# Petroleum Geology and Resources of the Nepa-Botuoba High, Angara-Lena Terrace, and Cis-Patom Foredeep, Southeastern Siberian Craton, Russia

*By* Gregory F. Ulmishek

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# Contents



# Figures



# Tables

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## Foreword

This report was prepared as part of the World Energy Project of the U.S. Geological Survey. In the project, the world was divided into 8 regions and 937 geologic provinces. The provinces were ranked according to the discovered oil and gas volumes within each (U.S. Geological Survey World Energy Assessment Team, 2000). Then, 76 "priority" provinces (exclusive of the U.S. and chosen for their high rank) and 26 "boutique" provinces (exclusive of the U.S. and chosen for their anticipated petroleum richness or special regional economic importance) were selected for appraisal of oil and gas resources. The petroleum geology of these priority and boutique provinces is described in this series of reports.

The purpose of this effort is to aid in assessing the quantities of oil, gas, and natural gas liquids that have the potential to be added to reserves within the next 30 years. These volumes either reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit (variable, but at least 1 million barrels of oil equivalent) or occur as reserve growth of fields already discovered.

The petroleum system constitutes the basic geologic unit of the oil and gas assessment. The total petroleum system includes all genetically related petroleum found in shows and accumulations (discovered and undiscovered) that has been generated by a pod or by closely related pods of mature source rock. This petroleum exists within a limited mappable geologic space, together with the essential mappable geologic elements (source, reservoir, and seal) that control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum.

An assessment unit is a mappable part of a total petroleum system in which discovered and undiscovered fields constitute a single relatively homogeneous population such that the chosen methodology of resource assessment based on estimation of the number and sizes of undiscovered fields is applicable. A total petroleum system might equate to a single assessment unit. If necessary, a total petroleum system may be divided into two or more assessment units, such that each assessment unit is sufficiently homogeneous in terms of geology, exploration considerations, and risk to assess individually.

A numeric code identifies each region, province, total petroleum system, and assessment unit; these codes are uniform throughout the project and will identify the same item in any of the publications. The code is as follows:

*Example*

| | |
|---|---|
| Region, single digit | **3** |
| Province, three digits to the right of region code | 3**162** |
| Total petroleum system, two digits to the right of province code | 3162**05** |
| Assessment unit, two digits to the right of petroleum system code | 316205**04** |

The codes for the regions and provinces are listed in U.S. Geological Survey World Energy Assessment Team (2000).

Oil and gas reserves quoted in this report are derived from Petroleum Exploration and Production database (Petroconsultants, 1996) and other area reports from Petroconsultants, Inc., unless otherwise noted.

A map, figure 1 of this report, shows boundaries of the total petroleum system and assessment unit; it was compiled using geographic information system (GIS) software. Political boundaries and cartographic representations were taken, with permission, from Environmental Systems Research Institute's ArcWorld 1:3 million digital coverage (1992); they have no political significance, and are displayed for general reference only. Oil and gas field centerpoints shown on this map are reproduced, with permission, from Petroconsultants (1996).

## Abstract

Three structural provinces of this report, the Nepa-Botuoba High, the Angara-Lena Terrace, and the Cis-Patom Foredeep, occupy the southeastern part of the Siberian craton northwest of the Baikal-Patom folded region (fig. 1). The provinces are similar in many aspects of their history of development, stratigraphic composition, and petroleum geology characteristics. The sedimentary cover of the provinces overlies the Archean–Lower Proterozoic basement of the Siberian craton. Over most of the area of the provinces, the basement is covered by Vendian (uppermost Proterozoic, 650–570 Ma) clastic and carbonate rocks. Unlike the case in the more northwestern areas of the craton, older Riphean sedimentary rocks here are largely absent and they appear in the stratigraphic sequence only in parts of the Cis-Patom Foredeep province. Most of the overlying sedimentary section consists of Cambrian and Ordovician carbonate and clastic rocks, and it includes a thick Lower Cambrian salt-bearing formation. Younger rocks are thin and are present only in marginal areas.

A single total petroleum system (TPS) embraces all three provinces. The TPS is unique in two aspects: (1) its rich hydrocarbon reserves are derived from Precambrian source rocks and (2) preservation of oil and gas fields is extremely long owing to the presence of the Lower Cambrian undeformed salt seal. Discovered reserves of the TPS are about 2 billion barrels of oil and more than 30 trillion cubic feet of gas. The stratigraphic distribution of oil and gas reserves is narrow; all fields are in Vendian to lowermost Cambrian clastic and carbonate reservoirs that occur below Lower Cambrian salt. Both structural and stratigraphic traps are known. Source rocks are absent in the sedimentary cover of the provinces, with the possible exception of a narrow zone on the margin of the Cis-Patom Foredeep province. Source rocks are interpreted here to be Riphean and Vendian organic-rich shales of the Baikal-Patom folded region. These rocks presently are deformed and metamorphosed, but they generated oil and gas before the deformation occurred in Late Silurian and Devonian time. Generated hydrocarbons migrated updip onto the craton margin. The time of migration and formation of fields is constrained by the deposition of Lower Cambrian salt and by the Late Silurian or Devonian metamorphism of source rocks. This time frame indicates that the TPS is one of the oldest petroleum systems in the world.

All three provinces are exploration frontiers, and available geologic data are limited; therefore, only one assessment unit has been identified. The largest undiscovered hydrocarbon resources are expected to be in Vendian clastic reservoirs in both structural and stratigraphic traps of the Nepa-Botuoba High province. The petroleum potential of Vendian–lowermost Cambrian carbonate reservoirs is smaller. Nevertheless, these reservoirs may contain significant resources. Gas is expected to dominate over oil in the resource base.

## Introduction

Three provinces of the southeastern Siberian craton, the Nepa-Botuoba High province 1210, the Angara-Lena Terrace province 1209, and the Cis-Patom Foredeep province 1211 (fig. 1), are described in this report. Areally, the provinces correspond to the regional structural units of the same names (fig. 7). The Nepa-Botuoba High province was named the Nepa-Botuoba Arch in U.S. Geological Survey World Energy Assessment Team (2000); however, the term “high” or “regional high” better translates the Russian term “anteclise,” and “high” is used in this report. The stratigraphy and petroleum geology of the three provinces bear many common characteristics. The largest hydrocarbon reserves, about 6 billion barrels of oil equivalent (BBOE), have been discovered in the Nepa-Botuoba High province. This province is ranked 51st among 102 provinces designated for appraisal of undiscovered oil and gas resources by the U.S. Geological Survey (U.S. Geological Survey World Energy Assessment Team, 2000). Total hydrocarbon reserves of the three provinces are listed at slightly more than 2 billion barrels of oil (BBO) and 30 trillion cubic feet (TCF) of gas in the Petroconsultants (1996) file. However, at present the reserves are known to be substantially larger, mainly owing to reserve growth in the giant Kovykta gas field and several recent significant discoveries. None of the fields discovered in all three provinces has been fully developed, and production is limited to local consumption.

The Baikal-Patom Foldbelt Riphean-Craton Margin Vendian total petroleum system (TPS) embraces all three provinces. The TPS received its name from the interpreted source rocks (Riphean) and principal reservoir rocks (Vendian) and their respective geologic locations. The time of hydrocarbon migration and formation of fields is constrained by the deposition of the regional salt seal in the Early Cambrian and by the metamorphism of source rocks of the Baikal-Patom folded region in the Late Silurian or Devonian. The TPS is unique, both with respect to the ancient age of the Upper Proterozoic source rocks and the extremely long period of preservation of the fields. Another uncommon feature is tectonic destruction of the generative part of the TPS, which occurred as early as in Late Silurian–Devonian time, and preservation of hydrocarbon accumulations in the undeformed cratonic part of the TPS.

All three provinces are exploration frontiers. Because of paucity of data, the entire TPS was assessed as a single assessment unit (AU). Definitions of the TPS and AU are given in the Foreword of this report. The assessment technique and procedure are described in U.S. Geological Survey World Energy Assessment Team (2000). The results of assessment are shown in table 1. The largest portion of undiscovered resources is expected to be in Vendian clastic reservoirs in structural and stratigraphic traps of the Nepa-Botuoba High province. Smaller, but still significant resources may be discovered in Vendian–lowermost Cambrian carbonate reservoirs. Gas is expected to prevail in the resource base.

