# Petroleum Geology and Resources of the Baykit High Province, East Siberia, Russia

*By* Gregory F. Ulmishek

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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 the World Energy Project is to aid in assessing the quantities of oil, gas, and natural gas liquids that have a potential to be added to reserves during 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 they occur as reserve growth of fields already discovered.

The total petroleum system constitutes the basic geologic unit of the oil and gas assessment. The total petroleum system includes all genetically related petroleum 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 may 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 be assessed individually.

A numeric code identifies each region, province, total petroleum system, and assessment unit; these codes are uniform throughout the World Energy Project and each code identifies the same item in all 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 the 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

The Baykit High province consists of two principal structural units—the Baykit regional high in the west, which occupies most of the province, and the Katanga structural saddle in the east. The province is on the western margin of the Siberian craton east of the Yenisey Ridge foldbelt. The province is an exploration frontier and only a few prospects have been drilled. The oldest sedimentary rocks of the province, Riphean carbonate and clastic strata of Late Proterozoic age (1,650–650 million years old) that were deposited on the passive margin, cover the Archean–Lower Proterozoic basement. Basal Vendian (uppermost Proterozoic, 650–570 million years old) clastic rocks unconformably overlie various units of the Riphean and locally lie directly on the basement. Younger Vendian and lowermost Cambrian rocks are primarily dolomites. The Vendian/Cambrian boundary is conformable, and its exact stratigraphic position has not been identified with certainty. The Lower Cambrian section is thick, and it consists of alternating beds of dolomite and evaporites (mostly salt). Middle and Upper Cambrian strata are composed of shale and dolomite. Ordovician-Silurian and upper Paleozoic rocks are thin, and they are present only in the northern areas of the province. Structural pattern of Riphean rocks differs substantially from that of Vendian-Cambrian rocks.

A single total petroleum system (TPS) was identified in the Baykit High province. Discovered oil of the system is chiefly concentrated in Riphean carbonate reservoirs of the Yurubchen-Tokhom zone that is currently being explored and that has the

potential to become a giant field (or group of fields). The TPS also contains about 5 trillion cubic feet of discovered recoverable gas in clastic reservoir rocks at the base of the Vendian section. Petroleum source rocks are absent in the stratigraphic succession over most of the TPS area. Riphean organic-rich shales and carbonates that crop out in the Yenisey Ridge foldbelt west of the Baykit high are probable source rocks. Their areal distribution extends from the foldbelt into the foredeep along the province's western margin. Potential source rocks also are present in platform depressions in eastern areas of the province. Hydrocarbon generation and migration west of the province started as early as Riphean time, before the beginning of the deformation in the Yenisey Ridge foldbelt that occurred about 820–850 million years ago. However, the presently known oil and gas accumulations were formed after deposition of the Lower Cambrian salt seal.

Available data allow identification of only one assessment unit, and it covers the entire TPS area. Undiscovered oil and gas resources are moderate, primarily due to the poor quality of reservoir rocks. However, the reserve growth in the Yurubchen-Tokhom zone may be large and may exceed the volume of undiscovered resources in the rest of the province. Most oil and gas resources are expected to be in structural and stratigraphic traps in Riphean carbonate reservoirs. Vendian clastic reservoirs are probably gas-prone.

## Introduction

The Baykit High province (1207) includes the Baykit regional high, a large regionally uplifted structure ("anteclise" in Russian terminology) in the southwestern part of the Siberian craton, and the Katanga structural saddle that connects the Baykit and Nepa-Botuoba highs (fig. 1). The province was named the Baykit Arch in U.S. Geological Survey World Energy Assessment Team (2000). However, in this report the name Baykit High is used in reference to the province to avoid confusion with the Baykit arch, which is an Upper Proterozoic uplift in the province. The Baykit High province is an exploration frontier and is defined as a "boutique" province for appraisal of undiscovered oil and gas resources by the U.S. Geological Survey (U.S. Geological Survey World Energy Assessment Team, 2000).

A single total petroleum system (TPS), the Yenisey Foldbelt Riphean-Craton Margin Riphean TPS (120701), encompasses the entire province. The name of the system reflects the location and age of major source rocks (Riphean rocks of the eastern margin of the Yenisey Ridge foldbelt) and principal reservoir rocks (Riphean carbonates of the Siberian craton margin). Only 4 or 5 oil and gas fields, with reserves listed by Petroconsultants (1996) at 35 million barrels (MMBO) of oil and about 5 trillion cubic feet (TCF) of gas, have been discovered. However, these numbers do not include the reserves of the Yurubchen-Tokhom zone that may be a single field or a few closely related fields (see fig. 5). Although proven oil reserves of the zone presently are relatively small (hundreds of million barrels), many Russian geologists believe that the zone contains giant oil and gas resources (Kontorovich and others, 1996; Kuznetsov, 1997). Consequently, the potential for reserve growth is high. At present, production infrastructure in the region is absent and none of the discovered fields have been exploited.

Because of limited 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 procedures are described in U.S. Geological Survey World Energy Assessment Team (2000). The results of assessment are shown in table 1. Expected quantities of undiscovered resources are moderate, primarily owing to poor quality of reservoir rocks. However, reserve growth in the Yurubchen-Tokhom zone is expected to be large, possibly exceeding the undiscovered resources in the rest of the province. Most of the undiscovered resources likely will be found in Riphean carbonate reservoirs in structural and stratigraphic traps. The resource potential of Vendian clastic reservoirs is lower, and discoveries of mainly gas fields are expected.

## Province Overview

### Province Location and Boundaries

The Baykit High province (1207) is in the southwestern part of the Siberian (East Siberian) craton, and it includes the Baykit regional high ("anteclise" in Russian terminology) in the west and the Katanga structural saddle in the east. The saddle connects the Baykit and Nepa-Botuoba highs (fig. 1). The Russian term "anteclise" is best translated into English as "high" or "regional high," and the latter terms are used in this report. The Baykit arch (not to be confused with the Baykit high) is a smaller structural feature that has been identified only in Riphean rocks in the northern part of the Baykit regional high (fig. 2). Both the Baykit high and the Katanga saddle are identified in the structure of Vendian–lower Paleozoic formations whereas the structure of underlying Riphean rocks is different (discussed in a subsequent section). The province area is approximately 220,000 square kilometers (km$^2$). West of the province is the Yenisey Ridge (fig. 1), a thrust-fold belt composed of strongly deformed and partially metamorphosed Riphean rocks that are overlain unconformably by significantly less deformed uppermost Riphean, Vendian, and lower Paleozoic strata. To the south, the slope of the Baykit high dips into the Cis-Sayan basin (fig. 1). The two structures are separated by a nearly latitudinal zone of folds along the Angara River (Angara zone of folds in fig. 5). This zone approximately coincides with the boundary of the Riphean Irkineev (Irkineev-Vanavar) aulacogen (Sokolov, 1989; fig. 3 of this report). The Tunguska basin, a late Paleozoic depression that is superposed on early Paleozoic structural units, is north of the Baykit high (fig. 1). Carboniferous to Triassic rocks of the Tunguska basin onlap the northern slope of the Baykit high.

### Tectono-Stratigraphic Development

The basement complex of the Baykit high, as in other regions of the Siberian craton, consists of Archean and Lower Proterozoic crystalline rocks. The basement is overlain by

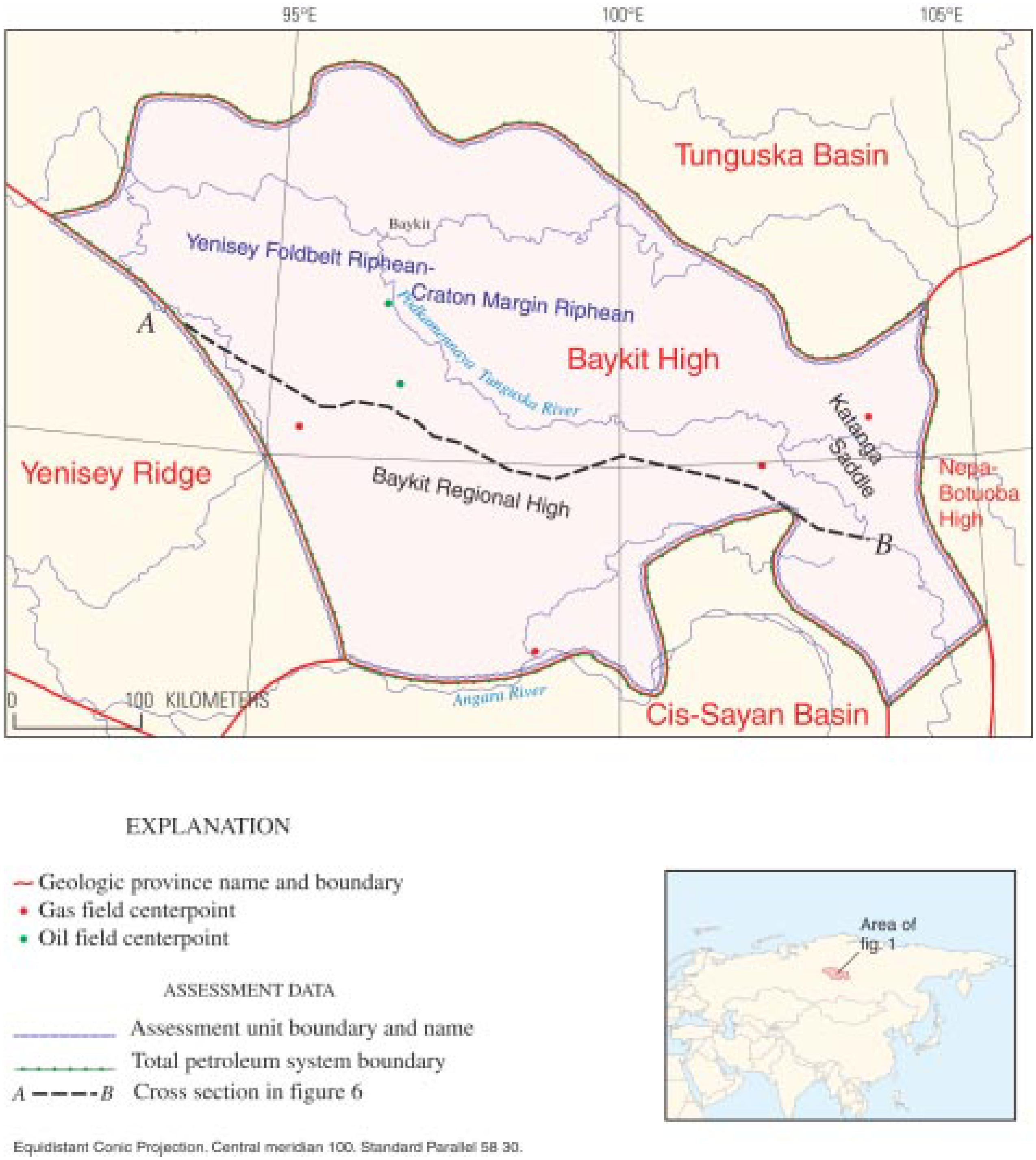


**Figure 1.** Total petroleum system and assessment unit of Baykit High province 1207. Cross section *A–B* is shown in figure 6.

