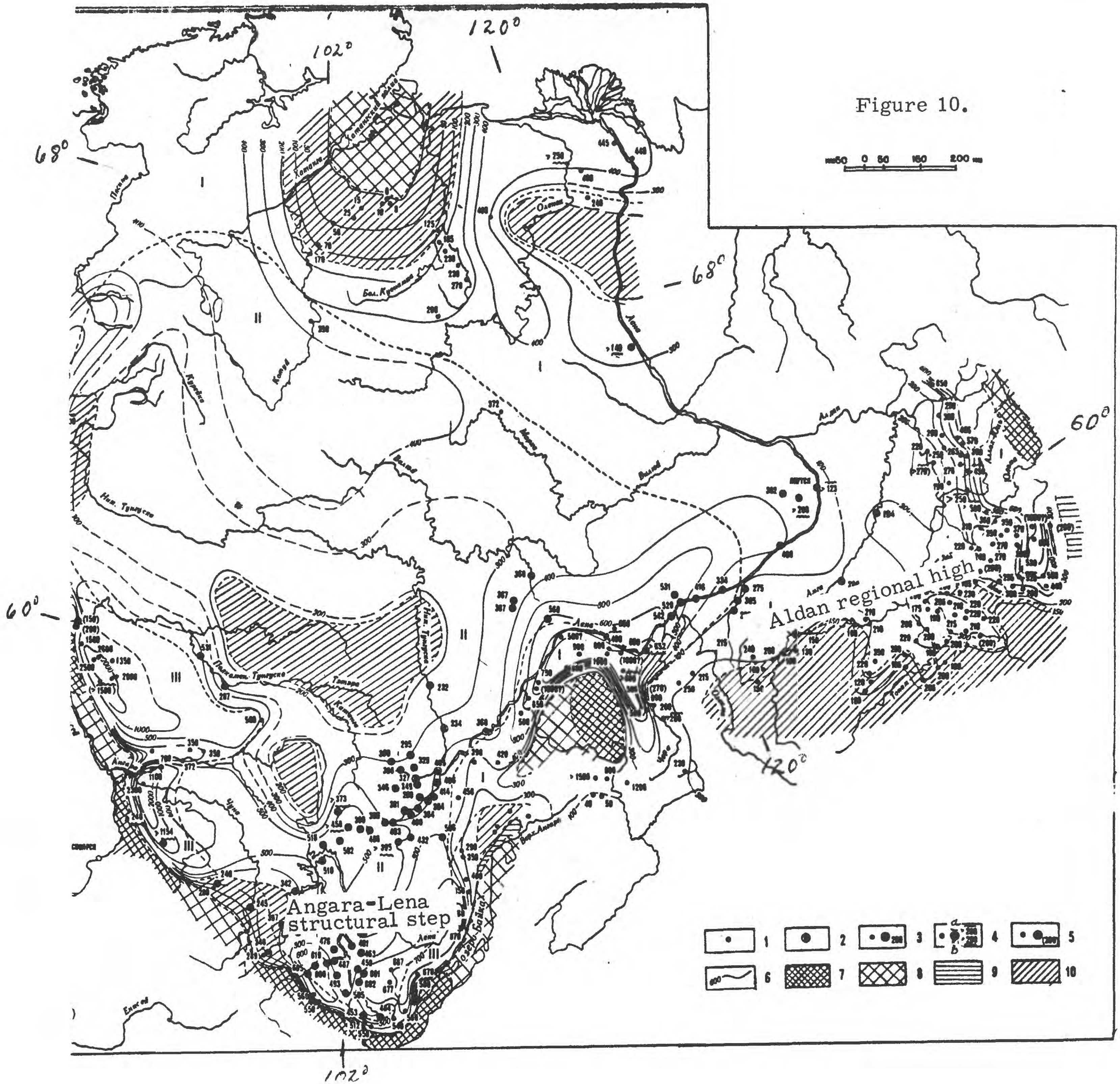


Figure 9.--Stratigraphic sections of the Kamov (18 on fig. 6A) and Sulomay-Ledyazhen arches. The latter is directly south of the Nizhnetunguska megadownwarp (7 on fig. 6A) on the western margin of the Siberian platform.

Figure 10.



Aldan regional high
Angara-Lena
structural step
120°
102°
68°
60°
1
2
3
4
5
6
7
8
9
10

Figure 10.--Isopach map of Vendian Stage of the Siberian platform (from Kirkinskaya and Polyakova, 1975, fig. 1).

1, outcrop; 2, drill hole; 3, thickness of sediments; 4, apparent thickness: a) without upper horizons, b) without lower horizons; 5, estimated thickness; 6, isopachs; 7, area of high mountains; 8, area of low mountains; 9, hilly plain; 10, land area only in early Vendian time; I, shallow open sea; II, basin with higher salinity; III, zone of shallow-water distillation of marine basin.

The Ushakovka Formation consists of sandstones, at the base of which is a thick conglomerate. The sandstones are gray, quartz-feldspathic, and medium- to coarse-grained. Thickness ranges from 30 to 1,300 m. Radiometric ages on glauconite from this unit are 597 and 609 m.y.

The Moty Formation rests on the eroded surface of the Ushakovka. It is widely distributed in the south part of the Siberian platform on the Angara-Lena structural step, the Sayan-Yenisey basin, Baykit regional high, Katanga saddle, and south flank of the Nepa-Botuobinsk regional high. It is exposed in outcrop and has been penetrated in numerous drill holes.

A cyclicity in sedimentation on a large part of the Siberian platform (fig. 11) began with deposition of the Moty Formation and continued uninterrupted on into the Middle Cambrian (Kontorovich, 1981, p. 42). Each cycle began with transgression and deposition of clastic rocks. These, typically but not everywhere, passed upward into carbonates and then into salt-carbonate sediments. Seven cycles are recognized in the Moty Formation (fig. 12). The boundary between the lower and middle Moty, and consequently between the Proterozoic and Cambrian, is in the upper part of the cycle mt-3.

The first cycle (mt-1) has sandstone and conglomerate at the base. Higher in the section are alternating siltstones and argillites. See figure 12 for thicknesses.

Cycle mt-2 begins with sandstones. The upper part is siltstone and argillite in some areas and sulfate-carbonate rocks in others.

At the base of cycle mt-3 are sandstones of the Parfenov Formation, which are productive in some areas. The middle part of this cycle is argillite and the upper is dolomite.

Cycle mt-4 consists of clayey dolomites, marls, and dolomites.

The next three cycles, mt-5, mt-6, and mt-7, are composed of carbonates and sulfate-carbonate rocks. Clayey varieties of carbonates are present in their lower parts. Salt beds appear in cycles mt-5 and mt-6 in the area of junction of the Sayan-Yenisey basin and the Angara-Lena structural step.

Radiometric ages determined on the Moty Formation range from 555 to 670 m.y. The upper part of the Moty is certainly Lower Cambrian (fig. 9).

Cambrian System

Aldan Stage.--The paleogeographic conditions of Vendian time continued into the Early Cambrian Aldan Stage uninterrupted (Kirkinskaya and others, 1975, p. 65). The entire Siberian platform was covered by an epicontinental sea, which was open ocean on the north and east and a salt basin on the south and west. The salt basin was bounded on the north and east by a reef belt (fig. 11).

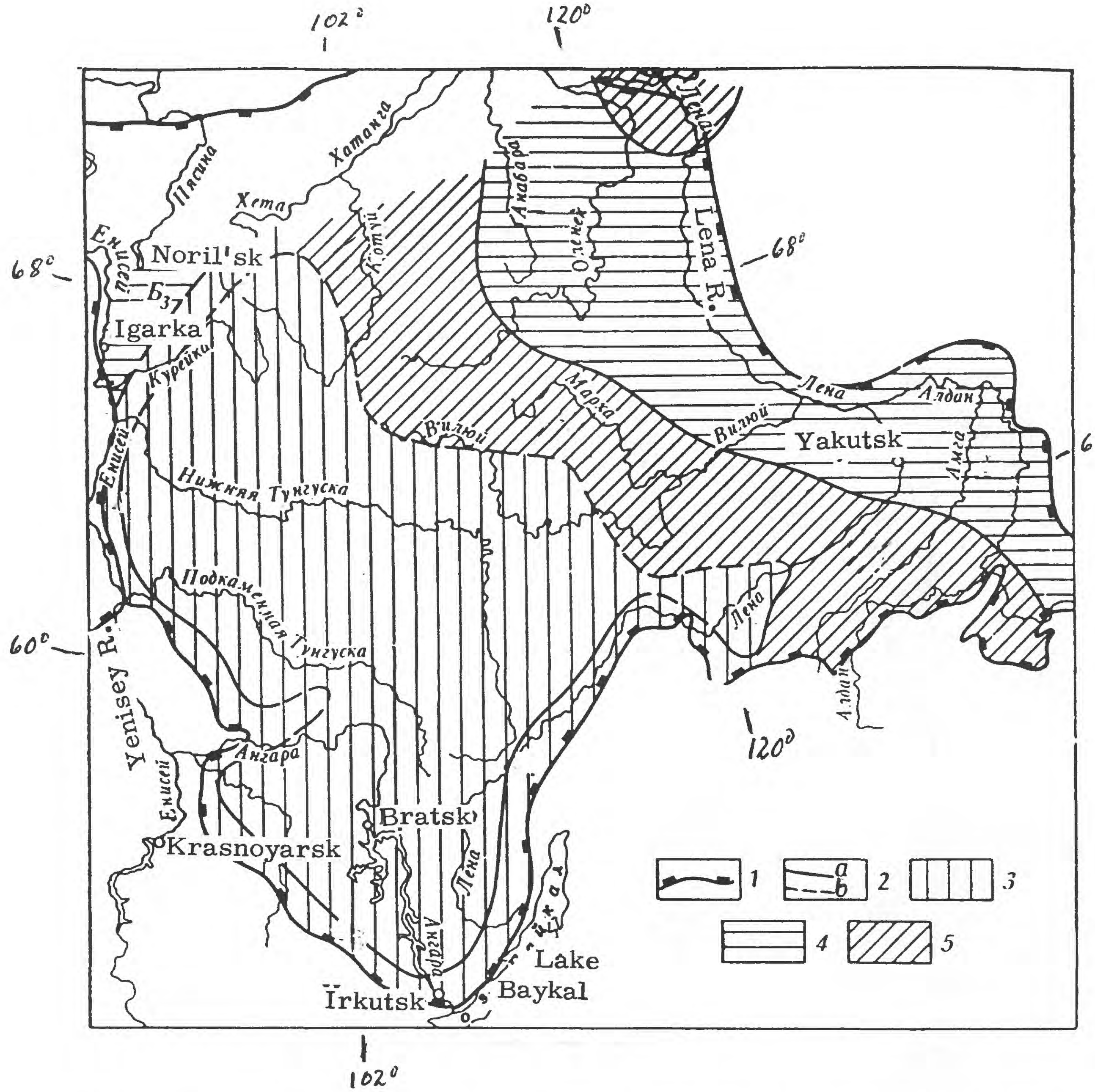


Figure 11.--Distribution of main types of sections of Cambrian sediments on Siberian platform (from Kontorovich and others, 1981, p. 42).

1, boundary of Siberian platform; 2, boundaries of facies regions (a - certain, b - presumed); 3, predominantly dolomites, extensive evaporites, cyclic deposition; 4, marine limestones; 5, zone containing extensive reef deposits.

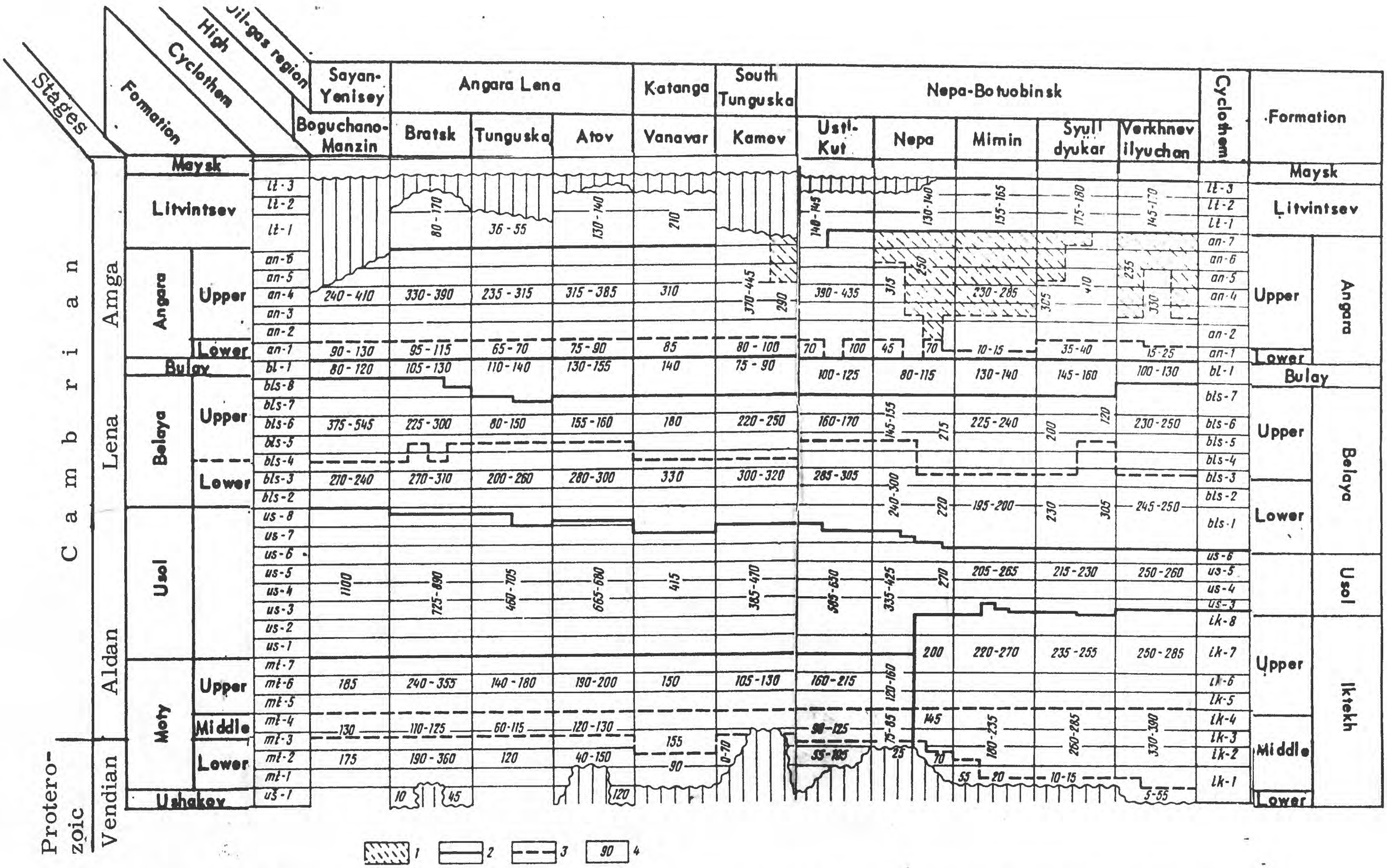


Figure 12.--Correlation of Vendian and Cambrian evaporite-carbonate sediments in southern part of Siberian platform (after Kontorovich and others, 1981, p. 46-47).

1 - interval of Angara Formation in which salt beds are leached; 2 - formation boundaries; 3 - member boundaries; 4 - thickness of sediments, m.

The thickness of the Aldan Stage ranges from 100 to 200 m in the northeast to 1,100 m in the south (fig. 13). The stage is represented by the middle and upper Moty Formation and the Usol Formation.

The Usol has been studied in detail because it is productive in many fields. Eight cycles are recognized (fig. 12).

The first cycle (us-1) consists largely of salt. A few beds of dolomite are present. Thickness is 80 to 170 m.

Cycle us-2 is composed of carbonates. It is the middle Usol and is about 50 m thick.

Cycle us-3 is salt and one to three beds of dolomite 3 to 10 m thick. Total thickness is more than 50 m.

Cycles us-4 and us-5 are largely salt. Three or four beds of dolomite are present in each unit. Total thickness of both cycles is 40 to 140 m.

Cycle us-6 is variable in composition. In the Sayan-Yenisey basin it is composed of carbonate rocks and salt, the latter predominating. On the Kamov and Vanavar arches, it is largely dolomite and subordinate salt. It is divided into three subcycles. Total thickness of the cycle is 20 to 300 m.

Cycle us-7 is salt-carbonate. It is divided into two parts. Its total thickness is 50 to 120 m.

Cycle us-8 is divided into two parts, each of which is largely carbonate in the lower part and salt in the upper.

Lena Stage.--The paleogeographic conditions of the Aldan Stage continued into the Lena Stage (fig. 14). The open sea on the northeast was separated from the salt basin on the southwest by an extremely shallow-water zone where reef bodies were abundant. Organic-rich muds were deposited in the open-sea areas; these and the reefs will be discussed in detail in the next section (Amga Stage). The Belaya and Bulay Formations constitute the Lena Stage in the southern part of the Siberian platform where cyclic deposition continued.

Eight cycles compose the Belaya Formation. Cycle bls-1 at the base of the formation is limestone and dolomite and is 100 to 200 m thick. Cycle bls-2 consists of 40 to 90 m of carbonate rocks. In most of the region bls-3 is limestone and dolomite; only in the north half of the Nepa-Botuobinsk regional high is the upper part salt. Its thickness is 80 to 115 m.

Cycle bls-4 in the Sayan-Yenisey basin and parts of the Angara-Lena structural step and Baykit and Nepa-Botuobinsk regional highs is limestone and dolomite in the lower part and salt in the upper. Elsewhere it is entirely carbonate. Thickness is less than 100 m.

The lower parts of the cycles bls-5, bls-6, and bls-7 are carbonate, and the upper parts are salt that contains dolomite beds. Thickness of each cycle is 40 to 145 m.

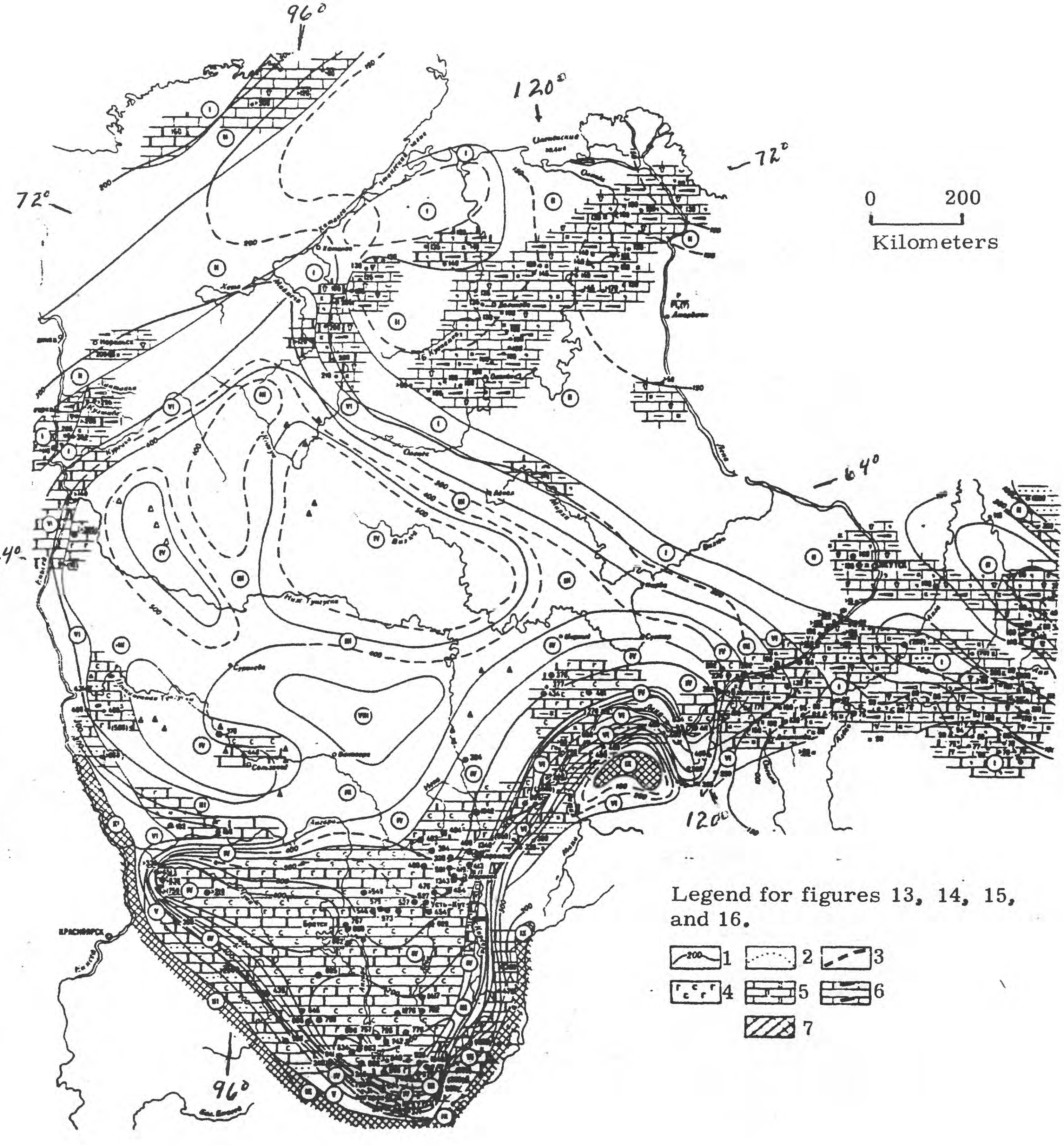


Figure 13.--Lithologic-Paleogeographic map of Siberian platform during Aldan Stage of Early Cambrian Period (from Kirkinskaya and others, 1975).

1, Isopachs in meters; 2, boundaries of formations; 3, faults; 4, sulfate-halogen sediments; 5, carbonate sediments; 6, clayey carbonate sediments; 7, land.

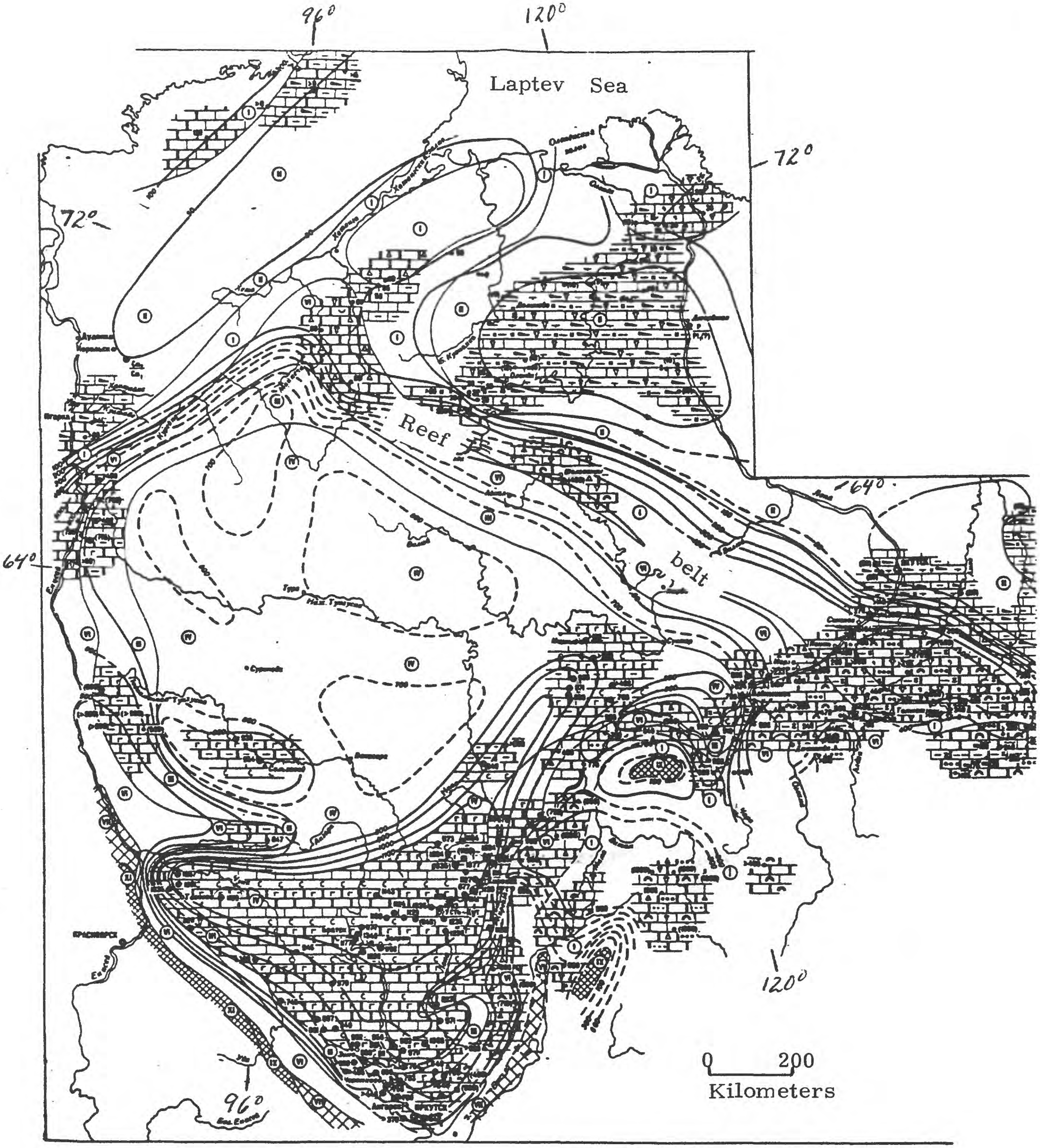


Figure 14. Lithologic-paleogeographic map of Siberian platform during Lena Stage of the Early Cambrian (from Kirkinskaya and others, 1975). See figure 13 for legend.

Cycle bls-8 is composed of salt and beds of dolomite. It is present only in the Sayan-Yenisey basin and Bratsk high. Thickness is 40 to 110 m.

The Bulay Formation is a single cycle in the southern part of the Siberian platform; here it is composed largely of dolomite and is 80 to 160 m thick. On the Nepa-Botuobinsk regional high two cycles are present: a lower composed of dolomite containing beds of argillite and anydrite and an upper of limestone.

Amga Stage.--The paleogeography of the Amga Stage repeats that of the earlier stages with some modification (fig. 15). A small area of uplift in the Tunguska region produced an island. This island was again covered by the sea at the end of the Amga Stage (Kirkinskaya and others, 1975, fig. 5).

In the salt basin this stage is represented by the Angara and Litvintsev Formations.

The Angara Formation has several cycles. Cycle an-1 constitutes the lower Angara and consists of 80 to 130 m of alternating beds of dolomite, clayey dolomite, and anhydrite dolomite.

Cycle an-2 is salt-carbonate in most sections. Dolomites predominate in the upper part and salt in the lower. Total thickness ranges from 45 to 130 m. On the Nepa-Botuobinsk regional high the section is largely salt.

The salt beds of the Angara Formation are not preserved where this cyclothem is close to the surface (depths less than 400-500 m). For example, these salt beds have been leached on the Nepa and Verkhnevilyuchan arches (fig. 12).

Cycle an-3 consists everywhere of dolomite in the upper part and salt in the lower. Thickness ranges from 20 to 50 m on the Baykit regional high to 120 m in the Sayan-Yenisey basin.

Alternating dolomites, salt, and sulfate rocks compose cycle an-4. Thickness is 60 to 150 m.

Cycles an-5 and an-6 have a clay-salt-carbonate composition in most of the region. Salt predominates in the lower part and sulfate-salt-carbonate rocks in the upper of each. Their thicknesses range from 40 to 140 m.

Cycle an-7 at the top of the Angara has a limited distribution (fig. 12). It consists of salt and beds of clayey, sulfate-bearing dolomites. Thickness is 40 to 50 m.

The Litvintsev Formation is represented generally by two cycles; a third is present only in the north half of the Nepa-Botuobinsk regional high. Cycle lt-1 is limestone and dolomite, which contain beds of anhydrite, marl, and argillite. Thickness is 60 to 100 m. Cycle lt-2 is composed of dolomite and anhydrite. Salt beds are at the top. Thickness is 50 to 120 m. Salt-bearing dolomites from 0 to 70 m make up cycle lt-3.

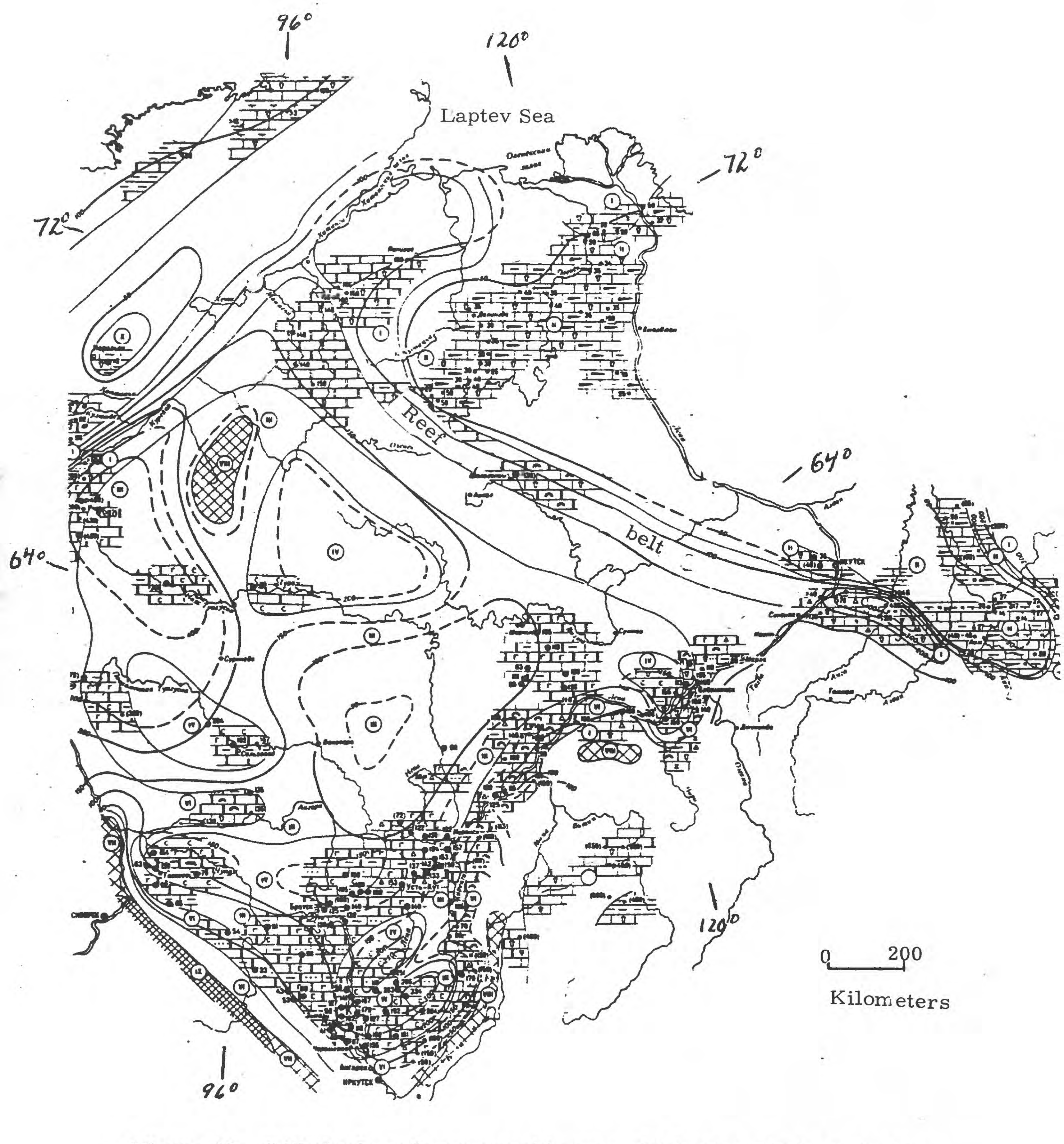


Figure 15. Lithologic-paleogeographic map of Siberian platform during Amga Stage of the Middle Cambrian (from Kirkinskaya and others, 1975). See figure 13 for legend.

During the Lena and Amga Stages, a system of barrier reefs extended across the Siberian platform from the Irkutsk region on the southeast to the area of the Katanga River on the northwest (fig. 16). Bituminous black shales were deposited in the open sea to the northeast of the barrier-reef system and evaporites and carbonates in the basin to the southwest. Some detailed descriptions of these reefs have been published recently (Savitskiy, 1979, 154 p.). They are composed of algal, archeocyathid-algal, detrital, and oolitic carbonate rocks, and lithologically they consist of reef-proper, back-reef, and fore-reef facies.

The northeast flank of the reef zone, which faced the open sea, was steeper than the flank that faced the salt basin on the southwest. The fore-reef facies contains organoclastic material in debris slides; this facies passes abruptly into organic-rich black shales (fig. 17).

One of the most detailed studied is the Oymuran reef, which crops out along the Lena River (Astashkin, 1979, p. 19-30). The host rocks of this reef are bedded limestones and marls. The transition from these bedded sediments into the reef rocks takes place in a distance of only a few tens of meters. In its lower part, the reef consists of 70 to 80 percent dolomitic algal and archeocyathid-algal bioherms, the space between which is filled by bedded dolomitic-clayey rock (fig. 18). The upper part of the Oymuran buildup has the characteristics of a large barrier reef, as indicated by organoclastic material, largely dolomite.

The open sea to the north and east of the Lena-Amga reef system was the site of deposition of carbonates and clays that are enriched in organic matter and silica. These rocks of the Kuonam and Inikan Formations are referred to as domanik-type, in reference to their similarity to the carbonaceous shales of the Devonian Domanik Formation of the Russian platform. They are present over an area 1,500 km long and 600 km wide (fig. 16).

The rocks of the Kuonan and Inikan Formations are dark brown to black in color and flaggy. Content of organic carbon ranges from 0.5 to 0.6 percent in the limestones and dolomites to 26 to 27 percent in the shales. The organic matter is sapropelic, planktonic. Their high silica content is due to authigenic chalcedony derived perhaps from sponge spicules or by precipitation in the form of silica-organic gels. The high organic matter of these sediments is attributed to flourishing phytoplankton in these Early and Middle Cambrian seas (Evtushenko, 1979, p. 5-11).

Maya Stage.--The early Caledonide phase of folding was manifest between the Amga and Maya Stages. A stratigraphic and in places structural discordance is present between these two stages (Kontorovich and others, 1981, p. 214; see also figure 12 of this report). The subsidence continued to prevail over most of the platform; however, two uplifts produced land areas in the central part (fig. 19). The salt basin, reef system, and bituminous clay deposition of the Lena and Amga Stages did not continue into this stage.

The Maya Stage is represented largely by the Verkhnelena Formation (Kirkinskaya and others, 1975, p. 63). It consists of six members, as follows (from the bottom upward). The Osa Member is composed of dolomitic, gypsiferous

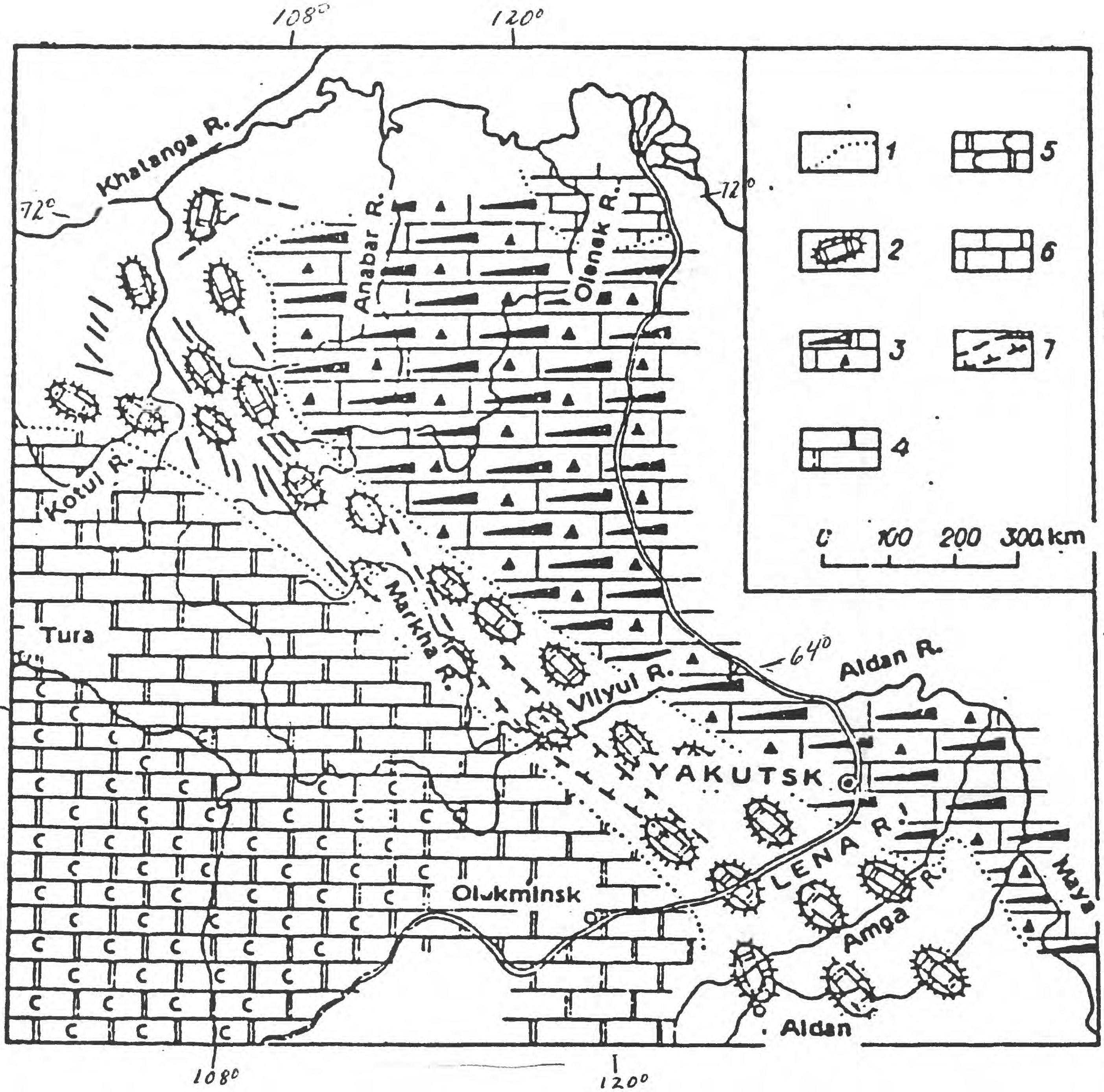


Figure 16.--Paleogeographic sketch map of eastern part of Siberian platform during the Lena and Amga Stages (from Evtushenko, 1979, p. 6).

1 - boundaries of zones in epicontinental marine basin; 2 - zone of barrier reefs; 3 - domanik-type (organic-rich black shales) deposits; 4 - predominantly dolomitic sediments; 5 - anhydrite-dolomite and salt deposits; 6 - calcareous deposits; 7 - faults at depth.