## Province Overview

### Province Locations and Boundaries

The Nepa-Botuoba High, Angara-Lena Terrace, and Cis-Patom Foredeep provinces 1210, 1209, and 1211, respectively, are described collectively because these three adjacent structural provinces share many common geologic characteristics and are encompassed by a single TPS of Precambrian and early Paleozoic age. All three provinces are in the southeastern part of the Siberian craton, northwest of the Baikal Lake rift and the Baikal-Patom folded region (fig. 1). The combined area of the provinces is about 665,000 $km^2$. The Baikal-Patom and Sayan folded regions border the provinces on the south and southeast. The northeastern zone of the Sayan is composed of the basement and Vendian-Cambrian rocks of the Siberian craton that were involved in thrusting and folding, probably in Ordovician time. The Sayan folded region southwest of this frontal zone is an accreted terrane deformed during Caledonian compression and orogeny. Thick Upper Proterozoic–lower Paleozoic rocks that probably represent deposition on the passive margin of the Siberian continent form the northwestern zone of the Baikal-Patom folded region. Tectonic movements in the Baikal-Patom region began in the Ordovician, but the main period of deformation, which was related to collision with the Barguzin microcontinent, did not take place until latest Silurian or Devonian time. To the southeast, the Baikal-Patom region contains volcanic and

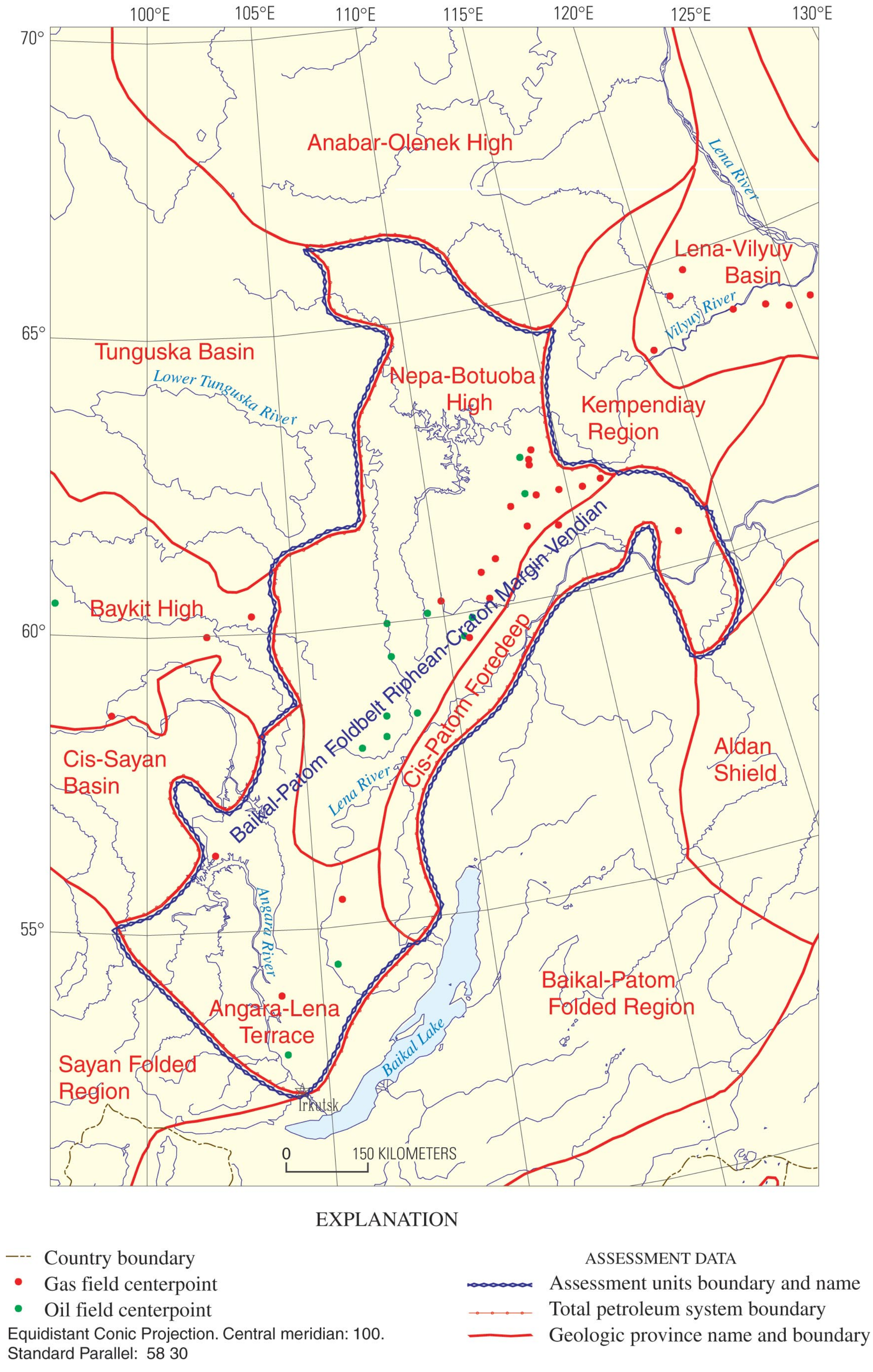


**Figure 1.** Petroleum systems and assessment units of Angara-Lena Terrace, Nepa-Botuoba High, and Cis-Patom Foredeep provinces 1209, 1210, and 1211.

**Table 1.** Baikal-Patom Foldbelt Riphean-Craton Margin Vendian Total Petroleum System 121001 assessment results summary.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. MFS, minimum field size assessed (MMBO or BCFG). Prob., probability (including both geologic and accessibility probabilities) of at least one field equal to or greater than the MFS. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

| Code and Field Type | MFS | Prob. (0-1) | Undiscovered Resources | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Oil (MMBO) | | | | Gas (BCFG) | | | | NGL (MMBNGL) | | | |
| | | | F95 | F50 | F5 | Mean | F95 | F50 | F5 | Mean | F95 | F50 | F5 | Mean |
| **12100101 Baikal-Patom Foldbelt Riphean-Craton Margin Vendian Assessment Unit** | | | | | | | | | | | | | | |
| Oil Fields | 5 | 1.00 | 376 | 1,422 | 3,487 | 1,611 | 1,761 | 6,911 | 18,244 | 8,052 | 99 | 402 | 1,139 | 482 |
| Gas Fields | 30 | | | | | | 14,961 | 37,808 | 61,776 | 37,987 | 641 | 1,649 | 2,989 | 1,711 |
| Total | | 1.00 | 376 | 1,422 | 3,487 | 1,611 | 16,722 | 44,719 | 80,020 | 46,039 | 740 | 2,051 | 4,128 | 2,194 |
| **121001 Total: Baikal-Patom Foldbelt Riphean-Craton Margin Vendian Total Petroleum System** | | | | | | | | | | | | | | |
| Oil Fields | | 1.00 | 376 | 1,422 | 3,487 | 1,611 | 1,761 | 6,911 | 18,244 | 8,052 | 99 | 402 | 1,139 | 482 |
| Gas Fields | | | | | | | 14,961 | 37,808 | 61,776 | 37,987 | 641 | 1,649 | 2,989 | 1,711 |
| Total | | 1.00 | 376 | 1,422 | 3,487 | 1,611 | 16,722 | 44,719 | 80,020 | 46,039 | 740 | 2,051 | 4,128 | 2,194 |

sedimentary rocks that were metamorphosed and cut by large granite plutons.

Present-day platform structures of the Siberian craton that are adjacent to the three provinces include the Kempendiay region, which is a distal part of the superposed Lena-Vilyuy basin (fig. 1). Upper Paleozoic–Mesozoic rocks of this region are underlain by a Devonian rift that is filled with thick volcanic rocks and salt deposits. The Anabar-Olenek regional high, to the north, is a large structure in the east-central Siberian craton. The crystalline basement crops out on top of the high, and relatively thin lower Paleozoic rocks cover its slopes. The Tunguska basin, to the northwest, is a deep depression superposed on the early Paleozoic platform of the craton. The depression is filled with thick upper Paleozoic–Triassic clastic rocks and effusive and intrusive volcanics. On the west, a structural saddle connects the Nepa-Botuoba and Baykit regional highs. The Cis-Sayan basin, farther southwest, is a deep early Paleozoic depression in which the basement occurs at depths of 5–7 km.