Riphean (most of Late Proterozoic age, 1,650–650 million years old (Ma)), Vendian (latest Proterozoic, 650–570 Ma), and early Paleozoic rocks. Younger rocks are relatively thin and are present primarily in the northwest part of the province. Several stages of structural development are recognized in geologic history of the Baykit high and adjacent structures.

The earliest stage of structural development is recorded by the thick (10–12 km) sequence of Riphean rocks exposed in the Yenisey Ridge foldbelt (figs. 1, 4, 5). These strata crop out in several major thrust plates that were tectonically transported eastward. At the base of the sequence are quartzose and feldspathic sandstones and dolomites of the lower Riphean Teysk series, of probable intracratonic origin. Rifting and opening of the Mongol-Okhotsk ocean west of the Siberian craton took place approximately at the time boundary between early and middle Riphean (≈1,350 Ma) (Surkov and others, 1996). The Irkineev rift (aulacogen) (fig. 3) that extends in a west-east direction in the south of the Baykit High province probably was formed at the same time. However, no wells as yet have penetrated that structure and no stratigraphic data on the rift fill are available. Younger Riphean strata of the Yenisey Ridge foldbelt (Sukhopit, Tungusik, and Oslyan series) were deposited on a passive continental margin that

**Table 1.** Yenisey Foldbelt Riphean-Craton Margin Riphean TPS 120701 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 |
| 12070101 | Yenisey Foldbelt Riphean-Craton Margin Riphean Assessment Unit | | | | | | | | | | | | | |
| Oil Fields | 5 | 1.00 | 147 | 1,007 | 2,979 | 1,213 | 695 | 4,864 | 15,456 | 6,054 | 40 | 282 | 958 | 362 |
| Gas Fields | 30 | | | | | | 1,109 | 9,284 | 26,350 | 10,929 | 49 | 407 | 1,232 | 492 |
| Total | | 1.00 | 147 | 1,007 | 2,979 | 1,213 | 1,804 | 14,147 | 41,806 | 16,983 | 88 | 689 | 2,190 | 854 |
| **120701** | **Total: Yenisey Foldbelt Riphean-Craton Margin Riphean Total Petroleum System** | | | | | | | | | | | | | |
| Oil Fields | | 1.00 | 147 | 1,007 | 2,979 | 1,213 | 695 | 4,864 | 15,456 | 6,054 | 40 | 282 | 958 | 362 |
| Gas Fields | | | | | | | 1,109 | 9,284 | 26,350 | 10,929 | 49 | 407 | 1,232 | 492 |
| Total | | 1.00 | 147 | 1,007 | 2,979 | 1,213 | 1,804 | 14,147 | 41,806 | 16,983 | 88 | 689 | 2,190 | 854 |

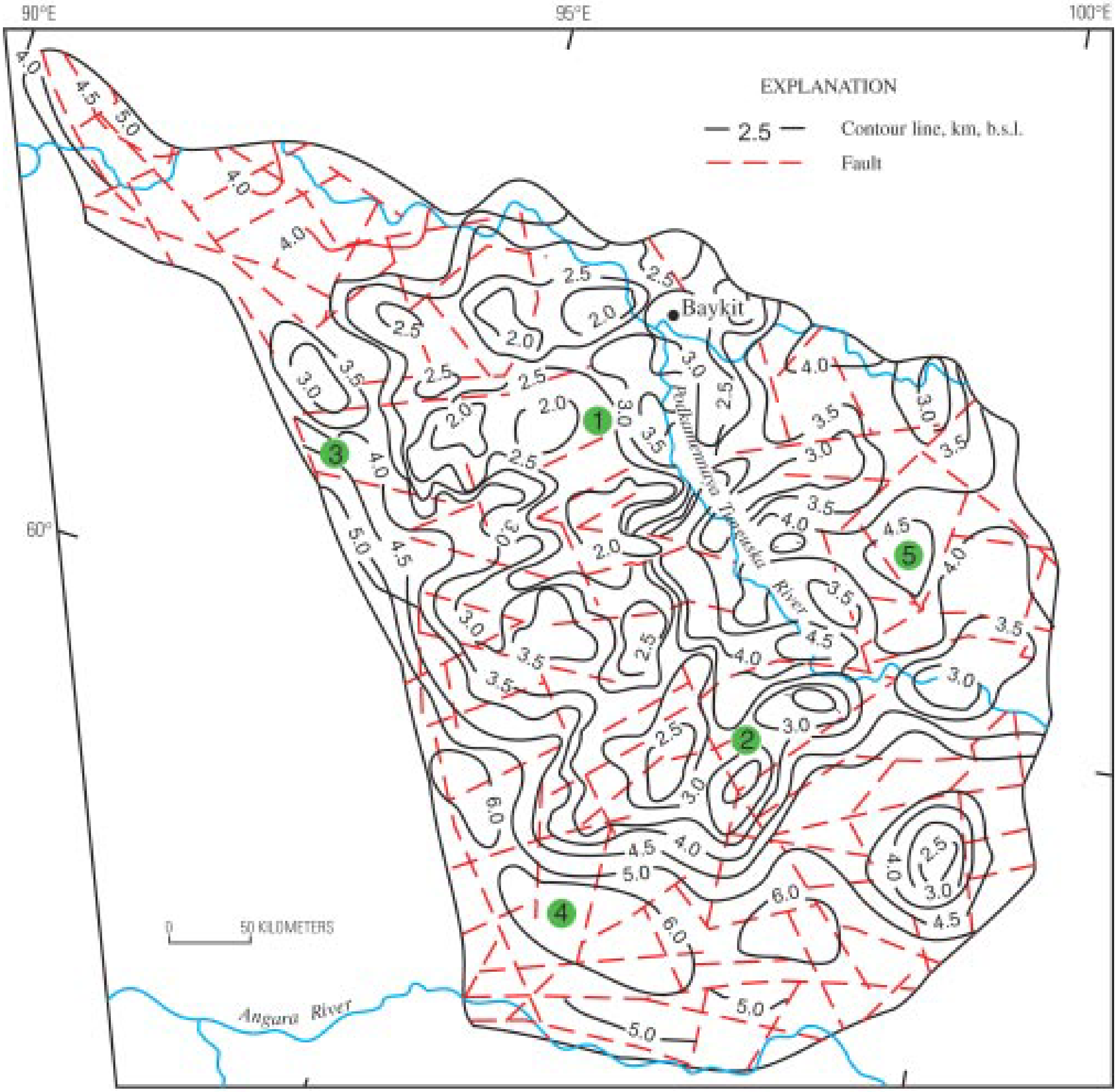


**Figure 2.** Contour map on top of crystalline basement of Baykit high. Modified from Kontorovich (1994). Numbers in circles indicate major structural units of Riphean sequence: 1, Baykit arch; 2, Delanin arch; 3, Cis-Yenisey foredeep; 4, Terin depression; 5, Madrin-Tychan depression.

originally faced the open ocean and later (since approximately 1,050–1,150 Ma) bordered a back-arc basin (Kontorovich and others, 1996; figs. 3, 4 of this report). Progressively more distal sedimentary facies were deposited from east to west on the passive margin. The rocks are primarily flyschoid clastics (turbidites) and some carbonates and shales, which presently compose thrust plates in the foldbelt. Volcanic rocks increase in abundance in the same direction. The westernmost plate (Isakov allochthon) is composed of an ophiolite association and is believed to represent a volcanic arc that was thrust onto the passive margin (Zonenshain and others, 1990). Eastward, slope turbidite facies grade into thick shelf carbonate and subordinate clastic formations. Shelf-edge barrier reef complexes are present at many stratigraphic levels (Khabarov, 1999).