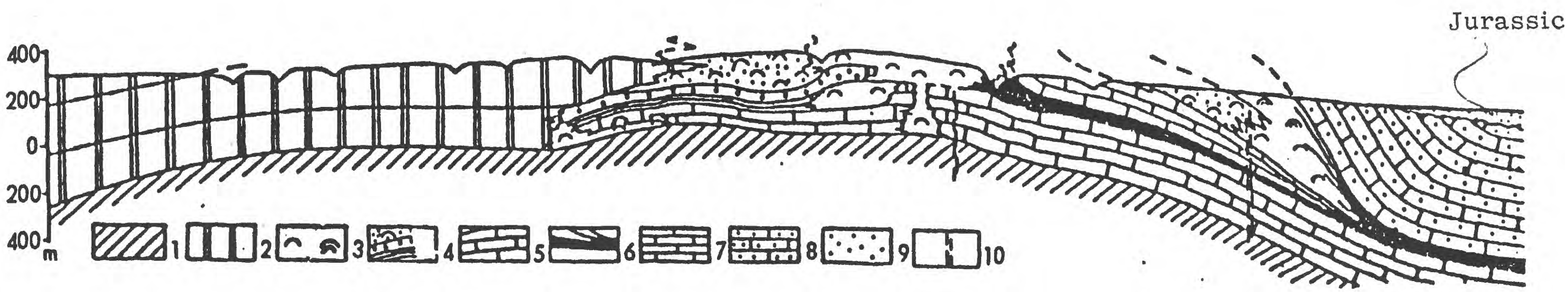


Figure 17.--Schematic section of the Cambrian reef systems along the Lena River of East Siberia (from Savitskiy and Astashkin, 1979, p. 8).

1 - Lower Cambrian Aldan sediments; 2-8 - types of Cambrian sediments: 2 - lagoonal, 3 - reef deposits, 4 - reef-flank lithofacies, 5 - limestones of Pestrotsvetnaya Formation, 6 - bituminous limestones and shales of Siney and Inikan Formations, 7 - dolomites and limestones of Kutorgina Formation, 8 - limestones of Ust'-Botom Formation; 9 - Jurassic clastic deposits; 10 - faults.

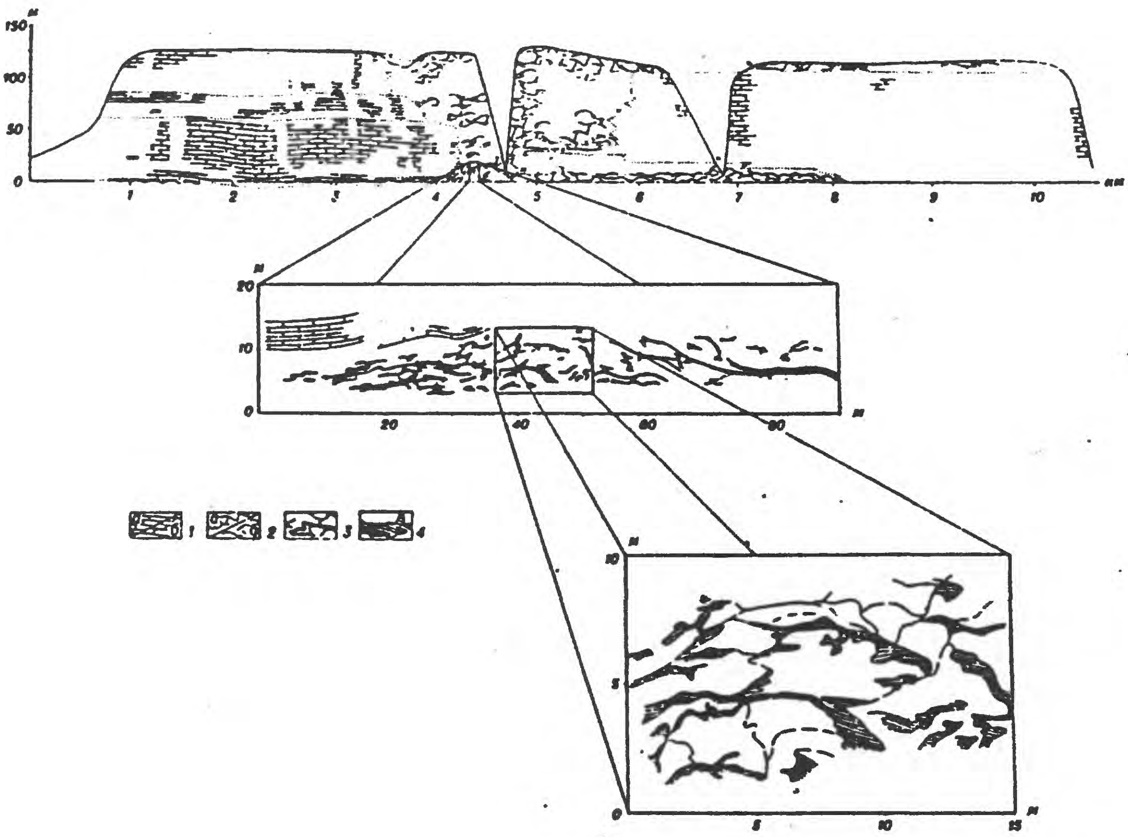


Figure 18.--Structure of Oymuran reef (from Astashkin, 1979, p. 21).

1 - Pestotsvet Formation (a - variegated limestones and marls, b - dolomites); 2 - rocks of Oymuran reef (a - dolomites, b - limestones); 3 and 4 - bedded interbioherm filling.

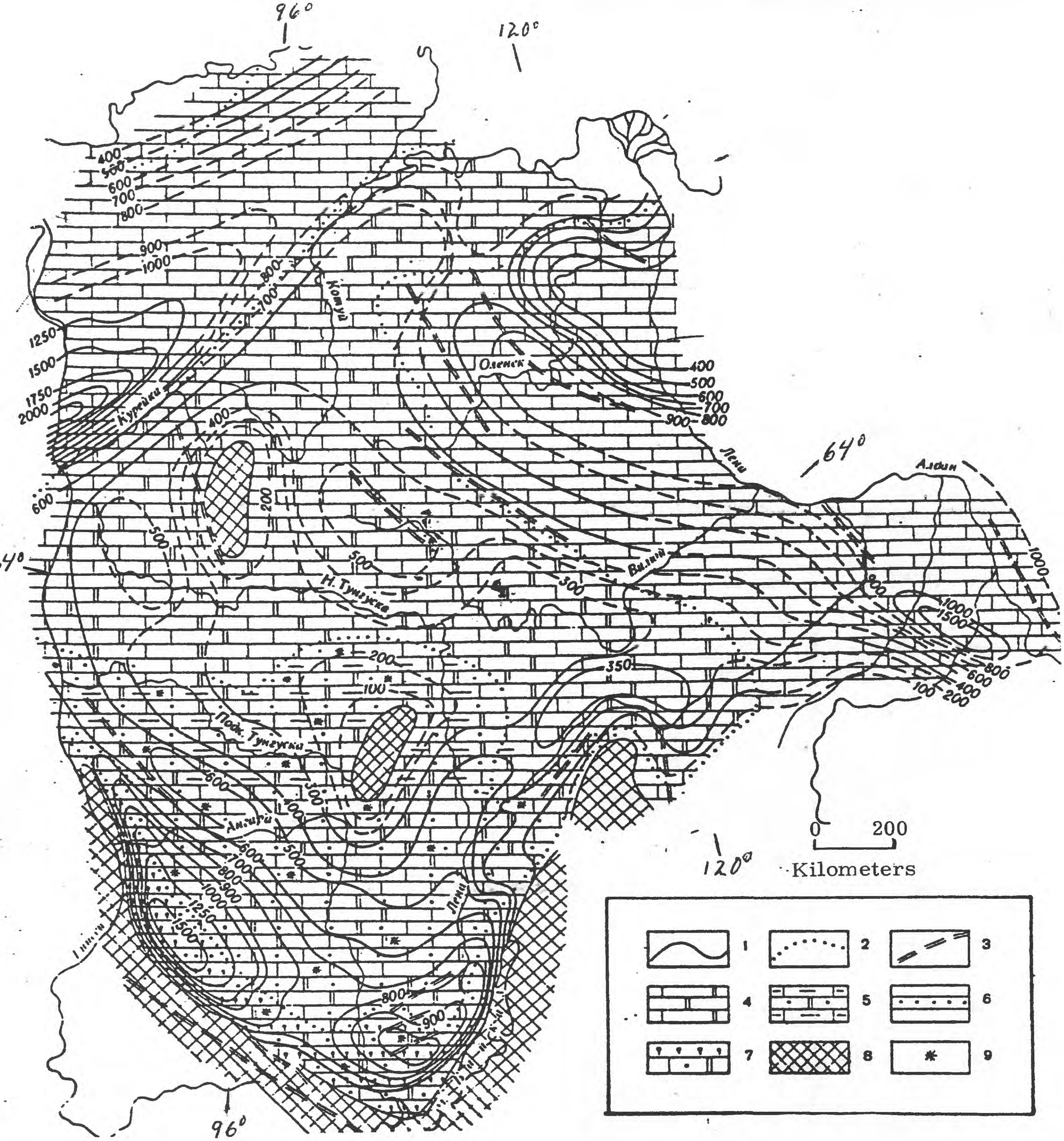


Figure 19.--Isopach and lithologic map of Maya Stage of Middle Cambrian age of Siberian platform (from Polyakova, 1975, fig. 3).

1 - Isopachs; 2 - boundaries between rock types; 3 - faults affecting sedimentation. Sediments: 4 - carbonate, 5 - carbonate-clastic, 6 - arkosic sandstones, 7 - sandy carbonate. 8 - land areas; 9 - redbeds.

marls 35 to 60 m thick. The Balagan Member is marl with some sand and is 200 to 300 m thick. The Ust'-Tal'kinskiy Member is largely sandstone and is 65 to 70 m thick. In its lower part, the Mikhaylov Member is alternating siltstone, marl, and sandstone, and in the upper part, it is siltstone; total thickness is 160 to 270 m. The Ryutino Member is largely sandstone and is 30 to 110 m thick. The Karda Member is composed of silty-marly rocks and is 170 to 320 m thick.

There is no erosional break between the Cambrian and Ordovician systems.

Ordovician System

Lower Ordovician

The paleogeography of the Siberian platform during Ordovician time was very different from that during the Cambrian. In the Early Ordovician on the south was a nonmarine part of the basin in which largely sandstones were deposited (fig. 20, pattern 4). This passed on the north and east into sandy, oolitic, and organoclastic limestones (fig. 20, pattern 3). Next on the north was a zone of reeflike stromatolitic, oolitic, and detrital dolomites (fig. 20, pattern 5). The stromatolitic dolomites are both bedded and biohermal.

The section of the basin to the north of the reeflike dolomites is composed of dolomites, which contain beds of gypsum, anhydrite, calcareous sandstone, siltstone, and marl (fig. 20, pattern 2).

The Lower Ordovician of the Taymyr is an open-sea facies that contains gray and black Dictyonema shales (fig. 20, pattern 1). The fauna of these beds differs markedly from that of the Lower Ordovician of the platform to the south. The barrier that separated these two basins (fig. 20, pattern 6) has been interpreted as being a barrier reef (Yadrenkina and others, 1979, p. 118).

Middle Ordovician

In several parts of the Siberian platform, the boundary between the Lower and Middle Ordovician is marked by a zone of weathering, which indicates a long break of continental character (Markov and Markova, 1977, p. 40). The Middle Ordovician sea covered only the western part of the platform, the eastern part being a coastal plain that was only periodically flooded (fig. 21).

The sediments of the Middle Ordovician are largely organoclastic limestones, marls, argillites, and dolomitic sandstones. They are in varying degree phosphoritized. Two formations are recognized. The lower is the Krivolutskiy and the upper is the Mangazeyskiy. These are well defined on a basis of an abundant fauna.

Upper Ordovician

Sediments of the Upper Ordovician are not as widespread as those of the middle division. Only the north and northwest parts of the platform were inundated (fig. 22).

The Upper Ordovician on the Siberian platform consists of two horizons: Dolbor and Keta. The Dolbor is composed of argillites and organic limestones that have a characeristic fauna. Redbeds at the base of the Keta horizon are a marker for the Upper Ordovician of the platform.

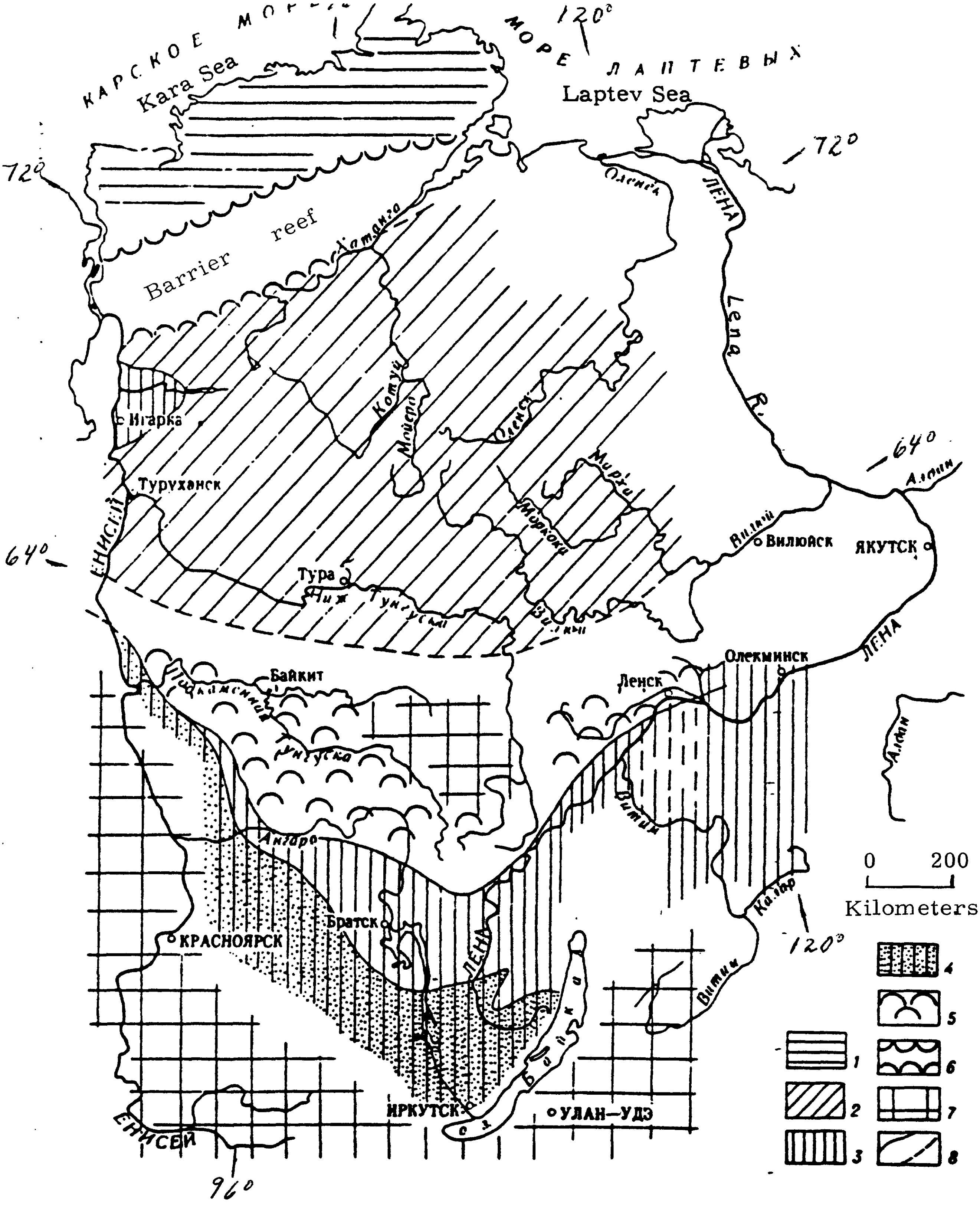


Figure 20.--Facies map of western part of Siberian platform for the Early Ordovician.

1, facies of open marine basin; 2, facies of saline part of basin; 3, facies of normal marine part of basin; 4, facies of probable freshwater part of basin; 5, zone of banks and islands; 6, probable barrier reef; 7, source area of sediment; 8, boundaries between regions with different types of sections.

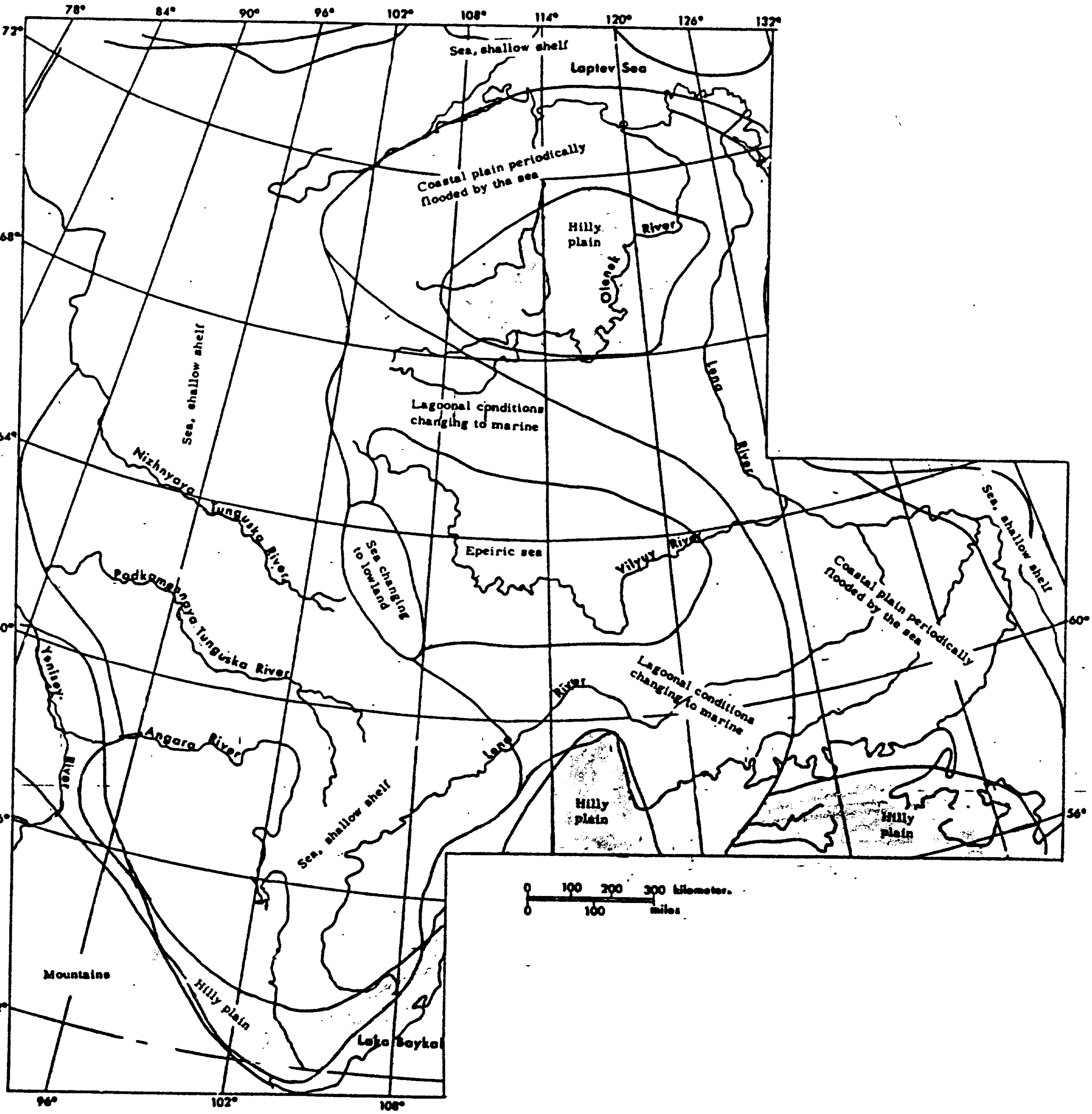


Figure 21. Paleogeographic map of the Siberian platform during the Middle Ordovician (Vinogradov, 1968).

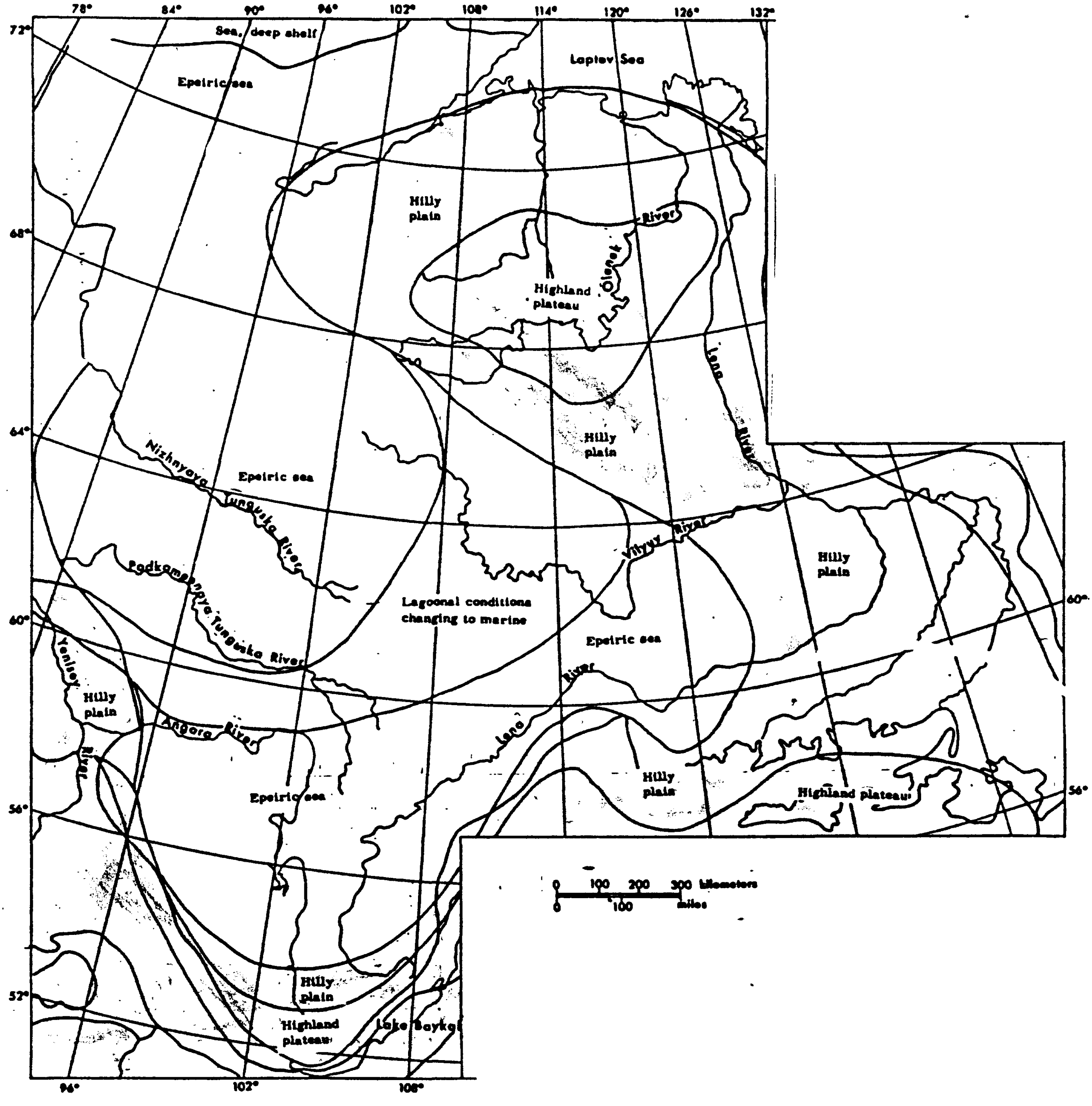


Figure 22. Paleogeographic map of Siberian platform during the Late Ordovician (Vinogradov, 1968).

Silurian System

The Silurian seaways in general are a repeat of the Late Ordovician but somewhat more extensive. The Lower Silurian rests unconformably on various horizons of the Ordovician.

On the basis of an abundant fauna, the Silurian section of the Siberian platform is divided into the Llandoverian and Wenlockian Stages of the Lower Silurian and the Ludlovian Stage of the Upper Silurian (Markov and Markova, 1977, p. 44).

Llandoverian Stage

In the Noril'sk region in the northwest part of the Siberian platform, the Llandoverian is represented by 220 to 450 m of clayey limestones and limey argillites. The same facies is found also in the eastern part of this sedimentary basin (fig. 23).

In the south of the basin in the area of the Irkutsk amphitheater, the Llandovarian consists of 40 to 120 m of light-gray sandstones, siltstones, argillites, and some dolomite and limestone.

In the southwest part of the Vilyuy basin along the middle course of the Vilyuy River are Llandovarian limestones, dolomites, and argillites that contain gypsum beds. Their total thickness is 170 to 312 m.

Wenlockian Stage

The Llandovarian passed into the Wenlockian without a break; the boundary is marked by the appearance of Wenlockian fossils. The Wenlockian sea was not as extensive as that of the previous stage (fig. 24).

In the northwest part of the platform in the Noril'sk region, the Wenlockian is composed of dark-gray to black nodular limestones up to 300 m thick. In the Turukhansk region are 120 to 140 m of algal and stromatolitic limestones.

In the central part of the Tunguska basin, the Wenlockian consists of a clastic-carbonate unit 130 m thick. It is divided into a lower marl and an upper limestone. The upper limestone contains thin beds of black argillite.

In the basin of the Podkamennaya Tunguska River, the Wendlockian is represented by gray limestones, sandy limestones, and dolomites. Total thickness is 95 m.

Ludlovian Stage

The lower boundary of the Ludlovian is drawn at the appearance of a new faunal assemblage; there is no lithologic change. The basin of deposition became more restricted as most of the platform stood above sea level (fig. 25).

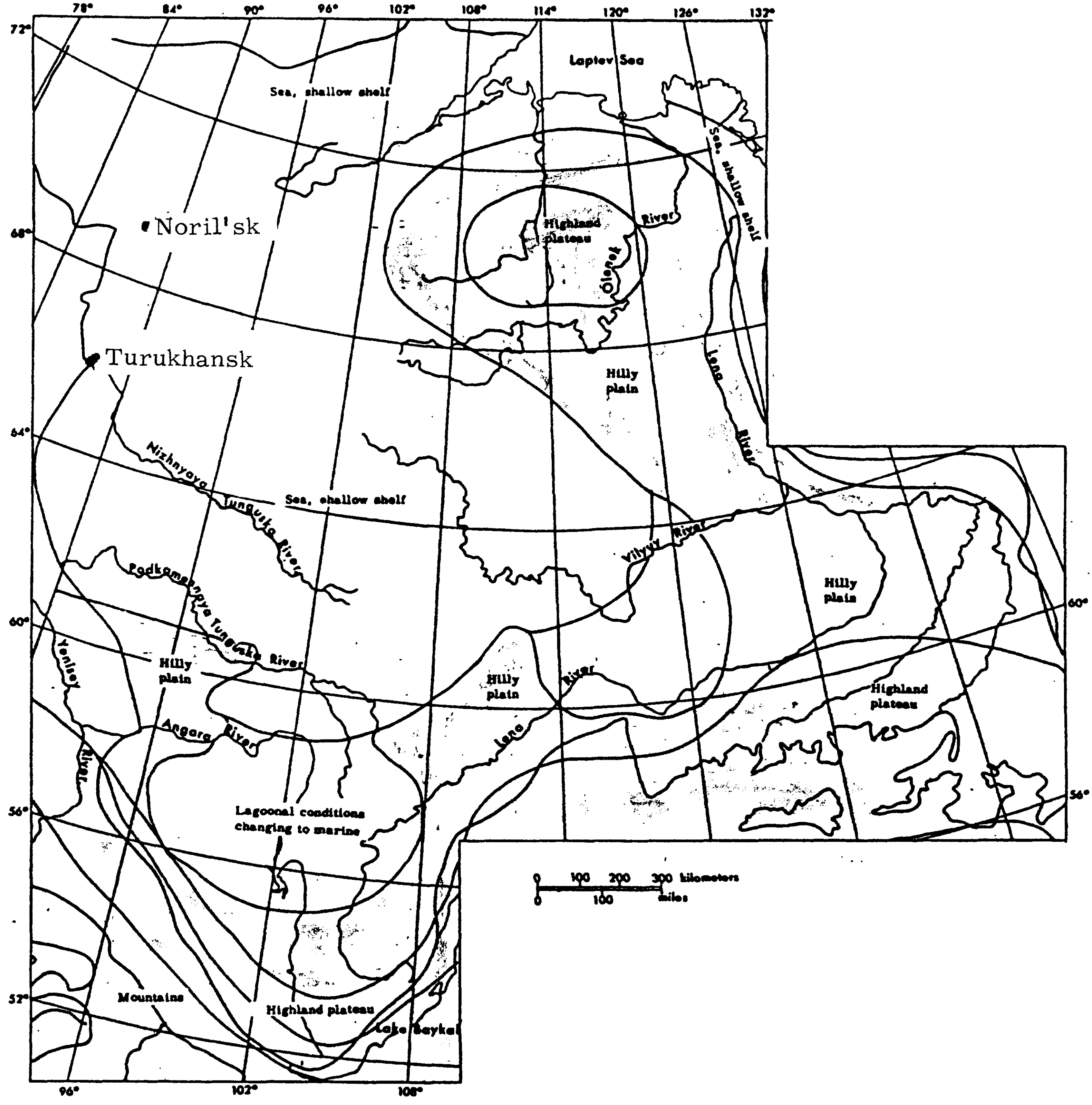


Figure 23. Paleogeographic map of Siberian platform during the Llandoverian Stage of the Early Silurian (Vinogradov, 1968).

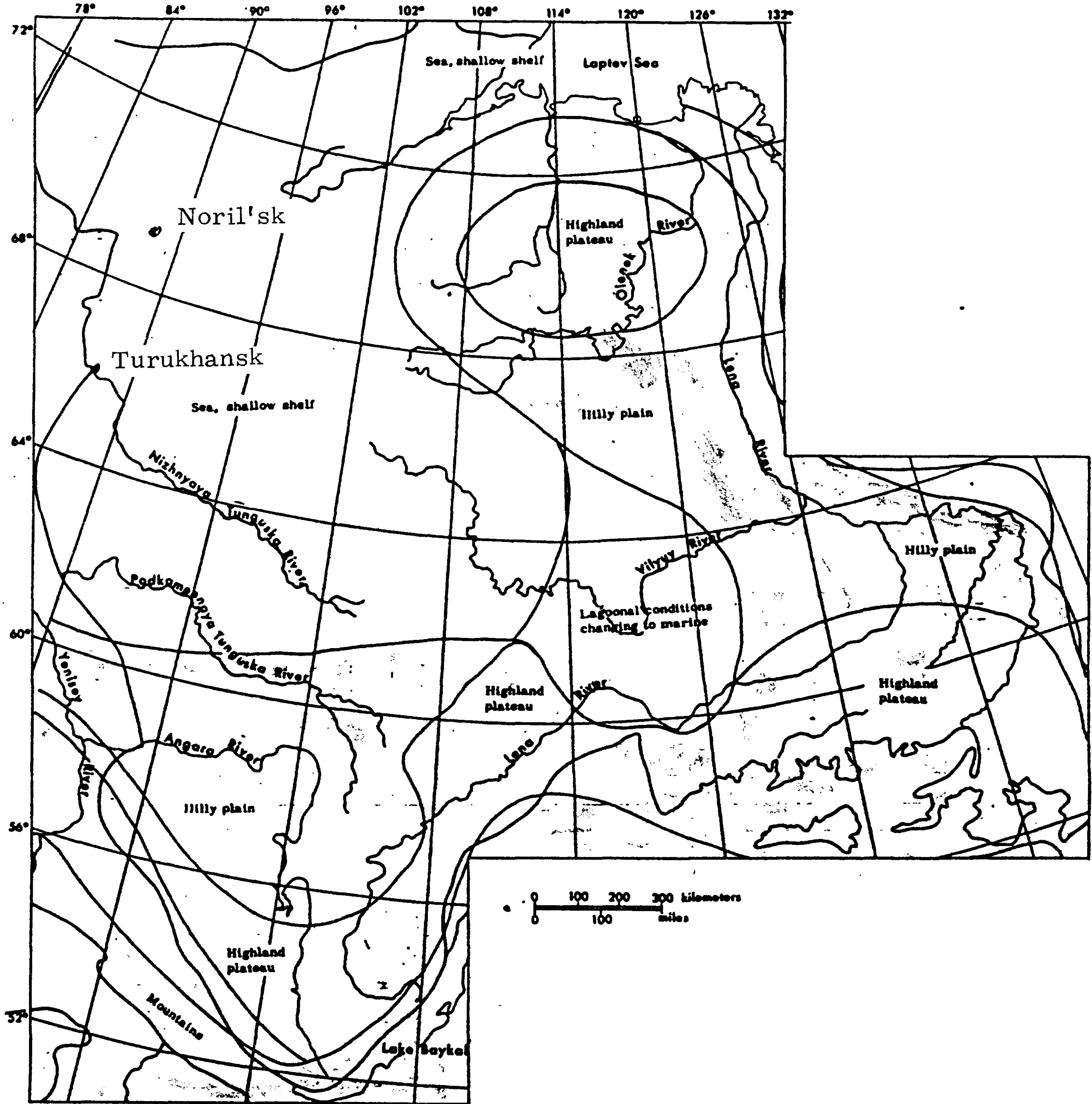


Figure 24. Paleogeographic map of Siberian platform during the Wenlockian Stage of the Early Silurian (Vinogradov, 1968).

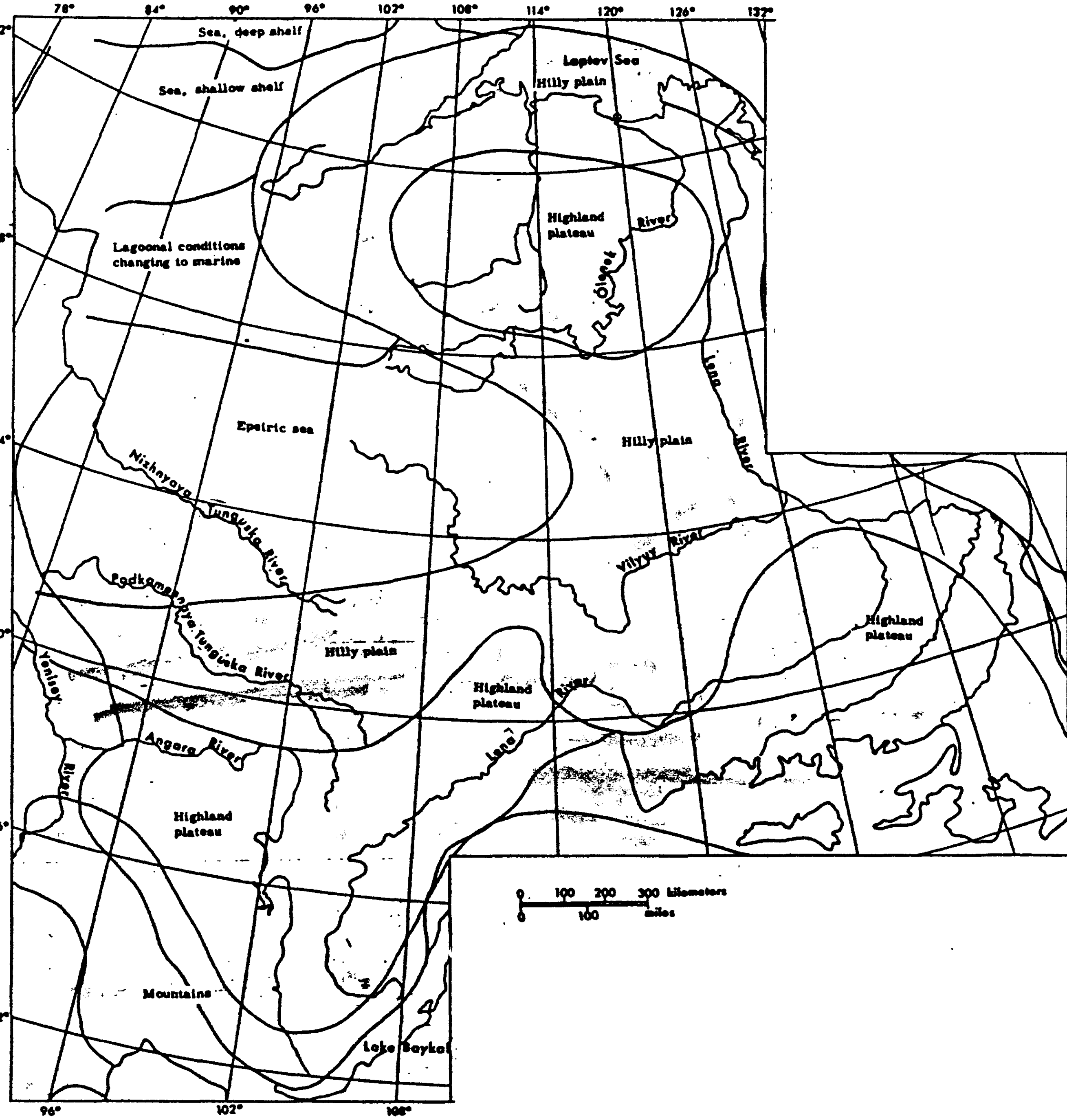


Figure 25. Paleogeographic map of Siberian platform during the Ludlovian Stage of the Late Silurian (Vinogradov, 1968).

The lower part of the Ludlovian consists of gray, medium- and thin-bedded limestones and dolomites. Thickness ranges from 30 to 140 m.

The upper Ludlovian is largely dolomite, which contains numerous beds and lenses of anhydrite and gypsum. Total thickness is as much as 250 m.

Devonian System

All three divisions of the Devonian are represented on the Siberian platform. The thickest and most complete is on the northwest in the Noril'sk region. Evaporites are common, though discontinuous, in the Devonian section (Fradkin and Menner, 1973, p. 70). In the central part of the Tunguska basin, ten such horizons are present (fig. 26).

Lower Devonian

An epicontinental sea continued to occupy the northwest part of the Siberian platform during Early Devonian time (fig. 27). Most of the platform was emergent and a source of detritus (Kontorovich and others, 1981, p. 215). The boundary with the underlying Ludlovian is placed at the appearance of variegated dolomites, dolomitic argillites, and anhydrites of the Zub Formation of Gedinnian age (Matukhin and Konstantinova, 1977, p. 49). Thickness of the Zub ranges from 20 to 230 m.

Overlying the Zub is the Kurey Formation of Siegenian age. It consists of calcareous argillites in its lower part and variegated phosphorite-bearing argillites in the upper. Thickness is 50 to 85 m.

At the top of the Lower Devonian section is the Razvedochninskaya Formation of Emsian age. It consists of brown phosphorite-bearing argillite. Some products of explosive volcanism are present. Thickness ranges from 130 to 170 m in the Noril'sk region to 65 to 70 m just south in the basin of the Kureyka River.

Middle Devonian

During the Middle and Late Devonian, most of the platform continued to be emergent (fig. 28). The Eifelian stage of the Middle Devonian is represented by the Manturov Formation. Its lower part is largely argillite and marl, and its upper part contains abundant evaporites, including some salt (fig. 26). Total thickness of the Manturov is 200 to 220 m.

The overlying Yuktin formation of the Givetian stage is a gray limestone, which in places is cavernous. Salt is sometimes found in its cavities and pores. Total thickness is as much as 80 m.