## Tectono-Stratigraphic Development

The basement of the entire Siberian craton, including the three provinces under consideration, is composed of Archean–Lower Proterozoic crystalline rocks. At the beginning of Riphean time (most of the Late Proterozoic, 1,650–650 Ma), the basement of the craton was rifted and the rifts were filled with thick clastic and carbonate rocks (fig. 2). Stages of extension and rifting supposedly repeated in the middle and late Riphean (Shpunt, 1988). However, the rifting history of the craton is poorly understood because the thick rift fill nowhere has been penetrated by wells. Much thinner Riphean sediments were deposited on uplifted blocks between the rifts, and some of the blocks, including the Nepa-Botuoba regional high, probably remained exposed throughout Riphean time (Kuznetsov, 1997). Riphean aulacogens are difficult to identify on seismic records because of insufficient seismic resolution. Therefore, locations of the aulacogens are poorly known (with a few exceptions), and they have been located in different places by different authors. Some geologists suggested that a large aulacogen cuts the northernmost part of the Nepa-Botuoba regional high and extends eastward under the Devonian Kempendiay rift (Sokolov, 1989). Riphean sequences also thicken along the craton boundaries, where they fill marginal cratonic depressions; apparently, the sediments were deposited on passive margins (fig. 2). Deformation of the sedimentary fills of aulacogens, widespread uplift, and erosion took place at the end of Riphean time. Various stratigraphic units of the Riphean sequence and rocks of the crystalline basement subcrop under the pre-Vendian unconformity.

Vendian–lower Paleozoic rocks compose a platform sedimentary cover of the three provinces similarly to the rest of the Siberian craton. Vendian (upper Late Proterozoic, 650–570 Ma) rocks are quartzose sandstones, quartzites, and shales in the lower part and dolomites, in places with anhydrite interbeds and inclusions, in the upper part. Thickness of the Vendian sequence increases from several tens of meters on the Nepa-Botuoba high to several hundred meters in the Cis-Patom foredeep. A number of formations are defined in different areas (fig. 3), but the exact regional correlation between the formations is commonly uncertain. The boundary between the Vendian and Cambrian is transitional and its exact stratigraphic position is not known. In figure 3, this boundary is arbitrarily shown at the base of the lowermost widespread salt bed. The overlying Osin Horizon contains Early Cambrian trilobites and archaeocyathids (Kontorovich and others, 1981). It can be also identified in areas where the lower salt bed is absent or where older salt beds are present between Vendian dolomites (mainly in the Cis-Sayan basin, fig. 1).

The Lower Cambrian is thick and is composed of cyclic alternations of carbonate (dominantly dolomite) and salt beds. Up to 50 salt/carbonate cycles are present. The sequence contains two carbonate units that are devoid of salt beds, the Bulay and the middle part of the Belsk Formations (fig. 3). Salt beds generally pinch out toward the craton boundary; younger salt beds are progressively smaller in areal distribution. On the southeastern margin of the craton, all salt beds pinch out and the entire Lower Cambrian interval is composed of carbonates with thin shale and anhydrite layers. The salt-bearing formation was deposited in a giant lagoon that covered the south half of the Siberian craton (fig. 4). The lagoon was separated from open sea in the north and northeast by a zone of shallow carbonate shelf that was bordered by a zone containing a large number of reefs that are as thick as 100 m (Savinsky and others, 1983; Gabrielyants, 1991). On the southeastern and southwestern sides, the lagoon was rimmed by shallow carbonate shelves. The total thickness of the Lower Cambrian sequence varies from 2,000 m on the central Angara-Lena terrace to about 1,300 m on the Nepa-Botuoba high, and to 1,000-1,500 m in the carbonate facies zone of the Cis-Patom foredeep.

The Middle–Upper Cambrian interval is composed of the Litvintsev and Verkholensk Formations. The Litvintsev Formation is chiefly dolomite. It contains layers of salt and anhydrite on the Angara-Lena structural terrace and also locally on the Nepa-Botuoba high. The Verkholensk Formation consists of red and variegated dolomitic marl, dolomite interlayered with anhydrite, and clastic rocks. The thickness of the Middle and Upper Cambrian interval varies from 200–300 m on the Nepa-Botuoba high to 500–750 m on the Angara-Lena terrace. Ordovician rocks have been eroded from most of the Nepa-Botuoba high; however, all three Ordovician series are present on the Angara-Lena terrace and in the Cis-Patom foredeep. The rocks are primarily carbonates in the lower part of the section, changing to mostly clastics with some carbonate beds in the middle and to red clastics in the upper part of the section. The proportion of clastic material increases toward the southeastern and southwestern borders of the craton. The thickness of Ordovician rocks is 300–400 m in the central Angara-Lena terrace; it is more than 1,000 m in the eastern part of the terrace and in the Cis-Patom foredeep. Silurian clastic rocks as thick as 250 m are present only locally.

Younger Paleozoic rocks are regionally absent from the provinces, and probably very little, if any, sediments of that age were ever deposited. Silurian and Devonian orogenic clastics may have accumulated in the Cis-Patom foredeep during thrusting and folding in the Baikal-Patom folded region. If so, they were removed by regional uplift and erosion in later periods. Deformation in the Baikal-Patom region was followed by regional uplift that probably was contemporaneous with rifting in the Kempendiay region.

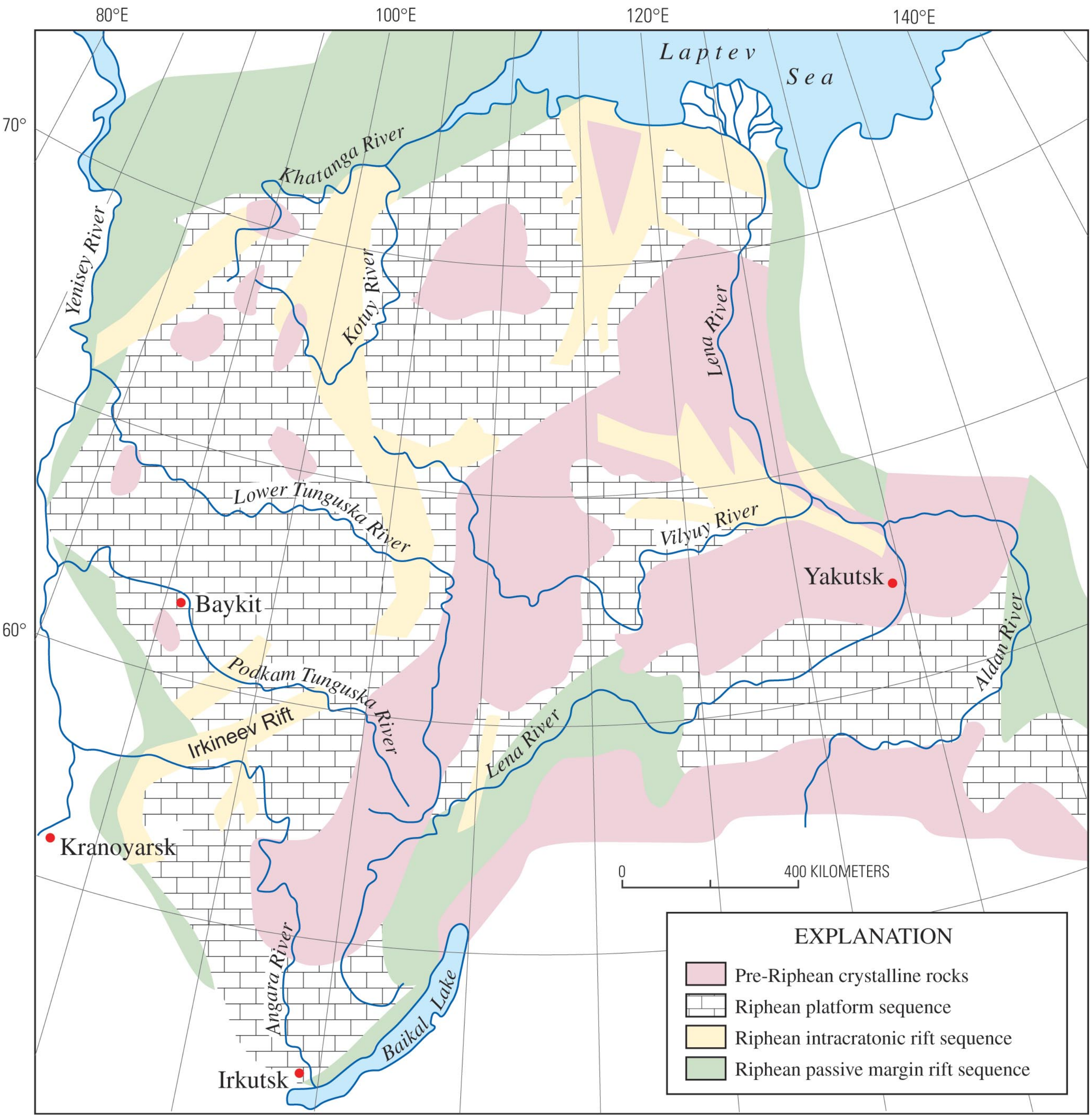


**Figure 2.** Distribution of Riphean rocks of Siberian craton beneath pre-Vendian unconformity. Modified from Kuznetsov (1997).