The entire Riphean passive margin sequence was strongly deformed, thrust faulted, and cut by granite intrusions in the middle of late Riphean time (820–850 Ma). The diastrophism (called the Baikalian orogeny) was related to collision of the Siberian continental margin with early Precambrian microcontinents that presently are incorporated in the basement complex of the West Siberian basin (for example, the Verkhneket microcontinent of Surkov and others, 1996). Riphean rocks were metamorphosed to phyllite and greenschist facies in the western thrust plates. The degree of metamorphism decreased eastward, and metamorphic

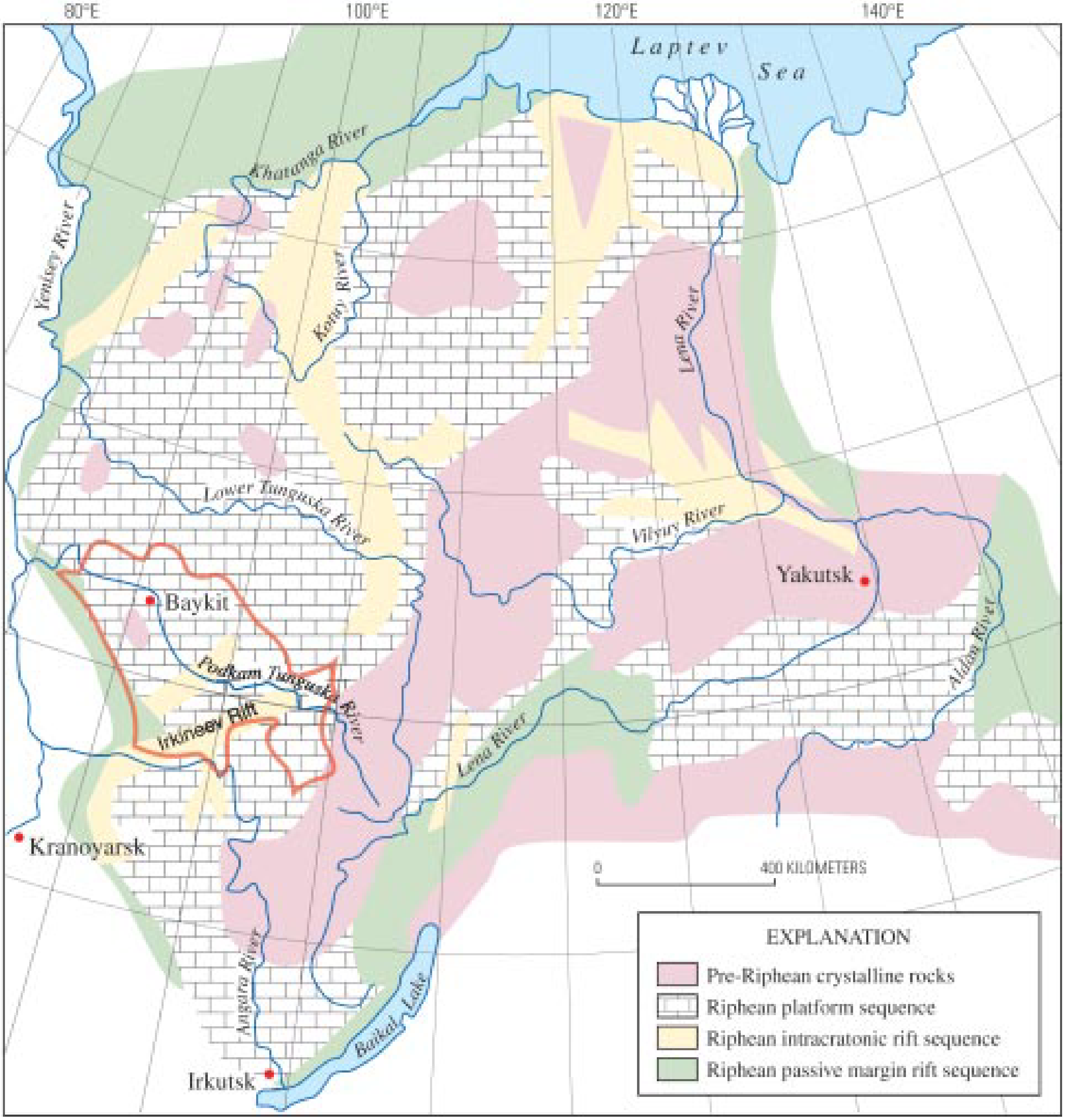


**Figure 3.** Distribution of Riphean rocks of Siberian craton beneath pre-Vendian unconformity. Modified from Kuznetsov (1997). Red line outlines Baykit High province.

rocks are virtually absent on the margin of the foldbelt and in the frontal depression of the Baykit High province. Many geologists believe that the principal Baikalian tectonism was preceded by deformational events and intrusions of palingenetic granitoids that possibly are correlative in age with the Grenvillian orogeny at approximately 1,050 Ma (Nozhkin and Boldyrev, 1979; Surkov and others, 1996). However, structural data indicate that such events either did not occur or they were minor and did not result in significant structural reorganization (Basharin and others, 1996).

Following Baikalian deformation, the thrust-fold system of the Yenisey Ridge was uplifted and eroded. The youngest Riphean, post-Baikalian, rocks of the Taseev series, that are primarily present in the southern part of the Yenisey Ridge, consist chiefly of orogenic, coarse red clastics. The Taseev series unconformably overlie various older Riphean and basement rocks. The existence of a pre-Vendian tectonic event, and even mild metamorphism, has been suggested by some investigators (for example, Kontorovich and others, 1996; Surkov and others, 1996). However, basal Vendian clastic rocks conformably overlie the Taseev series in some areas, and the two stratigraphic units are structurally concordant (Shenfil, 1991; Basharin and others, 1996). That indicates the absence of significant pre-Vendian deformation. However, regional uplift and erosion on the adjacent Siberian craton and probably on parts of the Yenisey Ridge are indicated by the unconformable occurrence of Vendian rocks on various pre-Baikalian

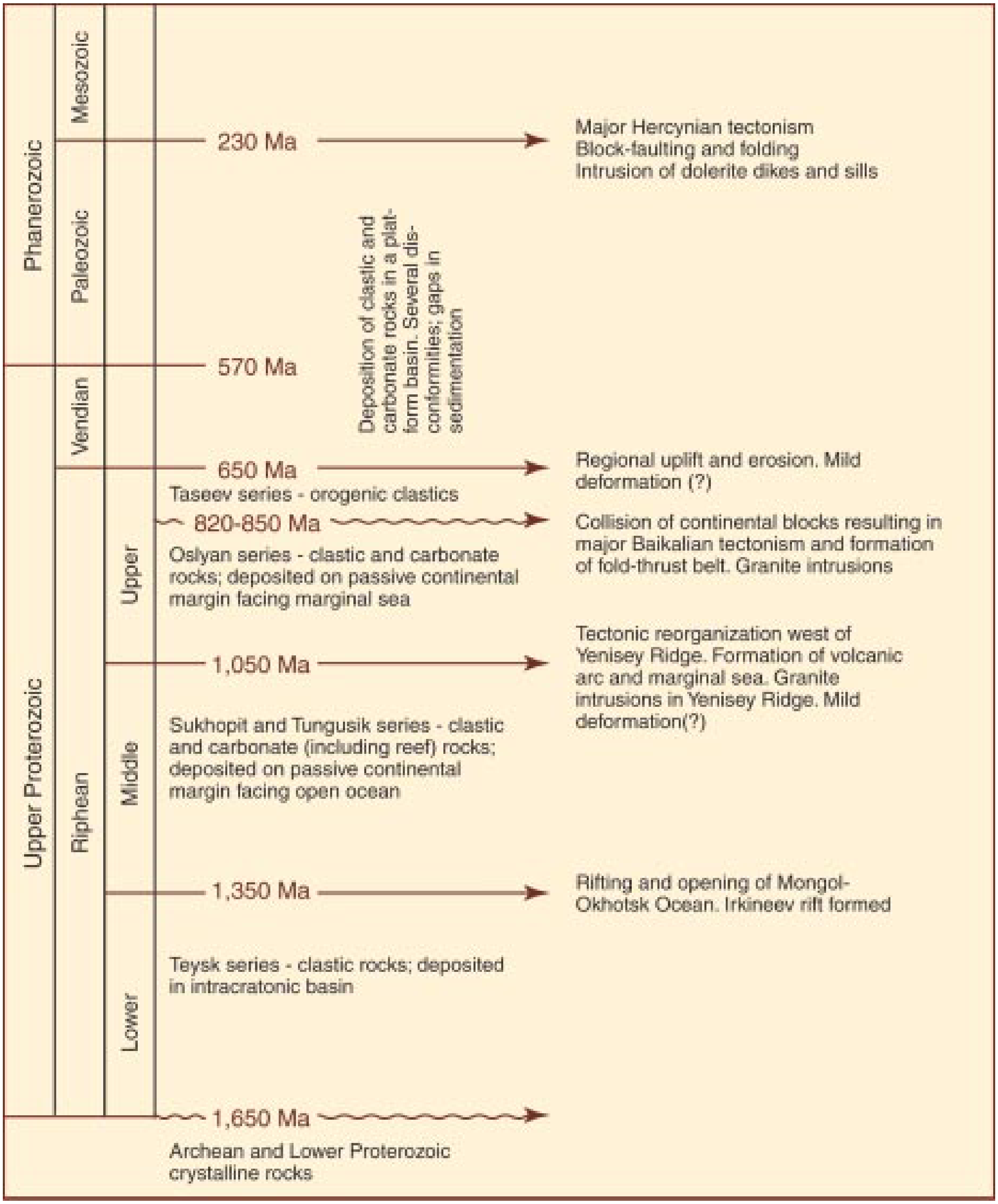


**Figure 4.** Generalized stratigraphic column of Upper Proterozoic–Paleozoic rocks of Yenisey Ridge foldbelt.

Riphean formations (fig. 4). Younger Vendian and Paleozoic rocks are preserved in local structural depressions of the Yenisey Ridge foldbelt. All of the rocks, from Vendian to Permian in age, were deformed concordantly during the Hercynian orogeny in Late Permian to earliest Triassic time, owing to collision of the Kazakh, and Siberian continents with Euroamerica (Basharin and others, 1996). Block faulting was the principal style of Hercynian deformation, and folds formed primarily along the faults. Folds of the Angara zone (fig. 5) also formed at that time. Therefore, the present-day Yenisey Ridge is a Hercynian structure that inherited the Baikalian foldbelt. On the basis of the local presence of flat-lying Jurassic and Cretaceous rocks, the foldbelt was buried by Mesozoic sediments and was again uplifted as a block by Neogene neotectonic movements.