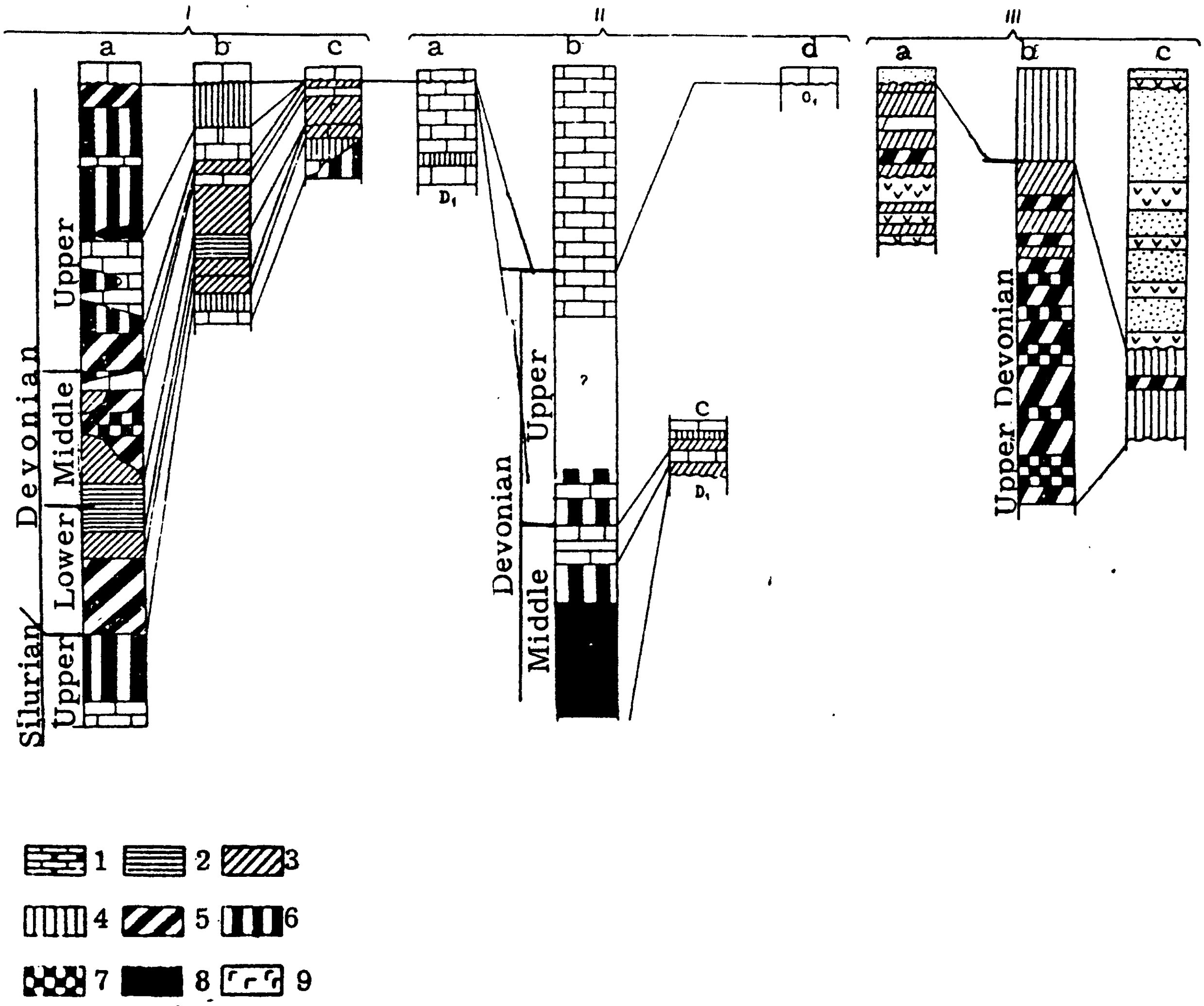


Figure 26. Correlation of Devonian sediments of individual salt regions of the Siberian platform.
I - Northwest part of platform: a-Noril'sk region, b-Kureyka River basin, c-basin of north course of Nizhnyaya Tunguska River; II - north part of platform: a-southern zone of East Taymyr, b-Khatanga downwarp, c-northeast border of Tunguska regional low; d- north flank of Anabar regional high; III - central part of platform: a-Ytyattan downwarp, b-Kempendyay downwarp, c-Berezov downwarp.
Legend: 1 - limestone and dolomite, 2 - Clastics and clastic-carbonates, 3 - clastic-carbonate redbeds, 4 - gray dolomites and clastic carbonates, 5- sulfate-bearing redbeds, 6 - gray sulfate-bearing sediments, 7 - salt-bearing redbeds, 8 - gray salt-bearing sediments, 9 - gypsum.

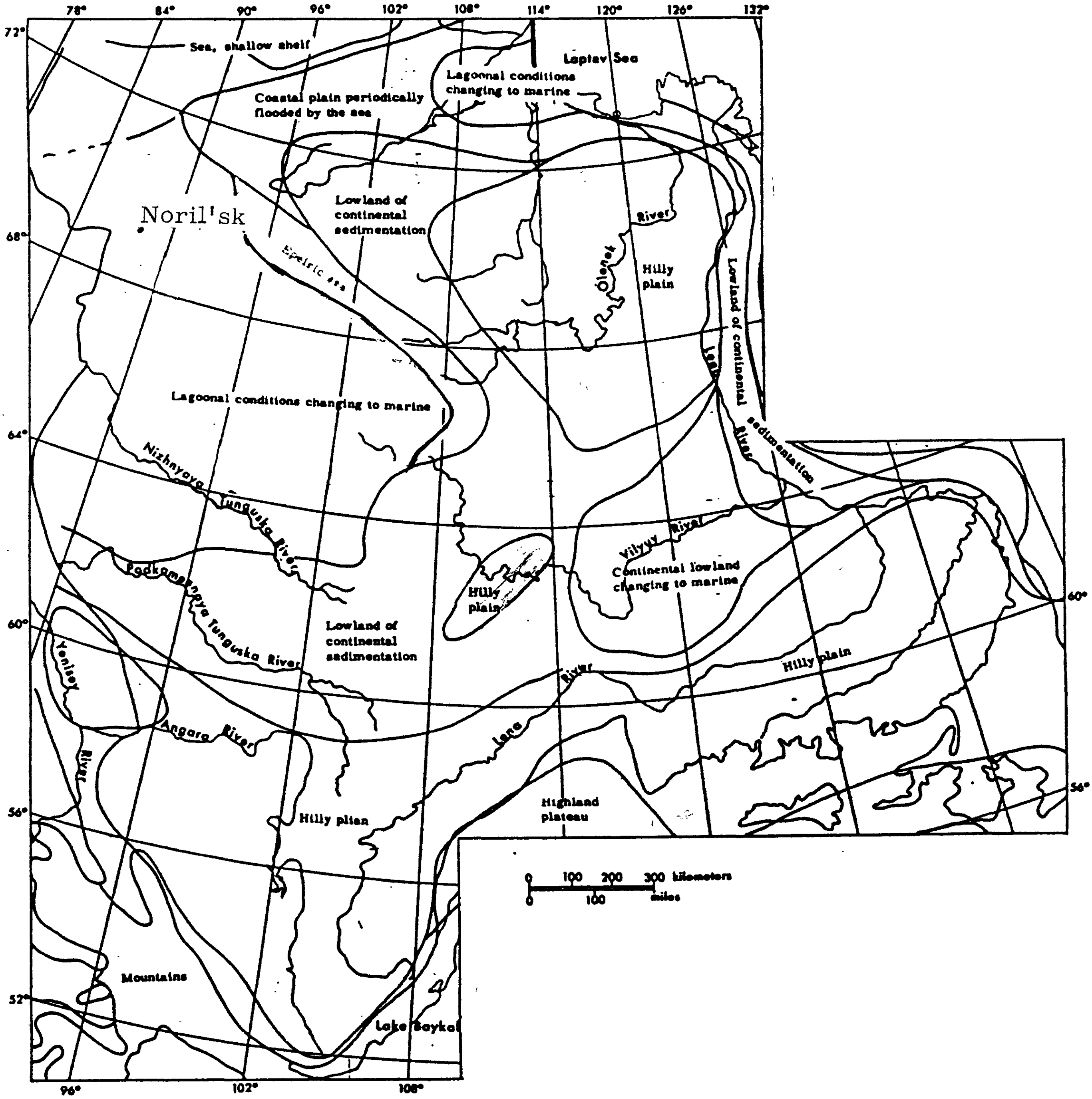


Figure 27. Paleogeographic map of the Siberian platform during the Early Devonian (Vinogradov, 1968).

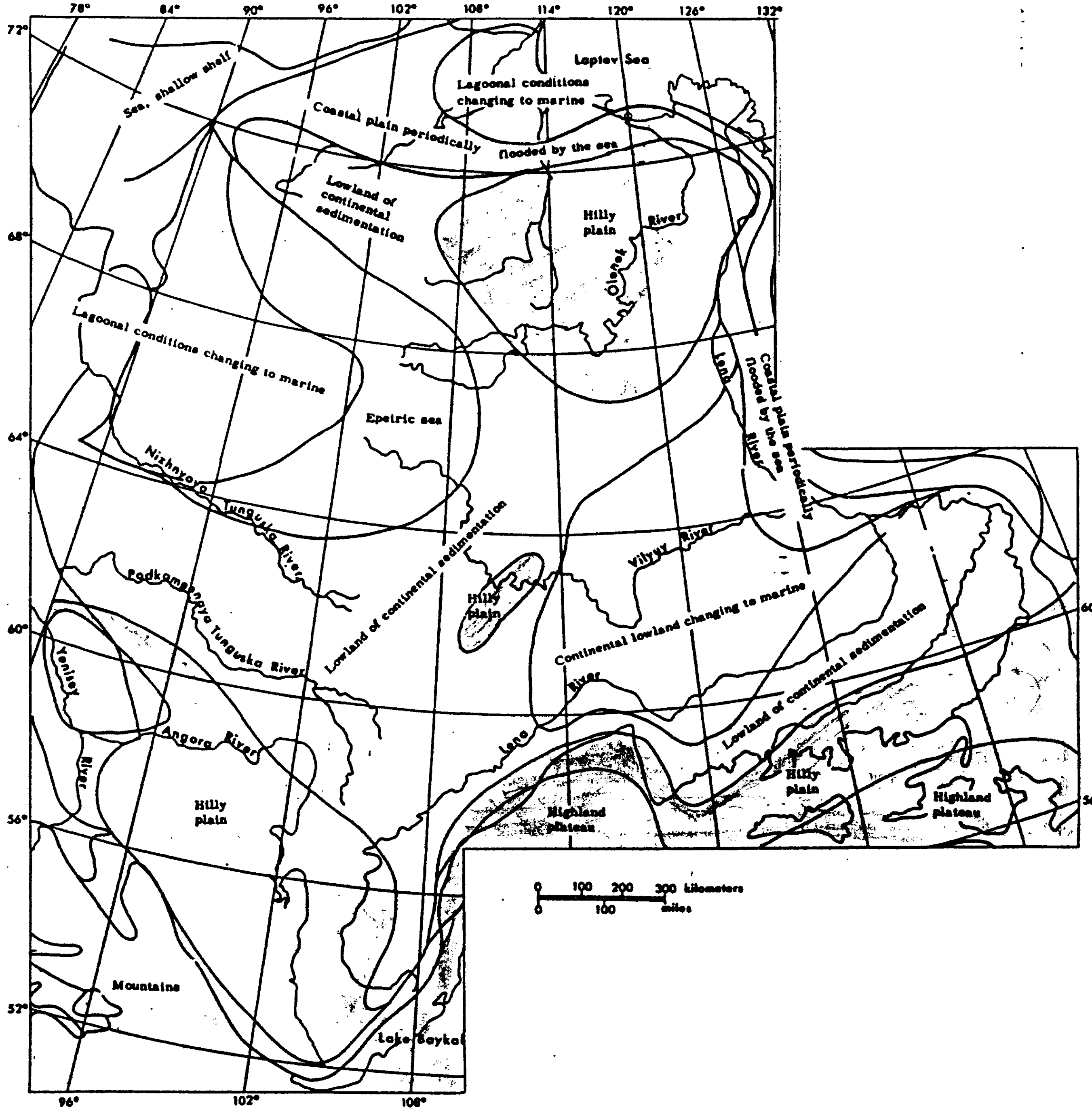


Figure 28. Paleogeographic map of the Siberian platform during the Eifelian Stage of the Middle Devonian (Vinogradov, 1968).

Upper Devonian

The Nakokhoz Formation of Frasnian age consists of calcareous and dolomitic argillites, which contain beds of clayey dolomite, gypsum, and anhydrite. Sections with sulfates are 90 to 120 m thick, and those without sulfates do not exceed 60 m.

The Kalargon Formation is middle Frasnian to early Famennian in age and consists largely of carbonate sediments. Thickness is 140 to 250 m in the Noril'sk region. Elsewhere it is 15 to 60 m.

At the top of the Devonian section is the Fokin Formation of Famennian age. It consists of two members of almost equal thickness separated by a persistent limestone 3 to 7 m thick. The lower member is largely gray marl, dolomite, and anhydrite. The upper part has more clastic and less sulfate components in comparison with the lower. Total thickness of the formation is 430 m.

Carboniferous System

Lower Carboniferous

The Anabar regional high dominated the northeastern part of the Siberian platform in the early part of the Carboniferous (fig. 29). It was surrounded on almost all sides by coastal plain, which was periodically inundated. A seaway continued to be present in the Yenisey-Khatanga regional low across the northern part of the platform.

In the northwest of the platform, the Lower Carboniferous consists of the Serebryanka, Khanel'birin, and Brusskaya Formations. The Serebryanka and Khanel'birin are largely limestones; they are of Tournaisian age. Total thickness of these units is up to 130 m (Vaag and others, 1977, p. 53).

An erosional surface is present between the Khanel'birin Formation and the overlying Brusskaya Formation of Visean-Namurian age. Sedimentary breccia at the base of the Brusskaya contains fragments of Tournaisian limestone (Kontorovich and others, 1981, p. 105). The upper part of this formation is largely siltstone and sandstone. Total thickness of the unit is 150 m.

In the central part of the Tunguska basin, the Lower Carboniferous is represented by the Dzhaltuli Formation, which is largely calcareous siltstone and clayey limestone. Thickness is 55 to 60 m.

In the southeast part of the platform in the Vilyuy basin, the most widespread Lower Carboniferous formation is the Kurung-Yuryakh. In its lower part, it is composed of alternating sandstones, siltstones, argillites, marls, dolomites, and tuffs up to 120 m thick. Above this are anhydrites and thin beds of sandstone, dolomite, and tuff up to 60 m thick. Next is 80 m of limestone. The section is topped by up to 200 m of volcanic-clastic-carbonate rocks. Total thickness is 100 to 530 m.

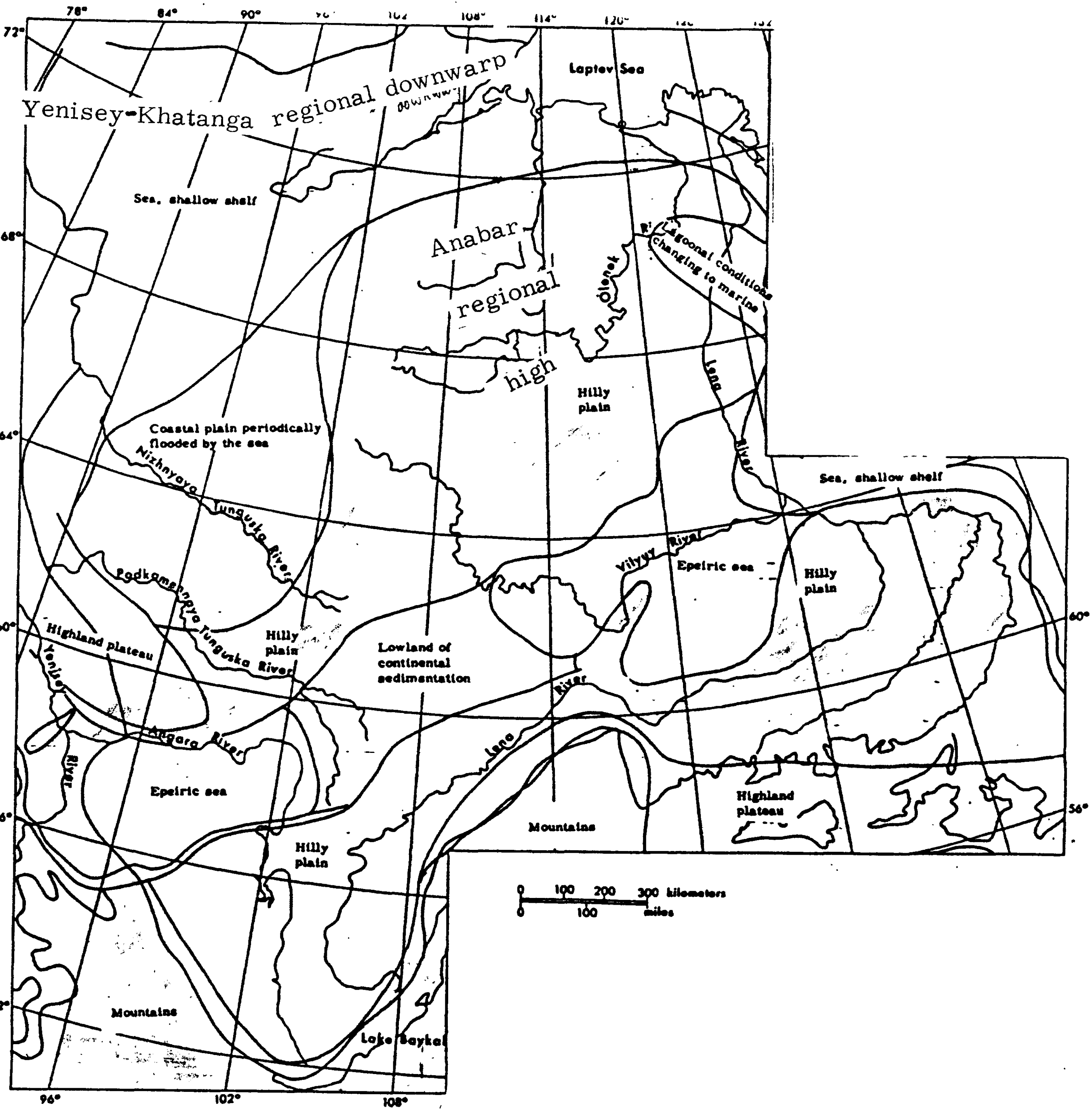


Figure 29. Paleogeographic map of the Tournaisian Stage of the Early Carboniferous of the Siberian platform (Vinogradov, 1968).

Middle-Upper Carboniferous

The paleogeographic distribution of land and sea continued essentially unchanged in Middle and Late Carboniferous time except for the belt between the 60° and 64° latitudes. Carboniferous, along with the Permian, is referred to as the coal-bearing section by Kontorovich and others (1981, p. 110). Coal beds 1 m thick or more are present in practically every stratigraphic subdivision of this section

In the Noril'sk region, the Middle and Late Carboniferous is represented by the Rudnaya Formation, which is composed of siltstone, argillite, fine-grained sandstone, and some clayey limestone. Thickness is 185 m. This unit extends on into the Lower Permian.

In the Tunguska basin, the Anakit Formation consists of alternating sandstones and siltstones 50 to 80 m thick.

To the south in the Angara region, the Kata Formation is a succession of alternating sandstones and siltstones and workable coal beds. Total thickness is generally 150 to 200 m but reaches 350 m in the Kokuy coal field.

Permian System

Lower Permian

Areas of marine and continental deposition expanded in Early Permian time in comparison with the Late Carboniferous. The Yenisey-Khatanga regional downwarp persisted in the north, and the Anabar regional high was still emergent (fig. 31).

In the Noril'sk region, the Carboniferous Rudnaya Formation is overlain by the Daldykan Formation, which consists of up to 110 m of siltstone, argillite, and coal. In the central and south part of the platform, the Lower Permian is represented by the Burgukli Formation, a unit composed of rhythmically alternating sandstones, siltstones, argillite, and subordinate beds of coal, coaly argillite, and clayey limestone. Thickness of individual beds is 5 to 6 m, and total thickness of the formation is 450 to 500 m.

In the area north of the Anabar regional high, the Lower Permian Tustakh Formation is 500 to 520 m thick. Sandstone predominates in its section; silty-clayey rocks are subordinate.

In the Cis-Verkhoyansk downwarp to the east of the Anabar regional high, more than 400 m of Lower Permian sediments are present in the section. From the base upward, they consist of coarse-grained arkosic sandstone and then fine-grained quartz-feldspar sandstones that contain beds of siltstone and argillite.

In the Vilyuy basin, the entire Permian section is about 1,600 m thick; half of this is Lower Permian and half is Upper. The section consists of massive sandstone beds up to 60 m thick and subordinate siltstone. A few thin coal beds are present.

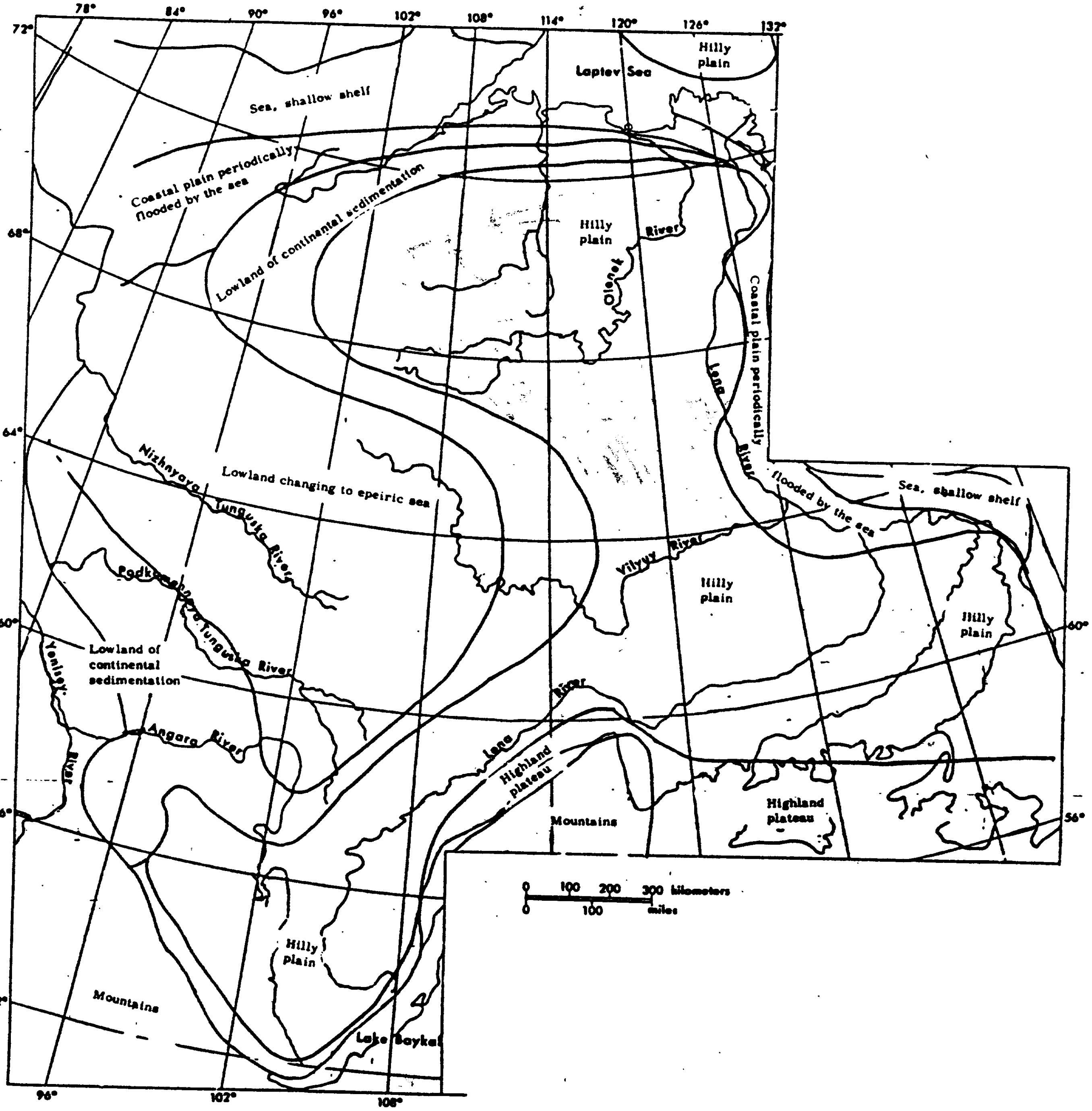


Figure 30. Paleogeographic map of the Bashkirian Stage of the Middle Carboniferous of the Siberian platform (Vinogradov, 1968).

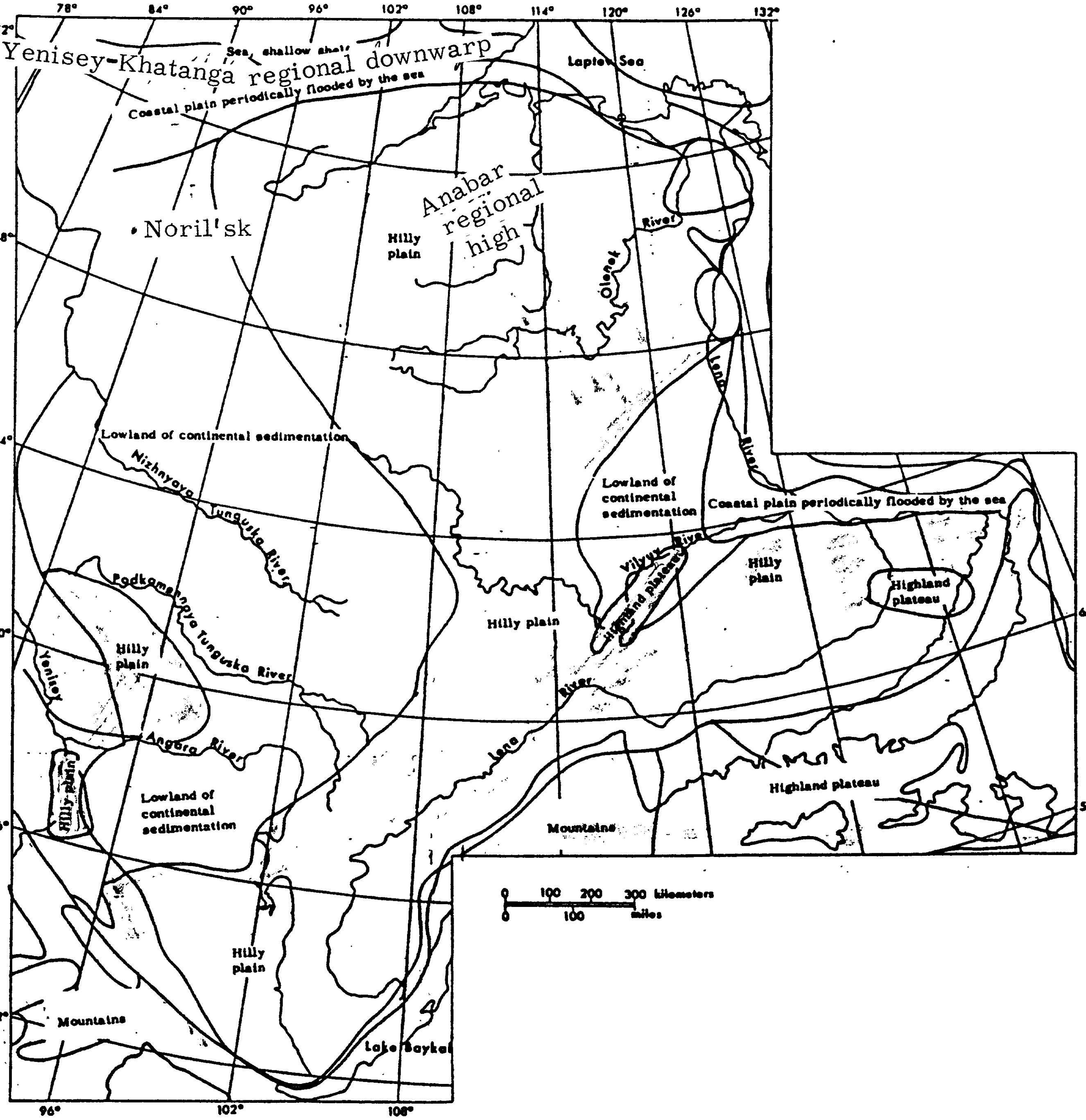


Figure 31. Paleogeographic map of the Siberian platform during the Asselian and Sakmarian Stages of the Early Permian of the Siberian platform (Vinogradov, 1968).

Upper Permian

The paleogeography of Late Permian time was essentially the same as that of the Early Permian (fig. 32).

In the Noril'sk area, the Shmidt Formation is at the base of the Upper Permian. It consists of 130 m of alternating argillite, siltstone, and coal. This is overlain by 90 m of sandstone, conglomerate, coal, siltstone, and shale of the Kayerkan Formation. At the top of the Upper Permian is the Ambarnin Formation, which is similar to the Kayerkan except that it carries no coal. Thickness is up to 50 m.

In the Tunguska basin at the base of the Upper Permian is the Noga Formation, which is composed predominantly of sandstone. Thickness is 60 m. Next in the section is the Chapkokto Formation, a unit of alternating sandstones, siltstones, argillites, and coals as much as 250 m thick. At the top of the Upper Permian, the Degali Formation, which is the same lithologically as the Chapkokto, is also 250 m thick. The boundaries of these formations are defined on a basis of abundant plant remains.

In the area north of the Anabar regional high, the section is composed of four formations from the bottom upward, as follows. The Nizhnekozhevnikova, composed of argillites and fine-grained sandstones, is 360 to 500 m thick. The Verkhnekozhevnikova consists of argillite, siltstone, and sandstone 400 to 480 m thick. The Masaylan is largely pelitic varieties, which contain beds of siltstone and sandstone; thickness is 70 to 100 m. The section is then topped by volcanics that contain a few beds of clastics. This "effusive-tuffaceous" unit is 230 m thick (Kontorovich and others, 1981).

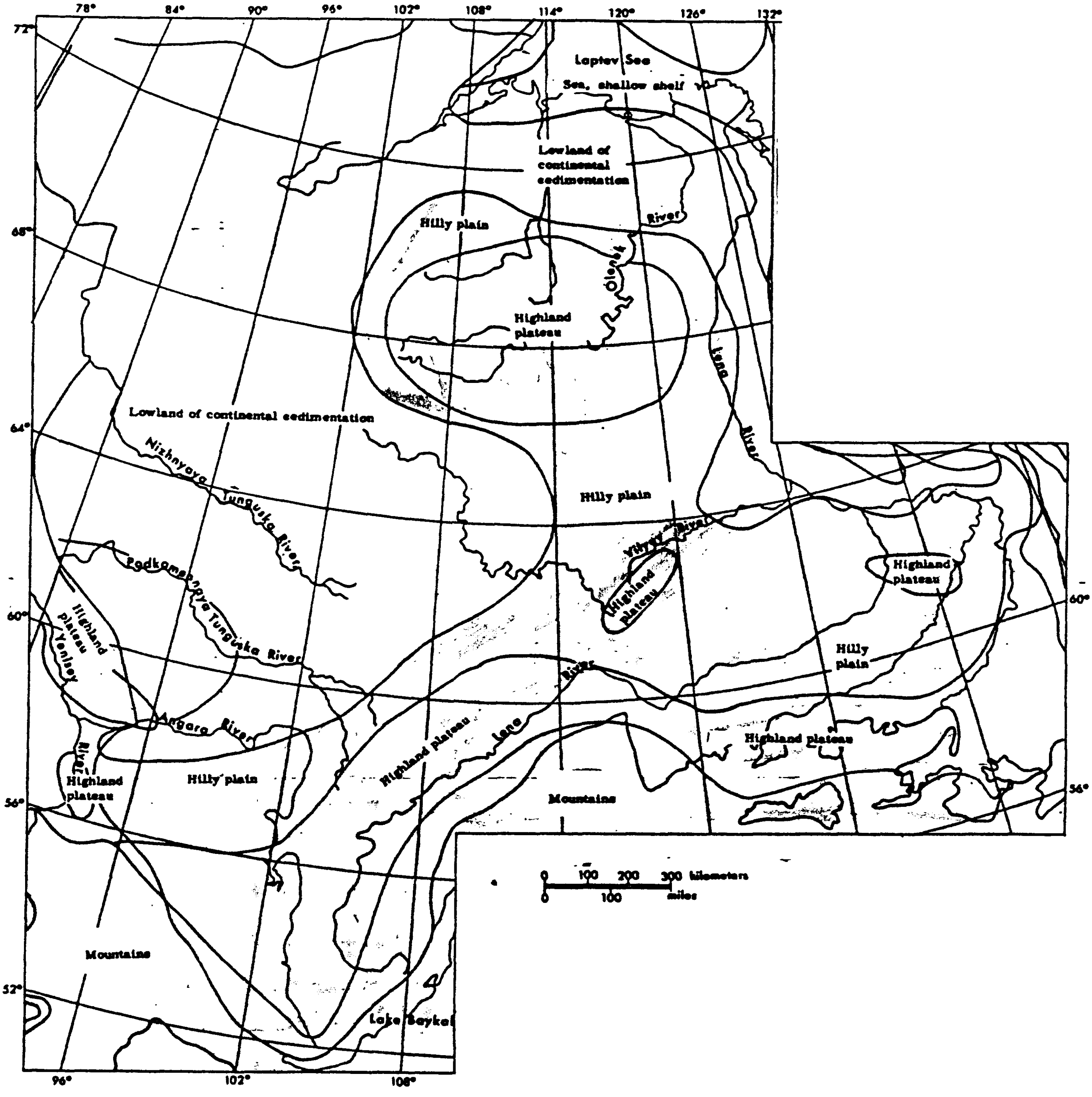


Figure 32. Paleogeographic map of the Siberian platform during the Tatarian Stage of the Late Permian (Vinogradov, 1968).

Triassic System

Within the Siberian platform are two large regions, the Tunguska-Kotuy and the Lena-Vilyuy, in which the Triassic sections are completely different. The Tunguska-Kotuy facies region includes the Tunguska basin and the northwest flank of the Anabar regional high. (Kotuy area). The Triassic here consists of volcanic rocks. The Lena-Vilyuy facies region embraces the Vilyuy basin, Cis-Verkhoyansk foreland downwarp, Yenisey-Khatanga regional downwarp, and Lena-Anabar downwarp. Continental and marine sediments predominate here (fig. 33).

Correlation between the Tunguska-Kotuy and Lena-Vilyuy facies regions has not been accomplished; therefore, each is described here separately.

Tunguska-Kotuy Facies Region

The Triassic here consists of plateau basalts, tuffs, and tuffaceous-sedimentary rocks that formed from basic and alkali-ultrabasic magmas. Their ages have been determined as Early Triassic on a basis of plant fossils. They cover an area of 1.0 million km^2 and are 2,800 to 3,000 m thick (fig. 33). Feeder dikes and sills associated with these volcanic rocks are abundant in the Proterozoic and Paleozoic sections over much of the Siberian platform.

In the Tunguska basin, basic volcanic rocks are referred to the Induan and Olenikian Stages.

Four Induan formations, representing the first volcanic stage, are recognized from the bottom upward. The Noril'sk Formation has 60 to 70 m of andesitic basalt flows at its base; these rest on an eroded surface of upper Paleozoic sediments. Overlying tholeiitic basalt flows are 100 to 120 m thick. The Tomulakh Formation consists of 145 to 170 m of porphyritic basalt flows. The Tuklon Formation has 30 to 50 m of tholeiitic basalt in its lower part and 25 to 33 m of tuffaceous sedimentary rocks in its upper. The Nadezhdin Formation is made up of 500 m of porphyritic basalt.

The Olenikian Stage consists of volcanics of the second stage of volcanism. The lavas of this stage, in contrast to those of the first, are largely undifferentiated. Four formations are recognized from the bottom upward. The Kutaramakan Formation is composed of doleritic flows 450 to 600 m thick. The overlying Khonna-Makit Formation is largely poikilitophyric basalt flows, but it also contains volcanic-sedimentary members that carry plant fossils. Total thickness of the formation is 550 to 600 m. The Nerakar Formation is composed of about 500 m of basalt flows. At the top of this volcanic pile is the Neguikon Formation, which consists of 150 to 200 m of volcanic-sedimentary rocks and basaltic flows.

The northwest flank of the Anabar high (Kotuy-Maymecha province) is smaller in area in comparison with that of the Tunguska basin. However, this may be only the south part of a large province of alkali-ultrabasic magmatism, which is now covered by the Jurassic and Cretaceous sediments that fill the Yenisey-Khatanga regional downwarp. In this case, the volcanics would encroach on Lena-Vilyuy facies. The Induan and Olenikian Stages of the Lower Triassic are both represented here.

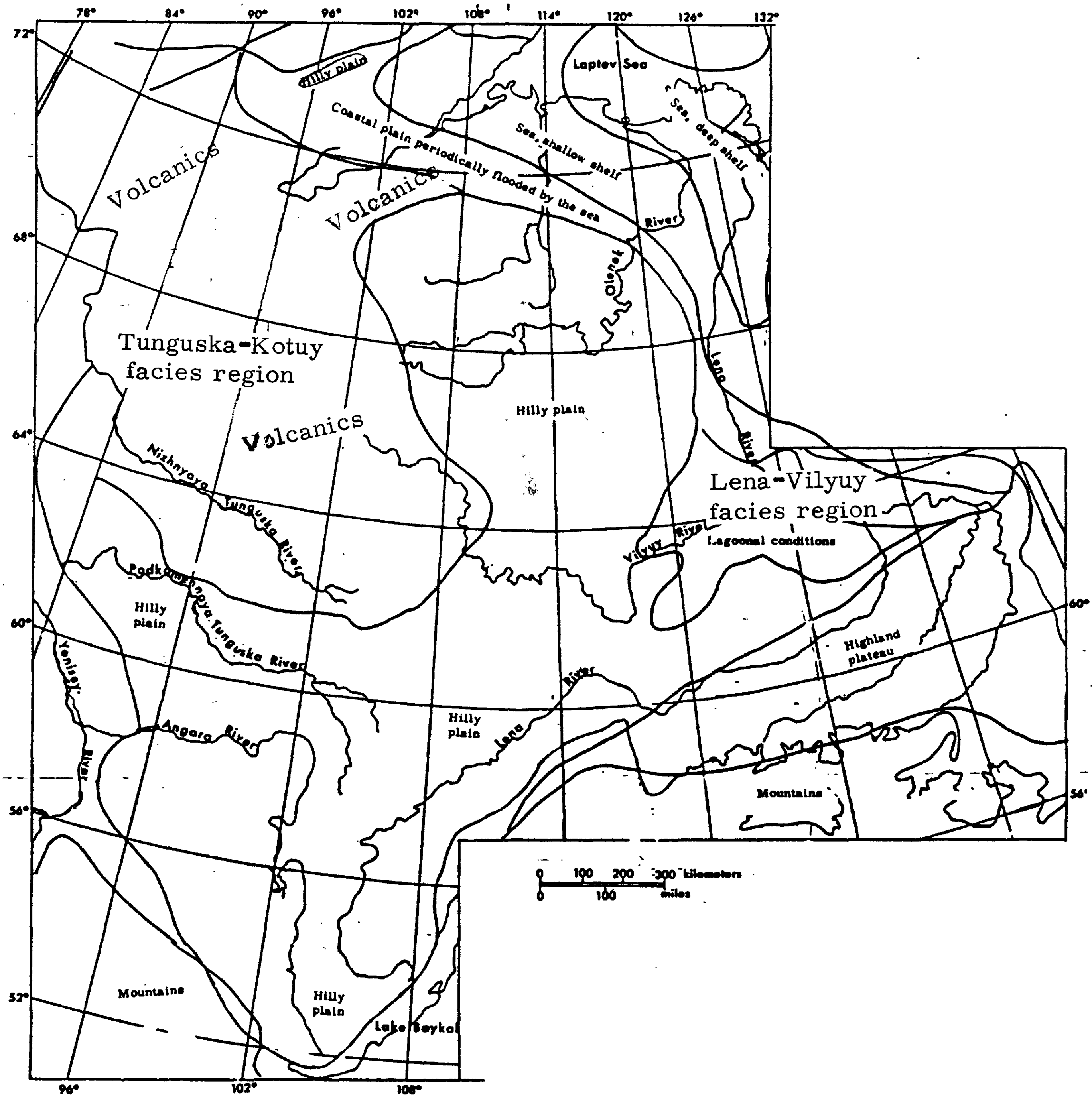


Figure 33. Paleogeographic map of the Siberian platform during the Olenekian Stage of the Early Triassic (Vinogradov, 1968).