The deformation in the Baikal-Patom folded region extended into the Cis-Patom foredeep and produced several salt anticlines (fig. 5). Outside the foredeep, plastic flow of salt is known only in the zone of the Nepa-Botuoba high adjacent to the foredeep. Elsewhere, Lower Cambrian salt beds are conformable with both underlying and overlying strata.

Few significant geologic events took place during the subsequent history of the southern Siberian craton. The most important event occurred in Triassic time, when the Siberian craton (together with Taimyr Peninsula and West Siberian plate) was an area of significant volcanic activity. The center of volcanism was in the Tunguska basin (fig. 1) in the northwestern part of the Siberian craton (Kontorovich and others, 1997). Basaltic lavas and tuffs many hundreds of meters thick were deposited in this basin and numerous dikes and sills intruded the sedimentary cover, primarily the Lower Cambrian salt measure. The sills preferentially occur between salt and carbonate beds. The number of sills in the vertical section decreases eastward and southward from the Tunguska basin. Commonly one to several beds of basalt are present in wells drilled on the Nepa-Botuoba high and Angara-Lena terrace. In Jurassic time, a small basin was superposed on the western Angara-Lena terrace along the boundary with the Sayan folded region. As many as several hundred meters of continental coal-bearing clastic sediments were deposited in this basin. Active neotectonic movements on the Siberian craton and in surrounding structures began in post-Eocene time and formed the present-day dissected topography with elevations exceeding 1,000 m (Kontorovich and others, 1981).

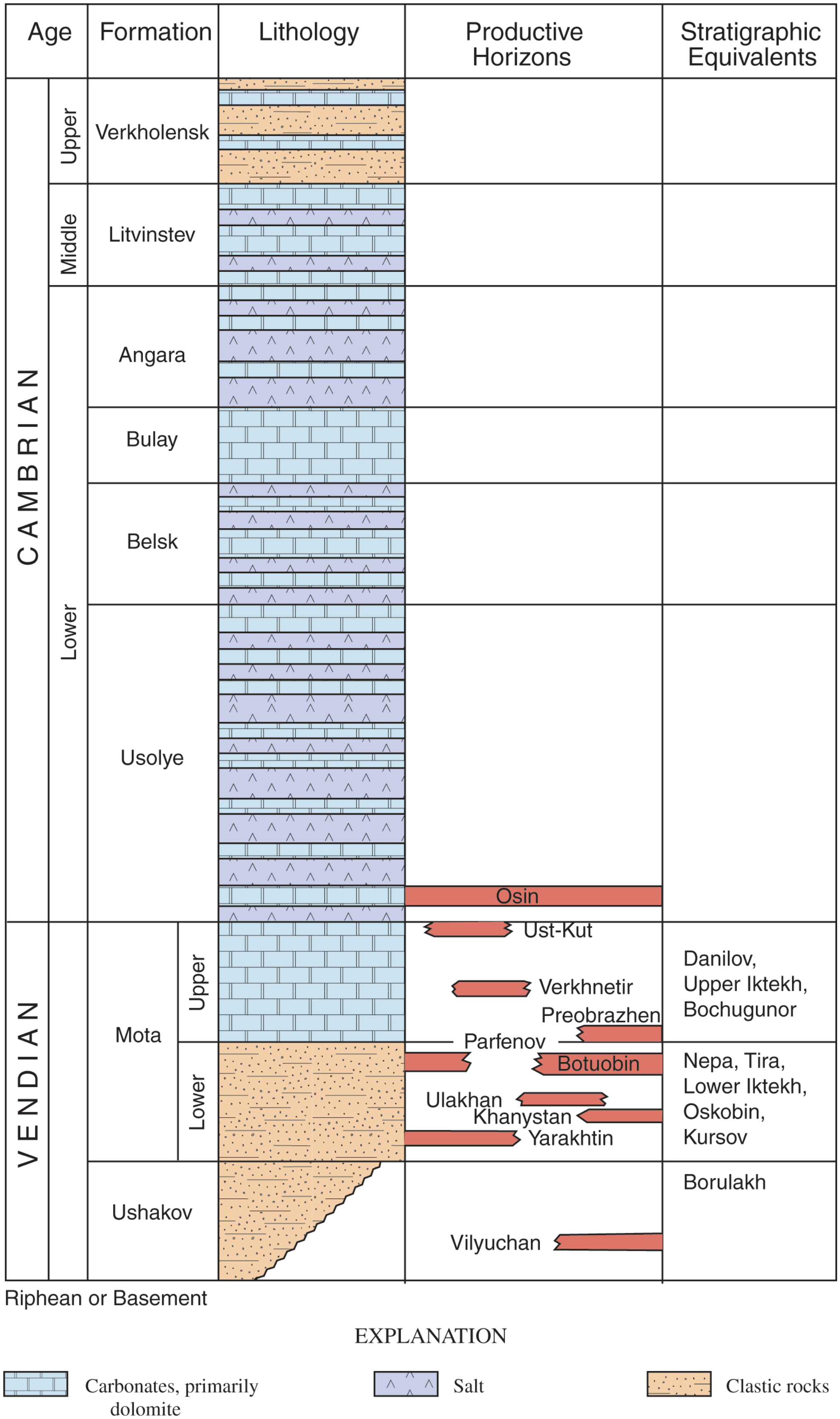


**Figure 3.** Generalized stratigraphic section of Vendian-Cambrian rocks of southern Siberian craton.

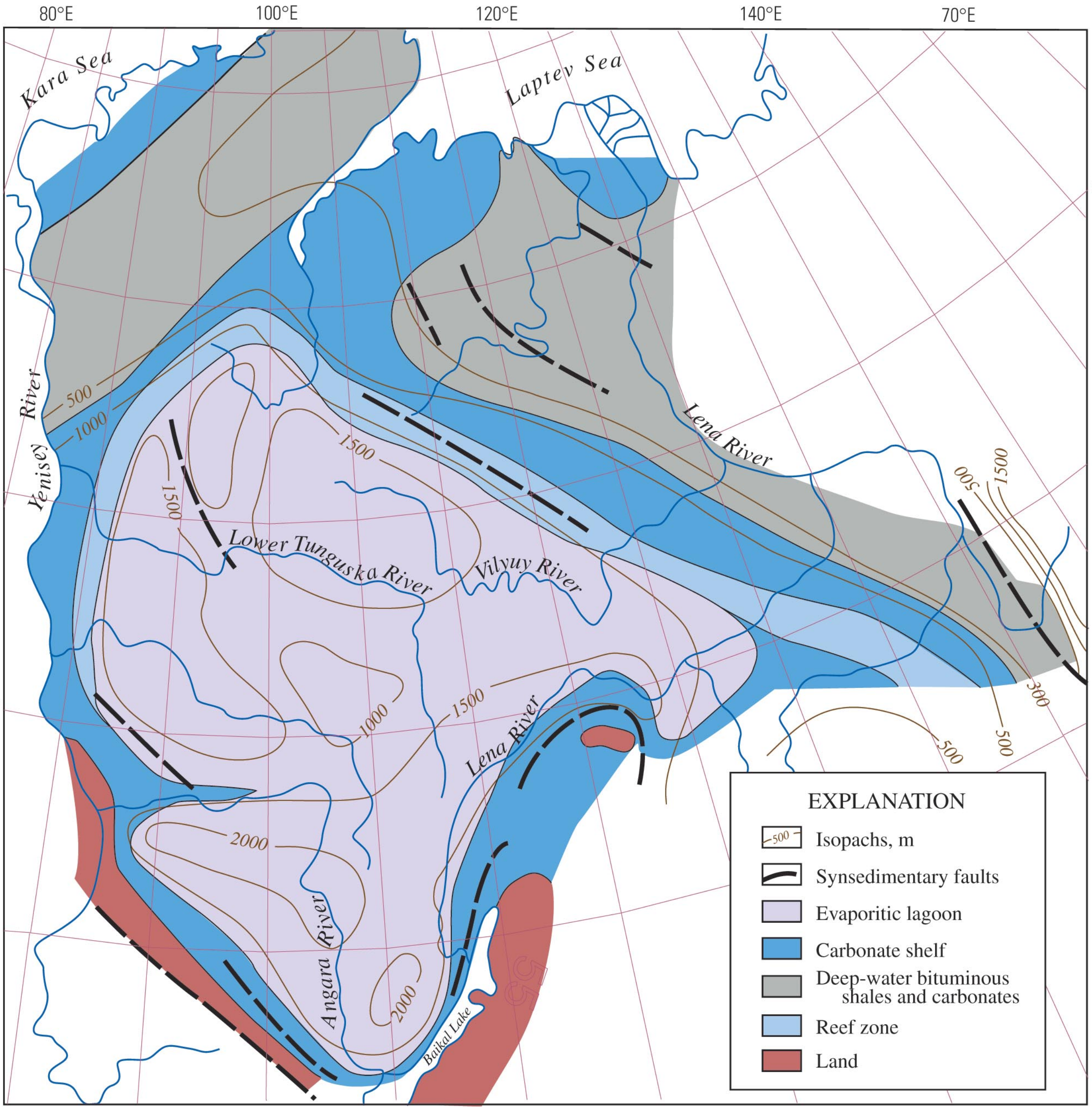


**Figure 4.** Paleogeographic map of Siberian craton during Early Cambrian and early Middle Cambrian (Amgan Age) time. Modified from Gabrielyants (1991).