Riphean rocks cover most of the Siberian craton, filling a number of deep intracratonic aulacogens and forming thick sequences on margins of the Riphean Siberian continent (presently deformed into foldbelts) (fig. 3). On basement blocks

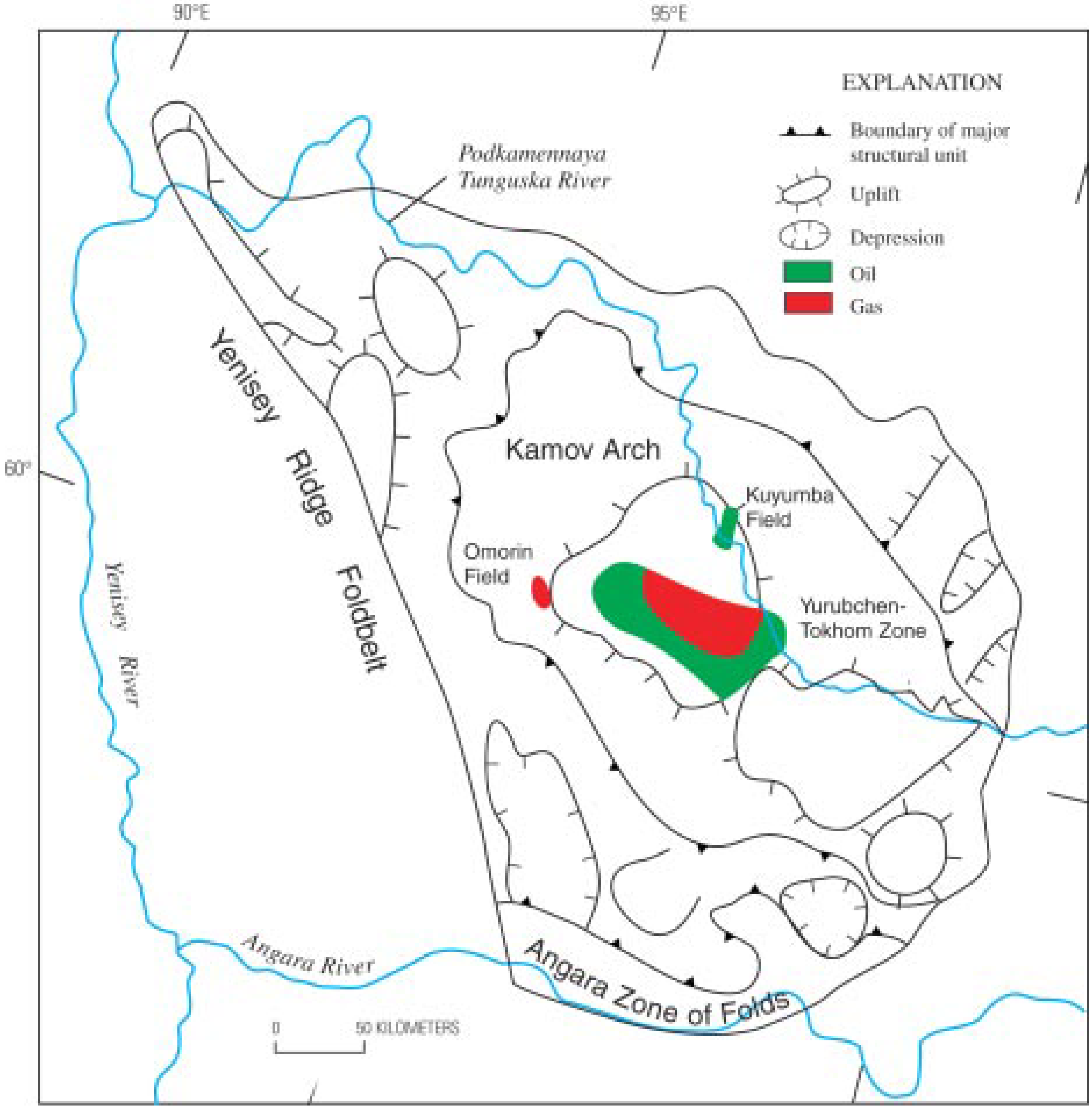


**Figure 5.** Vendian–lower Paleozoic structure of Baykit regional high. Modified from Kontorovich (1994).

between the aulacogens and continental margins, Riphean strata are much thinner. In some areas, the Riphean sequence is absent owing to nondeposition and (or) pre-Vendian erosion. The Riphean sequence of the Baykit regional high is represented by platform-type formations of the Kamov series, which is about 3 km thick in drilled areas and thickens to 4–5 km in the frontal foredeep of the Yenisey Ridge. This series is composed of the basal clastic Zelendukon Formation that is overlain by thick carbonate (dominantly dolomite) and thinner shale and (or) argillaceous dolomite units (see fig. 9). The sediments were deposited on the Archean–Lower Proterozoic crystalline basement. Two opposing points of view are held regarding the exact age of the Kamov series and its correlation with formations of the Yenisey Ridge. The first is that the Kamov series includes stratigraphic equivalents of the lower, middle, and upper Riphean sections of the Yenisey Ridge (Shenfil and Primachok, 1996; Kontorovich and others, 1996). In this model, the entire lower Riphean is represented by a thin (260 m or less), locally absent unit of feldspathic-quartzose sandstones (Zelendukon Formation in fig. 9) that is indicative of extremely slow sedimentation in a quiet tectonic regime over a span of about 800 million years of early Riphean time. The second point of view is that the Kamov series does not include rocks older than about 1,150 Ma (Surkov and others, 1996), and thus, it forms a back-reef carbonate platform that stratigraphically correlates only with the upper part of the pre-Baikalian Riphean sequence of the Yenisey Ridge, which records deposition on the margin of the back-arc basin.

The Baikalian tectonic event (approximately 850–820 Ma) that strongly deformed Riphean rocks of the Yenisey Ridge also affected the adjacent Baykit high. Block faulting was the principal style of deformation. The intensity of deformation is debated because of poor seismic resolution and difficulties in correlating drilled rocks. Descriptions of the Riphean structure by different authors vary, from its being virtually undeformed and flat-lying (Slavkin and others, 1994; Kuznetsov, 1997) to being significantly block faulted, tilted, and folded in separate areas (Kontorovich, 1994; Kontorovich and others, 1996; Shenfil and Primachok, 1996). Some geologists consider the entire Baykit regional high to be a distal part of the Yenisey Ridge foldbelt (Basharin and others, 1996). Both models of Riphean structure were proposed based on geologic and geophysical studies of the Yurubchen-Tokhom productive area (fig. 5). However, extensive seismic surveys in that area combined with data from more than 100 drilled holes cannot establish validity of the respective models. This emphasizes difficulties in stratigraphic correlations in the absence of fossils and poor quality of seismic imaging. Probably, the fault blocks are present; however, the intensity of faulting may be overestimated because, at least in some cases, facies changes are incorrectly interpreted to be stratigraphically different strata in adjacent fault blocks (Slavkin and others, 1994). Information is scarce on the Riphean structure and stratigraphy of the Katanga saddle, but the presence of Baikalian tectonic blocks is indicated by seismic and limited drilling data (Sokolov, 1989).

Following Baikalian deformation, the Baykit High province was uplifted and rocks were deeply eroded. In the structurally highest areas, all sedimentary rocks were truncated and the basement was exposed. Post-Baikalian Riphean rocks correlative to the Taseev series of the Yenisey Ridge are largely absent in the Baykit High province (except in the southernmost area), and Vendian–lower Paleozoic rocks directly overlie Riphean formations or the crystalline basement. In general, during Vendian-Cambrian time the Baykit High province developed as a regional monocline that gently tilted southwestward and southward. Across this monocline, Vendian rocks thin from about 1,400 m in the south to 160 m in the north (Kontorovich and others, 1996). Ordovician rocks and some Silurian rocks are preserved only in the northern areas of the province. The northern flank of the present-day Baykit regional high was formed in Carboniferous-Triassic time when the northern part of the Vendian–early Paleozoic monocline was overlain by the southern slope of the superposed Tunguska basin.

Vendian-Cambrian and younger strata also were deposited on the eroded surface of the Riphean rocks of the Yenisey Ridge. From there, these strata extended west across microcontinents that were accreted to the western margin of the pre-Baikalian Siberian continent, as is indicated by the presence of Vendian and Paleozoic platform-type rocks recently identified west of the Yenisey Ridge. The latter rocks, penetrated by drilling beneath Mesozoic sediments of the West Siberian basin, include thick Cambrian salt-bearing formations that are nearly identical to those of the Baykit high and other regions of the southern Siberian craton (Kashtanov and Filippov, 1994). A Cambrian sequence, primarily composed of strongly deformed basic volcanic rocks, which were deposited oceanward from the younger, early Paleozoic margin of the Siberian continent, was recently drilled farther west in an area 100–150 km west of the Yenisey Ridge (Kontorovich and others, 1999).

Hercynian deformations, which so profoundly affected the Yenisey Ridge, were mild on the Baykit high; they produced only scattered, gentle, platform-type structures in Vendian-Cambrian strata. These deformations also folded strata of the Angara zone along the southern boundary of the Baykit High province. The linear shape, en echelon arrangement, and high (several hundred meters) amplitudes of the Angara zone folds probably indicate their transpressional origin. Strike-slip movements probably occurred along a rejuvenated Riphean fault bordering the Irkineev rift (fig. 3). The Triassic volcanic event affected the Baykit High province to a stronger degree than the Nepa-Botuoba high and other eastern areas of the southern Siberian craton. Within the Baykit High province, the number of dolerite sills increases northward toward the Tunguska basin, and their total thickness in the sedimentary cover increases in the same direction from 85 to 525 m (Kontorovich, 1994).

## Present-Day Structure

Two structural complexes, with different structural patterns and separated by the pre-Vendian (Baikalian in the south) unconformity, are represented in sedimentary rocks of the Baykit high and Katanga saddle. The present-day structural patterns of the complexes are substantially different. The complex below the unconformity involves pre-Baikalian (older than 820–850 Ma) Riphean rocks. Its major characteristic is the fault-block structural pattern shown in figure 2, although many of the faults shown probably are confined to the basement and do not penetrate into stratigraphic units above the basement. The principal structural units are two arches, the Baykit arch in the northern area of the province and the Delanin arch in the central area (fig. 2). On the crest of the Baykit arch, Vendian rocks directly overlie the basement. Identification of the Delanin arch is based on seismic data; the arch has not been drilled. The deep Cis-Yenisey depression in front of the Yenisey Ridge foldbelt (structural unit 3 in fig. 2) is a remnant structure that formed after structural inversion of the foldbelt. The Terin and Madrin-Tychan depressions (structural units 4 and 5 in fig. 2) are in the southern and eastern parts of the province. Data on structures in Riphean rocks of the Katanga saddle area to the east of the Madrin-Tychan depression are lacking.