The Induan consists of the coeval Arydzhan and Pravoboyar Formations. The Arydzhan contains nepheline basalt flows and tuffs. Total thickness is 300 m. The Pravoboyar is composed of volcanic breccia and tuffaceous clastic deposits, which contain plant fossils. Thickness is 400 m.

The Olenikian is represented by a pile of basaltic flows up to 2,400 m thick.

Lena-Vilyuy Facies Region

All three divisions of the Triassic are represented in this facies region.

Lower Triassic

The sediments of the Lower Triassic in the Lena-Vilyuy region (fig. 28) are marine and continental clastic deposits; carbonates and volcanics are rare. Both Induan and Olenikian Stages are represented.

The Induan is represented by variegated sandstones, siltstones, and argillites, one or the other of these dominating in the section from place to place. Volcanics are present just north of the Anabar regional high. Thickness ranges from about 100 m in the Cis-Verkhoyansk area to more than 600 m in the Vilyuy basin.

The Olenikian in the area to the north of the Anabar regional high is represented by about 100 m of argillites and siltstones. The section thickens to the south to more than 300 m, and sandstones and conglomerates are present in the section.

Middle Triassic

Both the Anisian and Ladinian Stages of the Middle Triassic are represented in the Lena-Vilyuy facies zone; however, they are less widely distributed than the Lower Triassic (fig. 34).

The Anisian consists of marine sandy-clayey beds up to 140 m thick in the northern part of this facies region. The Ladinian Stage here is composed of 80 m of marine siltstones, sandstones, and argillites. To the south in the Cis-Verkhoyansk foreland downwarp and Vilyuy basin, the Middle Triassic is not divided and consists of 300 to 380 m of sandstones and beds of gravel and argillite.

Upper Triassic

During Late Triassic time, marine and continental, largely sandy sediments were deposited in the Lena-Vilyuy facies region (fig. 35), following a break in deposition in which some of the Middle Triassic sediments were eroded. The Carnian, Norian, and in some areas the Rhaetian are present.

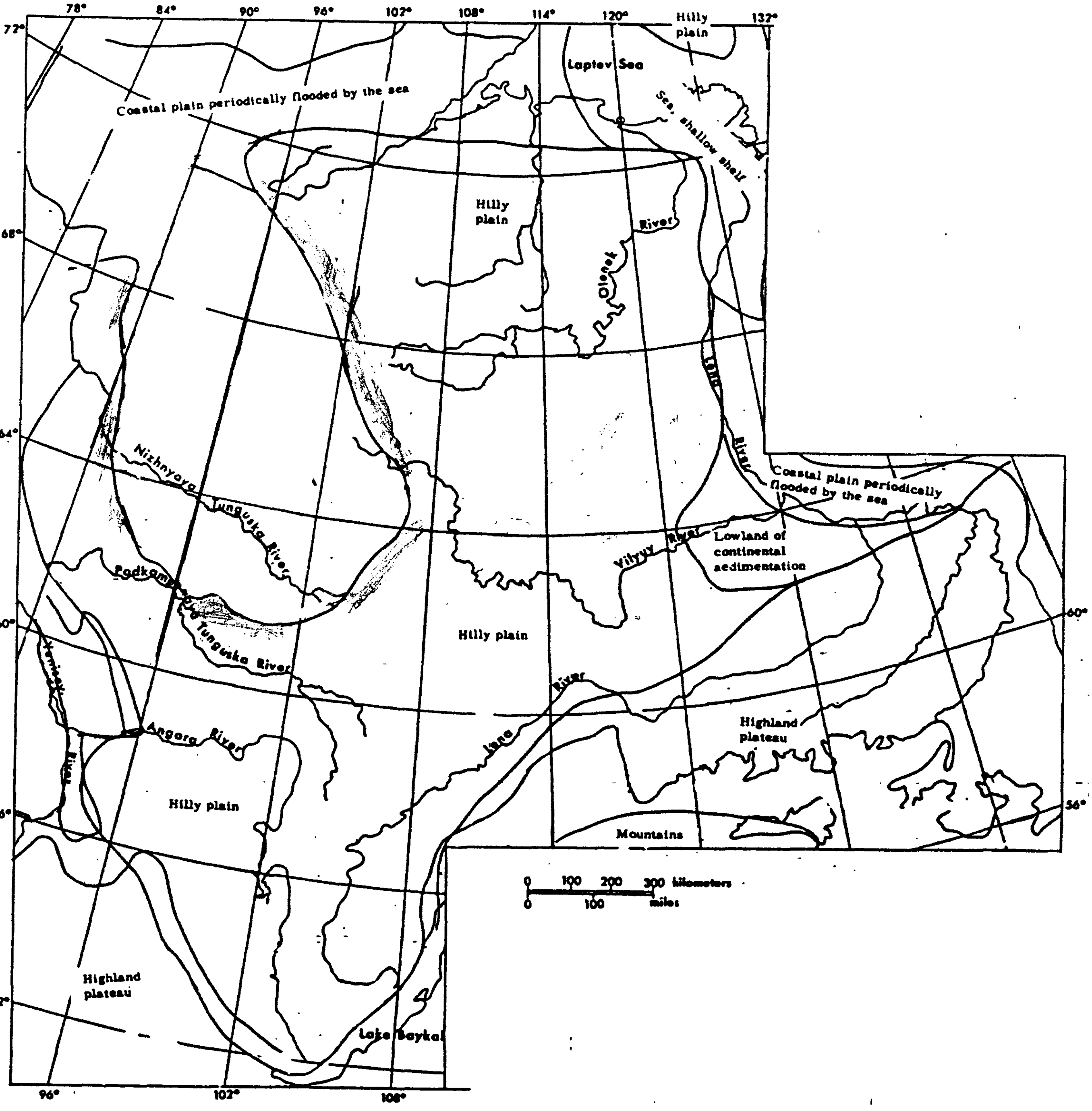


Figure 34. Paleogeographic map of the Siberian platform during the Middle Triassic (Vinogradov, 1968).

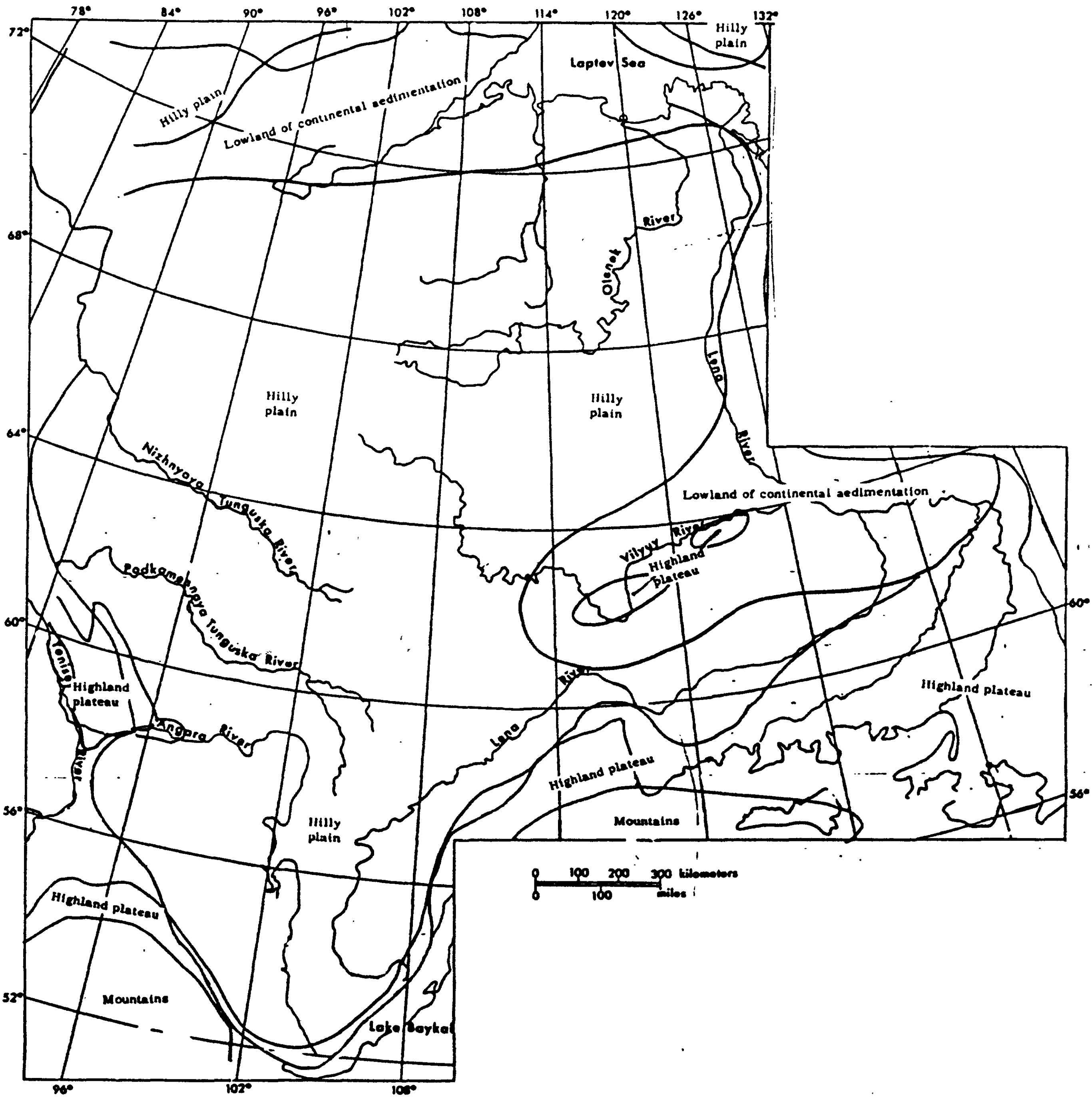


Figure 35. Paleogeographic map of the Siberian platform during the Norian Stage of the Late Triassic (Vinogradov, 1968).

In the northern part of this facies region, the Carnian is represented by 30 m of marine clastics, which grade upward into continental deposits. The section thickens to the south to as much as 350 m in the Vilyuy basin. In the western part of the Vilyuy basin is the Biodomonov Formation of Carnian and Norian age, which consists of argillites, sandstones, and coal beds. It is 50 to 100 m thick.

The Norian consists of marine sandstones containing beds of siltstone and conglomerate in the north. Thickness is 10 to 20 m. These rocks thicken to 125 to 200 m in the Cis-Verkhoyansk foreland downwarp.

The Rhaetian is represented only locally in the eastern part of the Vilyuy basin, where it consists of 170 to 200 m of marine sandstone, argillite, and siltstone.

Jurassic System

Jurassic sediments are present throughout the Mesozoic downwarps on the margin of the Siberian platform as gray clastic deposits more than 3 km thick. They are largely marine; only in the south of the Cis-Verkhoyansk foreland downwarp and Vilyuy basin do continental deposits predominate, and part of the lower and middle divisions here is marine. The Jurassic rests on an erosion surface on the Triassic rocks and is generally but not everywhere overlain conformably by the Lower Cretaceous sediments (Kontorovich and others, 1981, p. 126-134).

Lower Jurassic

Marine and continental deposits of Early Jurassic age extend as an arc through the Yenisey-Khatanga regional downwarp on the north, the Cis-Verkhoyansk foreland downwarp and Vilyuy basin on the east, and then across the southern part of the platform (fig. 36). Thickness ranges from 420 m in the lower reaches of the Yenisey River to 920 m in the Cis-Verkhoyansk foreland downwarp.

The Hettangian, Sinemurian, and lower part of the Pliensbachian Stages are represented by the Zimnyaya Formation in the Yenisey-Khatanga and Lena-Anabar downwarps. This unit is composed of sandstones containing beds of siltstone, dark gray argillite, and some conglomerate; thickness is up to 350 m.

In the Cis-Verkhoyansk foreland downwarp, the Hettangian and Sinemurian consist of marine sandstones, siltstones, and clays. In the Vilyuy basin, continental sandstones predominate.

The Pliensbachian Stage is represented almost everywhere by marine facies. At the mouth of the Yenisey, these are dark gray siltstones and argillites. In the Cis-Verkhoyansk foreland downwarp, they are siltstones, sandstones, and clays 400 to 500 m thick. In the Vilyuy basin, the Plienbachian consists of up to 75 m of clays, siltstones, and sandstones.

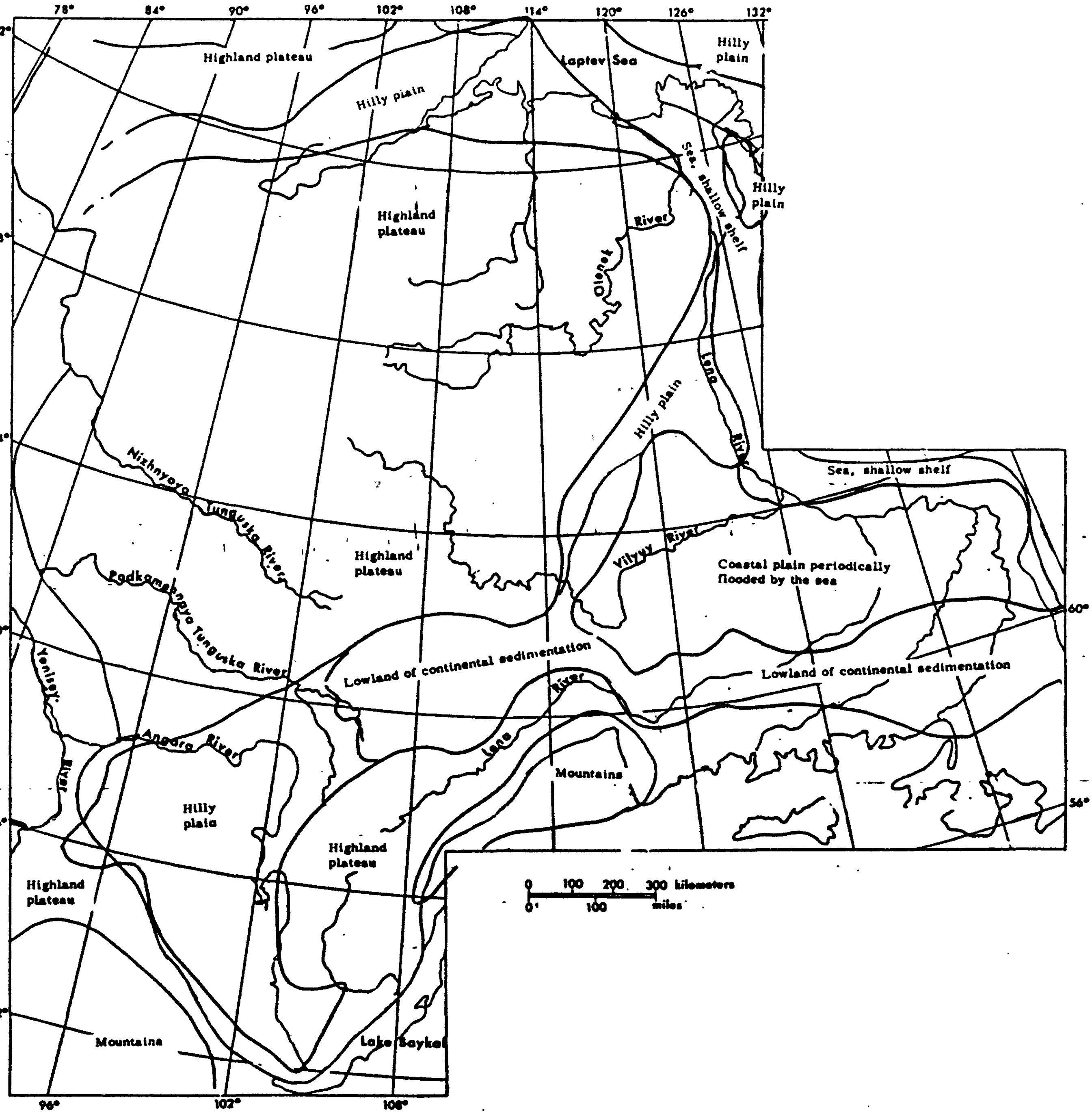


Figure 36. Paleogeographic map of the Siberian platform during the Hettangian and Sinemurian Stages of the Early Jurassic (Vinogradov, 1968).

The Toarcian is also composed of marine deposits. In the Yenisey-Khatanga regional downwarp, it consists of sandstones and siltstones 75 m thick. In the Cis-Verkhoyansk foreland downwarp, the Toarcian has been removed completely by erosion, and in the Vilyuy basin, it is represented by a few meters of shale and siltstone.

Middle Jurassic

Paleogeographic conditions were essentially unchanged in passing from Early to Middle Jurassic time (fig. 37). The Middle Jurassic consists of marine and lagoonal deposits, which range in thickness from 300 to 400 m in the Yenisey-Khatanga regional downwarp to 460 m to the north of the Cis-Verkhoyansk foreland downwarp and 200 to 280 m in the Vilyuy basin. The Aalenian, Bajocian, and Bathonian Stages are present.

In the Yenisey-Khatanga regional downwarp, the Aalenian is represented by about 100 m of argillite overlain by 200 m of sandstone containing siltstone and argillite. The Bajocian section here consists of as much as 1,170 m of clayey-silty rocks. The Bathonian is represented by the Malyshev Formation, a sandstone unit that contains beds of argillite, siltstone, and brown coal. Its thickness is 240 m.

The Middle Jurassic section in the Cis-Verkhoyansk foreland downwarp is made up of 100 to 200 m of Aalenian clays and sandstones; some 35 m Bajocian clays, sandstones, and siltstones; and about 400 m of Bathonian sandstones, siltstones, and shales.

In the Vilyuy basin, the Middle Jurassic is represented by the Yakutsk Formation, which is composed of light-gray kaolinized sandstones, siltstones, and clays. Some coal is present in the upper part of the formation. Thickness of the Yakutsk is about 200 m.

Upper Jurassic

In the northern areas, including the north part of the Cis-Verkhoyansk foreland downwarp, the Upper Jurassic is almost entirely marine. To the south in the main part of the foreland downwarp and in the Vilyuy basin, the sections are composed largely of continental coal-bearing deposits. Thickness of the Upper Jurassic is up to 600 m in the Yenisey-Khatanga regional downwarp, 500 m in the Cis-Verkhoyansk foreland downwarp, and 900 m in the Vilyuy basin. All four stages are represented, and its distribution is essentially the same as that of the Middle Jurassic.

The Callovian Stage in the Yenisey-Khatanga regional downwarp is composed of gray siltstones, clays, and sandstones about 60 m thick. In the Cis-Verkhoyansk foreland downwarp, the lower 250 m of the Dzhaskoy Formation is referred to the Callovian. These deposits are massive, cross-bedded sandstones. In the Vilyuy basin, the Nizhnevilyuy Formation consists of 320 m of coal-bearing sandstones that contain beds of siltstone and clay.

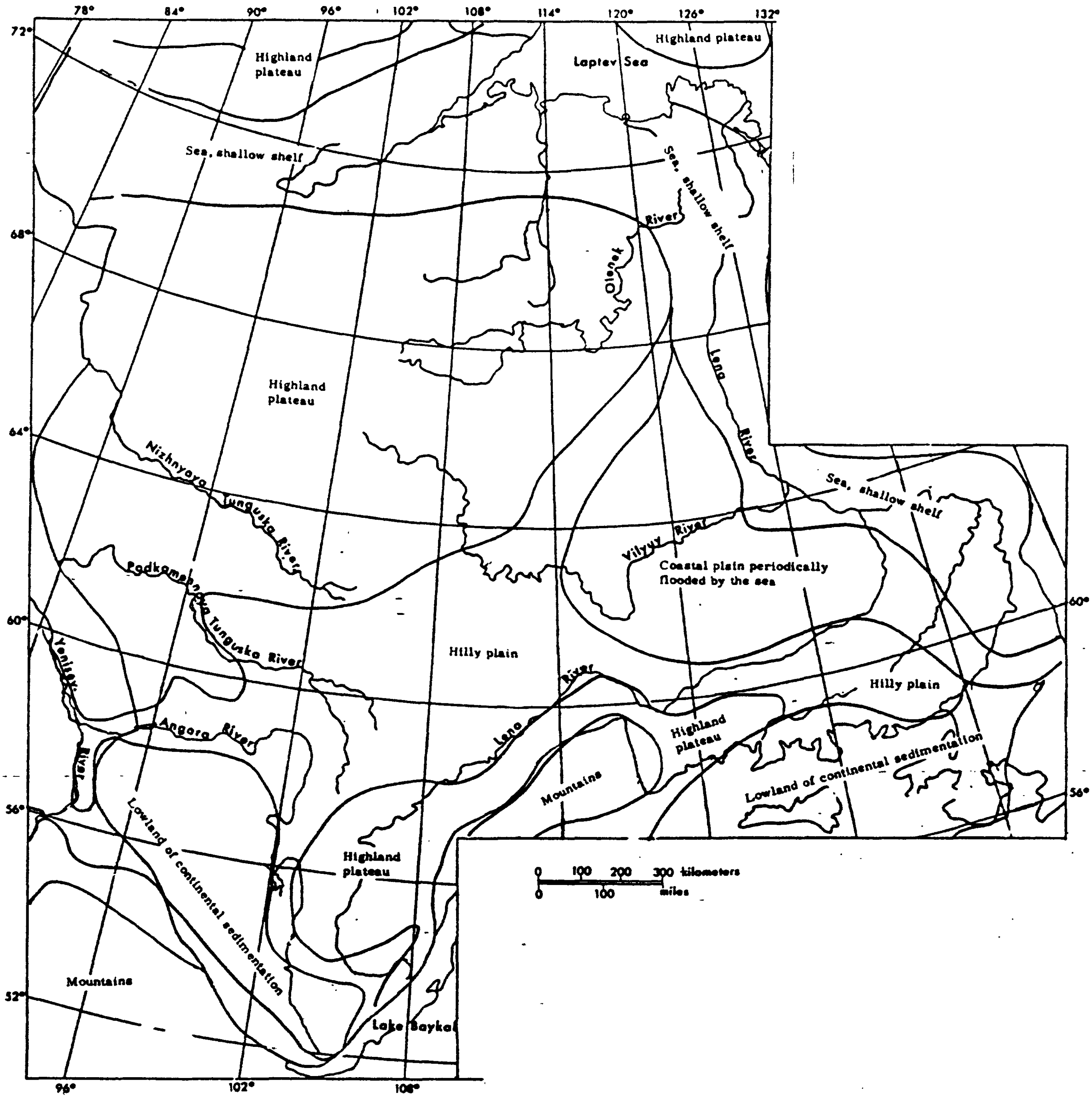


Figure 37. Paleogeographic map of the Siberian platform during the Bajocian and Bathonian Stages of the Middle Jurassic (Vinogradov, 1968).

In the Yenisey-Khatanga regional downwarp, the Oxfordian consists of 153 m of greenish-gray glauconitic sandstone, siltstone, and clay of the Sigov Formation. In the Cis-Verkhoyansk foreland downwarp, the Oxfordian portion of the Dzhaskoy Formation is composed of sandstones, which alternate with siltstone and a few coal beds. The section of the Vilyuy basin is made up of the upper part of the Nizhnevilyuy Formation and the entire Marykchan Formation. This section consists of up to 200 m of dark-gray argillites, siltstones, sandstones, and coal beds.

The Kimmeridgian in the Yenisey-Khatanga regional downwarp is represented by the upper beds of the Sigov Formation and the lower 170 m of the Yanovstan Formation. These rocks are dark-gray clays and siltstones. In the south of the Cis-Verkhoyansk foreland downwarp and in the Vilyuy basin, the Kimmeridgian includes the lower 470 m of the coal-bearing Bergein Formation. This unit consists of sandstones alternating with siltstones, argillites, and workable coal beds.

The Volgian in the Yenisey-Khatanga regional downwarp consists of the upper 500 m of the marine clastic Yanovstan Formation. In the Cis-Verkhoyansk foreland downwarp and Vilyuy basin, the coal-bearing Bergein Formation continues upward from the Kimmeridgean through the Volgian.

Cretaceous System

The Cretaceous system has essentially the same distribution along the north and east margins of the Siberian platform as does the Jurassic; it is composed of gray clastic units that have a total thickness of 3.5 km. The deposits are largely plant-bearing continental sediments, and they are commonly coal-bearing. Some marine deposits are present in the lower and upper parts of the section in the Yenisey-Khatanga regional downwarp. Only coal-bearing continental units are found in the Cis-Verkhoyansk foreland downwarp and Vilyuy basin (Kontorovich and others, 1981, p. 134).

The Cretaceous rests conformably on the Jurassic and is overlain by up to 250 m of Quaternary deposits.

Lower Cretaceous

In the Yenisey-Khatanga regional downwarp, the Lower Cretaceous is represented by 2,000 m of both continental and marine deposits. These sediments are a physical extension of the Cretaceous of the West Siberian basin. The Lower Cretaceous sediments of the Cis-Verkhoyansk foreland downwarp and Vilyuy basin are largely continental and are up to 3,850 m thick (fig. 38).

The Berriasian Stage in the Yenisey-Khatanga regional downwarp consists of the upper part of the Yanovstan Formation, which is composed of 0 to 703 m of dark-gray clays and siltstones. In the lower reaches of the Lena is the Khairgas Formation, a 120-m unit of near-shore siltstones, sandstones, and clays. To the south, the Berriasian is represented by the lower part of the Yngyr Formation in the Cis-Verkhoyansk foreland downwarp and by the lower part of

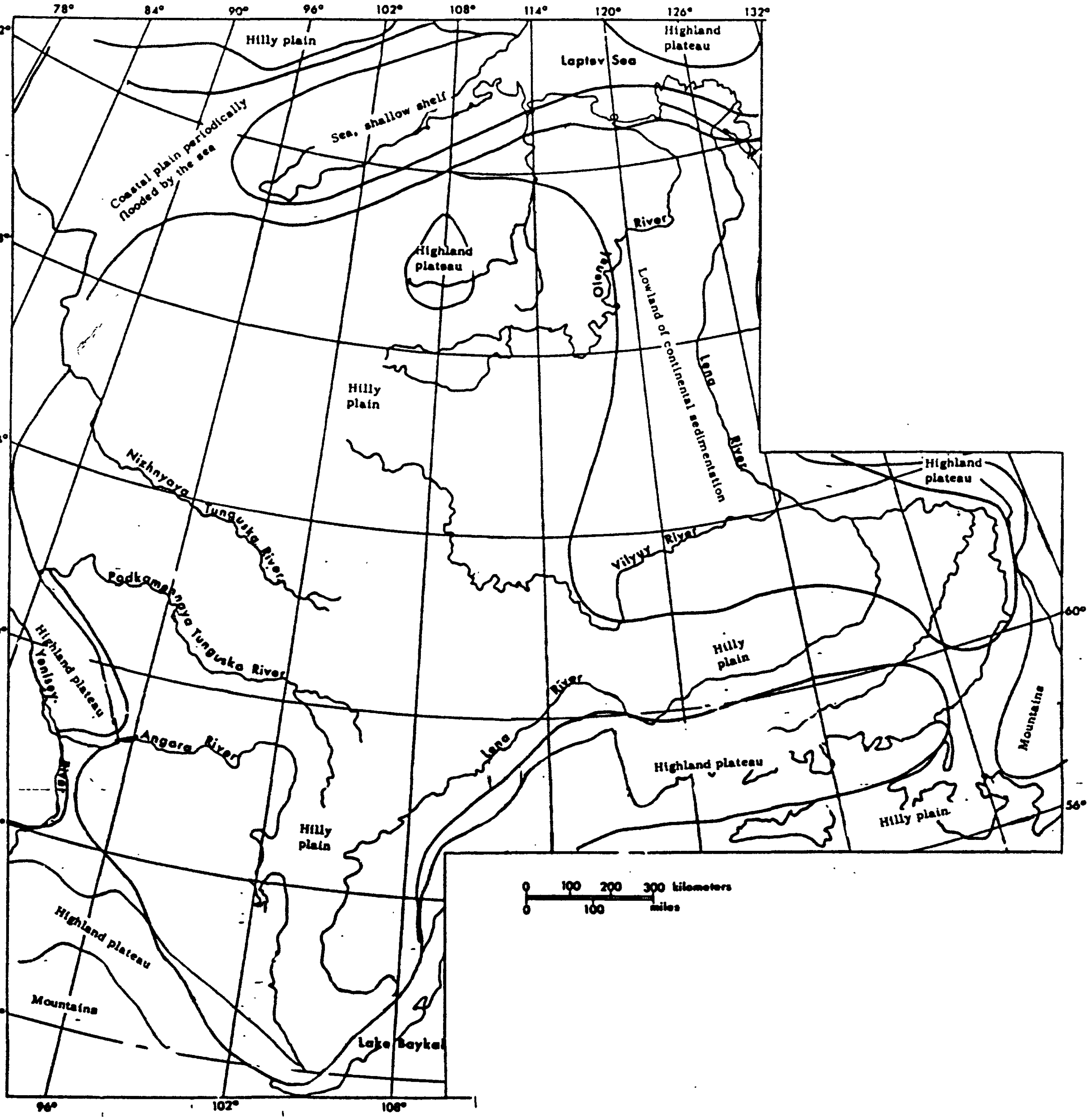


Figure 38. Paleogeographic map of the Siberian platform during the Hauterivian Stage of the Early Cretaceous (Vinogradov, 1968).

the Bukatyy Formation in the Vilyuy basin. Both these formations are coal-bearing clastic deposits. Total thickness of the Yngyr is 100 to 200 m and that of the Bukatyy is 1,000 to 1,250 m.

The Valanginian is represented by up to 825 m of marine sandstones, siltstones, and argillites in the Yenisey-Khatanga regional downwarp; these comprise the Nizhnekhet and the lower part of the Sukhodudin Formations. In the area of the Lena delta are 100 to 400 m of near-shore marine and continental clastics and coal beds of the Kigilyakh Formation. In the Cis-Verkhoyansk foreland downwarp is the upper part of the Yngyr Formation, and in the Vilyuy basin the middle part of the Bukatyy Formation.

The Hauteriv Stage is largely continental deposits in all the Mesozoic downwarps of the Siberian platform. Only the lower part in the Yenisey-Khatanga regional downwarp is marine. These marine deposits are clastics of the upper part of the Sukhodudin Formation. The overlying Malokhet Formation is continental and is composed largely of sands and sandstones. Thickness of the Malokhet within this stage is 170 to 590 m.

In the northern part of the Cis-Verkhoyansk foreland downwarp, the Hauteriv is represented by continental deposits of the Kyusyur Formation (45 to 200 m thick). In the southern part of the foreland downwarp and in the Vilyuy basin, the upper parts of the thick Batylyk Formation are present.

The Barremian Stage on the Siberian platform is represented exclusively by continental coal-bearing deposits. In the Yenisey-Khatanga regional downwarp, it includes the upper part of the Malokhet Formation; thickness of this entire formation is up to 940 m.

In the northern part of the Cis-Verkhoyansk foreland downwarp, the lower 400 m of the Siktyakh Formation is Barremian. This unit is composed of sands and sandstones. In the southern part of the downwarp and in the Vilyuy basin, the uppermost part of the coal-bearing Bukatyy Formation belongs to this stage.

The Aptian Stage is also exclusively continental. It is represented by the lower part of the Yakovlev Formation in the Yenisey-Khatanga regional downwarp. This unit is composed of clays and siltstones and subordinate sandstones and workable coal beds. Its total thickness is 150 to 400 m.

Continental deposition continued on through the Albian Stage. Marine condition prevailed only in the western part of the Yenisey-Khatanga regional downwarp, which was part of the Albian transgression of the West Siberian Sea. The upper part of the Yakovlev Formation represents the stage here.

In the northern part of the Cis-Verkhoyansk foreland downwarp are five successive Albian formations, from the botton upward: Oganer-Yuryakh (200 m), Lukumay (40 to 300 m), Ukin (60 to 490 m), Meng-Yuryakh (200 m), and Charchyk (250 to 320 m). These are sandy-silty-clayey rocks that contain coal beds.

In the southern part of the Cis-Verkhoyansk foreland downwarp and in the Vilyuy basin, the lower part of the Albian section is composed of 700 to

1,100 m of sandstones, siltstones, clays, and coal beds of the Khatyryk Formation. In the upper part are the coeval Mengkeren and Boskhin Formations, which are sandy-silty-clayey units 240 to 400 m thick.

Upper Cretaceous

In the Yenisey-Khatanga regional downwarp, the Upper Cretaceous is represented largely by near-shore marine facies, and in the Cis-Verkhoyansk foreland downwarp and Vilyuy basin only by continental deposits. The area of distribution is essentially the same as that of the Lower Cretaceous (fig. 38). In the area of the Lena-Anabar downwarp at the mouth of the Lena River, the Upper Cretaceous has been removed almost entirely by erosion.

To the Cenomanian Stage of the western part of the Yenisey-Khatanga regional downwarp is referred the Dolgan Formation, which is composed of sands, sandstones, and some clay and siltstone beds. Thickness is more than 500 m. Farther east in the downwarp is the essentially correlative Begichev Formation, which is a 180-m sandstone unit.

In the Cis-Verkhoyansk foreland downwarp, the Agrafenov Formation spans the Cenomanian and Turonian stages. It is composed of green-gray sands containing clay beds in its upper part. Total thickness is 400 to 500 m.

In the Vilyuy basin, the Timerdyakh Formation extends from the Cenomanian into the Maestrichtean. It is composed of sands and friable sandstones 500 to 700 m thick.

The Turonian Stage in the Yenisey-Khatanga regional downwarp is represented by near-shore marine deposits. The Dorozhkov Formation is 41 to 128 m thick and is composed of clays and clayey siltstones. The lower part of the overlying Nasonov Formation is also Turonian.

The Nasonov is a rhythmically alternating unit of clays, siltstones, and sandstones, and a phosphorite horizon occurs at the base of each member. It extends from the upper Turonian through the Campanian.

The Coniacian, Santonian, Campanian, and lower part of the Maestrichtean Stages in the Cis-Verkhoyansk foreland downwarp are represented by the Chirimyy Formation. This unit consists of sands and clays up to 500 m thick.

The Maestrichtean stage is represented by near-shore marine facies in the western part of the Yenisey-Khatanga regional downwarp and by continental facies in the eastern part of the downwarp, in the Cis-Verkhoyansk foreland downwarp, and in the Vilyuy basin. Total thickness of the Maestrichtean Stage nowhere exceeds 100 m.

Some Danian sands were deposited in the western part of the Yenisey-Khatanga regional downwarp.

The Siberian platform has stood above sea level since the end of Cretaceous time, except for some Tertiary subsidence in the Yenisey-Khatanga trough where Paleocene and Eocene sediments are present locally.

HISTORY OF PETROLEUM EXPLORATION

The first investigators of East Siberia in the late sixteenth and early seventeenth centuries found bitumens that had been washed ashore from Lake Baykal. Oil seeps were also recorded at that time in the area between the Vilyuy and Lena Rivers. In the late eighteenth century, an analogy was made between the bitumens of Lake Baykal and those of the Dead Sea. Numerous surface shows of oil and bitumen were recorded throughout the nineteenth century (Kontorovich and others, 1981, p. 10-23).

Four exploration wells were drilled to 360 to 400 m in 1905-1906 on the shores of Lake Baykal. They were unsuccessful, and exploration was essentially terminated. Interest was renewed during the twenties, and an exploration program began in 1935 in the Yakutsk ASSR. A flow of oil was recovered in 1937 from a depth of 370 to 385 m in a well on the Tolba River. Extensive geological mapping and a small amount of drilling had been accomplished along the periphery of the Siberian platform by the end of the thirties.

During World War II (1941-45), oil exploration was carried out in the Yakutsk ASSR, the north of Krasnoyarsk Territory, and in some areas of the Irkutsk Region. In Yakutsk ASSR in 1942, a well on the Tolba River penetrated the entire Cambrian section and tested 12 to 15 L of oil per day. In Krasnoyarsk Territory, a small flow of oil was recovered in 1942 from Permian sediments in the region of Cape Il'ya, and a year later a small yield was obtained from Triassic sediments on the Nordvik Peninsula. In the Irkutsk Region, medium- and large-scale geological surveys and drilling during these war years indicated a good Cambrian play in the south of the Siberian platform.

In the post-war years exploration was broadened. Study of the Cis-Verkhoyansk foreland downwarp and the Vilyuy basin began in the early fifties. Deep stratigraphic test drilling beginning in 1948 in the Irkutsk Region showed the possibility for oil and gas in sandstones and dolomites of the Moty Formation. In the Nordvik area, three small oil fields had been discovered by 1953.

Oil exploration on the Siberian platform entered a new phase in the second half of the middle fifties. On October 15, 1956, the first strong flow of gas with condensate was brought in from a well in the Ust'-Vilyuy area. This turned attention to the Mesozoic play of the Vilyuy basin and Cis-Verkhoyansk foreland downwarp. These investigations established the favorability of the lower course of the Vilyuy River where the large Khapchagay arch had been found. The concentration of exploration in this region, however, led to neglect of the rest of this vast platform. Stratigraphic drilling was accomplished, however, in many areas of the platform throughout the fifties. Extensive regional seismic studies were also undertaken during the fifties.

The sixties marked a new, indeed the current stage of oil and gas exploration on the Siberian platform. The Markovo oil-gas field was discovered in March 1962; this turned attention to the Nepa-Botuobinsk regional high and the Irkutsk Region in general. Although the rate of discovery has been low and disappointing, it seems to have been steady. More than thirty fields of more or less commercial significance are now known. Most of these are gas and gas condensate; however, four commercial oil discoveries have been reported (Takayev and Shcherbakov, 1983, p. 59).

In spite of a relatively large amount of drilling, the density of drilling for the Siberian platform is only 0.73 m per km^2. Only 1,005 deep wells had been drilled as of January 1, 1979 (table 1).

PETROLEUM GEOLOGY

Lena-Tunguska Oil-Gas Province

Introduction

The Lena-Tunguska oil-gas province is in general coincident with the pre-Mesozoic part of the Siberian platform (fig. 2). It is bounded on the southeast by the Baykal fold belt and Aldan regional high, on the southwest by the Sayan Archean terrane, on the west by exposures of Cambrian and older rocks along the Yenisey River, and on the north and east by the regional downwarps of the Khatanga-Vilyuy oil-gas province. The province covers an area of 2,800,000 km^2.

The sedimentary cover consists of rocks that range in age from Riphean to Cretaceous. Extensive salt deposits are present in the Cambrian in the south and Devonian in the northwest. Dolerite dikes, sills, and lava flows of Triassic age are extensive and underlie the surface in most of the northwestern part of the province (Dikenshteyn, 1977).

Eleven oil-gas regions are recognized (fig. 39). All discoveries and shows are in Vendian and Cambrian sediments (fig. 40).

Nepa-Botuobinsk oil-gas region

This oil-gas region is coincident with the Nepa-Botuobinsk regional high and Cis-Patom downwarp in the southern part of the Lena-Tunguska oil-gas province (figs. 39 and 41). The regional high, where all the discoveries have been made, extends 600 km in a northeast direction and is 250 km wide; it has an area of 220,000 km^2. Closure is more than 500 m (Samsonov and others, 1976). The Cis-Patom downwarp is not of interest for exploration.

The early exploration was encouraging. During the Ninth Five-Year Plan (1971-75), the goals for proving oil reserves were largely attained, and those for gas were exceeded (Samsonov and others, 1976). Since then, however, the pace of discoveries has slowed.