## Present-Day Structure

The three provinces described in this report are defined on the basis of major structural characteristics. The largest province is the Nepa-Botuoba regional high, which extends southwest to northeast for more than 1,000 km. The amplitude of the high at the base of Vendian–Lower Cambrian rocks is 1,000–1,300 m. The high consists of three uplifts that are separated by shallow structural saddles. The largest uplift is the Nepa arch in the southern part of the Nepa-Botuoba high. Riphean rocks are absent on the high, and basal Vendian clastics directly overlie the crystalline basement at depths less than 2 km (fig. 6). The northwestern and southwestern slopes of the Nepa-Botuoba high are gently tilted monoclines. A number of basement-related smaller structures control the locations of hydrocarbon fields. Several narrow, long anticlines are mapped above the Lower Cambrian salt-bearing sequence in the southwestern area of the high (Nepa zone of anticlines). These structures are absent in underlying strata. Geophysical information indicates that this zone probably contains thrusts extending here from the adjacent Cis-Patom foredeep (Smetanin, 2000; fig. 5 of this report).

The Angara-Lena structural terrace nearly everywhere is undeformed. The basement, at a depth of about 3 km, contains only a few local structures. Two or three salt swells are known in the eastern part of the terrace. The swells extend northeastward parallel to the boundary of the Baikal-Patom folded region; possibly they are related to thrusts. At the top of the Lower Cambrian salt, the swells are as high as 1,000 m, but they are not expressed in the basement structure (Surkov, 1987).

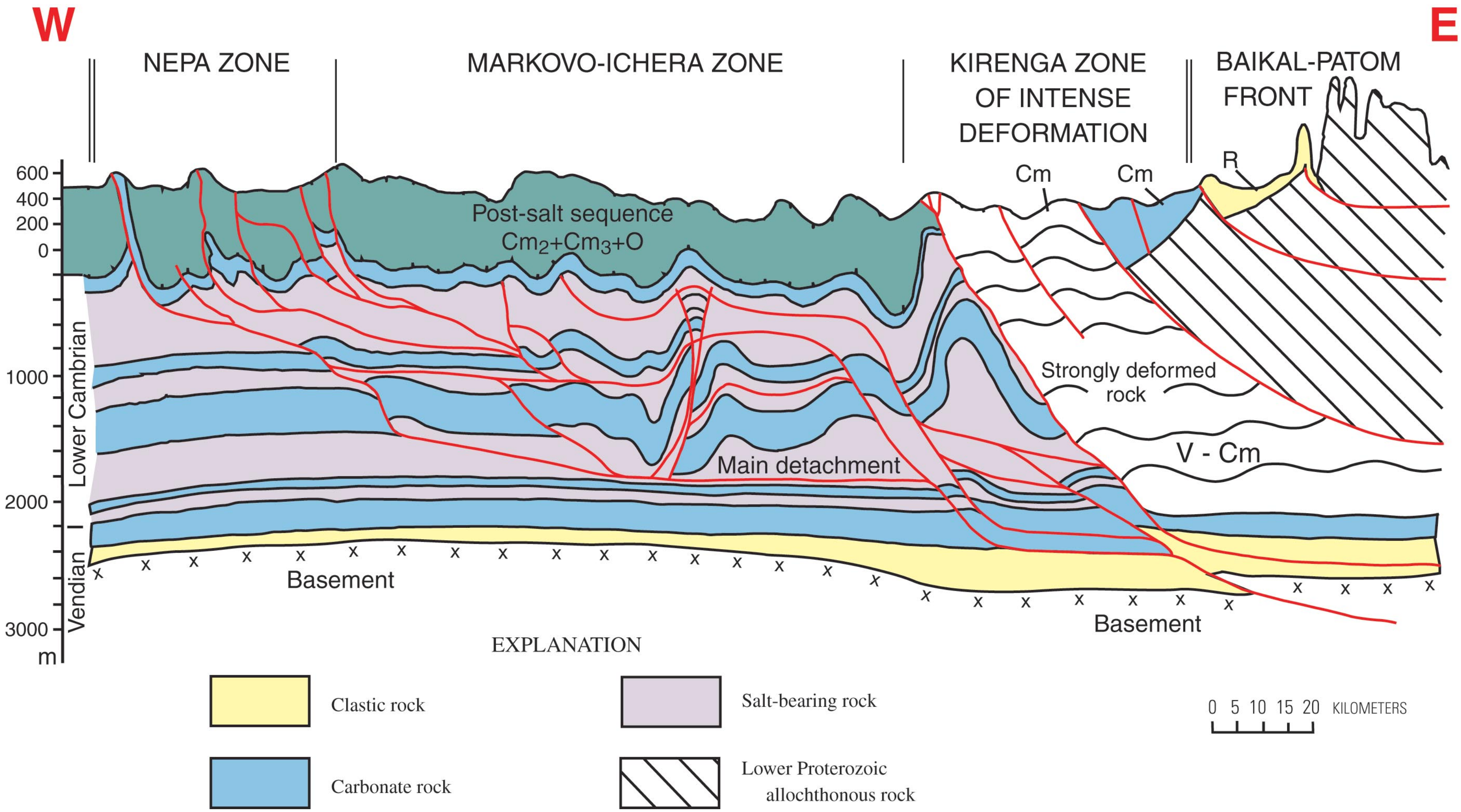


**Figure 5.** Cross section through southern part of Cis-Patom foredeep. Modified from Smetanin (2000). Exact location of section line is not available. R, Riphean; V, Vendian; $Cm_1$, $Cm_2$, and $Cm_3$, Lower, Middle, and Upper Cambrian, respectively; O, Ordovician.