The regional structural units and the majority of the faults in Riphean rocks do not extend above the pre-Vendian (Baikalian in the south) unconformity, and the structural pattern within the overlying Vendian–lower Paleozoic strata is less complex. The Baykit regional high (not to be confused with the Baykit arch of the Riphean structural complex) and Katanga saddle are the principal structural units identified in Vendian–lower Paleozoic rocks. A large positive structure known as the Kamov arch occupies most area of the Baykit regional high (figs. 5, 6). Maximum amplitude of the arch at the base of Lower Cambrian strata is about 500 m. A number of smaller, gentle positive and negative structures are present on the crest of the arch and on its slopes (fig. 5). The western slope is bounded by thrusts of the Yenisey Ridge foldbelt, and it probably extends beneath the thrusts. The Angara zone of folds is located in the southernmost part of the province (fig. 5).

## Total Petroleum System

The Baykit High province is a frontier area for petroleum exploration. The geology of the province is not well understood, and many questions remain regarding major elements of the petroleum system. The principal volumes of discovered oil and gas of the province are in Riphean rocks. Petroleum source rocks are not

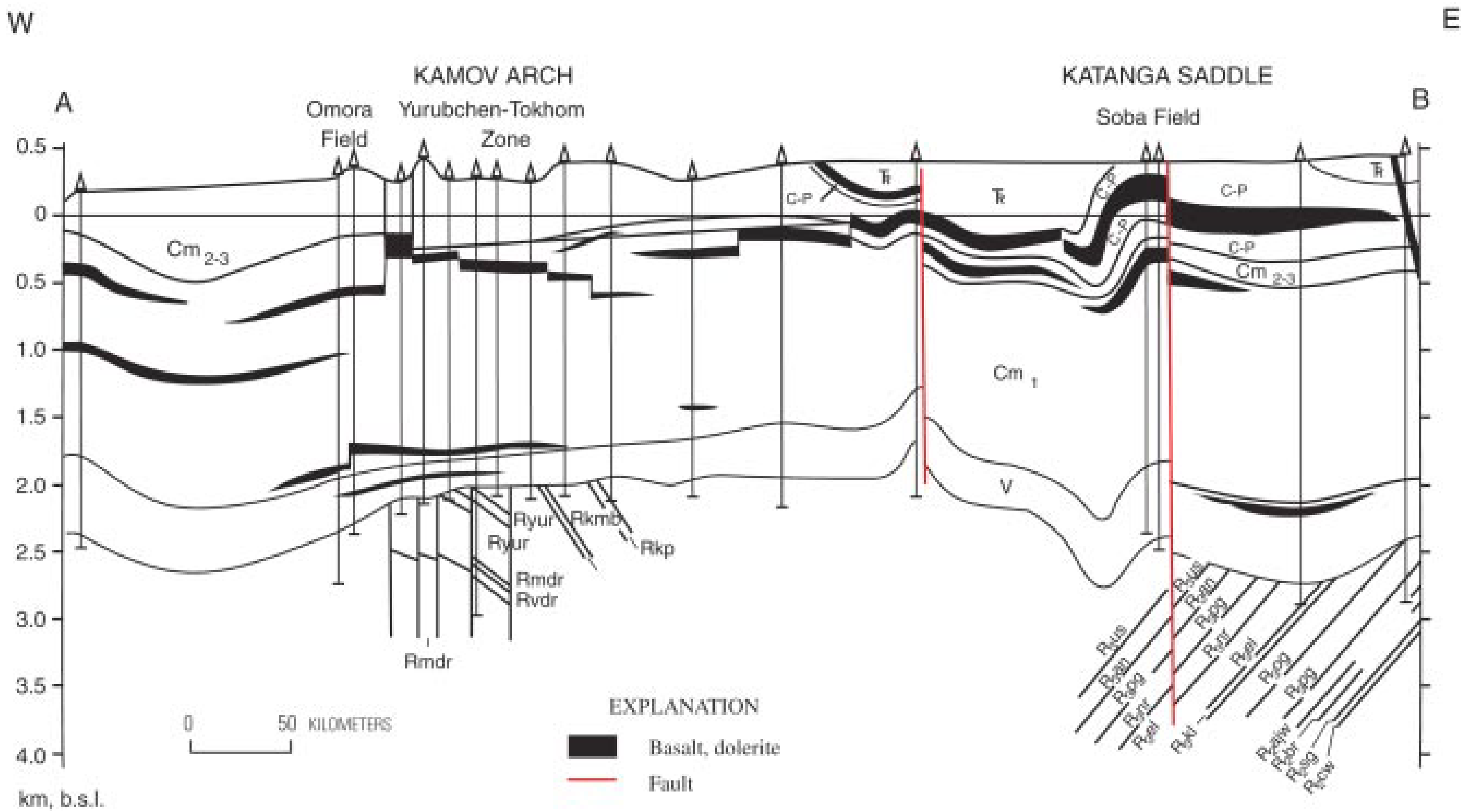


**Figure 6**. Regional cross section of Baykit High province. Modified from Filiptsov and others (1999). R, Riphean; V, Vendian; C, Carboniferous; P, Permian; , Triassic; $Cm_1$ and $Cm_{2\text{-}3}$, Lower and Middle-Upper Cambrian, respectively. See figure 9 for symbols of Riphean formations of Kamov arch. Formation names on Katanga saddle are different and are not explained. However, $R_3$an stands for Ayan Formation, which contains good source rocks. Location of cross section shown in figure 1.

well identified; probably they occur in the eastern zone of the Yenisey Ridge thrust-fold belt and the adjacent foredeep, and possibly also in the Madrin-Tychan and Terin depressions (fig. 2). Uncertainties, particularly in determination of source rocks and timing of hydrocarbon generation and migration, allow identification of only one TPS for the entire province, the Yenisey Foldbelt Riphean-Craton Margin Riphean Total Petroleum System (120701).

## Yenisey Foldbelt Riphean-Craton Margin Riphean Total Petroleum System

### Discovery History and Petroleum Occurrence

The first stratigraphic test borehole in the Baykit High province was drilled in 1970, and the first exploratory well was drilled in 1972 on a local uplift in Cambrian rocks. In the following year, that well tested gas in Riphean strata, which led to discovery of the Kuyumba field (fig. 5). Subsequent drilling in the field was largely unsuccessful, and seismic surveys were unable to effectively delineate the structure of Riphean rocks. Exploration in the field was terminated, but it was resumed in the 1980's.

During the early years of exploration in the province, drilling prospects primarily were structures that were mapped seismically on Lower Cambrian reflectors, although drilling targets also were in Riphean rocks. The first oil was tested in the Yurubchen-Tokhom zone (figs. 5, 6) in 1977. The Yurubchen local uplift was drilled, and it proved productive in 1982. Later in the 1980's, oil and gas flows were obtained in the Nizhne-Tokhom, Vedreshev, and Madrin prospects. Subsequent drilling demonstrated that those discoveries, possibly including the Kuyumba field, constitute a single productive area. That area, as large as 13,450 $km^2$ (Kontorovich and others, 1996), became known as the Yurubchen-Tokhom zone.

The Yurubchen-Tokhom field (zone) is in the southern part of the Kamov arch (fig. 7). Reservoir rocks are leached dolomites of Riphean formations that underlie the pre-Vendian unconformity. Along the northwestern and eastern boundaries of the field, the productive area is limited by the pinchout of Riphean vuggy dolomites against shaly Riphean strata and basement rocks, all of which subcrop at the pre-Vendian unconformity. The field contains a gas cap as thick as 90 m; however, throughout most of the area the gas-bearing reservoir is about 40–50 m thick (fig. 8). Underlying the gas cap is an oil zone 40 m in average thickness. Distribution of reservoir properties in carbonate rocks is highly variable and many wells appeared to be dry or only marginally productive when tested. In spite of data from more than 100 exploratory wells, the geology of the field remains poorly understood.

Oil of the Yurubchen-Tokhom field is light (42°–45° API) and has a low sulfur content (0.2–0.3 percent). Its group composition is dominated by paraffinic and naphthenic hydrocarbons, the amount of which averages 65 percent. The oil is devoid of asphaltenes, but has a significant content of resins (21–27 percent).

In addition to the Yurubchen-Tokhom field, a significant gas discovery was made in 1980 in basal Vendian clastics in the Soba field on the Katanga saddle (fig. 6). The field contains thermogenic gas with a high (as much as 27 percent) concentration of nitrogen (Fuks, 1998). Discovery of this field was the only exploration success in the Vendian–lower Paleozoic complex. Only two or three additional, but small, gas discoveries in Vendian clastic rocks have been made on both the Baykit regional high and Katanga saddle.

### Stratigraphic Section

As mentioned previously, the absence of fossils and the poor quality of seismic data have hampered correlation of Riphean rocks not only province-wide but also in much smaller areas, such as the Yurubchen-Tokhom zone. Only during the last few years have several deep wells penetrated sufficient thicknesses of Riphean rocks to help establish the stratigraphic succession of formations, although none of the wells was drilled through the entire Riphean sequence (fig. 9). Most of the Riphean sequence is composed of carbonate rocks, dominantly dolomites. The lithology of the dolomites varies from stromatolitic and oolitic to siliceous and argillaceous. Formations that are chiefly carbonate alternate with thinner formations that primarily consist of shales and argillaceous dolomites. Locally developed, tightly cemented sandstones are present at the base of the sequence.