Table 1.--Status of deep drilling on the Siberian platform as of January 1, 1979 (from Kontorovich and others, 1981, p. 21-22)

Area	Favorable area, 1,000 km^2	Year of first drilling	Total volume of drilling 1,000 m	Drilling density m/km^2	Number of wells
Lena-Tunguska Province					
North Tunguska region	400	1966	6.0	0.000015	3
Turukhano-Noril'sk region	55	1962	41.0	0.75	22
South-Tunguska region	180	1959	25.7	0.14	11
Baykit region	150	1970	37.1	0.25	16
Sayan-Yenisey region	135	1952	58.1	0.43	24
Katanga region	220	1976	3.3	0.02	1
Angara-Lena region	170	1948	427.7	2.52	195
Nepa-Botuobinsk region	335	1950	730.0	2.18	329
Anabar region	500	1962	4.8	0.01	3
West Vilyuy region	100	1959	21.2	0.21	8
North Aldan region	325	1953	18.7	0.06	11
For province as a whole	2,570	1948	1373.6	0.53	623
Khatanga-Vilyuy Province					
Yenisey-Khatanga region	280	1940	293.7	1.05	119
Lena-Anabar region	125	1934	66.7	0.53	42
Cis-Verkhoyansk region	135	1951	107.0	0.79	41
Vilyuy region	120	1951	521.0	4.34	180
For province as a whole	660	1934	988.4	1.51	382
For Siberian platform as a whole	3,230	1934	2,362.0	0.73	1,005

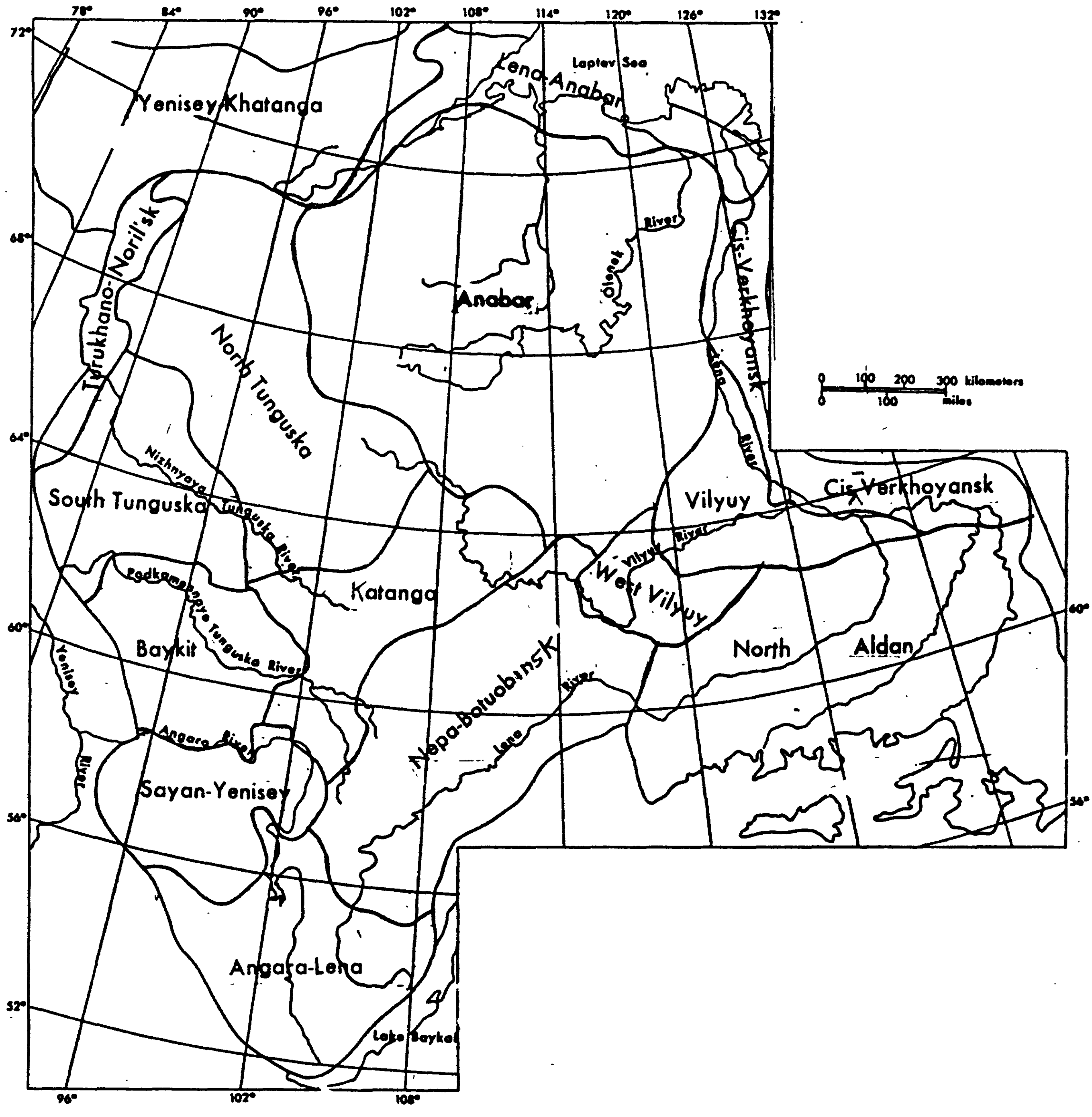


Figure 39. Oil-gas regions of East Siberia.

Left side of figure 40.

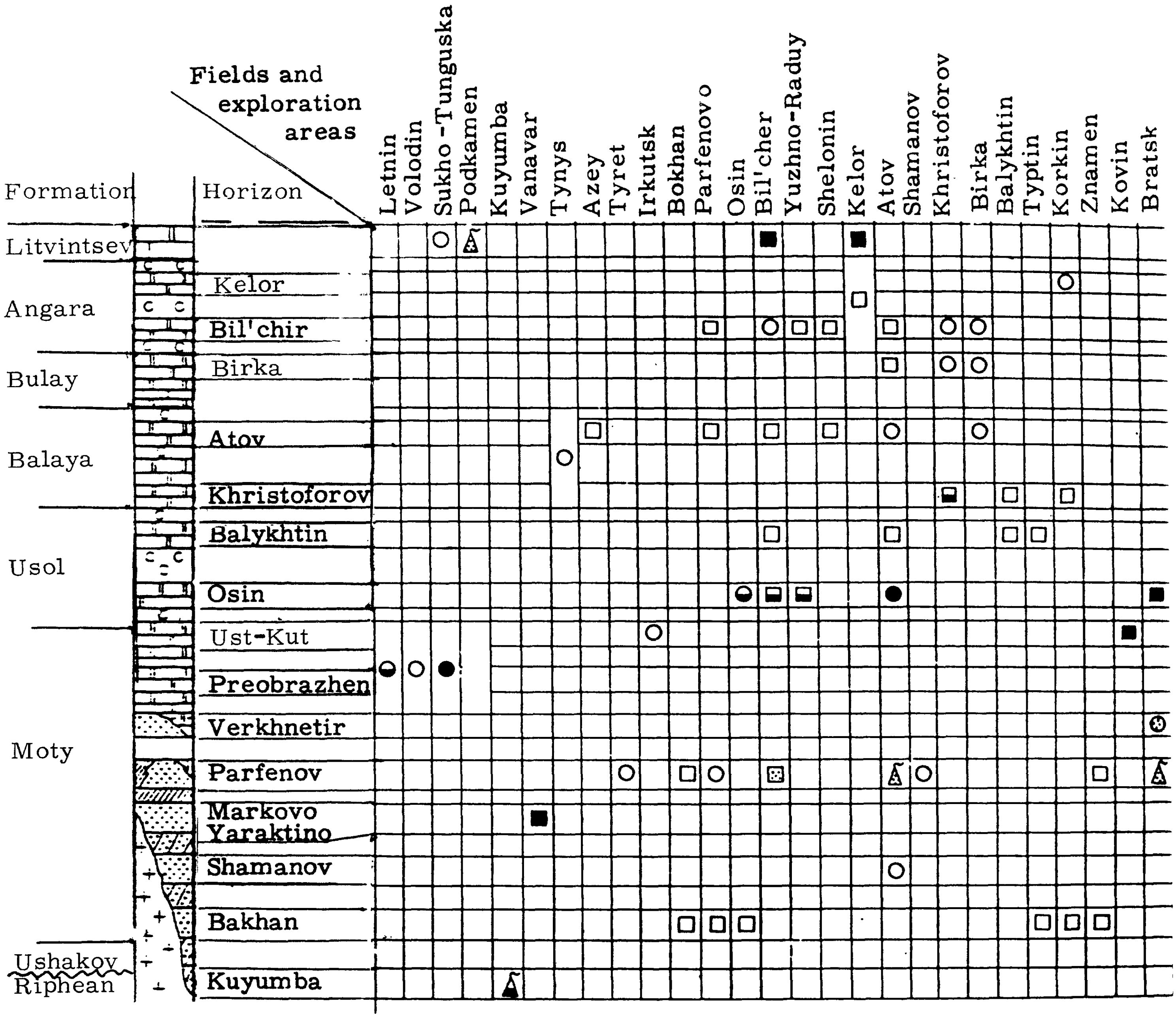
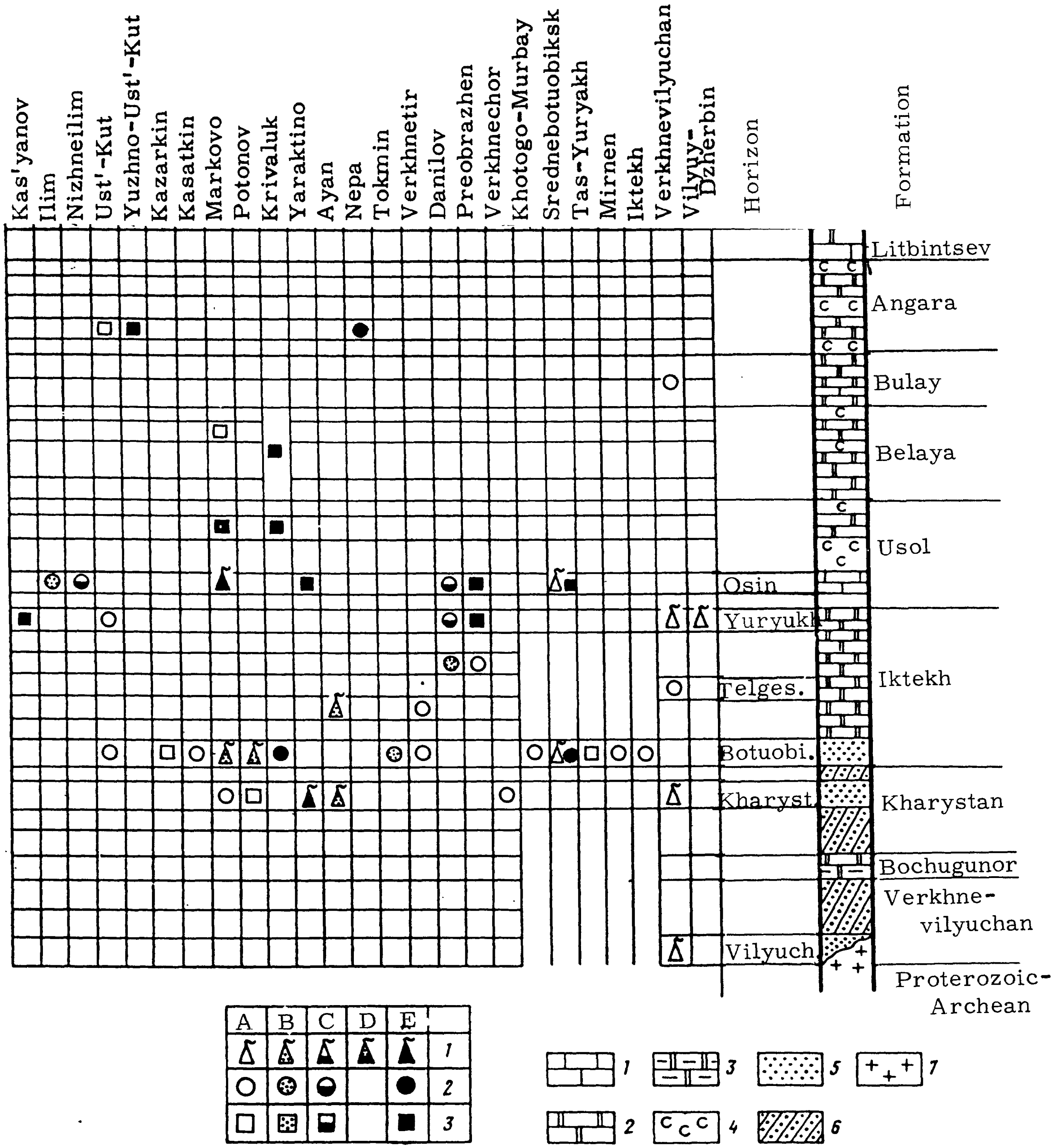


Figure 40.--Distribution of oil and gas pools in the Vendian and Cambrian sections of the Lena-Tunguska oil-gas province (from Kontorovich and others, 1981).

Legend on left: A, gas; B, gas condensate, C, gas-oil; D, gas condensate and oil; E, oil; 1, field; 2, commercial flow from single wells; 3, show.

Right side of figure 40.



Legend on right: 1, limestone; 2, dolomite; 3, clayey dolomite; 4, salt; 5, sandstone; 6, alternating sandstone, siltstone and clay; 7, rocks of basement.

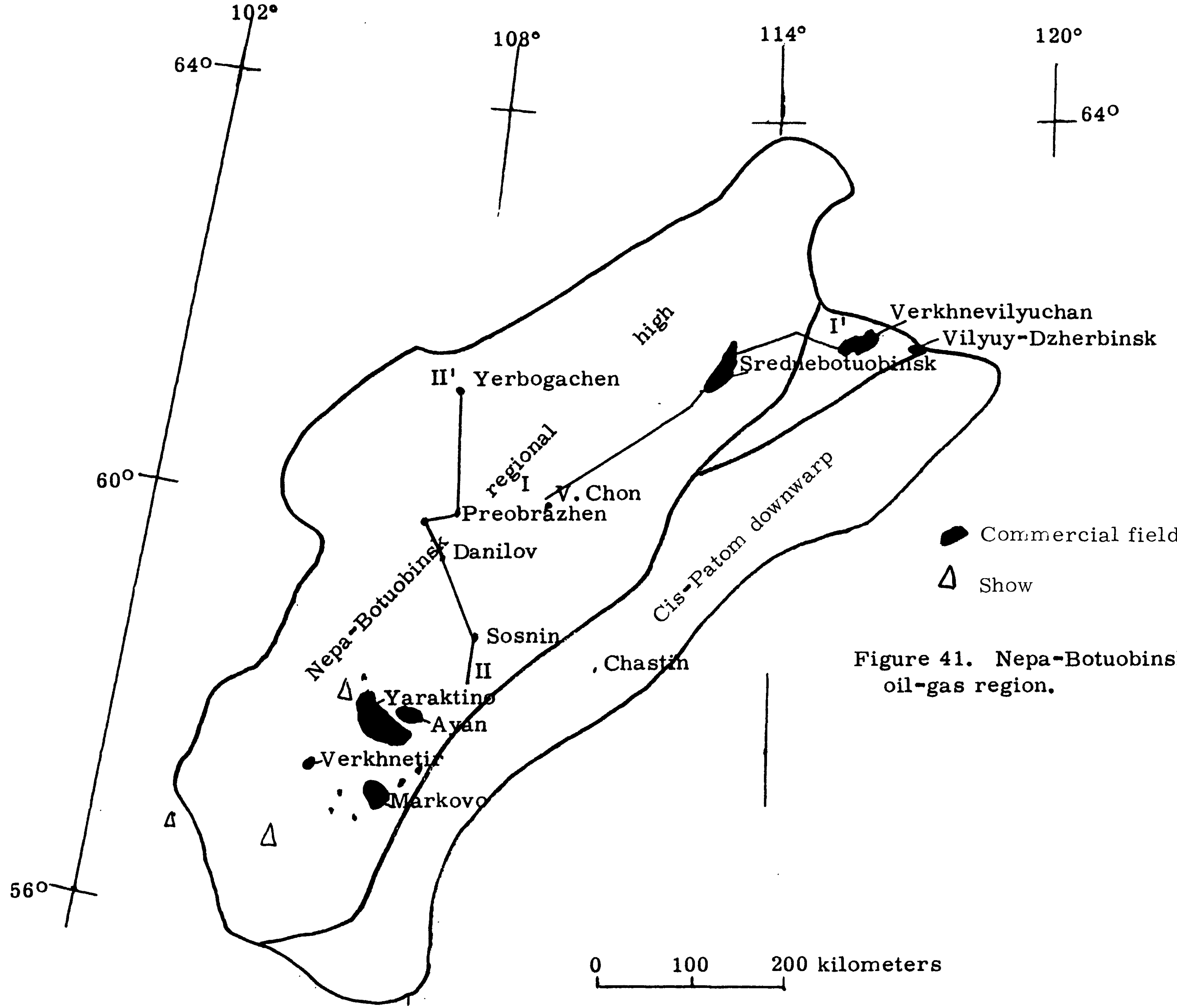


Figure 41. Nepa-Botuobinsk oil-gas region.

The basal complex on the Nepa-Botuobinsk regional high is composed of clastic-carbonate sediments of the Ushakov Formation and the lower and middle Moty Formation (fig. 40). They fill irregularities on the surface of the crystalline basement. Thickness ranges from 20 to 300 m. These sediments are known as the "sub-salt section." Overlying this basal clastic-carbonate (sub-salt) section is a complex of carbonate and carbonate-salt rocks of the upper Moty Formation and Usol, Belaya, Bulay, Angara, and Litvintsev Formations (fig. 12). Total thickness of this complex is 1,500-2,500 m (Bazanov and others, 1977; Antsiferov, 1974). This complex is known as the "salt-bearing section." Ordovician and Silurian clastic sediments overlie the Cambrian salt-bearing section. The Nepa-Botuobinsk regional high was particularly well expressed during Ordovician and Early Silurian time; sediments of this age pinch out toward the crest of the high (Knyazev and Trunov, 1976). During Late Silurian and Early Devonian time, the region experienced general uplift and was to remain emergent until the present.

The Nepa-Botuobinsk regional high developed over a long period of time (Mandel'baum, 1981). During Ushakov and early Moty time (deposition of the sub-salt section), clastic material was derived from the central part of the high and deposited in marine basins on the north and south. These deposits pinch out toward the crest of the high (figs. 42 and 43). Content of clastic material is highest in the zone of the ancient shorelines (Samsanov and others, 1976; Zheleznova and Sidorenko, 1977). Reservoir rocks here are quartz and quartz-feldspar sandstones. Porosity is as high as 22 percent, and permeability reaches 2 darcies. The clastic sediments pass upward into carbonate sediments (upper part of sub-salt section), which contain reef facies. The back-reef facies are on the north toward the Siberian platform, and the fore-reef facies are on the south toward the Cis-Patom downwarp, which then was open sea (fig. 43). The reservoirs here are limestones and dolomites. This sub-salt section contains more than half of the oil and gas pools of the Nepa-Botuobinsk regional high.

The salt-bearing section of the Nepa-Botuobinsk regional high is characterized by cyclic carbonate-salt deposits, which are persistent over large areas (fig. 12). Porosity of these carbonates is generally 1 to 3 percent and rarely exceeds 5 to 10 percent (Dikenshteyn and others, 1977). Fractured dolomites are reservoirs in this section (Mandel'baum, 1981). The salt is the seal for pools in both this part of the section and in the underlying sub-salt section.

Most of the known oil and gas pools on the Nepa-Botuobinsk regional high are in non-anticlinal traps. The sediments on the high were not buried deeply enough to reach the gas-condensate window, let alone the gas window. They reached only the oil window (Antsiferov, 1980). Migration of the gas that presently fills the pools was lateral, probably from the east, from Precambrian and lower Paleozoic sediments of the Nyuysko-Dzherbin and Ygyattin depressions (Chekanov, 1981).

Solid bitumens attest to the destruction of earlier oil pools in the region. Light oily bitumen is in sharp contact with black, nonluminescent bitumen, an occurrence that suggests more than one cycle of pool destruction (Odintsova and others, 1977).

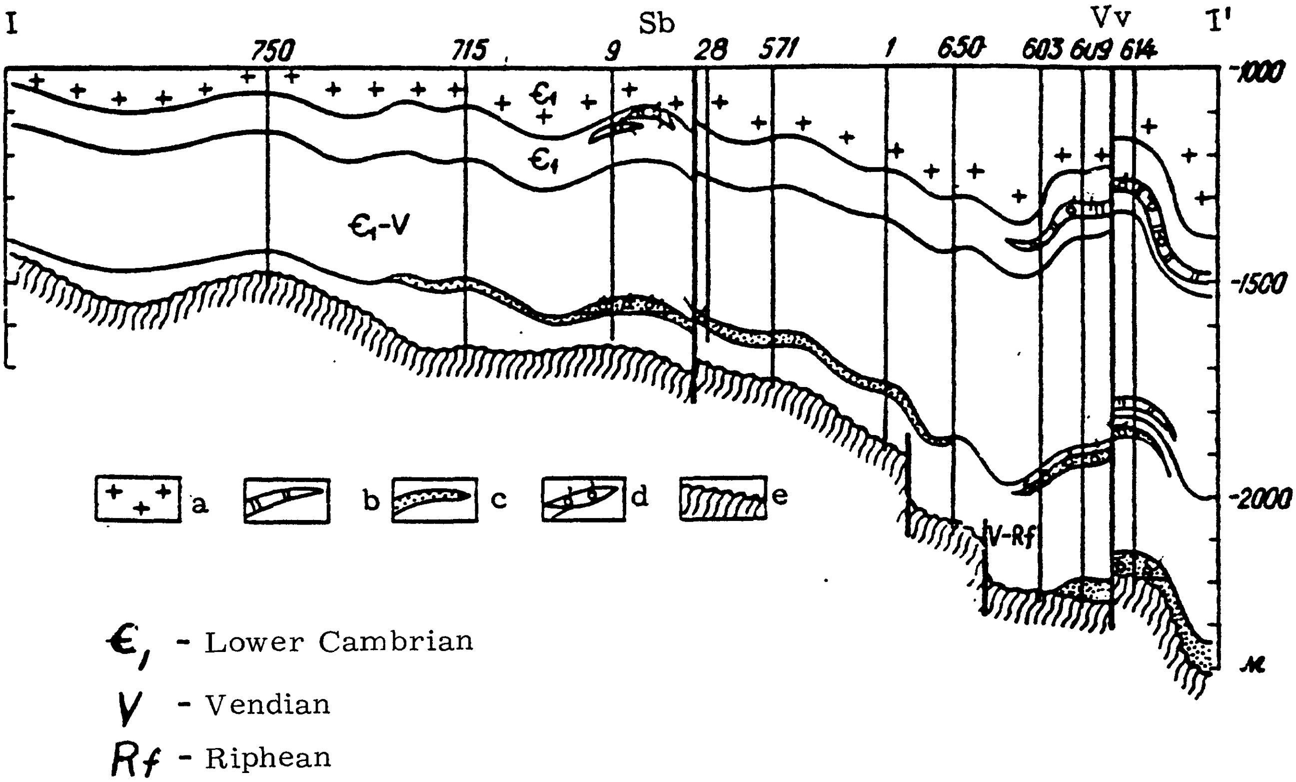


Figure 42.--Geologic profile through Nepa-Botuobinsk regional high along line I-I' (fig. 41) (from Ovcharenko and Bakin, 1979).

a, Halogen-carbonate sediments; b, carbonate-sulfate sediments; c, productive horizons in clastic reservoirs of the Vendian-Riphean clastic-carbonate complex; d, gas pools; e - basement. Fields: Sb-Srednebotuobinsk, Vv-Verkhne-Vilyuchan.

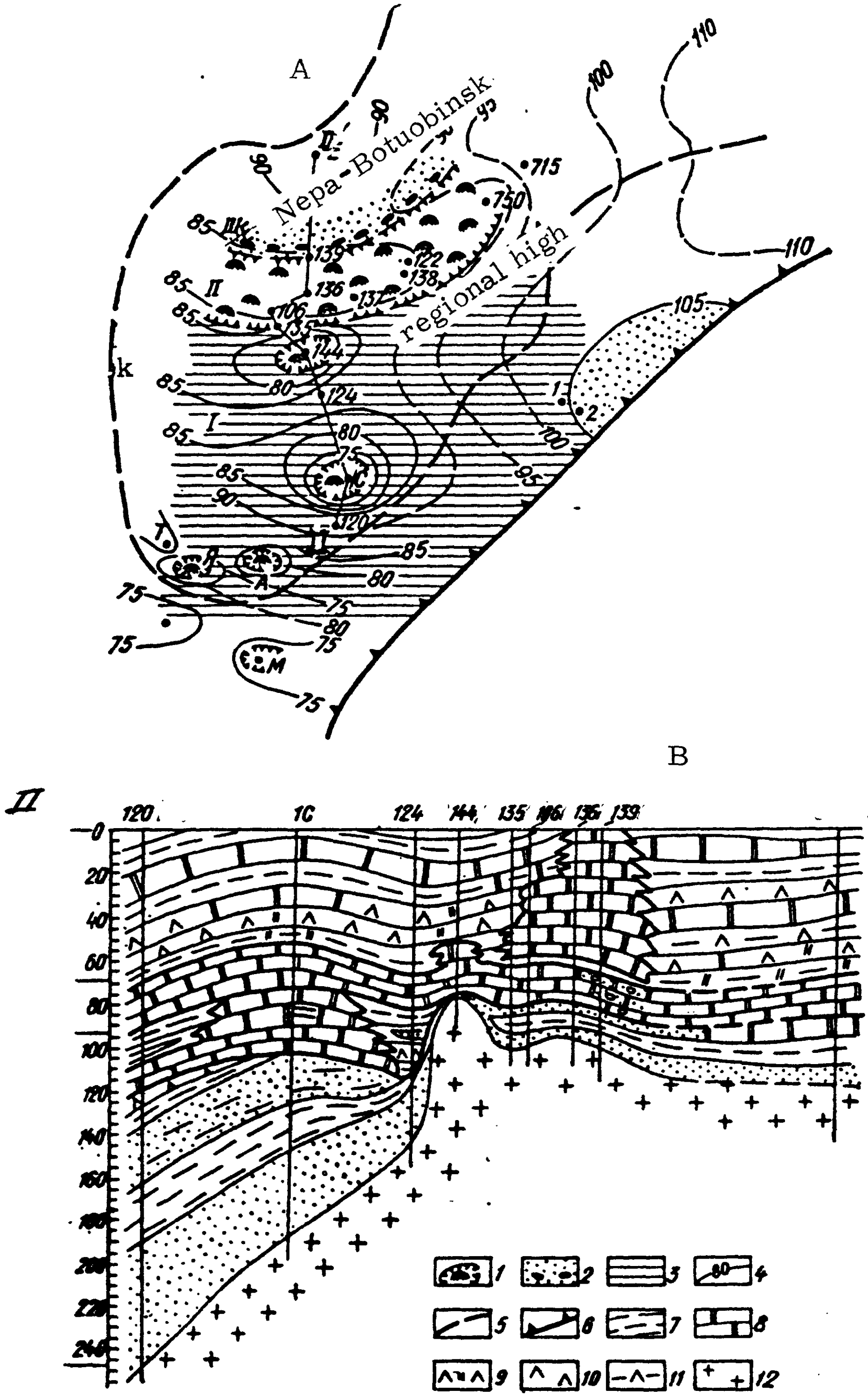


Figure 43.--Distribution of reef zones in sediments of the Moty Formation (from Kalinkina, 1981).
A, map view. B, cross section II-II'.

Zones: 1, reefs; 2, back reef; 3, fore reef; 4, isopachs on the middle Moty, m; 5, boundaries of the Nepa-Botuobinks regional high; 6, limit of the sedimentary cover of the Siberian platform; 7, clay; 8, dolomite; 9, anhydrite-dolomite; 10, anhydrite; 11, clayey dolomite; 12, crystalline basement.

The gas pools of the region are thought to be relatively young. As a result of epeirogenic uplift of the south part of the platform during the Cenozoic and extensive erosion of the upper part of the section, formation pressure in the aquifer complexes dropped by 10-30 mpa. This led to intensive separation of hydrocarbons from the formation waters into a free state. Mineralization of the formation water also increased sharply, thus reducing drastically the solubility of methane. This probably led to release of trillions of cubic meters of gas, which displaced oil from pools where an oil ring is now left (Antsiferov, 1980).

The distribution of fields by area is shown in figure 41, and distribution of pools by stratigraphic position in figure 40.

West Vilyuy oil-gas region

This area of 55,000 km^2 is within the Vilyuy basin; however, it is recognized as a separate oil-gas region because the plays are Paleozoic sediments rather than largely Mesozoic as in the Vilyuy oil-gas region. The principal structures are the Ygyattin depression, Suntar arch, and Kempendyay depression (figs. 39 and 44).

Maximum thickness of the sedimentary section is 9 km. The middle Paleozoic sediments here rest with sharp angular discordance on lower Paleozoic sediments. During the Early Devonian marine transgression, the Suntar arch was a region of erosion, and the Kempendyay and Ygyattin depressions were sites of deposition (Barykin, 1978). Near-shore marine and lagoonal sediments favorable for oil formation were deposited in these depressions on into the Early Carboniferous. Total thickness of these middle Paleozoic sediments is 2,000 m in the Ygyattin depression and 3,000 to 4,000 m in the Kempendyay depression.

Although the middle Paleozoic sediments are the most favorable play, exploration targets also include the Vendian and Lower Cambrian (Sokolov and Larchenkov, 1977; Bakin and others, 1980) and Permian and Mesozoic sediments (Sitnikov, 1975). No commercial discoveries have been made. The proximity of the giant Verkhnevilyuchan field and the Vilyuy-Dzherbinsk field just a few kilometers to the west is encouraging for the Vendian-Lower Cambrian play in the west Vilyuy region.

North Aldan oil-gas region

This region is on the north flank of the Aldan regional high. It extends 1,000 km in an east-west direction and is about 300 km wide. It covers an area of 405,000 km^2 (figs. 39 and 45).

Maximum thickness of the sedimentary cover is 6 km. The plays here are Riphean and Lower Cambrian clastic sediments and Lower Cambrian carbonate sediments. Flows of gas at 100,000 m^3/d have been recovered from Lower Cambrian carbonate sediments at Russko-Rechen, and oil-saturated Lower Cambrian sandstones have been found in several areas. Thickness of these sandstones ranges from 8 to 35 m, and their porosity is from 6 to 11 percent (Dikenshteyn, 1977).

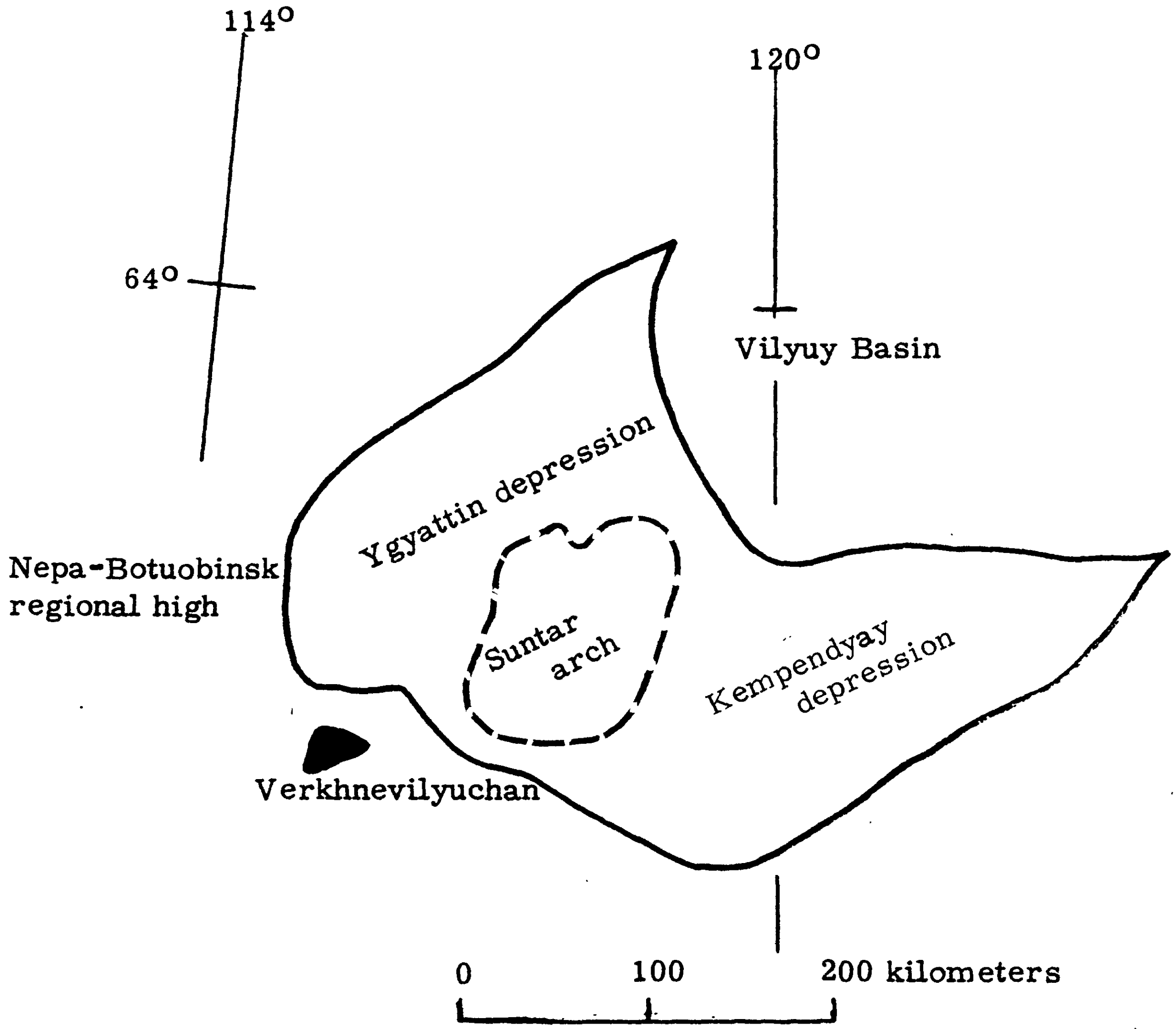


Figure 44. West Vilyuy oil-gas region.

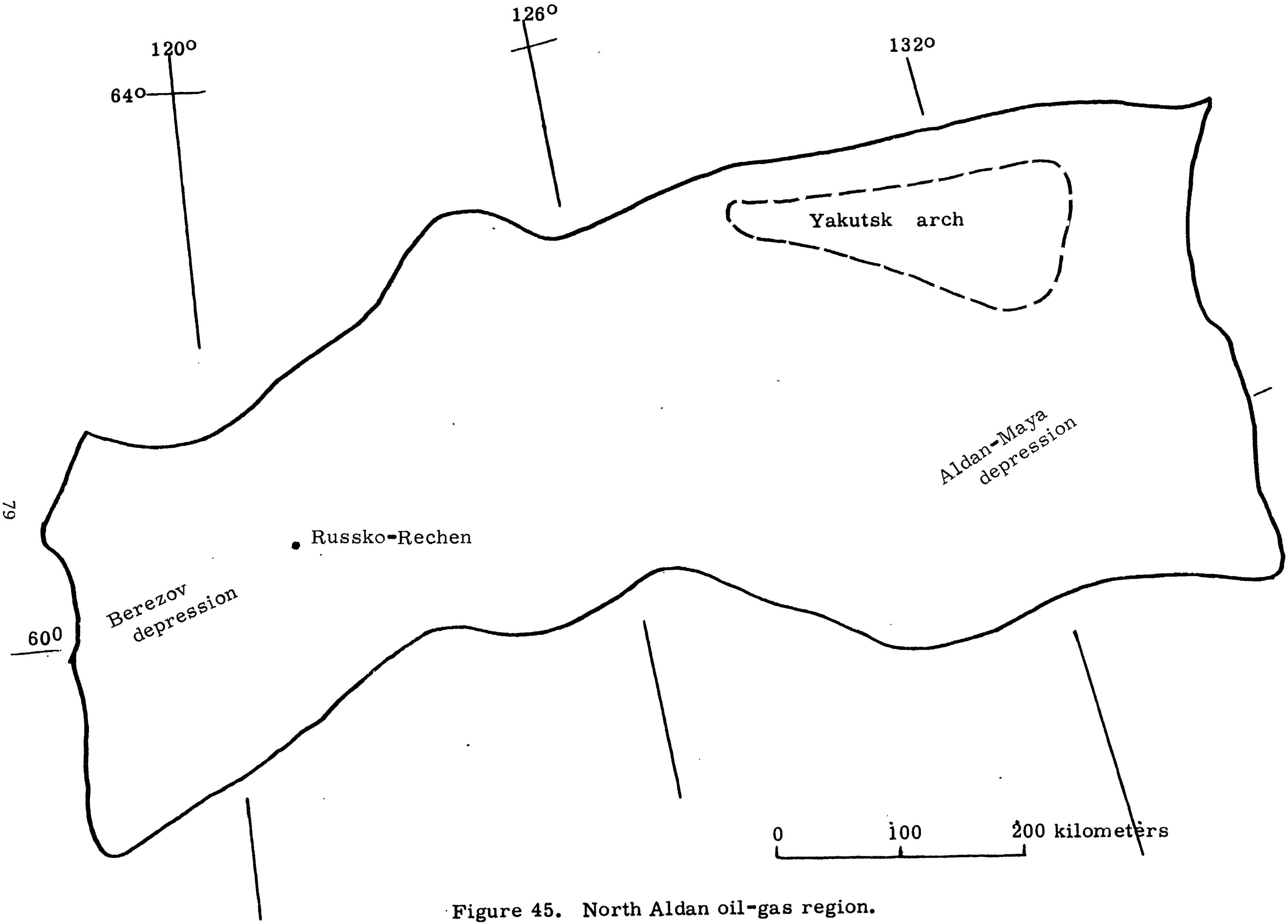


Figure 45. North Aldan oil-gas region.

Deep erosion of the Cambrian and Riphean sediments is a negative factor here. Further, the section is largely carbonate sediments and does not contain good seals.

The most favorable areas for exploration are the Berezov and Aldan-Maya depressions and the flanks of the Yakutsk arch (fig. 45).

Angara-Lena oil-gas region

This area of 235,000 km^2 at the southern tip of the Siberian platform is part of the Irkutsk amphitheater (figs. 39 and 46). A large number of gentle synsedimentary structures are present in the sub-salt section, whereas greater closure (200 to 500 m) characterizes the structures above the salt (Dikenshteyn and others, 1982).

Two plays are found in the region: sub-salt Vendian-Lower Cambrian clastic sediments (Markovo and Parfenov horizons) and Lower Cambrian carbonate sediments (Osin, Balykhtin, Birkin, and Bil'chir horizons) (fig. 40).

The thickness of the sandy horizons of the sub-salt clastic play is 50 to 60 m in the south and 10 to 30 m and less in the central regions. In this same direction the porosity ranges from 40-45 to 4-10 percent, and permeability from 100-300 to 20 md. Thickness of the carbonate reservoirs ranges from 60 to 70 m in the Osin horizon to 20 to 40 m in the Balykhtin and Bil'chir horizons.

Conditions are not favorable for oil and gas along the southern margin of the region because of infiltration of surface water. Both plays are favorable in the rest of the region, however.