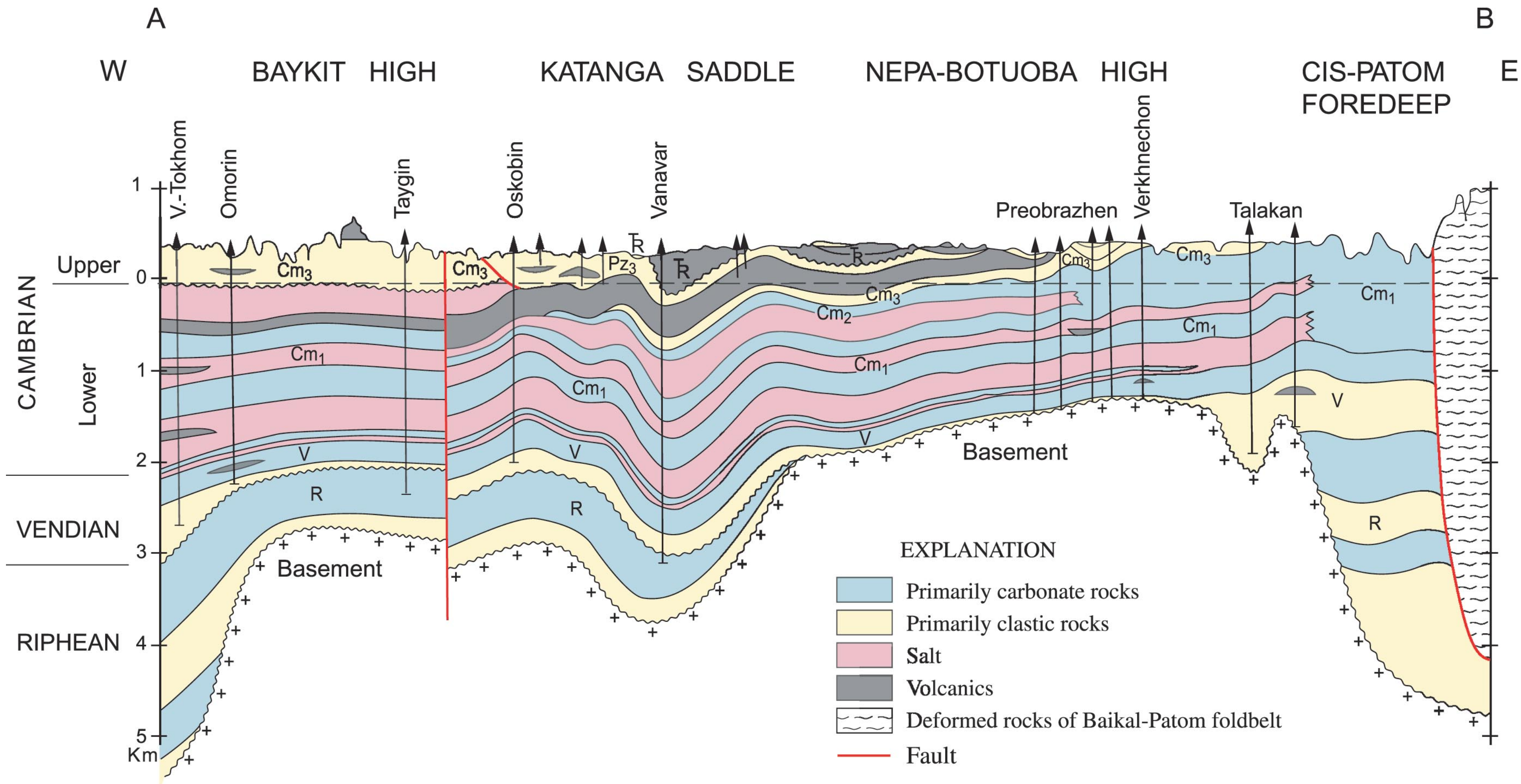


**Figure 6.** Cross section through southern Siberian craton (modified from Gabrielyants, 1991). Approximate location of cross section A–B in figure 7. $Cm_1$, $Cm_2$, and $Cm_3$, Lower, Middle, and Upper Cambrian, respectively; R, Riphean; V, Vendian; $Pz_3$, upper Paleozoic; Ŧ, Lower Triassic. Scale is not available. Approximate length of cross section 1,000 km.

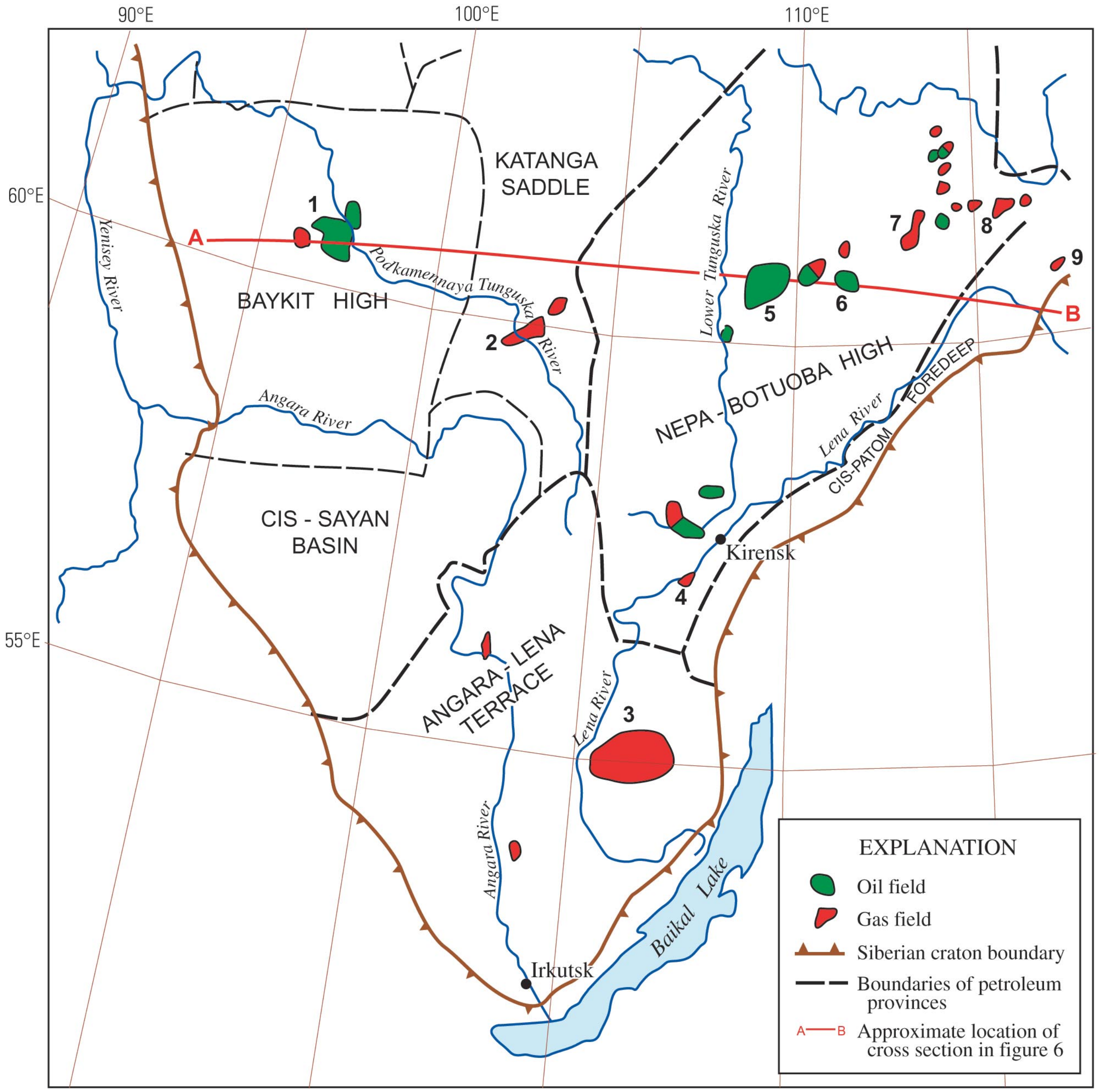


**Figure 7.** Oil and gas fields of southern Siberian craton. Modified from Fuks (1998). Numbers indicate largest fields and fields mentioned in text: 1, Yurubchen-Tokhom; 2, Soba; 3, Kovykta; 4, Markovo; 5, Verkhnechona; 6, Talakan; 7, Srednebotuoba; 8, Verkhnevilyuchan; 9, Basykhtakh.

The Cis-Patom foredeep separates the Nepa-Botuoba regional high from the Baikal-Patom folded region, and it also includes a segment (the Berezov depression) between the folded region and the Aldan shield (fig. 1). The foredeep consists of several depressions that are separated by transverse uplifts. The basement occurs at depths from 2.5 to more than 4 km (fig. 6). In the northwestern zone of the Cis-Patom foredeep, the basement is overlain by Vendian rocks. Thick Riphean formations are present in the sedimentary cover in the southeastern zone of the northern part of the foredeep. The internal structure of the foredeep is complex; it consists of thrust sheets formed in Late Silurian (?)–Devonian time during deformations in the adjacent Baikal-Patom folded region. Figure 5 shows a recent interpretation of this structure in the southern part of the foredeep. In most of the foredeep, the main detachment is along salt-bearing Cambrian strata, and it descends into the basement near the mountain front of the Baikal-Patom folded region. The intensity of deformation increases southeastward. Lower Proterozoic and Riphean formations are thrust on younger rocks of the Cis-Patom foredeep.

## Total Petroleum System

Oil and gas fields in the provinces of the southeastern Siberian craton are confined to a relatively narrow stratigraphic interval that includes Vendian and lowermost Cambrian rocks. Most fields have been discovered in the Nepa-Botuoba High province, but several fields are also present in the Angara-Lena Terrace and Cis-Patom Foredeep provinces (figs. 1, 7). Despite the very large combined area of the three provinces, only one total petroleum system

(TPS) can be identified. Source rocks for the TPS have not been positively identified, but all available geochemical data indicate that rocks that are capable of producing significant amounts of hydrocarbons are lacking in Vendian and younger strata of the provinces. Older Riphean rocks are absent from the provinces' area except possibly for a narrow southeastern zone of the Cis-Patom foredeep. The interpretation presented in this report is that source rocks for oil and gas fields of the provinces are located in the Riphean and possibly Vendian sequences of the Baikal-Patom folded region, where they are presently metamorphosed. However, hydrocarbons probably migrated from this region before Late Silurian or Devonian deformation and metamorphism took place.

## Baikal-Patom Foldbelt Riphean-Craton Margin Vendian Total Petroleum System

### Introduction

The Baikal-Patom Riphean-Craton Margin Vendian TPS (121001) that covers the Nepa-Botuoba High, Angara-Lena Terrace, and Cis-Patom Foredeep provinces of the southeastern Siberian craton is unique in that rich hydrocarbon reserves are derived from ancient Precambrian source rocks and also the preservation of fields has been extremely long. Another uncommon feature is that the source rocks in the generative part of the TPS were deformed and metamorphosed as early as in Late Silurian–Devonian time, whereas hydrocarbon accumulations from these source rocks have been preserved in the undeformed cratonic part of the TPS. The preservation of oil, and especially gas accumulations for such a long period, from early Paleozoic time to the present, is attributed to the presence of the thick undeformed Lower Cambrian salt seal.