In the Yurubchen-Tokhom zone, basal Vendian clastics of the Vanavara or Oskobin Formations unconformably cover stratigraphic units of the Riphean sequence (figs. 6, 10). Post-Baikalian Riphean sandstones of the Taseev series are absent from the zone, but they are present in the southernmost areas of the TPS. The younger Vendian and Lower Cambrian rocks are closely similar to those of other regions of the southern Siberian craton, consisting of carbonates (Vendian) and salt that is interbedded with dolomite beds (Lower Cambrian). The Middle and Upper Cambrian strata are primarily dolomite and shale. Younger rocks are relatively thin, and they are present only in the northern part of the TPS.

### Petroleum Source Rocks

Compositions of biomarkers and isotopic compositions of oils indicate that all oils discovered in the Baykit High and Nepa-Botuoba High provinces of the southern Siberian craton belong to a single genetic family (Kashirtsev and others, 1997). Based on the apparent absence of potential oil source rocks in the Vendian–Lower Cambrian sequence, it may be concluded that (1) the source rocks occur in the Riphean interval, and (2) in different areas of the southern Siberian craton, source rocks were deposited under similar paleogeographic conditions and they had similar chemical compositions. The similarity of the chemical compositions is probably related to the low content of oxygen in the atmosphere and the uniformity of the biotic association.

Two hydrocarbon generation areas are indicated for the TPS of the Baykit High province. Abundant, organic-rich source rocks are present at several stratigraphic levels in the pre-Baikalian Riphean sequence of the Yenisey Ridge foldbelt (Kontorovich, 1994; Surkov and others, 1996; Timoshina, 1997). Especially rich in organic matter are the black shales and argillaceous carbonates of the Shuntar Formation (Tungusik series of the upper Riphean in fig. 4), which is more than 1,000 m thick in outcrops (Shenfil, 1991).

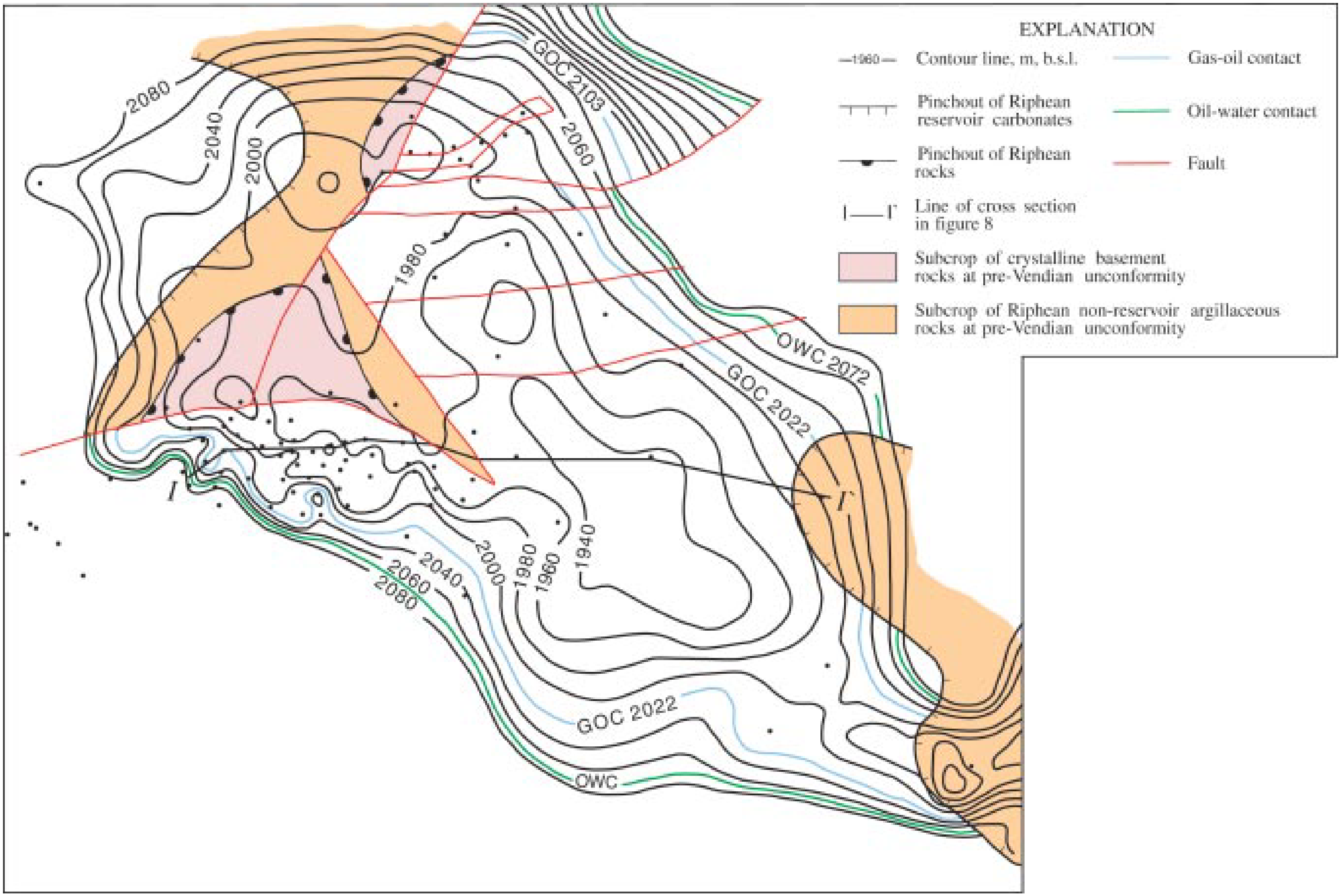


**Figure 7.** Contour map of Yurubchen-Tokhom zone. Modified from Kontorovich and others (1996). Location of zone shown in figure 5. Contours on erosional surface of Riphean rocks. Contour interval 20 m.

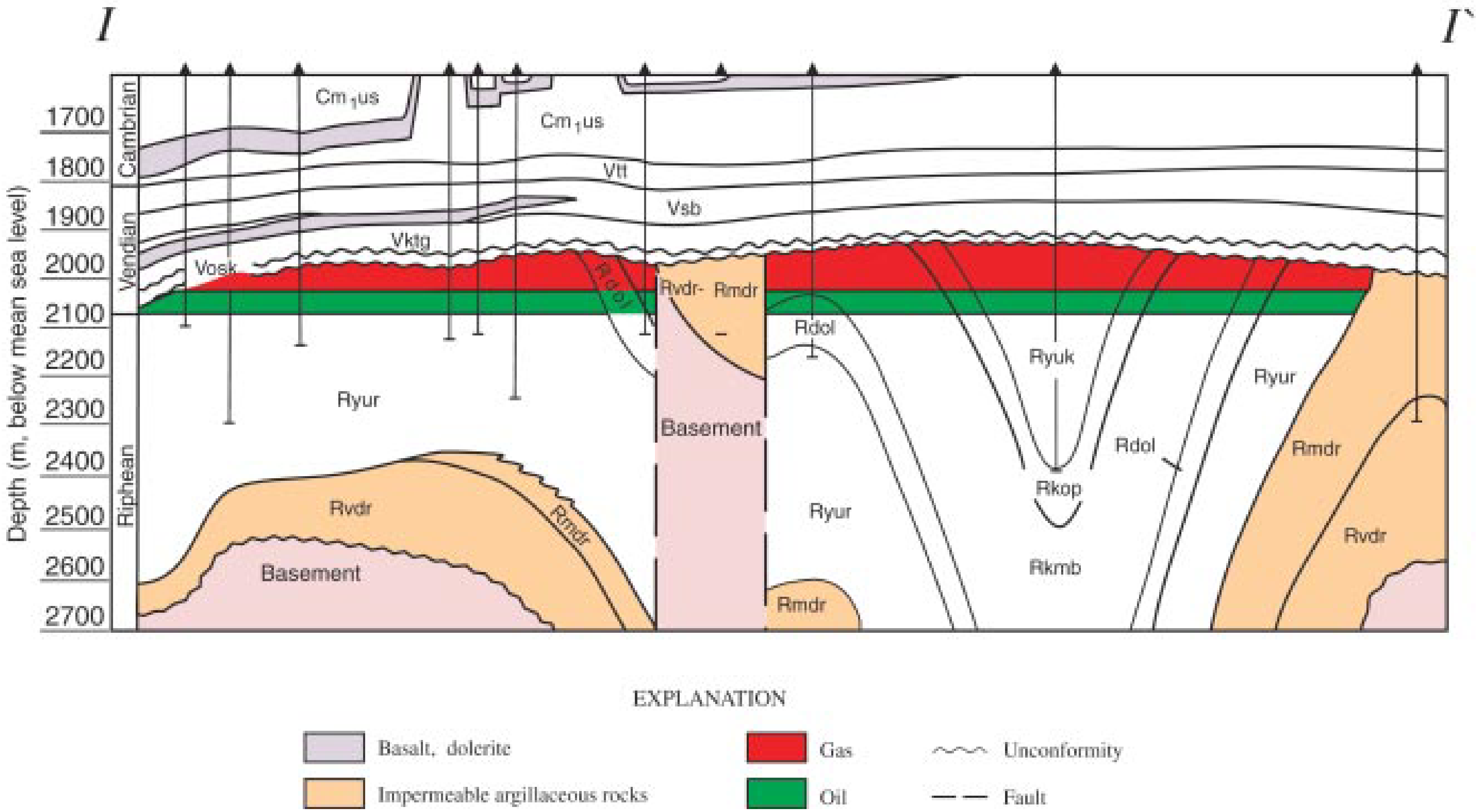


**Figure 8.** Cross section of Yurubchen-Tokhom zone. Modified from Kontorovich and others (1996). Location of cross section shown in figure 7. Symbols of formations are explained in figures 9 and 10. Scale not available. Length of section approximately 50–70 km.