Small gas pools have been found in sandstones of the Parfenov horizon in the Bratsk, Atov, and Parfenovo areas (fig. 40). Yields reach 280,000 m^3/d. The Osin horizon of the Usol Formation has yielded oil in the Atov, Yuzhno-Raduy, and Osin areas and gas in the Ilim area. A flow of gas was recovered at 175,000 m^3/d from the Balykhtin horizon in the Balykhtin area. Commercial flows of oil have been obtained in the Khristoforov area and of gas in the Birka area from carbonates of the Belaya Formation. The Bil'chir horizon of the Angara Formation has yielded gas in the Khristoforov and Bil'chir areas.

Sayan-Yenisey prospective oil-gas region

This oil-gas region coincides with a regional low that covers an area of 160,000 km^2 on the southwest margin of the Siberian platform (figs. 39 and 47). The main large structures are the Kat, Mursko-Chun, and Dolgomostov depressions and the Boguchano-Manzin regional terrace. Magnetic surveys indicate depth to basement here at 5 to 7 km (Uspenskaya and Tabasaranskiy, 1966). This region was a foreland downwarp during late Precambrian and early Paleozoic time.

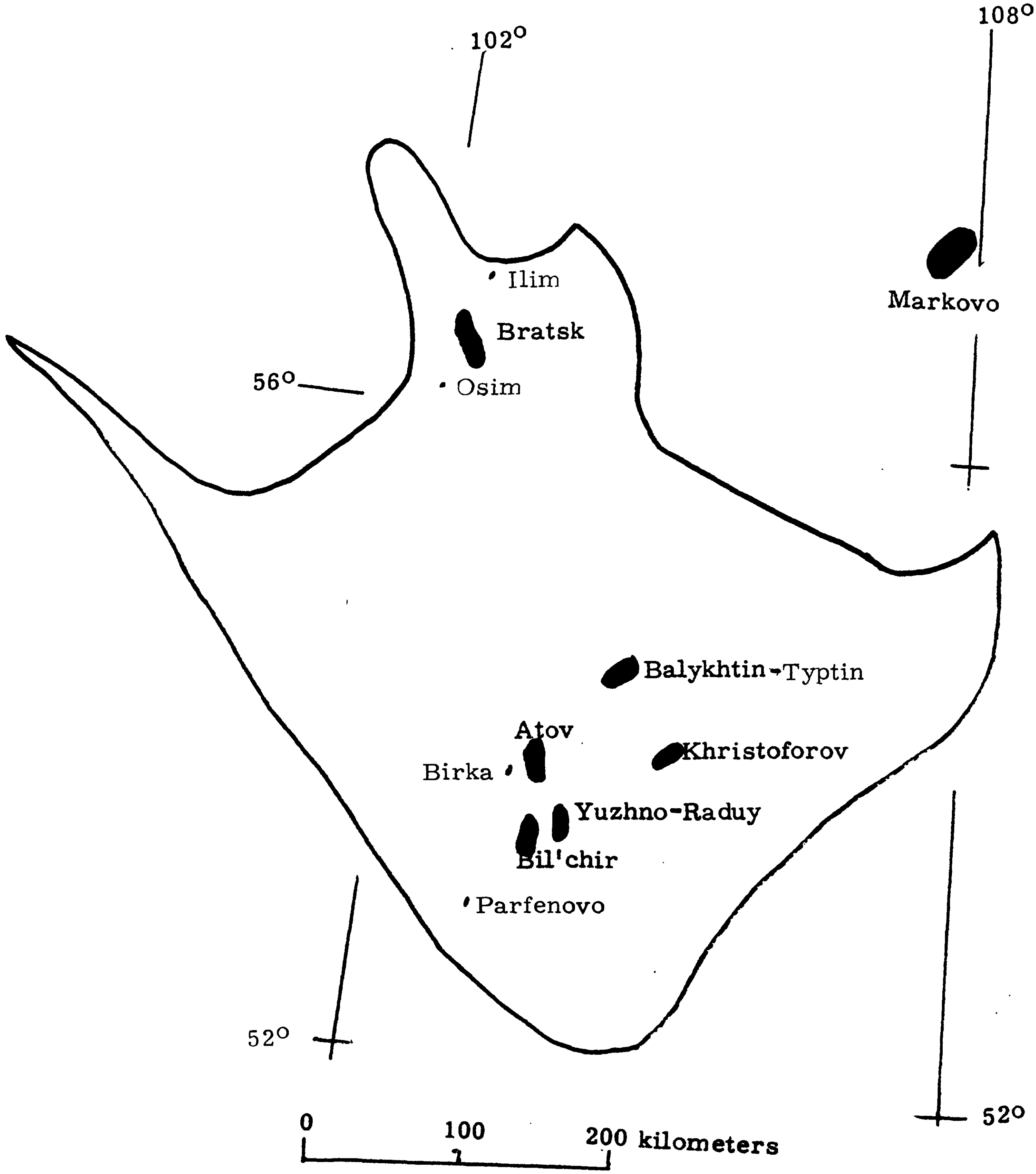


Figure 46.--Angara-Lena oil-gas region.

Locations of Ilim, Osim, Birka, and Parfenovo are approximate.

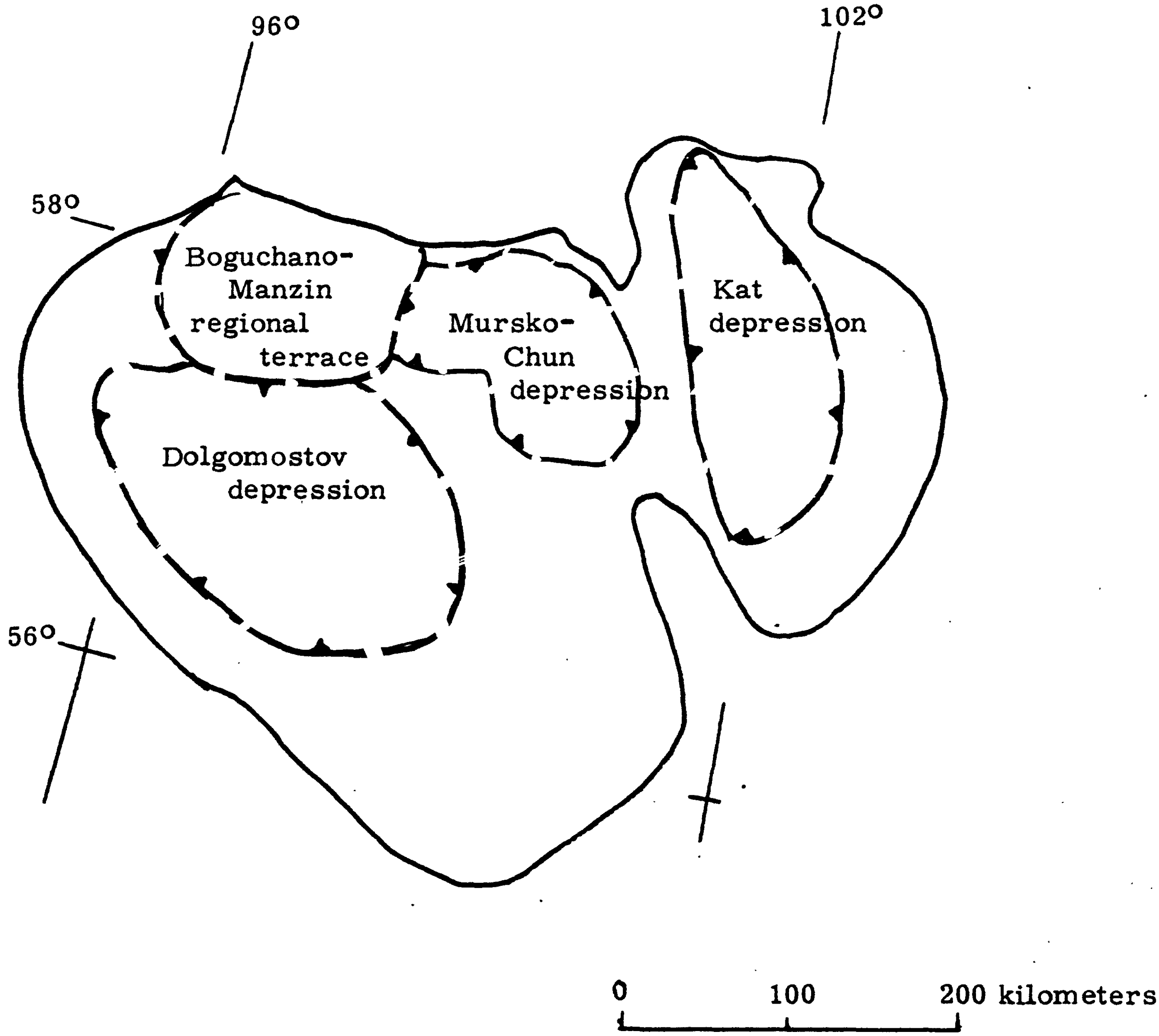


Figure 47. Sayan-Yenisey prospective oil-gas region.

No commercial discoveries have been made in this region. The main plays are sub-salt clastic sediments of the lower Moty Formation and carbonate sediments of the Lower Cambrian. Reservoir properties of that part of the Cambrian section that has been drilled are not very favorable; open porosity is 5 to 11 percent. A good Cambrian salt seal is present, however, and this lends some optimism for the region.

Baykit oil-gas region

The Baykit oil-gas region covers an area of about 120,000 km^2 in the southwestern part of the Siberian platform and is coincident with the Baykit regional high. Within the territory of this regional high are the Kamov arch and several other highs as well as the Terin megadownwarp along the southern border (figs. 39 and 48). Closure on the Baykit regional high on the top of the Lower Cambrian sediments exceeds 1,000 m.

Thickness of the sedimentary section is up to 6 km on the flanks of the regional high and 2 km at the crest. These sediments are clayey-carbonate deposits of Riphean age, which are more than 1,400 m thick, and clastic-carbonate deposits of Vendian and early Paleozoic age, which are up to 3,000 m thick. On the east flank are carbonate-clayey and volcanic rocks of middle and late Paleozoic and Triassic age; these are up to 1,000 m thick. Thick salt beds are present in the Cambrian section (Dikenshteyn, 1982).

The Kuyumba gas-condensate field was discovered in this region in 1974 (Ministry of Geology, USSR, 1975). The pool occurs in Riphean dolomite, the age of which is 740 to 1440 million years (Bakin and others, 1980). Clayey dolomites of the Moty Formation are the seal. The field is a massive, multipay accumulation on the monoclinal flank of an ancient high. Some of the delineation wells have penetrated granite directly beneath the Moty seal (Mel'nikov, 1977; Mel'nikov and others, 1978).

Katanga prospective oil-gas region

This area covers 205,000 km^2 in the southeastern part of the Tunguska regional low (figs. 39 and 49). The principal structures within it are the Katanga saddle, Chun regional terrace, and Ilimpey arch (figs. 49 and 50). One well has been drilled in the region (Kontorovich and others, 1981). Maximum thickness of the sedimentary section is 5 km.

The main plays are sandstones of the basal beds of the Lower Cambrian and carbonate sediments of the Lower and Middle Cambrian. In the northern part of the region, Lower Ordovician sandstones hold some promise. The Ilimpey, Chun, and Vanavar structures have closures of several hundred meters and may prove to be zones of oil-gas accumulation (Dikenshteyn and others, 1977).

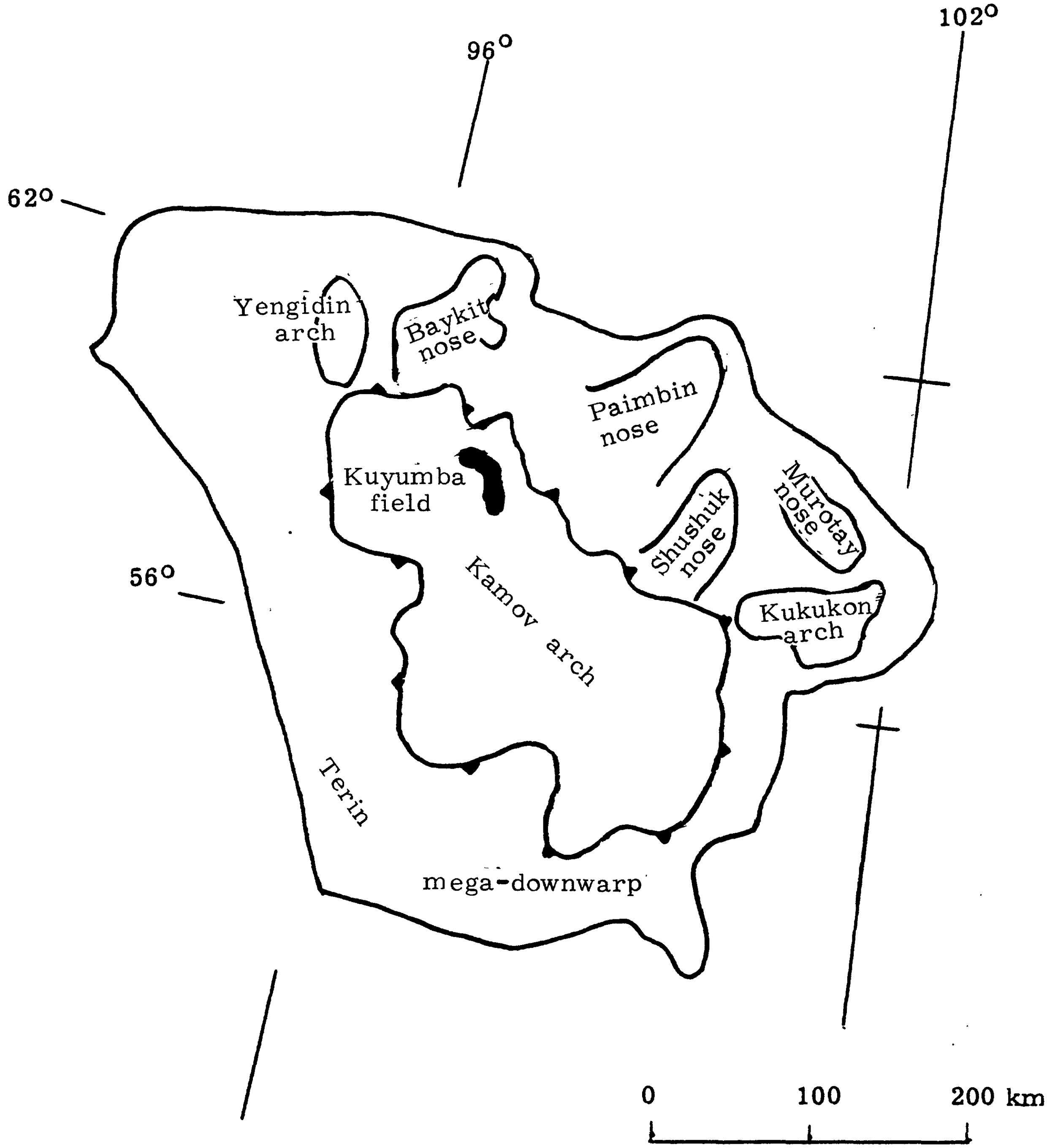


Figure 48. Baykit oil-gas region.

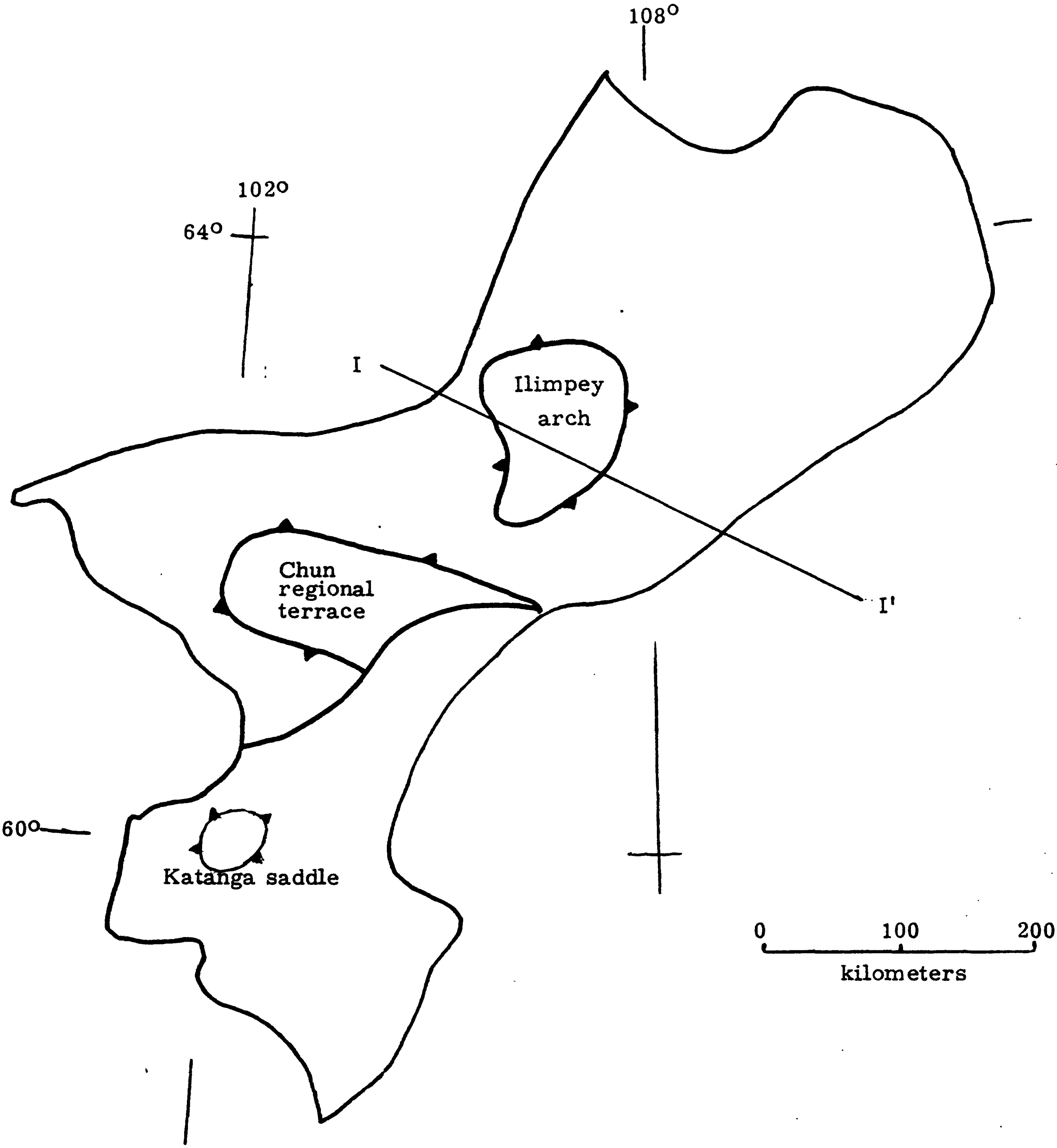


Figure 49. Katanga prospective oil-gas region.

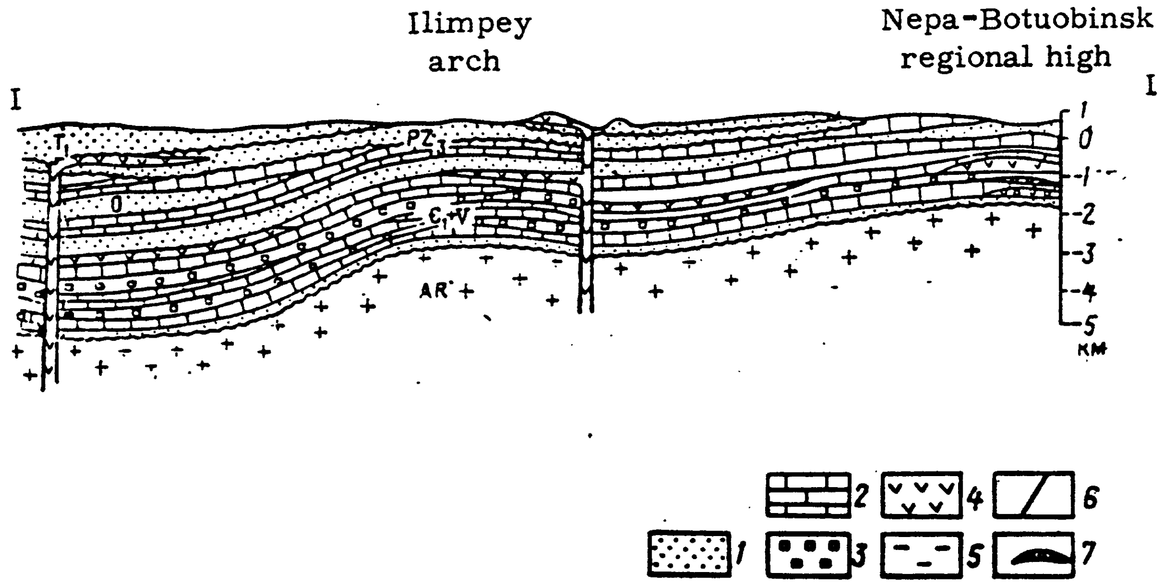


Figure 50.--Geologic section along profile I-I' in Katanga prospective oil-gas region (fig. 49). (After Dikenshteyn and others, 1982).

1, clastics; 2, carbonates; 3, salt-bearing; 4, basaltic trap rock; 5, basement; 6, faults; 7, hydrocarbon deposits.

South Tunguska prospective oil-gas region

This region covers about 180,000 km^2 in the west-central part of the Siberian platform (figs. 39 and 51). The Surindakon arch lies in the central part of the region. It is flanked on the west by the Nizhnetunguska mega-downwarp and on the south by the Bakhtin regional terrace.

Archean basement is overlain by upper Proterozoic clastics and Cambrian carbonates. Salt is present in the Cambrian section. Triassic lava flows cover much of the surface. Total thickness of the sedimentary section is 5-6 km (fig. 52).

Only eleven wells have been drilled in the region, and no discoveries have been reported (Kontorovich and others, 1981). The area of the Bakhtin regional terraces is considered favorable, however.

North Tunguska prospective oil-gas region

This region covers about 400,000 km^2 in the northwest part of the Siberian platform (figs. 39 and 53). It is largely within the Kurey regional low, a broad structural feature of about 700,000 km^2, which also includes the South Tunguska and Katanga regions. Depths to basement range from 3.5-4 km on the arches to 6-8 km in the depressions (fig. 54).

The section of the sedimentary cover of the basin consists of Vendian, Cambrian, Ordovician, Silurian, Devonian, and Lower Carboniferous sediments overlain unconformably by up to 1,000 m of Triassic dolerite. The Devonian contains salt beds.

Only three wells have been drilled in the region, and no commercial discoveries have been made.

Anabar oil-gas region

This region corresponds with the Anabar regional high, which covers an area of 750,000 km^2. Precambrian crystalline rocks are exposed at the surface in the central part of the high, and consequently the area favorable for oil and gas is much less, given variously as 500,000 and 685,000 km^2 (figs. 39 and 55).

Thickness of the sedimentary cover increases toward the periphery to 3 to 5 km. The sedimentary section consists largely of Riphean to lower Paleozoic clastic-carbonate and limestone-dolomite assemblages. Upper Paleozoic and Mesozoic sediments are also present. The Sukhan depression separates the Anabar arch on the west from the Olenek and Muna arches on the east.

Only three exploration wells have been drilled in this vast area, and no discoveries have been made. Extensive bitumen deposits are present, however. The Olenek bitumen deposits contain about half the bitumen resources of the entire country. The bitumen occurs in sediments of Riphean, Vendian-Early Cambrian, Middle-Late Cambrian, Permian, and Early Jurassic age.

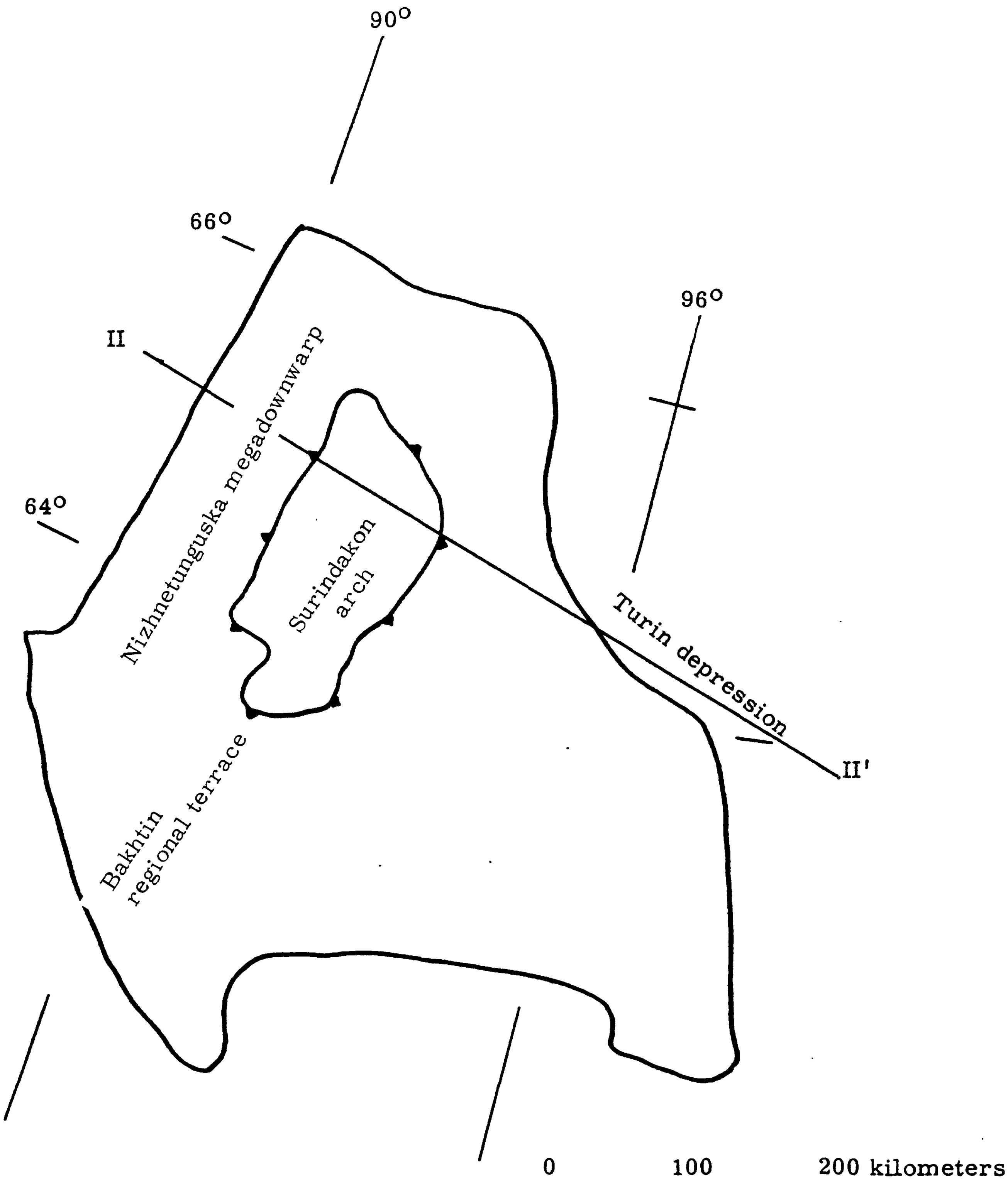


Figure 51. South Tunguska prospective oil-gas region.

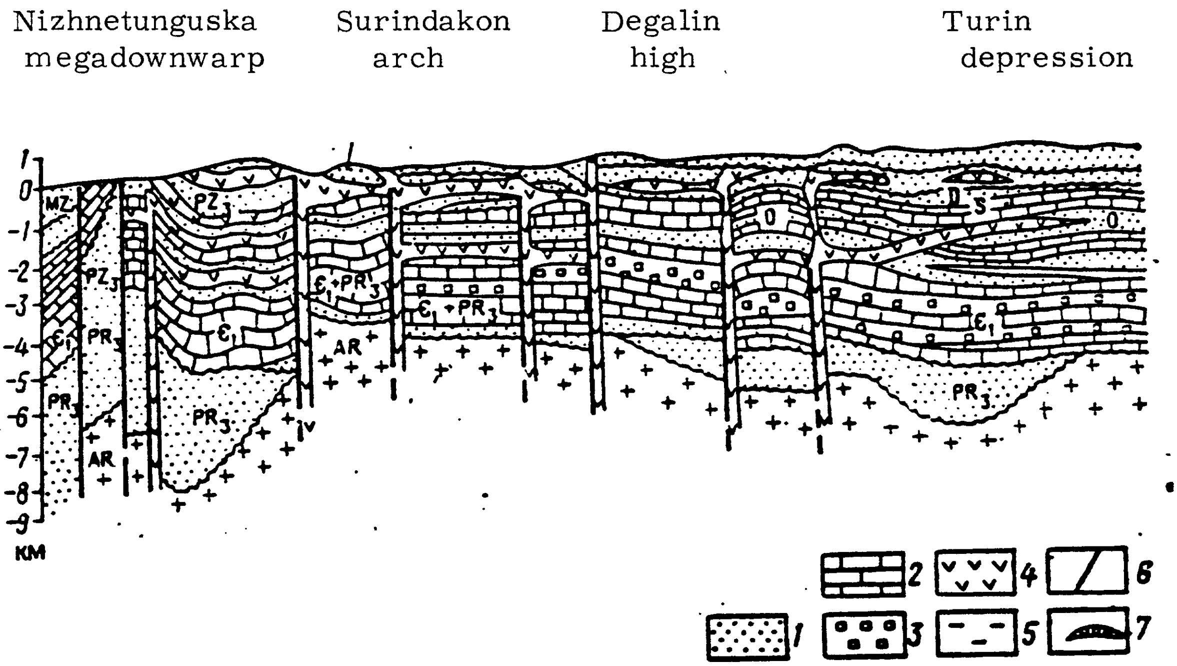


Figure 52.--Geologic section along profile II-II' in South Tunguska prospective oil-gas region (fig. 51). (After Dikenshteyn and others, 1982).

See figure 50 for explanation of symbols.

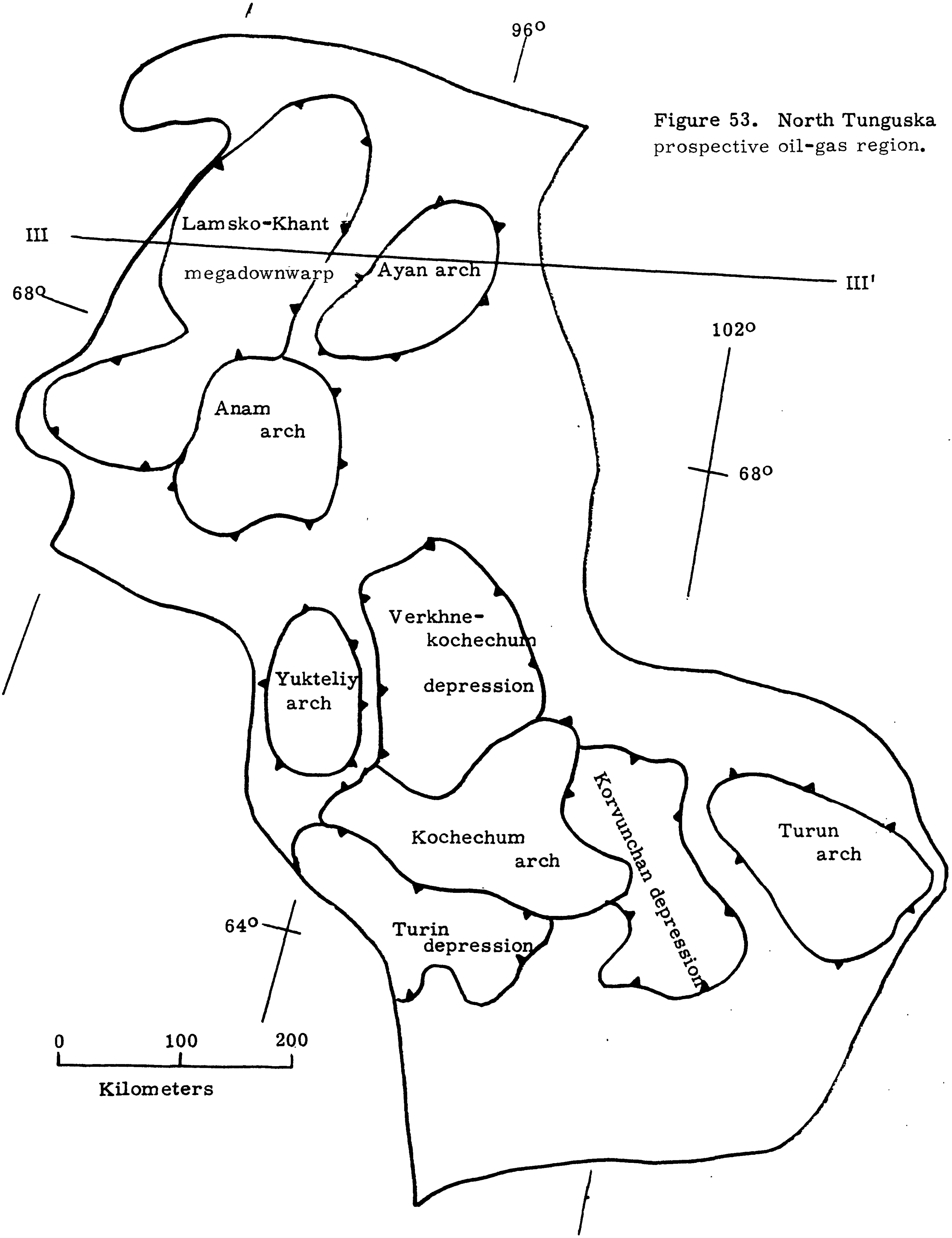


Figure 53. North Tunguska prospective oil-gas region.

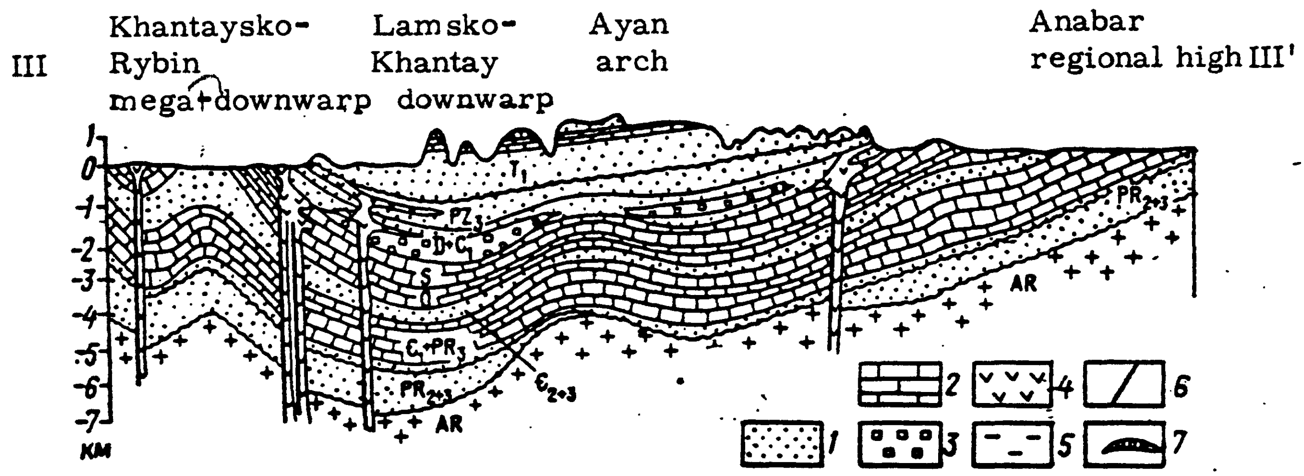


Figure 54.--Geologic section along profile III-III' in North Tunguska prospective oil-gas region (fig. 53). (After Dikenshteyn and others, 1982).

See figure 50 for explanation of symbols.

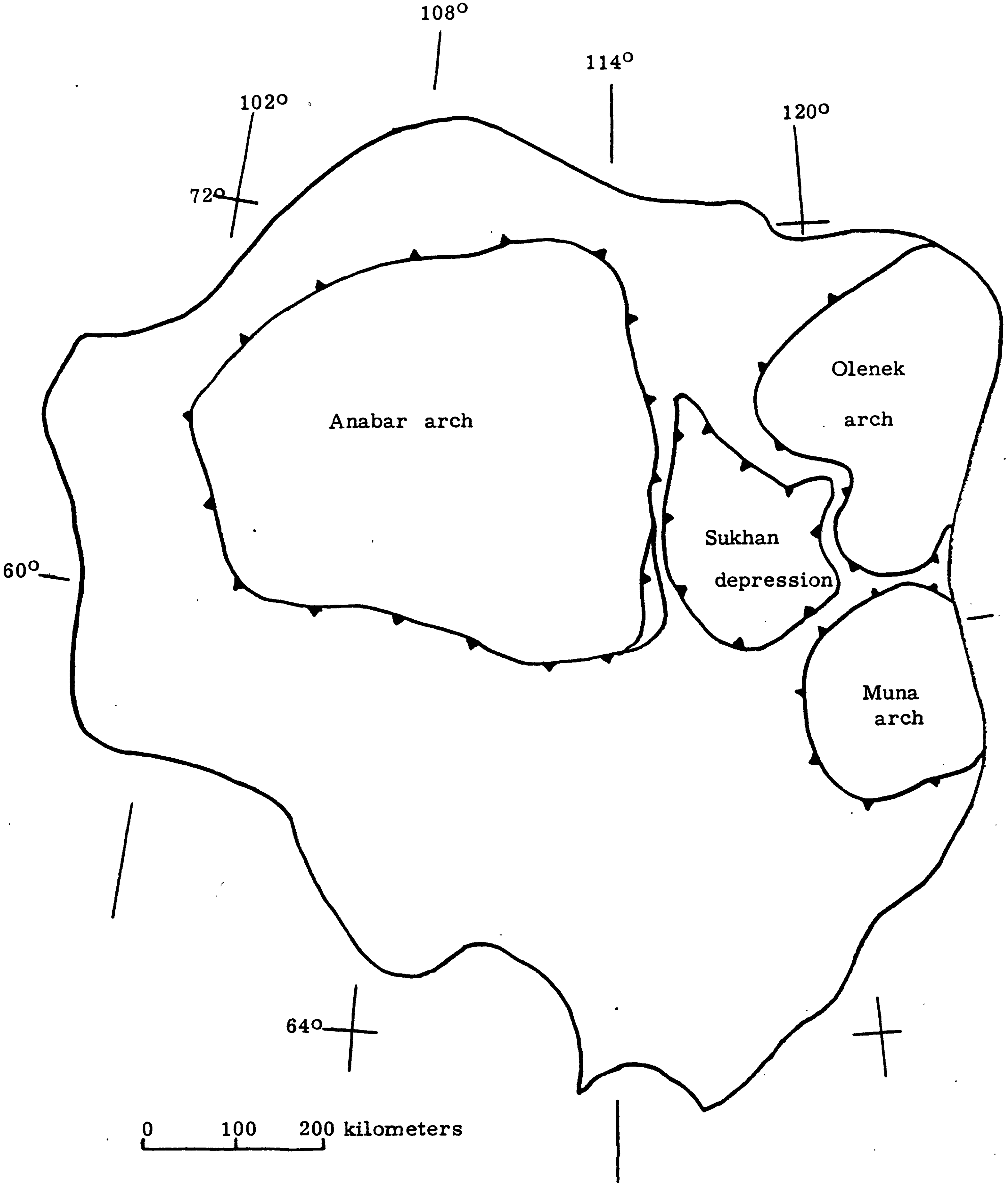


Figure 55. Anabar oil-gas region.

Turukhano-Noril'sk oil-gas region

Two en-echelon arches comprise this region, the Kureysko-Baklanikhin on the south and the Khantaysko-Rybnin on the north. Total area of the region is 55,000 km^2. Twenty-two wells have been drilled here, and one commercial discovery, the Podkamen gas field, has been made (figs. 39 and 56).