The TPS was named for the interpreted source rock (Riphean) and principal reservoir rock (Vendian) intervals and their respective geographic locations. The TPS embraces all three structural provinces of this report. Known oil reserves of the TPS slightly exceed 2 billion barrels (Petroconsultants, 1996). Listed gas reserves are more than 30 TCF, but at present the reserves are substantially larger primarily due to reserve growth in the giant Kovykta (Kovyktin) field (fig. 7, no. 3). Identified gas reserves of that field, which were less than 10 TCF in the early 1990's (Petroconsultants, 1996), increased to 35 TCF by late 1999 and are expected to reach 56–63 TCF (V.A. Kazakov, oral commun., 2000). In addition, there are several new significant oil and gas discoveries, including the large Talakan oil field (fig. 7, no. 6); data on these fields are absent from the Petroconsultants file. None of the fields of the TPS has been fully developed because of the absence of infrastructure. Present small production is limited to local consumption.

### Discovery History

Several surface shows in Vendian–lower Paleozoic rocks on the southern margin of the Siberian craton were known in the 19th century. The first drilling record relates to 1904–1905, when four wells were drilled near the Baikal Lake to depths of 350–400 m. A substantial number of regional surveys that included shallow drilling were conducted before World War II. After the war, the main exploration efforts were concentrated in the Mesozoic superposed Lena-Vilyuy basin. The first commercial gas discovery, made in this basin in 1956, gave a boost to exploration in the entire region. In 1962, a flow of gas and oil was obtained in the Markovo field in the southern part of the Nepa-Botuoba high (fig. 7). In following years, several more hydrocarbon fields were discovered on the high. Many years of exploration on the Angara-Lena terrace resulted only in a few small discoveries, until the giant Kovykta gas field in a stratigraphic trap was discovered in 1987. Although more than 1,000 exploratory and delineation wells have been drilled in the Nepa-Botuoba High and adjacent provinces, the region has been lightly explored.

### Petroleum Occurrence

The majority of discovered oil and gas fields of the TPS are located on the Nepa-Botuoba regional high (fig. 7). The Angara-Lena terrace contains the giant Kovykta gas field, but other known fields are small. Only two relatively small gas fields have been found in the Cis-Patom foredeep. The stratigraphic interval of productivity in all three provinces is narrow because the vertical distribution of hydrocarbons is restricted by the base of the Lower Cambrian salt sequence, which served as an upper seal for hydrocarbon migration. No commercially productive reservoirs have been found above the Osin carbonate reservoir near the Cambrian/Precambrian boundary (fig. 3). Principal reserves of the TPS are in Vendian clastic reservoirs of the lower Mota Formation and its stratigraphic equivalents (commonly called the Nepa-Tira sequence in the literature). This sequence contains about 80 percent of the TPS hydrocarbon reserves and more than 95 percent of the oil reserves (Dmitrievsky and others, 1989). Substantially smaller reserves are known in carbonate reservoirs of the Vendian(?) upper Mota Formation and Lower Cambrian Osin Horizon. Both clastic and carbonate reservoirs are commonly underpressured, and they are characterized by low formation temperatures that resulted from Cenozoic cooling of the crust. For example, temperature at a depth of 1,700 m in the Verkhnechona oil and gas field is only 15.9°C (Diyashev and others, 1999). The lowest temperature recorded in the productive reservoir is 6.5°C. Thick and continuous permafrost is present in the northern part of the Nepa-Botuoba high; its distribution in more southern areas is patchy (Slavin and others, 1980). Formation of gas hydrates in pipes, owing to low temperatures, complicates production and transportation of hydrocarbons.

Oils in fields of the Nepa-Botuoba high are of low gravity (37°–45°API) and they have low sulfur (0.1–0.3 percent) and low paraffin (0.6–1.7 percent) contents (Kontorovich and others, 1981). The oils contain small amounts of resins (0.8–5.9 percent), and asphaltenes are almost completely absent. In the group composition, alkanes dominate over naphthenes, and the content of aromatics is small. Condensates are light and they contain no sulfur, resins, or asphaltenes. Gases are thermogenic. In most fields they contain high percentages of ethane and heavier homologues (12–15 percent) and small amounts of carbon dioxide (less than 1 percent); commonly they have significant concentrations of nitrogen (5–8 percent) and helium (to 0.2 percent). Gas of the Kovykta field contains more methane (91–93 percent), less heavier hydrocarbon gases (3.5–4.5 percent), and a high concentration of helium (0.26–0.36 percent).

## Source Rocks

Biomarker studies show that all of the Riphean and Vendian–Lower Cambrian oils in the southeastern Siberian craton form a single genetic family and that they were generated by similar source rocks (Kashirtsev and others, 1997). The source rocks hypothesized for the TPS are Riphean and Vendian organic-rich black shales occurring in the Baikal-Patom folded region. Geochemical changes in oils of fields across the slope of the Nepa-Botuoba high indicate upslope migration from that region (Larichev and others, 1997). Presently, the black shales are strongly deformed, variably metamorphosed, and partly eroded. However, they could have generated hydrocarbons before the deformation, structural inversion, and intrusion of granite plutons that occurred in Devonian and later times. Upper(?) Riphean deep-water organic-rich shales and carbonates of the Kochergat Formation and similar Vendian rocks of the Tinnov Formation crop out southeast of the Cis-Patom foredeep, and they probably extend in the subsurface onto the foredeep slope (Bakhturov, 1985). Beds of organic-rich shales are also exposed in outcrops of the upper Riphean Uluntay Formation west of the Baikal Lake (Shenfil, 1991). Riphean rocks northwest of the Nepa-Botuoba high have not been drilled. The presence of rift structures in that area that can contain source rocks is unlikely but not impossible.

Vendian and Lower Cambrian rocks, which overlie the crystalline basement and include the entire hydrocarbon reserves of the TPS, probably do not contain source rocks. The largest concentrations of total organic carbon (TOC) in Vendian clastic rocks were recorded in the southern area of the Angara-Lena terrace (Kontorovich and others, 1981). There, TOC in analyzed samples averaged only 0.5 percent and did not exceed 1 percent. In other areas of the TPS, TOC in Vendian clastics ranges from 0.1 to 0.3 percent. Only a single well in the Cis-Patom foredeep has drilled Vendian organic-rich rocks about 10 m thick (Kontorovich and others, 1986). Carbonate rocks that both underlie the salt measure and compose beds alternating with salt have very low TOC contents generally not exceeding 0.2 percent. In addition, Vendian rocks over most of the area occur at depths shallower than 3 km. Considering the cooling effect of thick salt, these rocks probably are immature to low mature. However, the composition of biomarkers in oils indicates high maturity of source rocks (Kashirtsev and others, 1999). Therefore, oil and gas fields of the TPS were probably derived from different source rocks.

The time of hydrocarbon generation of oil and gas in the TPS and the adjacent Baikal-Patom folded region cannot be determined from geochemical modeling. However, the time of secondary migration of hydrocarbons that formed oil and gas fields of the TPS is geologically constrained by deposition of the salt seal in Early Cambrian time and by the destruction of source rocks in the folded region that took place not later than in Devonian time. The TPS that presently covers the Nepa-Botuoba high, Angara-Lena terrace, and Cis-Patom foredeep also extended into the Baikal-Patom folded region in pre-Silurian time. In early Paleozoic time, the TPS generated hydrocarbons from Late Proterozoic source rocks. Thus, the TPS is probably the oldest productive petroleum system in the world.

## Reservoir Rocks

Most oil and gas reserves of the TPS are concentrated in the lower Vendian clastic reservoirs (fig. 3). An important characteristic of reservoir sandstones is their limited lateral extent. Therefore, correlation of sandstone beds drilled in different areas is difficult and commonly uncertain, and the nomenclature of the sandstone beds is complicated (Zinovyev and Lukinov, 1994). The principal productive horizons are shown in figure 3. In general, deposition of clastic sediments began on the periphery of the Nepa-Botuoba high and gradually progressed toward the top of the high (fig. 6). The basal sandstone bed (the Yaraktin Horizon of the southwestern Nepa-Botuoba high and the Vilyuchan Horizon of more northern areas) includes alluvial and deltaic deposits (Savinkin and others, 1991). The sandstones are poorly sorted; they are characterized by poor reservoir properties and only locally are they productive, mainly from stratigraphic traps. Higher in the section, reservoir rocks are primarily of marine origin and their porosity and permeability are better. Much of reserves are in the upper part of the clastic section that overlaps the crest of the Nepa-Botuoba high (primarily in the Parfenov and Botuobin Horizons). Most commonly, porosity of productive sandstones ranges from 10 to 15 percent; in places it is somewhat lower or higher. Permeability varies widely, from near zero to hundreds of millidarcies, and it is strongly correlated with fracturing. In many fields, the reservoir properties of productive sandstones strongly deteriorate outside the oil-water or gas-water contact. This indicates an important role of late diagenetic processes in the loss of porosity. Earlier diagenetic changes that occurred prior to hydrocarbon entrapment are also recognized. As a result of these changes, sandstones with quartzose cement are typically impermeable and are not productive, whereas the porosity and permeability were preserved in sandstones with clay and carbonate cement at the time of field formation.