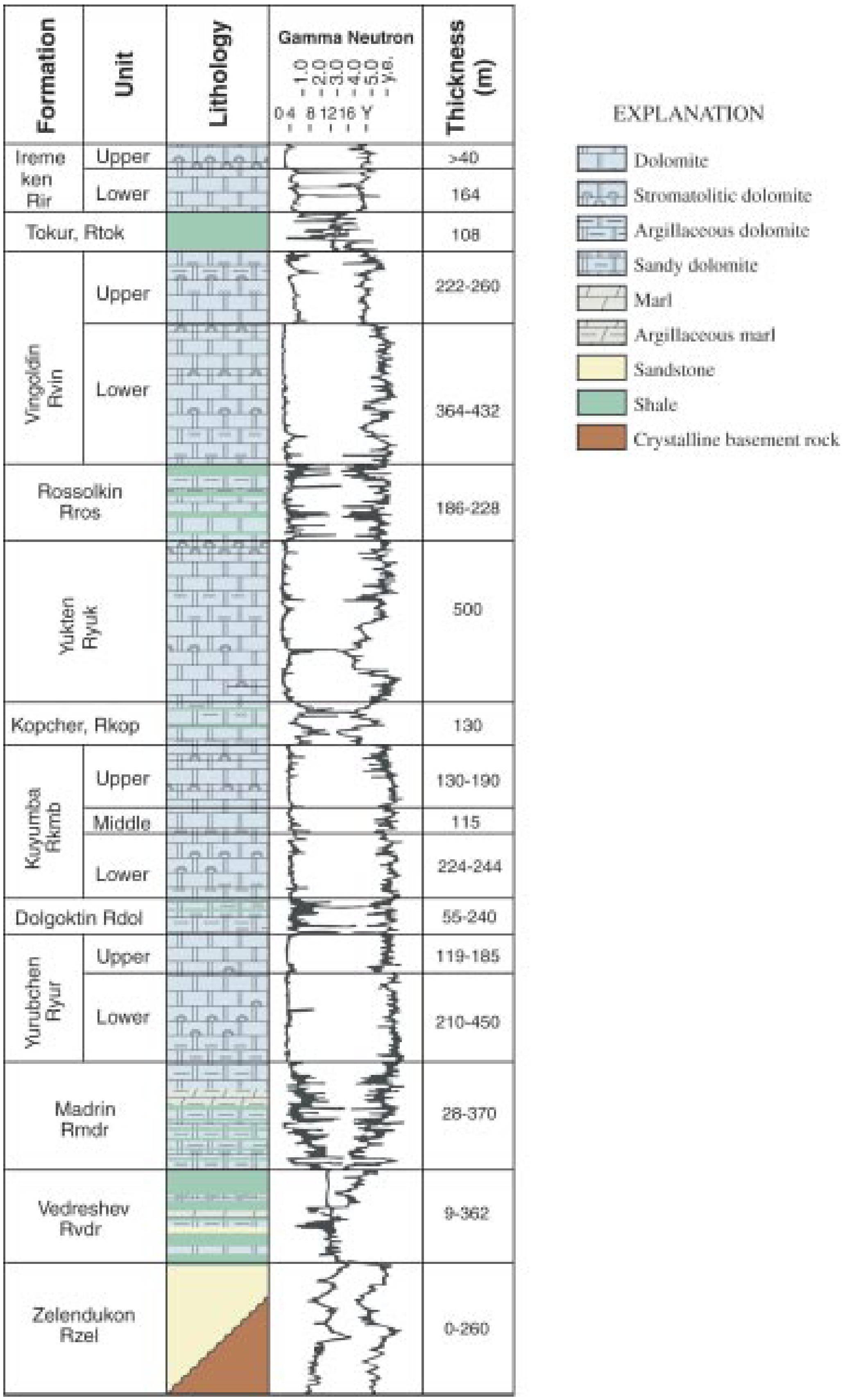


**Figure 9**. Composite columnar section of Riphean Kamov series of Yurubchen-Tokhom zone. Modified from Kontorovich and others (1996).

The content of total organic carbon (TOC) in those rocks reaches 8.7 percent, and rocks with more than 4 percent TOC constitute one-third of the formation thickness (Kontorovich and others, 1996). Several other intervals above the Shuntar Formation are also rich in organic matter. The organic-rich rocks were accumulated in relatively deep, anoxic waters of a back-arc basin that existed in the Yenisey Ridge area in late Riphean time. The rocks presently are strongly overmature and metamorphosed in the western part of the Yenisey Ridge foldbelt, and their hydrogen index (HI) values are low. Hydrocarbons were generated during Riphean time, but the accumulations were destroyed by Baikalian tectonism. Paleogeographic reconstructions and correlation of basinal, slope, and shelf-edge facies exposed in the Yenisey Ridge foldbelt (Khabarov, 1999) indicate that at least part of the black-shale facies was deposited across the upper zone of the continental slope and possibly the shelf edge. These facies probably extend into the present-day Cis-Yenisey foredeep (fig. 2) and could have generated oil and gas after deposition of the Lower Cambrian salt seal.

The other group of probable Riphean source rocks was identified recently in the Terin and Madrin-Tychan depressions on the southern and eastern slopes of the Baykit regional high (fig. 2). Only a small number of wells were drilled in these depressions, and information about the location and areal distribution of the source rocks is limited. The best quality source rock was encountered in a single well in the Iremeken Formation (fig. 9), which was preserved from pre-Vendian erosion only in structural depressions. The source rock is described as a dark-brown shale bed about 10 m thick (Filiptsov and others, 1999); it may be substantially thicker in undrilled areas. TOC of the shale exceeds 8 percent, and measured HI is 724 milligrams of hydrocarbons per gram of total organic carbon (mg HC/g TOC). Rock-Eval Tmax data show that the maturity of the source rock corresponds to the middle part of the oil window. The pyrolysis data also demonstrate that the abrupt increase of maturity (maturity leap) between the Iremeken Formation and the unconformably overlying basal Vendian rocks is absent. This suggests that the maximum maturity was reached in early Paleozoic time, after deposition of Lower Cambrian salt (Filiptsov and others, 1999).

The most extensive potential source rocks known on the Baykit regional high are shale intervals in the Vedreshev and Madrin Formations (fig. 9). The combined thickness of the intervals is 100–120 m. Black shales and marls containing 0.5–2 percent TOC occur in the upper part of the gas window (Kontorovich and others, 1996), as indicated by low HI readings (80–160 mg HC/g TOC). Tmax data in wells that penetrated the Vedreshev and Madrin Formations indicate the presence of a maturity leap across the pre-Vendian unconformity (Filiptsov and others, 1999). This indicates that the source rocks reached a maximum level of thermal maturity before Vendian time, and thus they did not generate significant amounts of hydrocarbons after formation of the salt seal. In deeper portions of the depressions, where a smaller part of the Riphean sequence was eroded in pre-Vendian time, the maximum maturity level was probably reached in early Paleozoic time, and the source rocks could have generated hydrocarbons (largely gas) after deposition of the regional Cambrian salt seal. The undrilled Riphean sequence of the Irkineev aulacogen (fig. 3), adjacent to the southern boundary of the TPS, also may contain significant source rocks.

Petroleum source rocks were recently discovered in several wells in the northern and central parts of the Katanga saddle, including a well in the Soba field (fig. 6) (Filiptsov and others, 1999). The rocks are black shales and marls of the Riphean Ayan Formation, which is an approximate stratigraphic equivalent of the Tokur Formation of the Baykit regional high (fig. 9). In the Soba field the source rock interval is 140 m thick, and the TOC reaches 3.2 percent (average 1.45 percent). The rocks are in the oil window, and HI ranges from 200 to 460 mg HC/g TOC.

## Reservoir Rocks

The principal known and potential reservoir rocks of the TPS are Riphean vuggy dolomites and dolomitic limestones that contain oil and gas reserves of the Yurubchen-Tokhom zone (fig. 8). The generally inferior quality of these reservoir rocks and their discontinuous lateral distribution substantially limit the estimated petroleum resources. Several gas accumulations have also been found in sandstone reservoirs in the lower part of the Vendian section.

Porosity and permeability of Riphean dolomite reservoirs, which were studied in the Yurubchen-Tokhom zone, were enhanced due to diagenetic leaching and fracturing. The intensity of diagenesis depended on sedimentologic and lithologic features of dolomites and their locations in the section relative to the pre-Vendian unconformity. Four main types of dolomite rock packages with different original reservoir properties have been distinguished in the zone (Varaksina and Khabarov, 2000): (1) carbonate grainstones, which originally had the highest porosity but limited stratigraphic distribution; (2) interbedded stromatolitic dolomites, grainstones, and packstones that are widely distributed; (3) grainstones and stromatolitic dolomites alternating with shale and mudstone beds that had poor original porosity and permeability; and (4) carbonate mudstones and clastic rocks whose original reservoir properties were of the poorest quality. The first two types of reservoir rocks listed above are abundant in the Yurubchen and Kuyumbin Formations and, to a lesser extent, in the Yukten Formation, but are much less common in other parts of the sequence (fig. 9). The sediments were deposited on shoals and in shallow depressions between marine bars. It should be emphasized that lateral facies variations are poorly understood and are difficult to distinguish from vertical stratigraphic changes, even within the Yurubchen-Tokhom zone, and several competing sedimentological models have been proposed (Varaksina and Khabarov, 2000; Kuznetsov, 1997; Slavkin and others, 1994, 1999; Larskaya and Goryunova, 1995).