The sedimentary section in the Podkamen field consists of Riphean, Cambrian, Ordovician, and Silurian rocks. The pay zone is a porous dolomite of the Middle Cambrian.

Khatanga-Vilyuy oil-gas province

Introduction

The Khatanga-Vilyuy oil-gas province is divided into four oil-gas regions: Yenisey-Khatanga, Lena-Anabar, Cis-Verkhoyansk, and Vilyuy (figs. 2 and 39). These regions are coincident with a belt of Mesozoic depressions that border the Siberian platform on the north and east. Distal from the platform, these depressions are bordered by fold belts. The Yenisey-Khatanga and Vilyuy regions are gas prone, whereas the Lena-Anabar and Cis-Verkhoyansk are more oil prone (Grebenyuk and others, 1983).

The main source rocks for the Vilyuy and Cis-Verkhoyansk regions are Upper Permian and Lower Triassic sediments; for the Lena-Anabar region, Permian and Lower Triassic sediments; and for the Yenisey-Khatanga region, Lower and Middle Jurassic sediments. Generation of hydrocarbons was most intense in the areas toward the fold belts and also in the central part of the Yenisey-Khatanga (Central Taymyr) regional downwarp.

Calculations suggest that about equal amounts of liquid and gas hydrocarbons were generated by the source beds of the province (Polyakova and others, 1983). The province as a whole, however, is gas prone. It appears that oil once occupied many of the traps but was later displaced by thermal gas from Permian coal-bearing rocks of the Vilyuy and Cis-Verkhoyansk regions and Jurassic subbituminous rocks of the Yenisey-Khatanga region. Part of this oil may have remained as the oil rings or gas condensate now so common in the region.

Yenisey-Khatanga oil-gas region

This oil-gas region is a continuation of the West Siberian oil-gas province into a regional low between the folded Taymyr mass on the north and the Siberian platform on the south. It is about 1,200 km long, 200 to 400 km wide, and has an area of 250,000 km^2 (figs. 39 and 57). This Yenisey-Khatanga regional low has also been called the Cis-Taymyr foreland downwarp (Varentsov and others, 1976, 1979). Bakirov (1979) designates most of the region, including the 10 fields shown in figure 57, as part of the West Siberian oil-gas province. The region is well above the Arctic Circle, and permafrost extends to depths of 600 m (Bakirov and others, 1979).

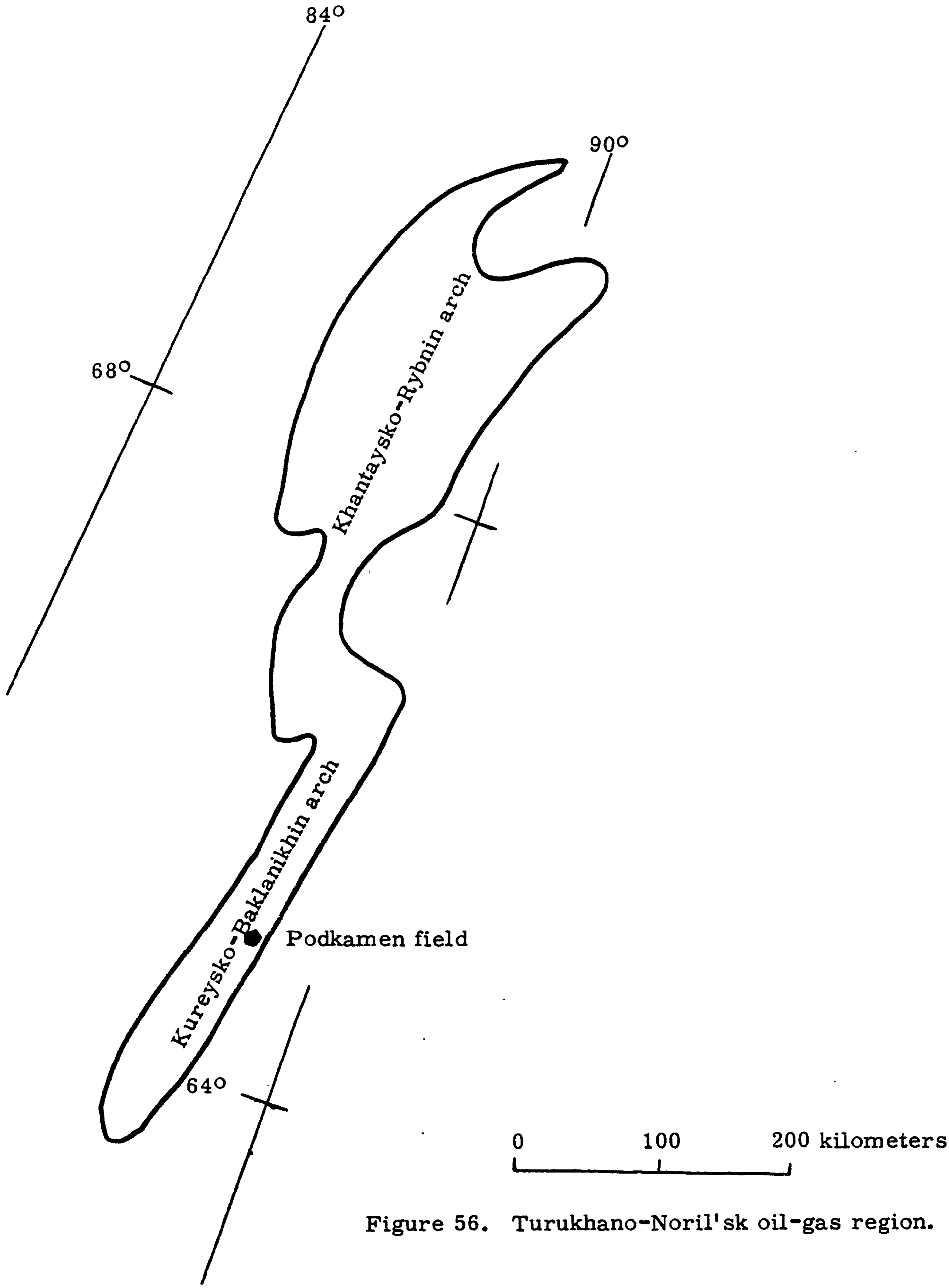


Figure 56. Turukhano-Noril'sk oil-gas region.

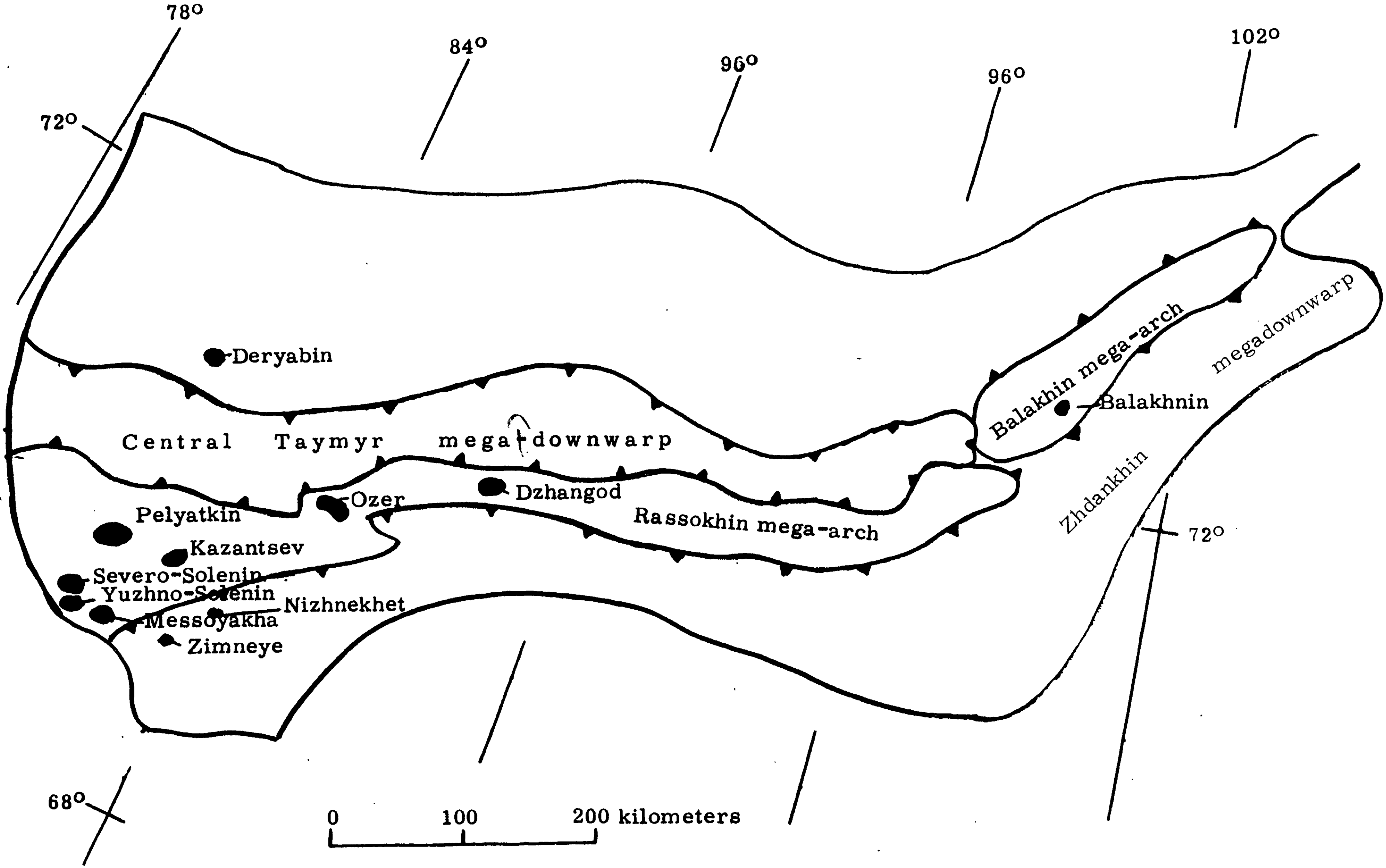


Figure 57. Yenisey-Khatanga oil-gas region.

The Taymyr mass on the north of the Yenisey-Khatanga oil-gas region is part of the Hercynian fold belt that extends through the Ural Mountains, north through Novaya Zemlya, and then southeast across the Kara Sea into the Taymyr Peninsula.

The principal arches and downwarps of the Yenisey-Khatanga region are shown in figure 57. The Balakhin mega-arch coincides with a topographic high, and the Central Taymyr and Zhdanikhin megadownwarps with topographic lows. The main structural forms developed during Berriasian and Valanginian time in the Early Cretaceous. Some further tectonic movements took place during the Tertiary.

The dimensions of 77 individual highs in the Yenisey-Khatanga oil-gas region show a wide range; lengths range from 3 to 35 km and widths from 1 to 23 km. Most are less than 20 km long and 10 km wide. About half have areas of 25 to 100 km^2, and another 22 percent are 100 to 200 km^2.

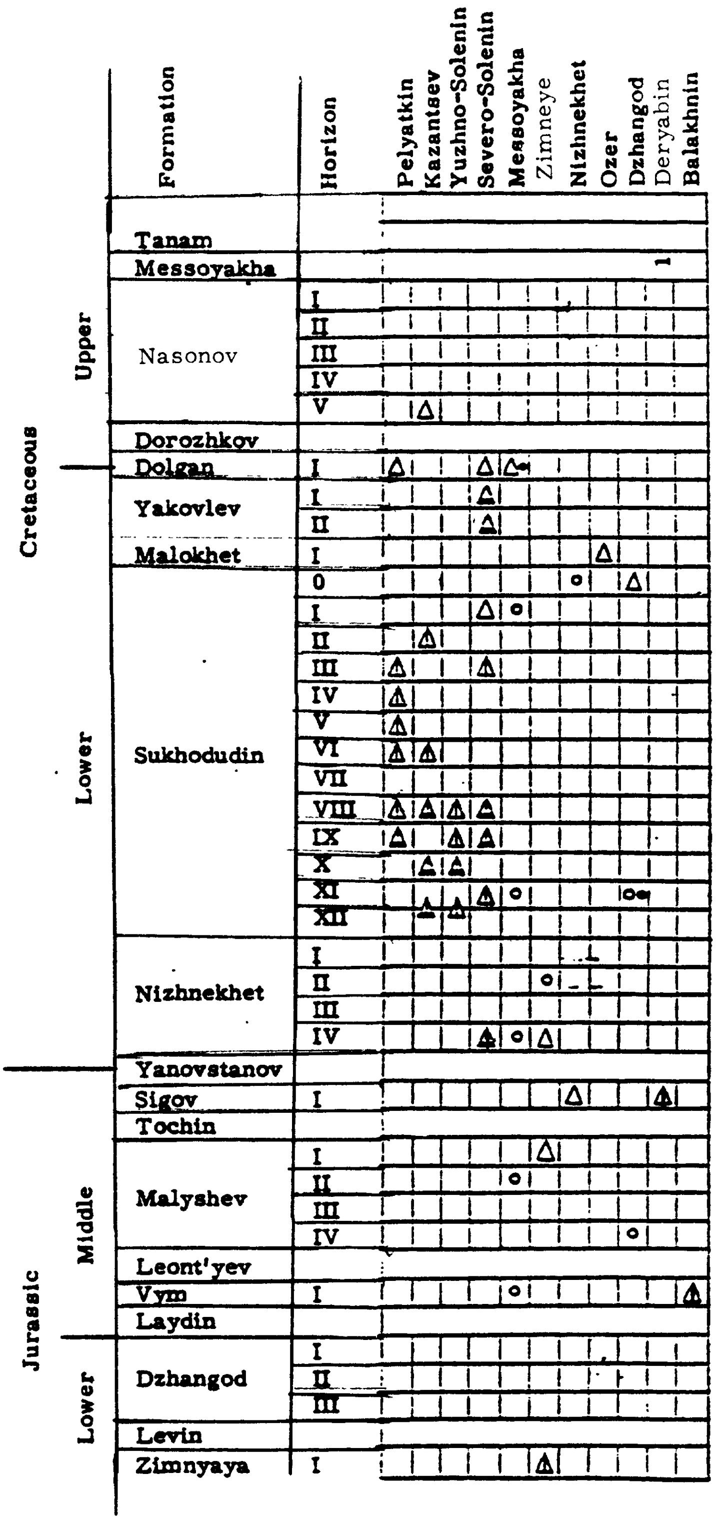
The Yenisey-Khatanga regional low is filled by Mesozoic sediments that are as much as 8,000 m thick. A small amount of upper Paleozoic sediments at the base are included in the basin fill. These Mesozoic sediments were deposited for the most part in a marine basin and consist of near-shore (sandstones) and deep-water (clays) facies (Danyushevskaya and others, 1977). The Lower Cretaceous is terrestrial.

The rocks of the Permo-Triassic are less fractured than those of the basement but are more fractured than those of the Jurassic and Cretaceous. This fracturing increases permeability of clay seals, and it also improves the porosity and permeability of the reservoirs (Mikulenko and others, 1979).

About equal amounts of humic and sapropelic organic matter are present in the source beds. At the time of the first cycle of uplift and erosion in the Early Cretaceous, the Jurassic source beds had not yet entered the oil window except perhaps in some of the structural lows. At the end of the Mesozoic, the organic matter of the Lower and Middle Jurassic sediments could have generated both liquid and gaseous hydrocarbons. Strong regional uplift in post-Oligocene time led to a drop in formation pressure by 3-5 mpa. This led to release of gas from solution in formation waters at shallower depths (less than 2,500 m), and this gas displace oil present in the reservoirs. Consequently, gas pools pass downward into condensate pools and then into condensate pools with an oil ring (Lugovtsov and Moskvin, 1980; Levchuk and Fomin, 1983).

Eleven gas and condensate fields have been discovered in Jurassic and Cretaceous sediments in the province (Varentsov and others, 1979). Most of the gas and condensate reserves of this region are in the Sukhodudin Formation of the Lower Cretaceous (fig. 58). It is present over an area of 55,000 km^2. The reservoir rock is sandstone, which contains silty-clayey beds. Porosity is 15 to 20 percent, and permeability is as high as 1290 md. Gas yields range up to 500,000 m^3/d in the Zimneye area. The other reservoir rocks of the region are also sandstones that contain silty-clayey beds.

Gas hydrates are widespread; indeed, the Messoyakha field is referred to as a gas-hydrate deposit (Cherskiy and others, 1983).



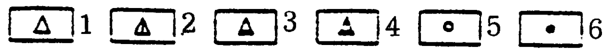


Fig. 58 Distribution of pools along the section of the Yenisey-Khatanga oil-gas region (from Kontorovich and others, 1981).

Pools: 1 - gas, 2 - gas-condensate, 3 - gas with oil ring, 4 - gas-condensate with oil ring. Shows: 5 - gas, 6 - oil.

Lena-Anabar oil-gas region

The Lena-Anabar oil-gas region is an arcuate belt more than 1,000 km long and 100 to 200 km wide, which is a continuation of the Yenisey-Khatanga region on the west and the Cis-Verkhoyansk region on the south (figs. 39 and 59). It includes some offshore areas of the Laptev Sea. The region is largely in the tundra belt; only the southern part is in the taiga zone (Kalinko, 1958). Permafrost is very thick, extending to a depth of 600 m at Nordvik. Five small oil fields have been discovered.

The principal structural elements of the region are the Khatanga saddle on the west and the Lena-Anabar megadownwarp on the east (fig. 59). These large structures are in turn host to a large number of highs and intervening troughs. The area of these highs ranges from a few tens of square kilometers to 250 to 300 km^2. Some are 80 to 90 km long and 20 km wide (Mikulenko and others, 1979).

More than 100 salt domes are present in the area of the Khatanga saddle. Devonian salt has actually broken to the surface at some places. The highs on the base of the Mesozoic at localities 1, 2, and 3 of figure 60 are associated with salt domes.

The stratigraphic section that has potential for hydrocarbons includes not only the Mesozoic fill of the downwarp that encircles the Siberian platform on the north and east, but also the underlying Paleozoic sediments. Thickness of the section ranges from 2 to 9 km, and units favorable for oil and gas are present in Cambrian, middle and upper Paleozoic, Triassic, Jurassic, and possibly Cretaceous sediments (Kontorovich and others, 1976).

The main source rocks of this region are Permian-Lower Triassic shallow-water marine and lagoonal-continental sediments, which contain humic-sapropelic organic matter. Some coal beds up to 1.5 m thick are present on the Khatanga saddle. Average content of organic carbon for Permian sediments is 0.98 percent. These source beds are now in the oil window (Polyakova and others, 1983).

Much exploration has been concentrated on the Nordvik and Kozhevnikov salt domes, both of which are exposed at the surface and are surrounded by outcrops of Triassic and Jurassic rocks. At Nordvik the diameter of the salt dome is 3,800 m, whereas the structure has dimensions of 18 by 30 km. To the south and east of the salt-dome area is a zone of not less than 20 anticlines. The Yuzhno-Tigyan field (fig. 60) occurs on one such anticline.

Oil shows have been found in outcrops and drill holes in Riphean-Cambrian carbonates and sandstones, Devonian and Carboniferous carbonates that include evaporites and reefs, Permian sandstones, Triassic sandstones and siltstones, Middle Jurassic sandy-clayey sediments, and Cretaceous sandstones (Bakirov, 1979). None of the fields are in production, however. The pools occur in structural and fault traps. Flows of oil have been recovered from friable Permian and Jurassic sandstones on the salt-assist structures as well as from sandstones at the base of the Triassic. The anticlines are more favorable than the salt-assist structures, however. The pools of the Yuzhno-Tigyan

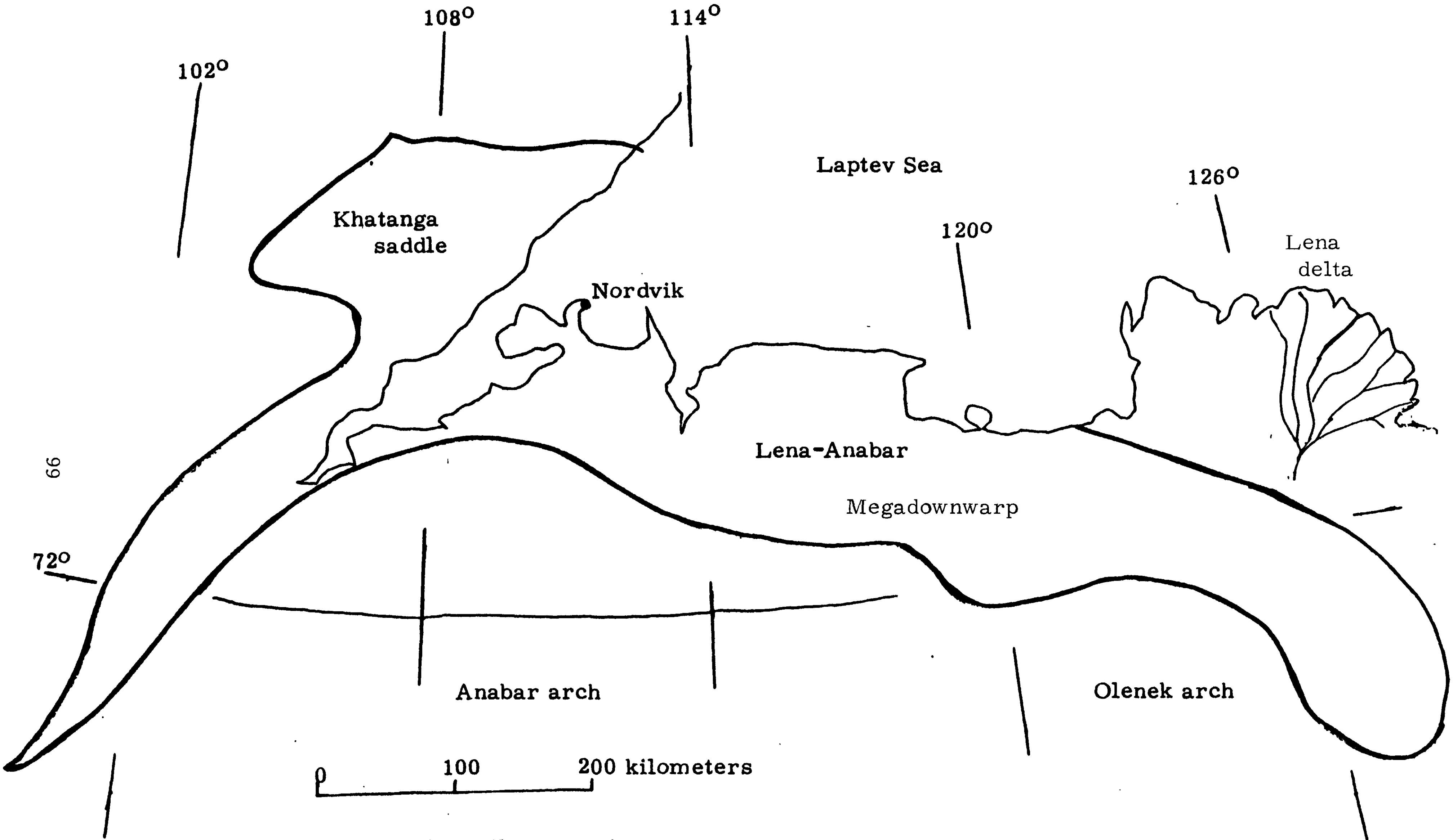


Fig. 59. Lena-Anabar oil-gas region.

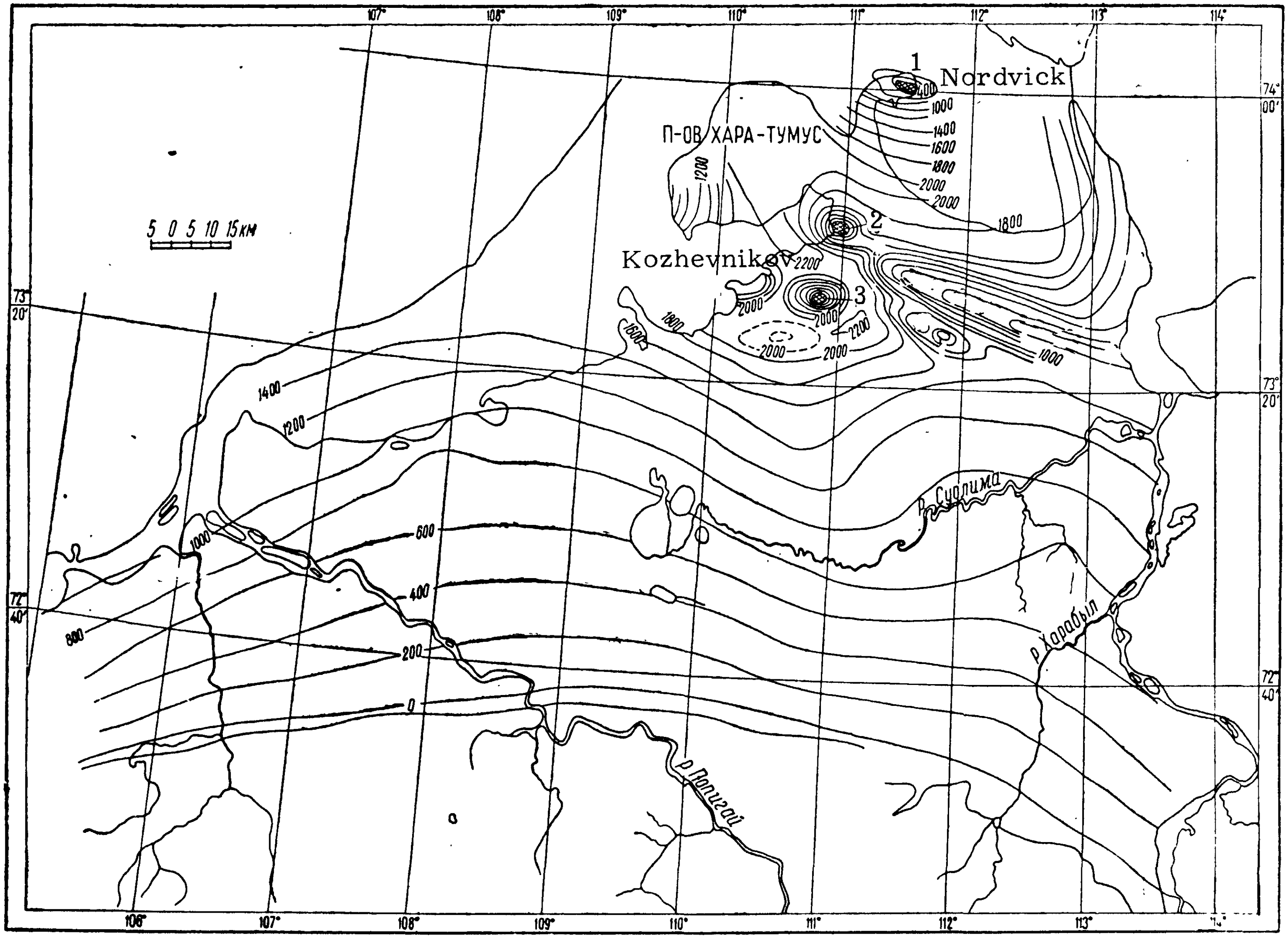


Figure 60. Structure map on base of Mesozoic sediments of the Anabar-Khatanga interfluve. Structure contours in meters. (from Kalinko, 1958)

field are in Permian sandstones, although shows of oil were recorded along the entire section from the Lower Cretaceous to the Lower Permian, inclusively (Kalinko, 1958).

The Lena-Anabar oil-gas region is the only demonstrated oil-prone area of East Siberia. Perhaps the reason for this is that recent uplift in the region has been minimum, and consequently no significant amounts of gas have been released from formation waters to displace the oil out of the traps. Such lack of destruction of the oil pools in the upper part of the section suggests that the deeper Paleozoic plays may contain oil pools that also have escaped destruction.

Cis-Verkhoyansk oil-gas region

The Cis-Verkhoyansk region coincides with a foreland downwarp between the Siberian platform on the west and south and the Verkhoyansk foldbelt on the east and north. It is 1,300 km long, 40 to 170 km wide, and has an area of 195,000 km^2 (figs. 39 and 61). On the west and south, the Mesozoic sediments of the downwarp pinch out against the platform. On the east, the folded rocks of the Verkhoyansk range are overthrust onto the sediments of the downwarp. Based on this, the downwarp is divided laterally into two parts: an outer, platform part where the sediments are relatively thin and undeformed, and an inner part where the sediments are thicker and to various degree deformed.

The downwarp has two segments, the north-south-trending Lena branch and the east-west-trending Aldan branch. They are separated by the Kitchan high, a transverse structure. The sedimentary fill in the Aldan branch is 5 to 8 km thick in the outer part and 10 to 12 km thick in the inner. The sediments of the Lena branch are 1 to 3 km thick in the outer part and 4 to 6 km thick in the inner.

More than a hundred highs have been mapped or are indicated in the Cis-Verkhoyansk foreland downwarp. Most of these are known from surface data. About half of these have areas of 50 to 100 km^2, and 35 percent have areas of 100 to 300 km^2. More than 40 percent have closures of 50 to 200 m (Mikulenko and others, 1979).

The sedimentary section of the downwarp consists of Permian, Triassic, Jurassic, and Cretaceous rocks. A thick Paleozoic section is also present in the Aldan branch.

The Lena branch of the Cis-Verkhoyansk foreland downwarp has received considerable study. The axis of the downwarp during deposition was to the east of the present boundary of the downwarp with the Verkhoyansk foldbelt (Safronov, 1974). The thrusting came at the end of the Mesozoic as part of the Laramide orogeny. The organic matter in the Permian, Triassic, Jurassic, and Lower Cretaceous sediments was humic and humic-sapropelic. The amount of sapropelic material is much greater in the Lower Cretaceous sediments. These source beds are in the oil window. The reservoirs are sandstones; their properties are better with distance from the foldbelt toward the platform.

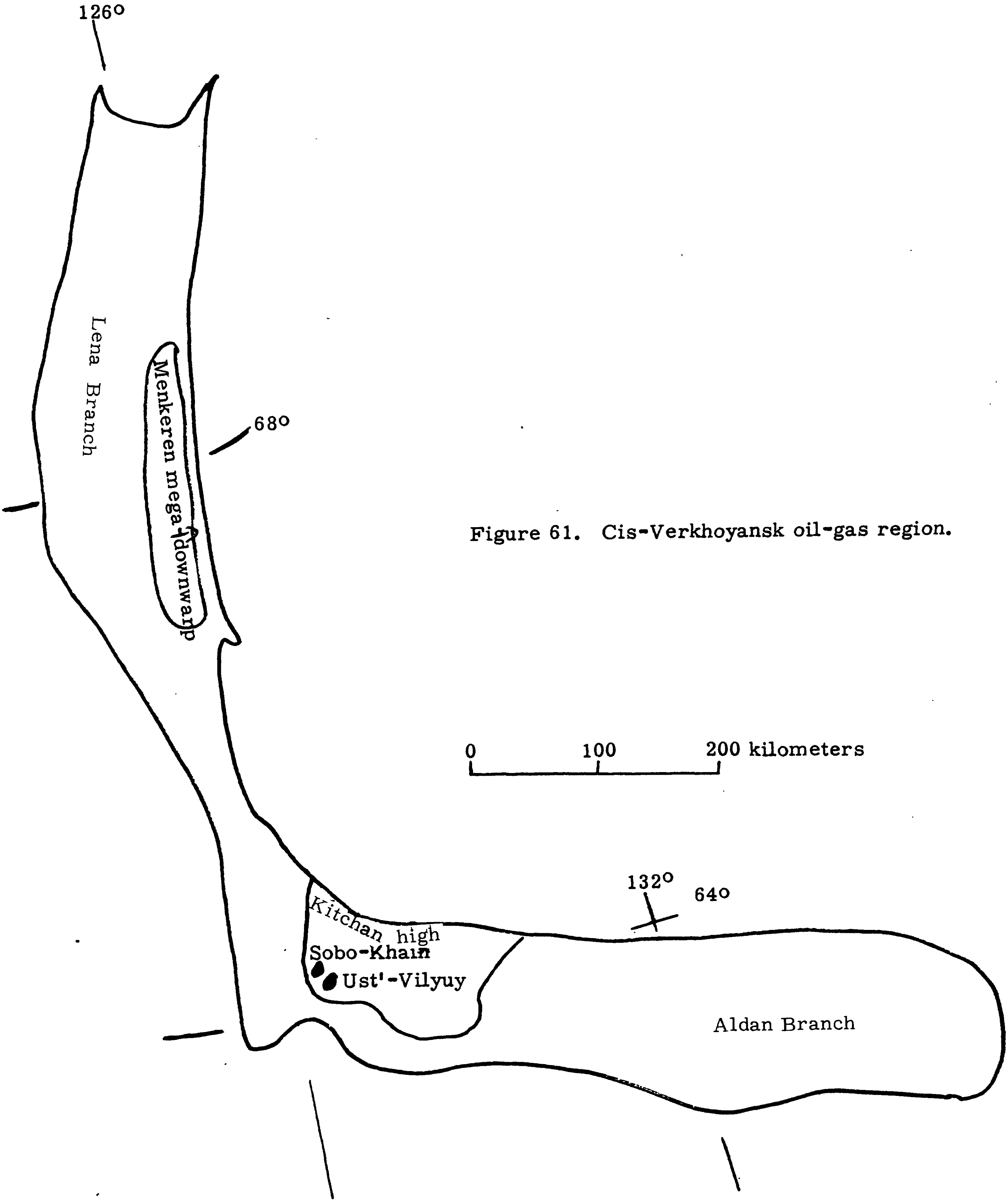


Figure 61. Cis-Verkhoyansk oil-gas region.

Two gas fields have been discovered: Ust'-Vilyuy and Sobo-Khain. These are commonly included in the Vilyuy basin (Uspenskaya and Tabasaranskiy, 1966). The pays are in the Lower Jurassic. The seal is a shale member 10 to 20 m thick. Much condensate is present at Ust'-Vilyuy. Six pools are present in sandy-silty reservoirs. Some gas has been recovered from the Upper Jurassic sediments. The field has been produced for local use (Muzychenko and others, 1978). Reserves are placed at 1 billion m^3 (0.035 Tcf).

Many areas of this oil-gas region are favorable for gas-hydrate deposits. Such deposits are themselves potential targets and are also seals of gas pools.

Vilyuy oil-gas region

The boundaries of this oil-gas region are defined differently in various works. Sitnikov (1975) includes the West Vilyuy region. Kontorovich and others (1981) and Dikenshteyn and others (1977) include the Cis-Verkhoyansk region. This report follows the map (Kontorovich and others, 1979) that accompanies Kontorovich and others (1981) and does not include the West Vilyuy nor the Cis-Verkhoyansk regions (figs. 39 and 62). The region coincides with the Vilyuy basin and covers an area of about 120,000 km^2.

Exploration began in the thirties, and the first discovery was in 1956 in the Taas-Tumus area near the confluence of the Vilyuy and Lena Rivers. The first discovery on the Khapchagay arch was in 1956.

The Vilyuy basin is a triangular downwarp between the Anabar regional high on the northwest, the Aldan regional high on the south, and the Cis-Verkhoyansk foreland downwarp. In the central part of the basin is the Khapchagay arch, which divides the basin into two depressions, the Linden on the north and the Lunkhin on the south. This arch is about 300 km long and 30 to 50 km wide. Closure on the top of the Permo-Triassic sediments is 800 m (Maksimov and others, 1979).

Mikulenko and others (1979) state that, on a basis of seismic surveys, more than a hundred local highs are present in the region. Their study, however, may include some of the area of the West Vilyuy oil-gas region. Closure on the main structures, which have been drilled extensively, decreases upward along the section from Lower Triassic to Upper Cretaceous sediments. Most of this loss of closure is connected with an unconformity between the Lower and Upper Cretaceous (fig. 63).

The Permian-Mesozoic section of the Vilyuy basin consists largely of permeable or weakly permeable sandy-clayey rocks. The impermeable units are not persistent in thickness nor in clay components and on the whole are subordinate in the section (Bakin, 1979). There are six plays (fig. 64).

The sediments of the Permian-Lower Triassic play consist of alternating members of sandstone, siltstone, and shale. Maximum thickness is 1,000 m. Commercial gas has been found in this play in the Srednevilyuy, Tolon, Mastakh, and Nedzhelin fields of the Khapchagay arch as well as in the Srednetyung area. The seal is the Nedzhelin Formation of the Lower Triassic; it is 80 to 100 m thick (Muzychenko, 1978). This play contains 36 percent of the reserves of the region.

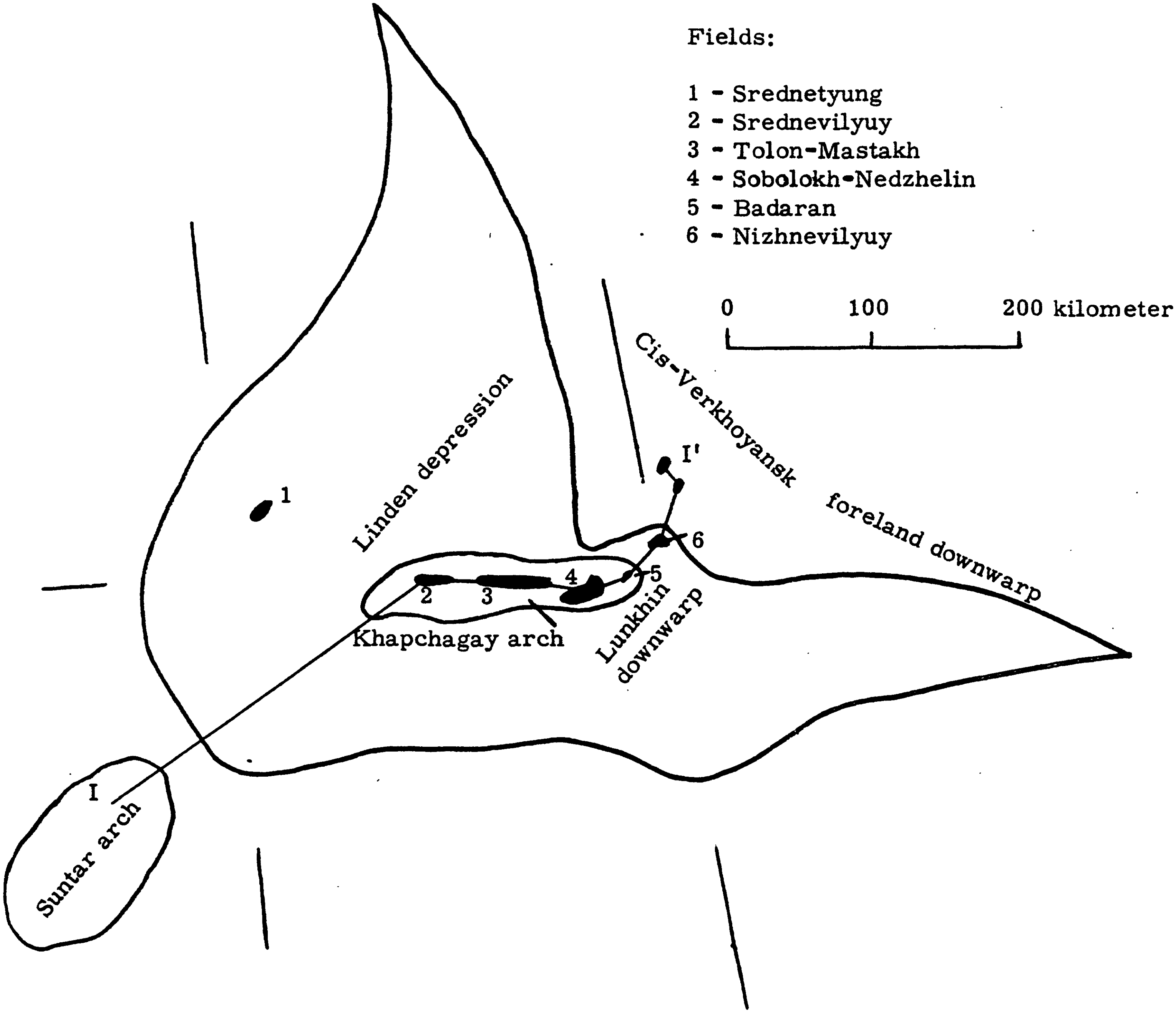


Figure 62. Vilyuy oil-gas region.