The Vendian carbonate section (the Danilov Formation of the Nepa-Botuoba high and the upper Mota Formation of the Angara-Lena terrace) contains two reservoir beds in the lower part and one bed at the top (fig. 3). The effective thickness of each bed commonly varies from 10 to 20 m. Dolomites, which developed from organic detrital limestones, have better reservoir properties (Kontorovich and others, 1986). The porosity of carbonate reservoirs in productive fields of the Nepa-Botuoba high commonly ranges from 6 to 13 percent and rarely is as high as 20–22 percent (Drobot and others, 1991). Permeability varies from less than one to a few hundred millidarcies. Porosity was chiefly caused by recrystallization and leaching of carbonates. Reservoir rocks in the Danilov Formation are primarily present in the central and northwestern zones of the Nepa-Botuoba high (Shemin, 1999). Southward and southeastward, reservoir properties deteriorate rapidly and productivity is lacking. One gas field in low-porosity (2–7 percent) dolomites has been discovered in the northern Cis-Patom foredeep (Kuznetsov and others, 1993).

The Osin Horizon in the basal part of the Lower Cambrian sequence (fig. 3) contains three commercial pools, and it produced a number of hydrocarbon flows in tests in other fields. Reservoir rocks are algal limestones that were dolomitized to a various degree. The best reservoir rocks are in barrier reefs surrounding the top of the Nepa-Botuoba high (Kuznetsov and others, 1996; Yefimov, 1997). The reefs separated the shallow-water shelf that covered the high from deeper water sea outside the high. Local carbonate buildups are also present, but they are inadequately studied. The thickness of reefs in different areas is 40 to 80 m; however, net reservoir thickness does not exceed 20 m. The porosity of reservoir rocks ranges from 8 to 15 percent, and permeability ranges from 10 to 100 mD. Hydrocarbon shows in several areas were detected in younger carbonate beds of the Lower Cambrian sequence, primarily in the Belsk and Bulay Formations. However, no commercial-size accumulations have been found.

## Traps

Both structural and stratigraphic traps are productive in the TPS. All major hydrocarbon accumulations, with the exception of the Kovykta field, are in structural traps. The traps are moderately faulted anticlinal uplifts that drape over basement highs. Discontinuous reservoir beds modify the outlines of many pools, and a number of traps can be considered combinations of structural and stratigraphic elements. The Cis-Patom foredeep contains many thrust-related anticlines. The Basykhtakh gas field in the northern part of the foredeep (fig. 7) is probably in such an anticline. Closer to the northwestern border of the foredeep, the detachment surface rises into the Lower Cambrian salt-bearing sequence, and thrust anticlines are developed above flat-lying Vendian strata that contain the principal reservoirs.

Several productive stratigraphic traps have been discovered on the Nepa-Botuoba high, especially in its southern part. The stratigraphic traps are related to onlap and updip pinchout of lower Vendian sandstones on the southeastern slope of the high. The Markov field (fig. 7), which was the first discovery in the TPS, is of this type. Some stratigraphic traps probably have a significant diagenetic component. Supposedly, pools in these traps originally were formed in local structural uplifts. Later, diagenetic processes destroyed porosity outside the oil-water or gas-water contact and the pools were preserved in spite of the subsequent regional tectonic tilting that opened the structural traps updip (Vinogradov, 1978).

The giant Kovykta field on the Angara-Lena terrace (fig. 7) is on a monocline that gently dips northwestward. In 1999, the proved productive area was about 2,000 $km^2$, and it is expected to increase to 7,000–7,500 $km^2$ as exploration progresses (V.A. Kazakov, 2000, oral commun.). Presently available data do not reveal the trapping mechanism. The southern pool boundary is a large northeastward-trending fault. A gas-water contact is inferred to limit the pool on the north. The western and eastern pool boundaries have not been determined, and controls on pool distribution along those boundaries are unknown. Two northwest-striking faults have been mapped, but they do not control the pool outlines.

## Assessment Units

The Baikal-Patom Foldbelt Riphean-Craton Margin Vendian TPS includes a single assessment unit that covers all three provinces, the Nepa-Botuoba High, the Angara-Lena Terrace, and the Cis-Patom Foredeep, of the southeastern Siberian craton. Although significant hydrocarbon reserves have been discovered, a paucity of data precludes more detailed assessment. The assessment unit is only sparsely explored. Although more than 1,000 exploratory wells have been drilled, the majority of them are step-out and delineation wells. Difficult seismic conditions (such as dissected topography, heavy forest cover, permafrost, presence of discontinuous basalt layers, and changing thickness of salt) complicate subsurface mapping of platform-type, low-amplitude uplifts.

The results of assessment of undiscovered oil and gas resources are shown in table 1. Complete statistical data and the methodology of the assessment are available in U.S. Geological Survey World Energy Assessment Team (2000). In spite of the generally mediocre to poor quality of reservoir rocks and the dependence of field formation on long-distance lateral migration of hydrocarbons, the estimated undiscovered resources are relatively high, especially for gas. These high estimates result from the presence of the high-quality regional salt seal that covers almost the entire TPS. The petroleum potential of East Siberian provinces beyond the limits of the Lower Cambrian salt area is low because of poor preservation conditions. This is manifested by the occurrence of giant tar deposits in several regions north of the area of Lower Cambrian salt (fig. 4).

Most future resources of the assessment unit are expected to be discovered in lower Vendian clastic reservoirs in both structural and pinch-out stratigraphic traps. The latter likely will be primarily on the southeastern slope of the Nepa-Botuoba high. Several zones that have potential for exploration for stratigraphic traps have been delineated there (Matveyev and others, 1996). The potential for updip pinch-out zones of sandstones on the northwestern slope of the high is uncertain; it depends strongly on the presence or absence of Riphean source rocks in undrilled adjacent areas of the Tunguska basin (fig. 1). The majority of productive structural traps probably also are located on the Nepa-Botuoba high.

In the Cis-Patom foredeep, reservoir rocks are nearly absent in the Vendian clastic section because sandstones are replaced by shales there and the rocks have been strongly diagenetically altered (Korzh and Mazanov, 1990). In addition, conditions for preservation of hydrocarbons since at least Devonian time in thrust-related anticlines of the Cis-Patom foredeep are poor, especially considering the deformation of the salt seal in the foredeep.

The Angara-Lena terrace is nearly everywhere undeformed. Very few local structural uplifts have been identified and the potential for structural traps is low. Because the entrapment mechanism of the giant Kovykta field (fig. 7) is not known, it is difficult to predict whether new fields of this type may be found. However, discovery of another field of comparable size is unlikely.

Upper Vendian to Lower Cambrian carbonate rocks are underexplored, partly owing to technological difficulties in testing and completion of low-permeability carbonate reservoirs (Drobot and others, 1991). Presently, carbonate reservoirs contain a small part of discovered oil and gas in the TPS. The proportion of future resources in these reservoir rocks will probably be larger. The principal potential zone of Vendian carbonate reservoirs is in the central area of the Nepa-Botuoba high. The basal stromatolitic dolomite bed (the Preobrazhen Horizon, fig. 3) of this area originated as a carbonate platform, and it contains a number of stratigraphic oil and gas condensate pools (Shemin, 1999). Significant additional reserves may be discovered there with the use of proper drilling and completion techniques.

The Lower Cambrian Osin Horizon (fig. 3) also may contain significant undiscovered resources, especially in reef reservoirs (Melnikov, 1996). Some fields in the upper part of the carbonate section, particularly in the Osin Horizon, could have been destroyed by Triassic basalt volcanism. The lower basalt sills commonly were intruded along the lowermost salt beds. However, the heating effect from a sill rapidly decreases with increasing distance from the sill (Kontorovich and others, 1997), and the degree to which volcanism could have damaged hydrocarbon-bearing reservoirs is uncertain. The petroleum potential of Lower Cambrian and younger rocks above the Osin Horizon is negligible.

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