The original porosity and permeability of dolomites controlled fluid flow, and thus significantly affected subsequent diagenetic changes including recrystallization, leaching, silicification, formation of stylolites, and fracturing (Varaksina and Khabarov, 2000). Recrystallization was extensive, especially in originally porous and permeable rocks, and it caused much deterioration of reservoir properties. Intercrystalline pores are small and infrequent, and their role in productivity is limited. Silicification preferentially affected grainstones and stromatolitic dolomites, and it enhanced fracturing of those rock types. Fractures also actively formed along stylolites. Fracturing played the most important role

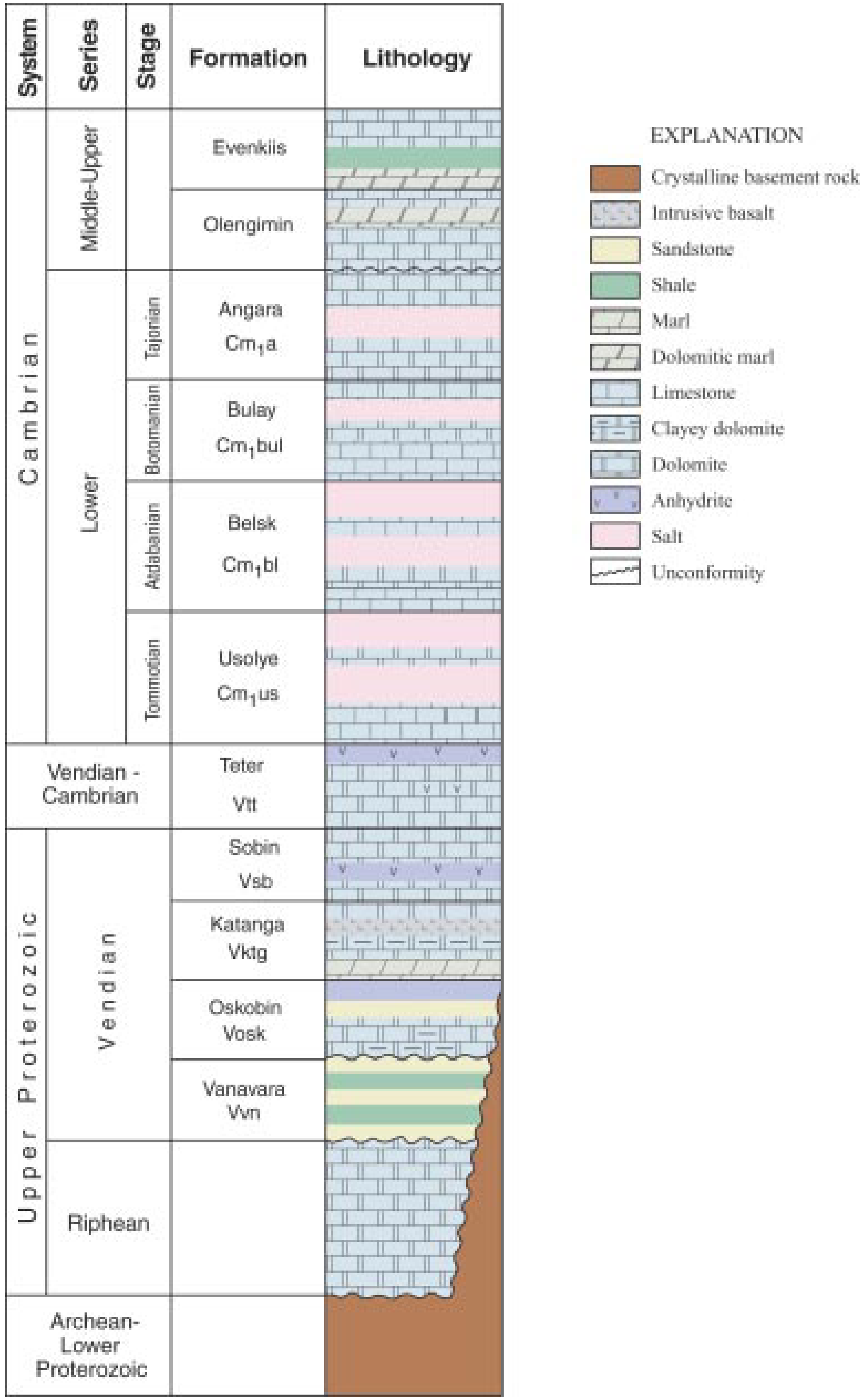


**Figure 10.** Columnar section of Vendian-Cambrian rocks of Baykit regional high. Modified from Kuznetsov (1997).

in formation of reservoirs. Several generations of fractures are present, but the earlier ones are filled with secondary minerals. Open fractures—vertical, oblique, and horizontal—are believed to be of late generation (Makarov and others, 1998).

Because matrix porosity and permeability of dolomites are very low, their role in hydrocarbon production is extremely limited (Makarov and others, 1998). Pore space was formed by leaching, which chiefly occurred during pre-Vendian subaerial uplift and erosion. Leaching created a system of vugs that selectively formed along fractures, and catastrophic mud losses during drilling indicate the presence of large caverns. Leaching preferentially also developed in grainstones and stromatolitic dolomites (Varaksina and Khabarov, 2000). The paleogeomorphology of the pre-Vendian erosion surface also could have played an important role in the filtration of meteoric waters and resulting leaching (Kuznetsov, 1997).

In conclusion, Riphean reservoir rocks are limited to areas, where carbonate formations occur in the leaching zone below the pre-Vendian unconformity. Even in those areas, reservoir quality of Riphean carbonates is highly variable laterally, and is commonly poor. The lateral variability is due to facies changes and different intensities of diagenetic processes in different facies. Presently, the geologic factors that control reservoir quality are poorly understood because of inadequate seismic data, sparse drilling, and difficulties in stratigraphic correlation. The rock matrix is largely nonproductive, and secondary porosity, consisting mainly of vugs and fractures, is unevenly distributed. Oil yields in tests vary widely, from more than 1,000 barrels per day to noncommercial shows. Better reservoir stimulation, especially hydrofracturing, as well as horizontal drilling, may play important roles in future field development.

Data on the quality of Vendian–lower Paleozoic reservoir rocks also are limited. The principal reservoir rocks are sandstone beds in the basal Vendian section. Individual sandstone beds of the Vanavara Formation are as much as 10 m thick on the Kamov arch (Kontorovich, 1994). The sandstones have a maximum porosity of 22 percent and permeabilities as high as 25 millidarcies (mD). Sandstone beds as thick as 11 m, with similar reservoir quality, also are present in the overlying Oskobin Formation (fig. 10) in the southwestern area of the arch. Lower Vendian sandstones are substantially thicker on the Katanga saddle. In the Soba field, for example, individual reservoir sandstones are as thick as 30 m, with maximum porosities of 18 percent and permeabilities of 10 to 50 mD (Maksimov, 1987). The total thickness of lower Vendian clastic rocks in the Angara zone of folds (fig. 5) reaches 350 m. The clastics are red, largely fine grained, poorly sorted, and strongly compacted sandstones that are not of reservoir quality (Kraevsky and others, 1996; Kontorovich, 1994). Reservoir properties of Vendian–Lower Cambrian dolomites of the Baykit High province are likewise generally poor. Some dolomites of reservoir quality are present in the Oskobin Formation and were identified in several wells in the lowermost Usolye Formation (fig. 10), where reef buildups are present among the dolomites (Kuznetsova, 1995).

## Traps

The types of potential traps in the Riphean structural complex are poorly understood. Both the Yurubchen-Tokhom and Kuyumba fields apparently are in a combination of stratigraphic and structural traps (fig. 7). The closer spaced drilling in the southwestern part of the Yurubchen-Tokhom field south of the basement subcrop (fig. 6) indicate that this part of the field is stratigraphically sealed updip. The trapping mechanisms in other areas of Riphean production are difficult to determine with certainty. More stratigraphic and structural studies of Riphean rocks are necessary to understand the distribution of trap types and their relative petroleum potential.

The large Soba gas field in Vendian clastic rocks is in a faulted anticline in the southern part of the Katanga saddle (fig. 6). No data on the geometry and origin of this high-amplitude fold are presently available; however, published reports indicate that structural traps on the Katanga saddle are rare (Lebedev, 1997). Local structural uplifts in Vendian rocks on the Baykit regional high are known, but sandstone beds on most of them pinch out on the crests of the uplifts (Lebedev, 1997). As indicated in a preceding section, a number of large, high-amplitude folds are present in the Angara fold zone in the south of the Baykit High province (fig. 5); however, these folds are devoid of reservoir rocks. The Omorin gas field in Vendian clastics west of the Yurubchen-Tokhom field (fig. 5) probably is a stratigraphic trap. Other stratigraphic traps are expected to be found on the south slope of the Baykit regional high, where sandstone beds in the lower Vendian section pinch out toward the top of the Kamov arch (Kontorovich, 1994; Lebedev, 1997). Additionally, reef buildups may form traps in the basal part of the Lower Cambrian Usolye Formation (Kuznetsova, 1995).

## Assessment Unit

The Yenisey Foldbelt Riphean-Craton Margin Riphean TPS is considered to be a single assessment unit because of the frontier character of the province and the scarcity of data on which a more detailed analysis can be based. The unit covers both the Baykit regional high and the Katanga saddle. Probably, no more than 150 exploratory wells have been drilled in the area of more than 220,000 $km^2$, fewer than one well per 1,000 $km^2$. The majority of these wells were drilled in the Yurubchen-Tokhom and Kuyumba fields (fig. 5) leaving the rest of the TPS area nearly unexplored. Inadequate seismic resolution thus far has prevented reliable structural mapping of Riphean rocks that have the greatest petroleum potential.

Results of the assessment of undiscovered oil and gas resources are shown in table 1. Full statistical data are provided in U.S. Geological Survey World Energy Assessment Team (2000). The relatively low assessed values reflect generally pessimistic expectations of discovery of giant or very large fields similar to the Yurubchen-Tokhom field. The pessimism arises from (1) the poor quality of reservoir rocks, (2) the absence of source rocks in most of the TPS area and related risk of hydrocarbon charge, and (3) the unique character of giant hydrocarbon accumulations in stratigraphic and combination traps of the Yurubchen-Tokhom type. Reserves in smaller, platform-type structural and stratigraphic traps are not expected to be large, because of low effective porosity and lateral discontinuity of reservoir rocks. The reserve growth in the Yurubchen-Tokhom zone may be very significant, and possibly it will exceed the undiscovered resources in the rest of the province. Future oil discoveries probably will be mostly in Riphean carbonate reservoirs, whereas gas potential is related primarily to Vendian sandstone reservoirs in structural and stratigraphic traps in the southern part of the Baykit regional high and in the Katanga saddle. However, the Baykit High province is a frontier region and new data may change these perceptions in the future.

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