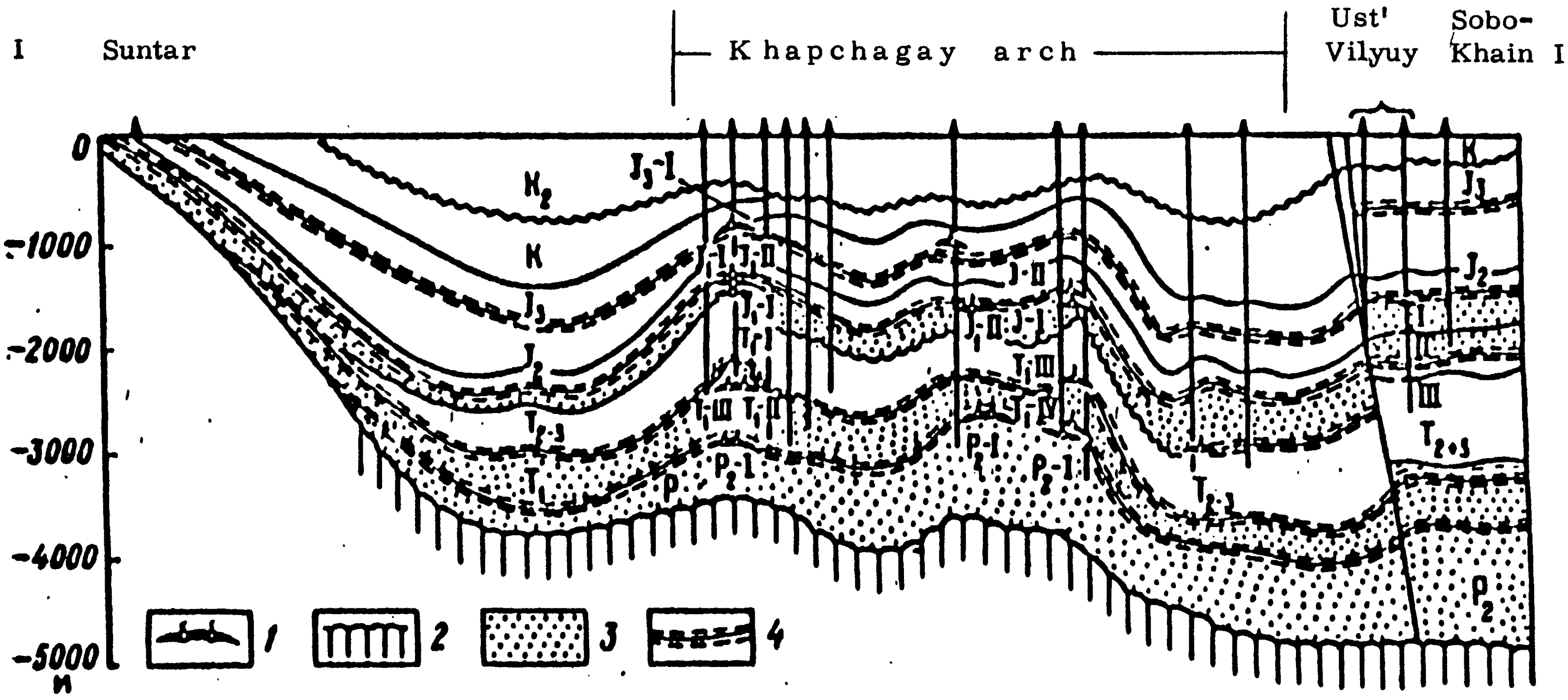


Figure 63. Geologic profile through Vilyuy Basin and Cis-Verkhoyansk foreland downwarp (from Bakirov, 1979). See figure 62 for location.
1- Gas pools, 2 - older Paleozoic sediments, 3 - productive units, 4 - seals.

System	Series	Formation	Stratum	Srednevilyuy	Tolon	Mastakh	Sobolokh	Nedzhelin	Badaran	Sobo-Khain	Ust'-Vilyuy	Srednetyung	Nizhnevilyuy	Plays
			K_1-a						Δ					
Jurassic	Upper	Bergein	J_3-a								Δ			Upper Jurassic
		Marykchan	J_3-I	Δ●										
		Nizhnevilyuy	J_3-II	Δ							Δ			Middle-Upper Jurassic
		Yakutsk	J_2-I	Δ●										
	M	Suntar												
	Lower	Kyzylsyr	J_1-I	⍋●		Δ●	⍋	Δ●					⍋	
			J_1-Ia							⍋				
			J_1-Iб	Δ							Δ			
			J_1-II	○●				Δ●						
			J_1-IIв								⍋			Lower Jurassic
			J_1-IIг								⍋			
			J_1-IIд								⍋			
			J_1-IIe								⍋			
			J_1-IIIa							⍋	⍋			
Triassic		Begidzhan												Middle-Upper Triassic
	Lower	Monom	T_1-I	⍋	⍋									
			T_1-Ia	⍋										
			T_1-II	⍋●	⍋●									
		Tagandzhin	T_1-III	⍋●	⍋●				⍋			⍋	⍋	
			T_1-x	○●	⍋	⍋	○●		⍋				⍋	Lower Triassic
		Nizhnekel'ter	T_1-IVa		⍋	⍋	●	⍋●						
			T_1-IVб			⍋	⍋	⍋●						Permian-Lower Triassic
			T_1-IVв		⍋	○								
Permian	Upper		P_2-I	⍋	⍋	⍋	⍋	⍋						
			P_2-II		⍋	⍋	⍋	⍋						
			P_2-III		○●		⍋	⍋						
			P_2-IV			○								

Δ 1 ⍋ 2 ○ 3 ● 4

Figure 64. Distribution of pools along the section of the Vilyuy and Cis-Verkhoyansk oil-gas regions (from Kontorovich and others, 1981).
1 - Gas pools, 2 - gas-condensate pools, 3 - gas shows, 4 - oil shows.

The Lower Triassic play is the clastic Tagandzhin Formation, which ranges from 435 to 555 m in thickness. It has a nonpersistent internal seal, which is responsible for some gas accumulation. The principal seal, however, is the overlying Monom Formation, which controls the main gas-condensate pools (57 percent of reserves) of the region (Shashin and Samsanov, 1980). Commercial pools are present in this play in the Srednevilyuy, Tolon, and Badaran fields. The Monom Formation in addition to being the seal for this play also contains gas-condensate pools in the Srednevilyuy and Tolon fields (Muzychenko, 1978).

The Middle-Upper Triassic play is the Begidzhan Formation, which consists of sandstones and beds of siltstone and shale. Thickness is 510 to 690 m. The seal is an argillite 10 to 20 m thick at the base of the Lower Jurassic Kyzylsyr Formation. No commercial pools have been found in this play, due perhaps to the seal being so thin.

The Lower Jurassic play consists of sandstones of the Kyzylsyr Formation and is 180 to 290 m thick. The seal is the Suntar Formation, a unit of swelling clays 35 to 60 m thick. Gas pools are associated with this seal only in the central part of the Khapchagay arch where the underlying Monom seal is not effective. Pools are present in the Srednevilyuy, Mastakh, Sobolokh, Nedzhelin, and Nizhnevilyuy fields. Prospects seem good for oil along the north border of the basin (Sokolov and others, 1979). This play accounts for 6 percent of the reserves of the region.

The Middle-Upper Jurassic play is composed of sandy-clayey deposits of the Yakutsk and Nizhnevilyuy Formations. Sandstones predominate, and coal beds are present in the upper part of the section. Thickness is 310 to 355 m. The seal is carbonaceous clay of the Marykchan Formation, which itself contains a gas pool in the Srednevilyuy field. This play is not important commercially.

The Upper Jurassic play is the Bergein Formation, which consists of sandstone, siltstone, and shale. It is productive only in the Ust'-Vilyuy field of the Cis-Verkhoyansk region (fig. 64).

The gas fields of the Khapchagay arch are on the crests of anticlinal structures (figs. 65 and 66). Fracturing is at a maximum on the crests of the highs and has improved the reservoir properties (Sechkina, 1979; Polyakova and Stepanenko, 1980).

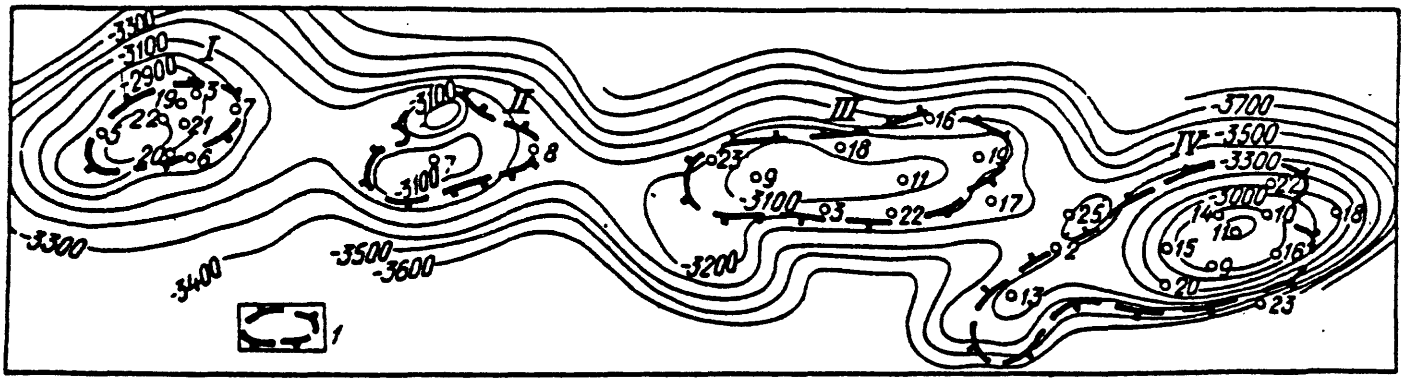


Figure 65. Structure map on top of Permo-Triassic (after Maksimov and others, 1979).
1 - Outer margins of fields.
Gas-condensate fields: I - Srednevilyuy, II - Tolon, III - Mastakh,
IV - Sobolokh-Nedzhelin.

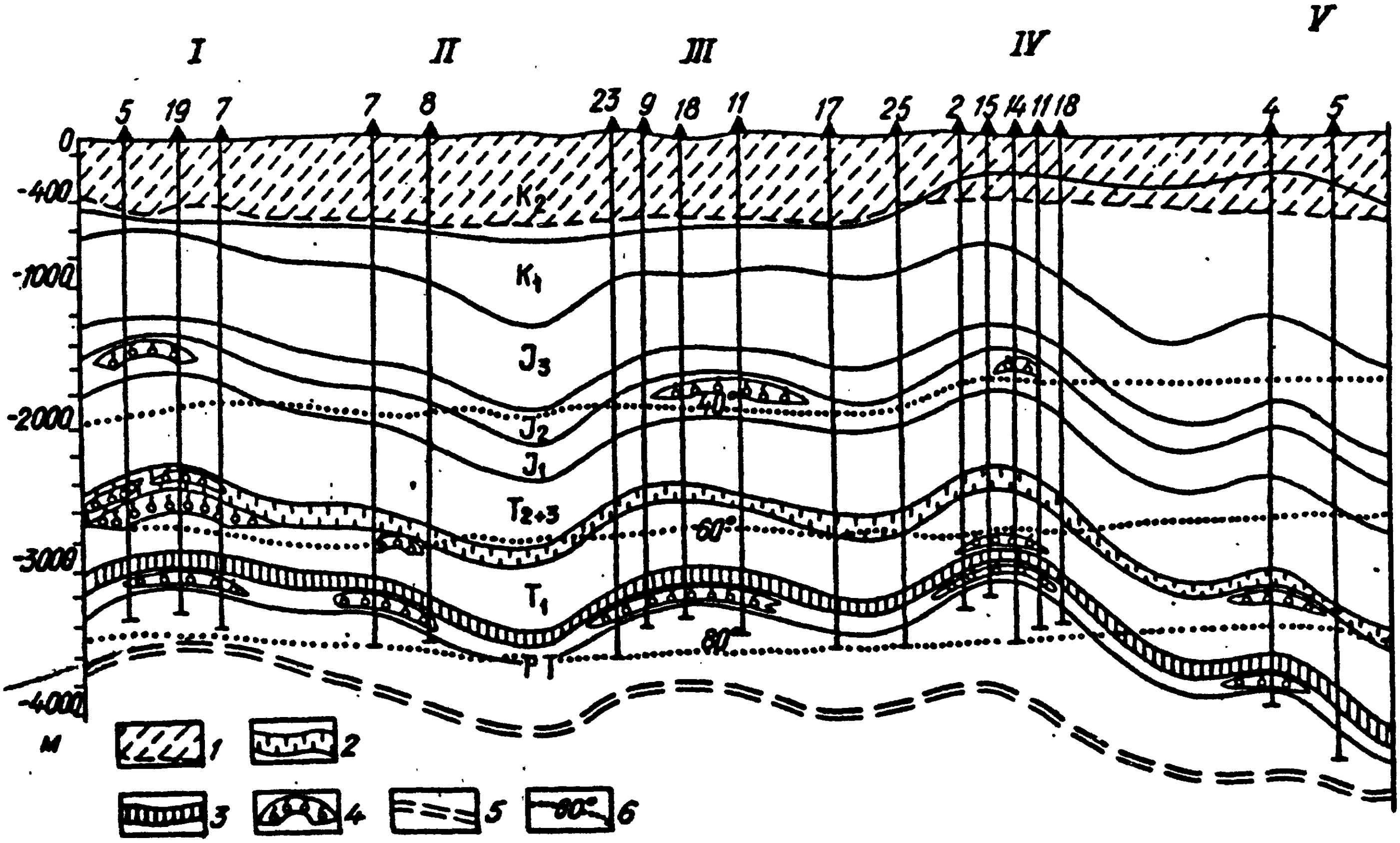


Figure 66.--Geologic profile through fields of Khapchagay arch (from Maksimov and others, 1979). See figure 62.

1, permafrost; 2, good seals; 3, poor seals; 4, gas-condensate pools;
5, position of Permo-Triassic complex at end of Late Cretaceous;
6, isotherms °C.

Fields: I, Srednevilyuy; II, Tolon; III, Mastakh; IV, Sobolokh-Nedzhelin; V, Badaran.

ASSESSMENT OF UNDISCOVERED PETROLEUM RESOURCES

This assessment was made as part of a study by the World Energy Resources Program of the U.S. Geological Survey (USGS). The study utilizes geologic and petroleum engineering data, in conjunction with statistical techniques, to estimate undiscovered resources by a process involving a team of geologists and statisticians. The estimates represent the view of the USGS estimation team and should not be regarded as an official position of the U.S. Department of the Interior.

Table 2 lists estimates of the petroleum resources of the Lena-Tunguska and Khatanga-Vilyuy oil-gas provinces separately and for the East Siberian region as a whole. Figures 67 to 72 are computer-generated graphs showing the probability of occurrence relative to specific amounts of oil and gas resources. The Yenisey-Khatanga portion of the Khatanga-Vilyuy province was not included in the assessment because it had been included earlier with the assessment for West Siberia.

Figure 67. **Lena-Tunguska province undiscovered recoverable oil.** Assessment date - 7/30/82

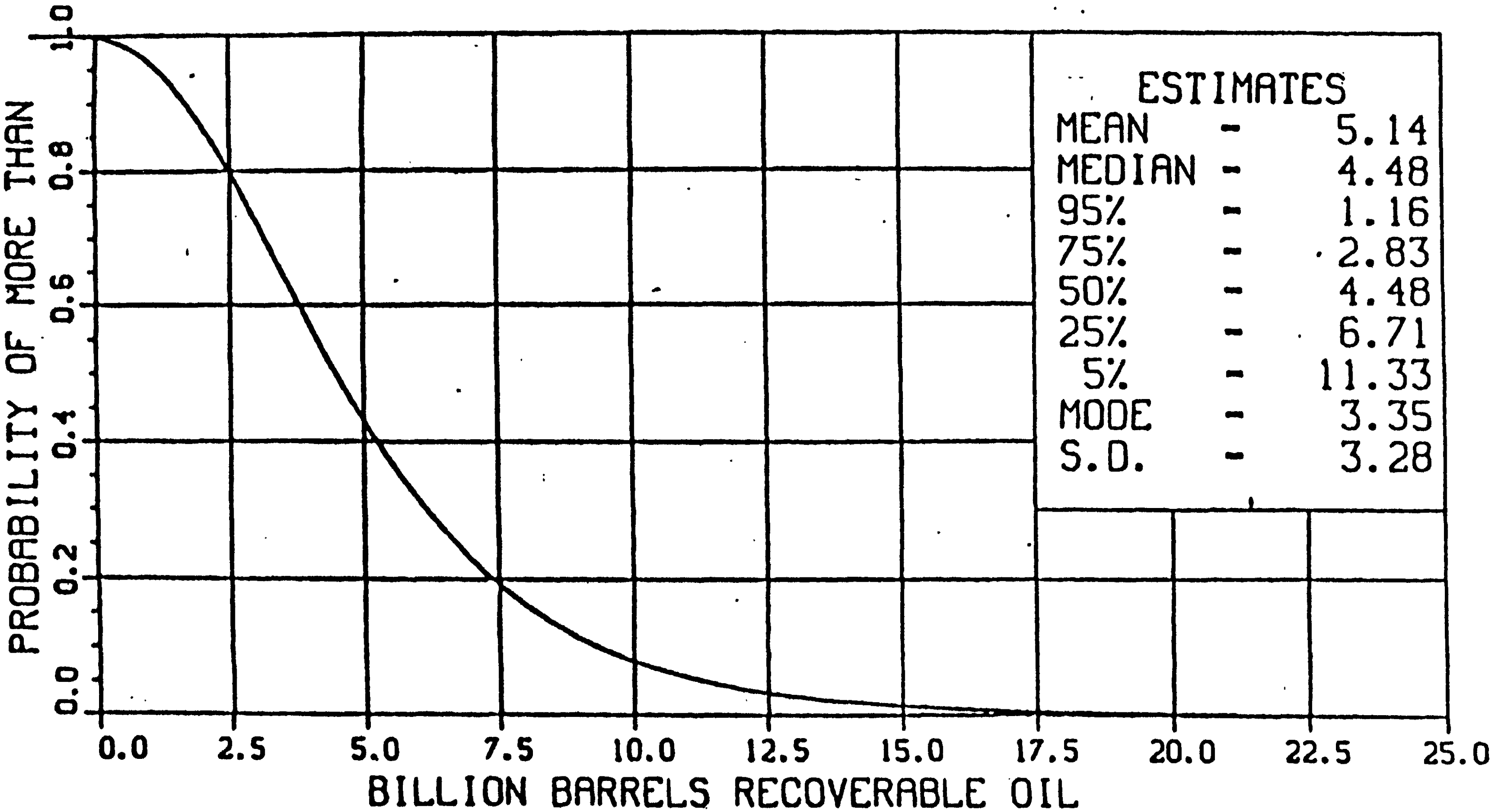


Figure 68. Lena-Tunguska province undiscovered recoverable total gas. Assessment date - 7/30/82

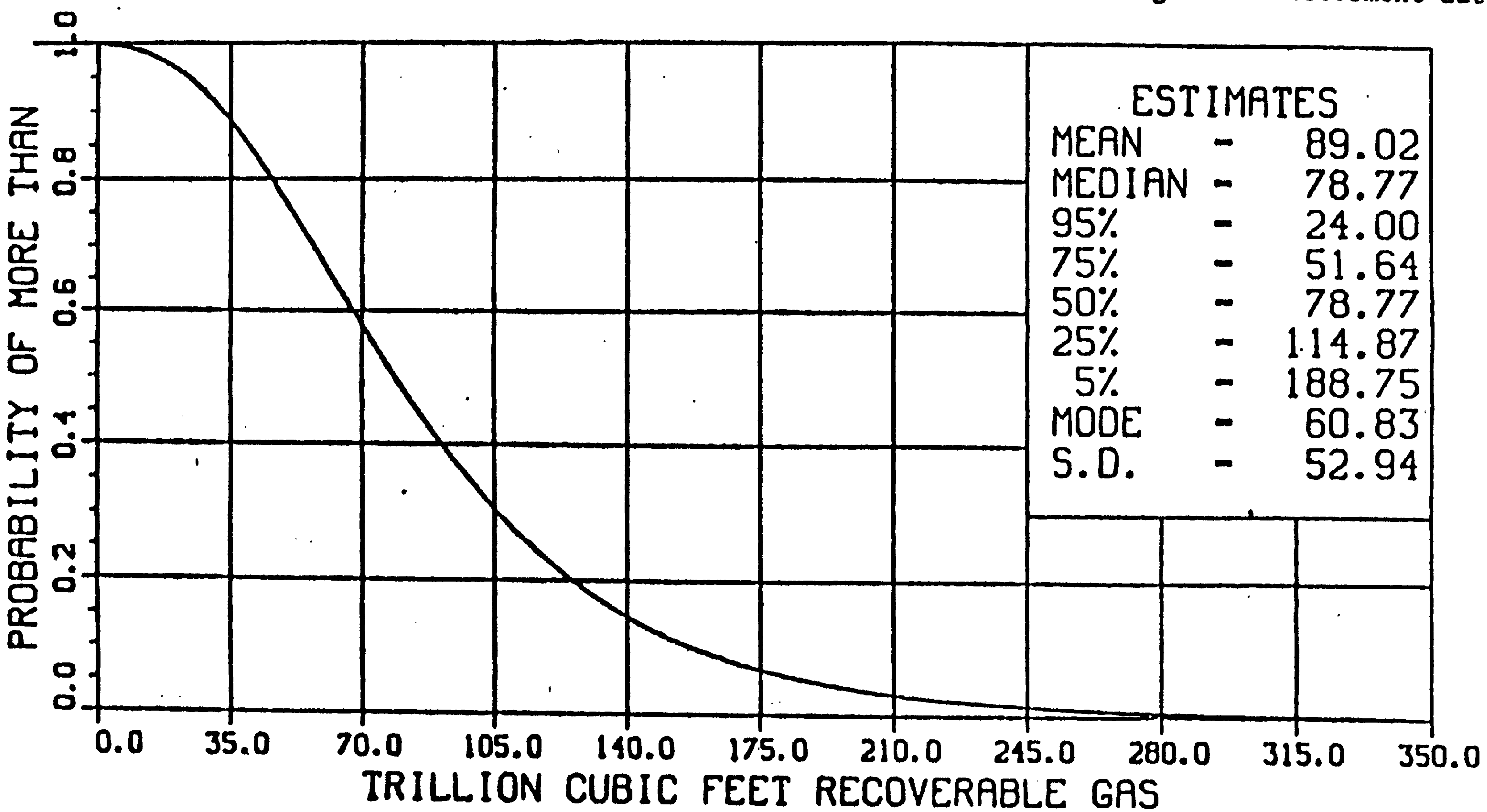
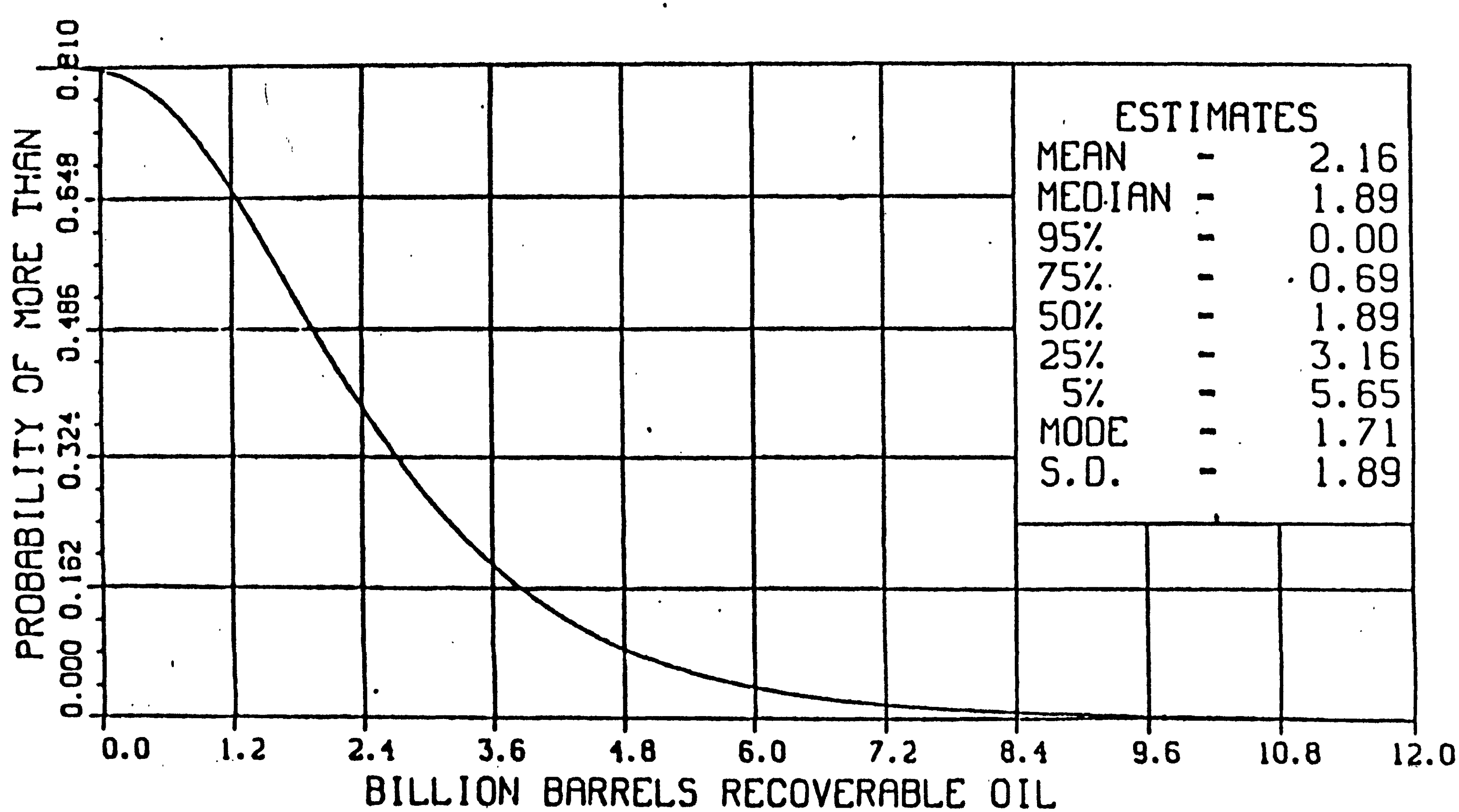


Figure 69. Khatanga-Vilyuy province undiscovered recoverable oil. Assessment date - 7/30/82



Note that no commercial oil has as yet been discovered in the Vilyuy basin; the marginal probability of commercial occurrence is .81.

Figure 70. Khatanga-Vilyuy province undiscovered recoverable total gas. Assessment, date - 7/30/82

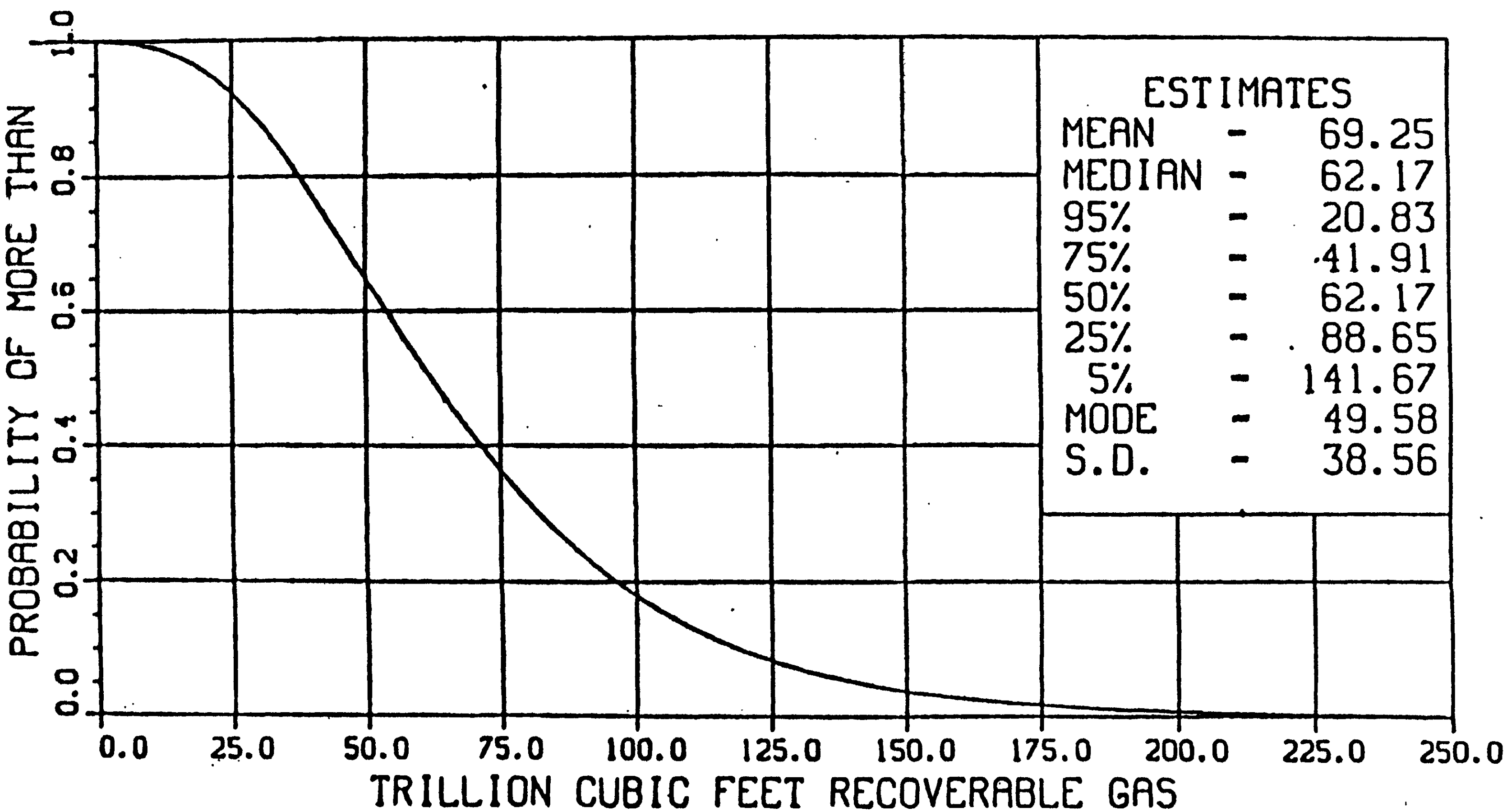


Figure 71. --East Siberia undiscovered total recoverable oil. Assessment date - 7/30/82

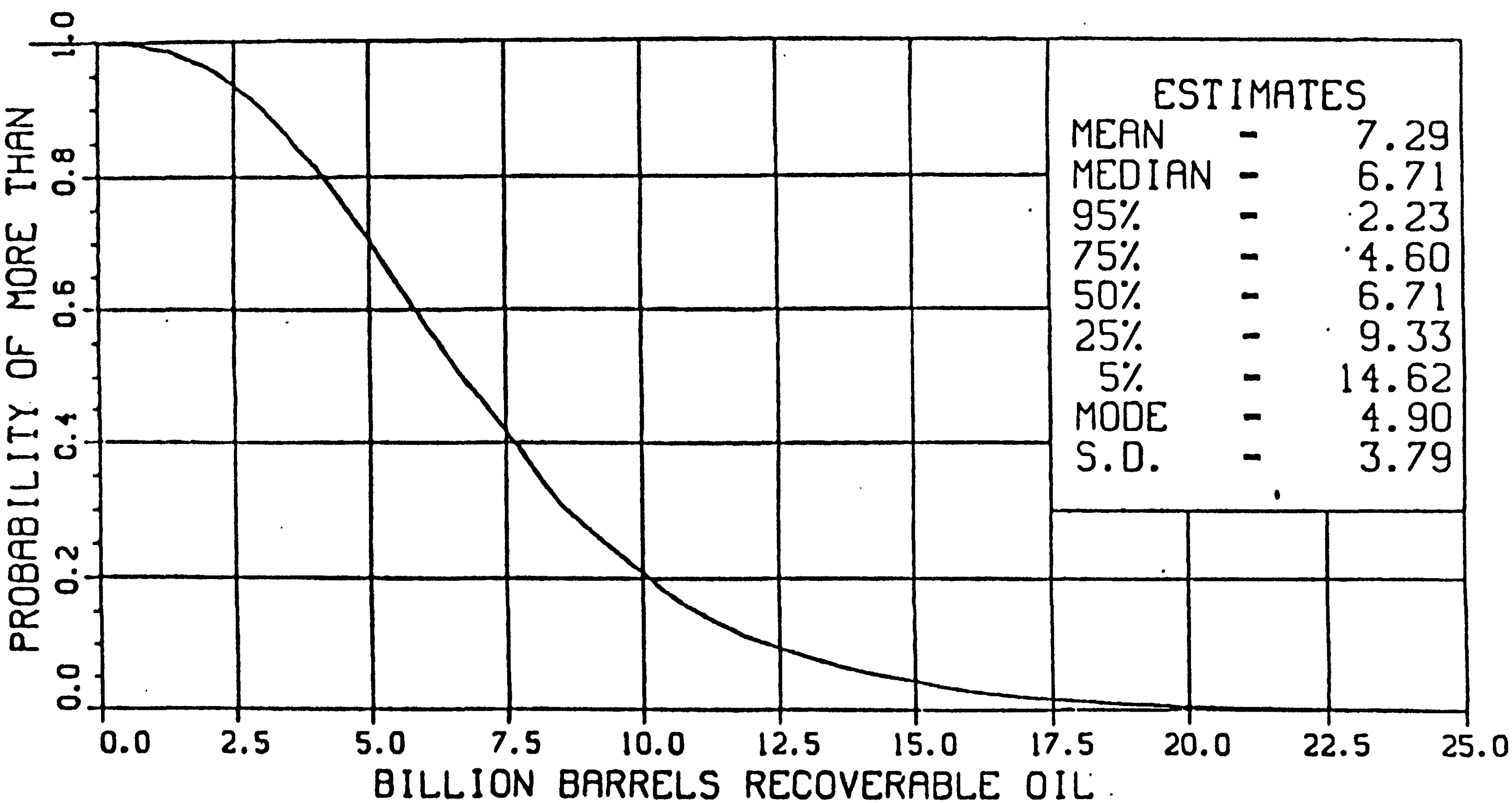


Figure 72, --East Siberia undiscovered total recoverable gas. Assessment date - 7/30/82

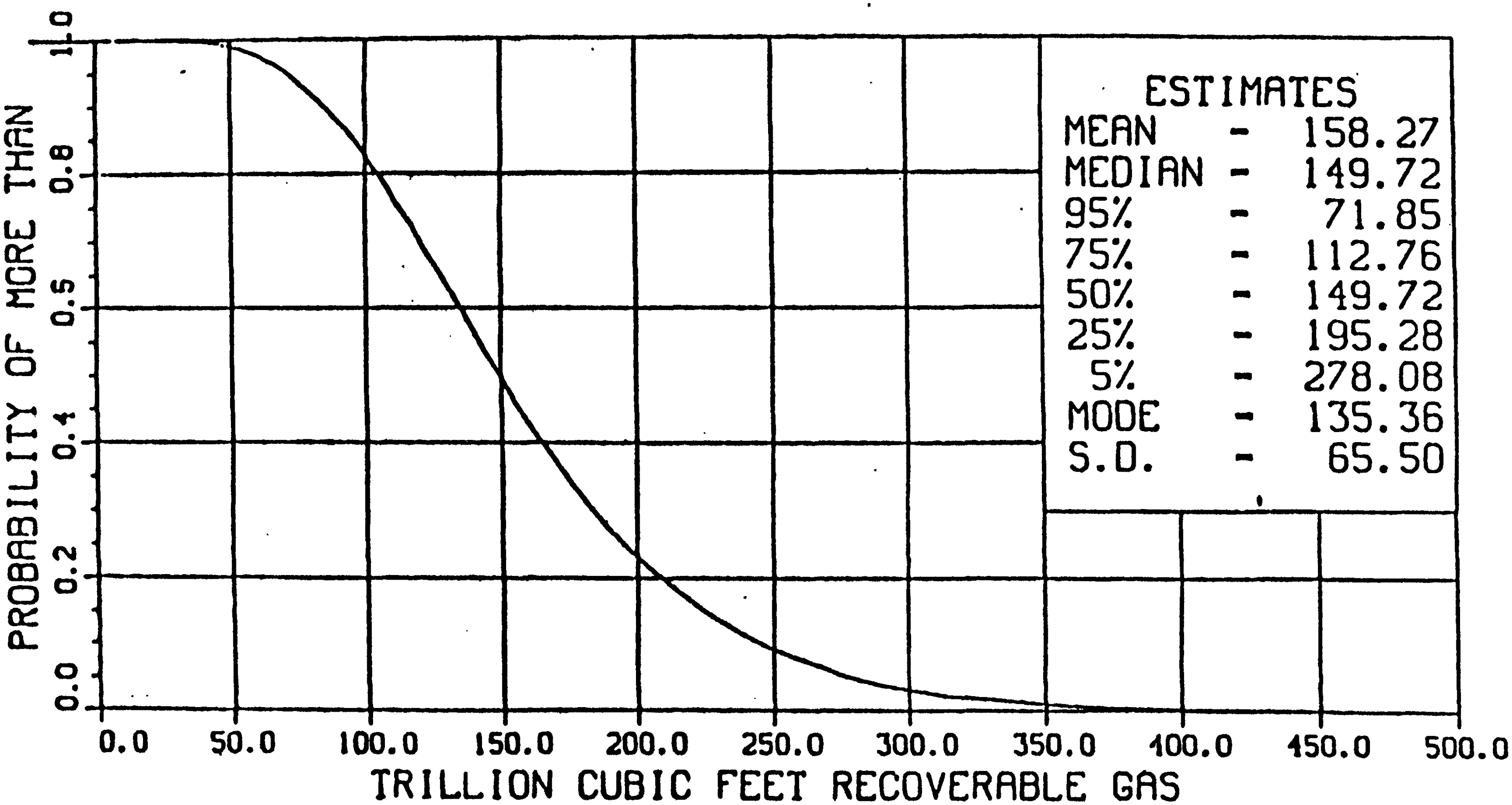


Table 2.--Assessment of undiscovered conventionally recoverable petroleum resources of East Siberia, U.S.S.R.

Region	Crude oil in billions of barrels (BB)				Natural gas in trillions of cubic feet (Tcf) and billions of barrels of oil equivalent (BBOE) @ 6,000 ft^3/bbl.		
	Low (F_{95})[1/]	High (F_5)[1/]	Mean		Low (F_{95})[1/]	High (F_5)[1/]	Mean
Lena-Tunguska basin	1.2	11.3	5.1		24.0	188.8	89.0
Khatanga-Vilyuy basin	0.0	5.6	2.2		20.8	141.7	69.2
Total for East Siberia[2/]	2.2	14.6	7.3		71.8	278.1	158.3
				BBOE	12.0	46.4	26.4

1/ F_{95} denotes the 95th fractile; the probability of <u>more than</u> the amount F_{95} is 95 percent. F_5 is defined similarly.

2/ Totals are derived by statistical aggregation; only the mean total equals the sum of the component parts.

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